Articole în Reviste indexate ISI

1. Maurizio Murroni, Matteo Anedda, Mauro Fadda, Pietro Ruiu, POPESCU VLAD, Zaharia Corneliu, Daniele Giusto, „6G-Enabling the New Smart City: A Survey", SENSORS, vol. 23, no. 17, 2023. https://doi.org/10.3390/s23177528
2. Jalal L., Puddu R., Martini M., POPESCU VLAD, Murroni M., „A QoE Model for Mulsemedia TV in a Smart Home Environment", IEEE TRANSACTIONS ON BROADCASTING, vol. 69, no. 1, pp. 179-190, 2023. https://doi.org/10.1109/TBC.2022.3217676
3. Alexandru Marian, POPESCU VLAD, Gavrilă Cristinel, „An SDR-Based Satellite Gateway for Internet of Remote Things (IoRT) Applications", IEEE ACCESS, vol. 8, pp. 115423-115436, 2020. https://doi.org/10.1109/ACCESS.2020.3004480
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1. N. Amarie, G. Fadda, A. A. Simiscuka, VLAD POPESCU and M. Murroni, "EmoLoop: A Bi-Directional System for Emotion-Driven Interaction Between Remote Audiences and Live Performers," 2025 IEEE 6TH INTERNATIONAL SYMPOSIUM ON THE INTERNET OF SOUNDS, L'Aquila, Italy, 2025, pp. 1-5, https://ieeexplore.ieee.org/abstract/document/11284604
2. Amarie Nicușor, Gianluca Fadda, Maurizio Murroni, Alexandru Marian, POPESCU VLAD, Daniele Giusto, Alin Ludu Dumbrava, „Immersive Application for Real-Time Interactive Music Performances Using Spatial Audio", 2025 IEEE INTERNATIONAL SYMPOSIUM ON BROADBAND MULTIMEDIA SYSTEMS AND BROADCASTING, BMSB, pp. 354-357, 2025. https://doi.org/10.1109/BMSB65076.2025.11165553
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Review

6G—Enabling the New Smart City: A Survey

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Abstract: Smart cities and 6G are technological areas that have the potential to transform the way we live and work in the years to come. Until this transformation comes into place, there is the need, underlined by research and market studies, for a critical reassessment of the entire wireless communication sector for smart cities, which should include the IoT infrastructure, economic factors that could improve their adoption rate, and strategies that enable smart city operations. Therefore, from a technical point of view, a series of stringent issues, such as interoperability, data privacy, security, the digital divide, and implementation issues have to be addressed. Notably, to concentrate the scrutiny on smart cities and the forthcoming influence of 6G, the groundwork laid by the current 5G, with its multifaceted role and inherent limitations within the domain of smart cities, is embraced as a foundational standpoint. This examination culminates in a panoramic exposition, extending beyond the mere delineation of the 6G standard toward the unveiling of the extensive gamut of potential applications that this emergent standard promises to introduce to the smart cities arena. This paper provides an update on the SC ecosystem around the novel paradigm of 6G, aggregating a series of enabling technologies accompanied by the descriptions of their roles and specific employment schemes.

Keywords: smart city; smart mobility; 5G; 6G

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1. Introduction

The sixth-generation (6G) wireless communication is the successor of fifth-generation (5G) communication. From a technological point of view, it makes use of higher frequency radio bands and provides a higher capacity combined with lower latency, enabling the integration into a single network with increased throughput and reliability. These characteristics make 6G networks ideal for the large-scale adoption of the Internet of Things (IoT) paradigm, especially considering that, in a short time, the devices connected to the IoT infrastructure are expected to reach billions of devices [1]. At the moment, little information is available on the new 6G wireless standard, but considering the rapid advancements in wireless systems, the arrival of 6G communication is inevitable [2]. The passage to the new 6G standard is expected to be a potential game-changer, as underlined in ref. [3], due to the wider frequency range and enhanced transmission rates, and unlike 5G, 6G does not require high-power consumption. In terms of security, data processing, threat detection, and data encryption are among the issues for which 6G networks will bring improvements by using decentralized security systems and handling the data traffic locally in a dynamic manner [4].

In ref. [5], emerging applications, together with key enabling technologies, are analyzed, outlining current research projects and discussing technical challenges on future research directions toward 6G. Ref. [6] provides a comprehensive portrayal of the 6G vision, technical requirements, and application scenarios also describing some existing testbeds and advanced 6G verification platforms. In ref. [7], one of the key innovations, which is the use of the terahertz (THz) band, is deeply analyzed in terms of channel propagation characteristics, modeling techniques, and measurement capabilities for 6G communication applications, presenting recommendations to allow for efficient use of it. Ref. [8] discusses the roles of 6G, considering five main IoT application domains: healthcare, unmanned aerial vehicles, vehicular and autonomous driving, satellite, and industrial IoT.

In this article, we further explore the main key technologies of 6G, identifying how they can be exploited by another paradigm, which has emerged in the realm of new technologies, i.e., the smart city (SC). An SC is a municipality where communication networks and traditional services are made more efficient through the use of digital and real-time solutions, with technical, economic, and social benefits to residents and businesses. SCs employ digital technologies for better use of resources by ensuring smarter urban transportation networks, better monitoring and water supply facilities, optimized waste disposal, and more efficient ways of lighting and heating buildings. On the other hand, the city government becomes more interactive and responsive, ensuring safer public spaces and meeting the needs of an aging population.

As research and market studies show [2], there is a need for a critical reassessment of the entire wireless communication sector for SCs in the light of energy-efficient communication. This should also include the IoT infrastructure, economic factors that could improve their adoption rate, and strategies that enable their operations of SCs. The development of the SC concept relies heavily on ubiquitous connectivity because the existing communication infrastructure cannot keep pace with the rapid growth and extended operation of SCs, this leading to the main reason for adopting a technology with an increased, energy-efficient transmission rate such as the ones provided by the 6G communication. In conclusion, it is safe to affirm that the development of the SC concept will happen in parallel to the development of 6G technologies [2].

The idea behind this article is to update an SC ecosystem around the novel paradigm of 6G, aggregating the enabling technologies accompanied by a description of their role and employment schemes. Upon a rigorous survey of existing literature, it is evident that while diverse surveys on the subject of 6G are extant, a dearth of sufficiently comprehensive endeavors exists, expounding on the holistic spectrum of 6G's application potential within SCs. This paper presents a comprehensive survey of 6G and the related technologies in the SC context along with the challenges posed by these emerging paradigms and technologies.

The paper is structured as follows. Section 2 delves into the pivotal enabling technologies that underpin the functioning of SCs. It investigates the critical components and infrastructural elements that drive the realization of SCs, establishing a foundational understanding for subsequent discussions. In Section 3, the paper conducts a concise yet informative analysis of the evolutionary trajectory from preceding mobile network generations to the nascent 6G era. This examination not only traces the historical development but also underscores the significant shifts that have transpired over time. Section 4 is dedicated to a thorough exploration of the resource management intricacies within the realm of SCs, particularly within the context of the 5G era. It navigates through the challenges and complexities that emerge while conceptualizing and implementing SCs against the backdrop of the 5G technological landscape. Section 5 constitutes a detailed narrative, tracing the very genesis and emergence of the groundbreaking 6G technology. This section embarks on a journey that unveils the compelling factors necessitating the development of this next-generation technology, offering an insightful perspective into its motivations. In Section 6, the paper succinctly encapsulates the vast potentialities that 6G technology brings to the realm of SCs. This segment delineates how the integration of 6G can catalyze innovative solutions and amplify the capabilities of SCs, fostering a holistic and transformative urban ecosystem. Section 7 elucidates a panoramic overview of SCs empowered by 6G technology, drawing insights from an array of pertinent literature sources.

This comprehensive exploration provides a snapshot of the envisaged enhancements and advancements within SCs, catalyzed by the integration of 6G capabilities. Section 8 presents some examples of SCs already implemented throughout the world. Finally, in Section 9, the paper distills the collective insights garnered from the preceding discourse. It encapsulates a list of currently existing challenges, implications inferred, and offers a set of comprehensive conclusions that underscore the pivotal takeaways from this comprehensive study. The abbreviations section at the end of the manuscript, lists all the acronyms in order of appearance with their descriptions, to facilitate reading.

2. Overview of Smart Cities

This section briefly describes the main characteristics of an SC, focusing on the enabling technologies (Section 2.1) and the management of involved resources (Section 2.2). Moreover, challenges and opportunities are shortly analyzed and discussed (Section 2.3).

2.1. Enabling Technologies

The ever-increasing computing power, together with the affirmation of 5G and the development of 6G, are key ingredients for the innovation of SCs, designed around people and sustainability. Blockchain, quantum computing, extended reality, and digital twins represent a non-exhaustive list of players that can inspire better cities. The key factors of SCs trace several closely interrelated areas.

- Artificial Intelligence (AI): AI has the potential to play a major role in the development of SCs by improving efficiency, sustainability, and the quality of life for citizens. AI-powered solutions can help SCs to reduce energy consumption, optimize traffic flow, and improve public safety. For example, AI algorithms can analyze traffic patterns to reduce congestion and air pollution, or to monitor energy usage in buildings to identify inefficiencies and reduce waste. SC initiatives can also benefit from AI-powered chatbots and virtual assistants, which can provide citizens with real-time information and support, such as directions or information on local services. Additionally, AI can be used to analyze data from various sources, such as social media, to understand citizens' needs and preferences, and to make data-driven decisions that benefit the entire community.
- Data: Data analytics, data management, data storage, and data infrastructure are all critical components of the development of SCs. With the rise of the IoT and the increasing use of technology in cities, the amount of data generated is massive and growing every day. These data provide valuable insights into the functioning of a city, including traffic flow, energy consumption, and public safety. Data analytics allow cities to make sense of these data and make data-driven decisions to improve the efficiency and sustainability of the city. Proper data management and storage are critical components of an SC system, as they ensure that the data generated are secure and easily accessible for analysis [9,10]. A strong data infrastructure is also necessary for SCs, as it provides the foundation for all data-related activities. This includes the network, hardware, and software required to store, process, and analyze large amounts of data [11,12]. With the right data infrastructure in place, cities can take full advantage of the benefits of big data and data analytics, leading to a smarter and more sustainable future.
- Connectivity: Connectivity, 5G, 6G, latency, Wi-Fi 6, and IoT play a crucial role in the development of SCs providing the foundation for a smarter and more connected future. High-speed, reliable connectivity is necessary for the seamless functioning of SC systems, such as traffic management, energy management, and public safety systems. The roll-out of 5G and the upcoming 6G networks will provide faster and more reliable connectivity, allowing for the efficient transmission of large amounts of data generated by IoT devices. Low latency is also important in SCs, as it enables real-time decision-making and responsive actions. Wi-Fi 6 provides faster and more reliable Wi-Fi connectivity, allowing for the seamless functioning of IoT devices. IoT plays a

key role in SCs by providing the data necessary for data-driven decision-making and by enabling the implementation of SC systems.

- Digital services: Simulated environments, digital twins, metaverse, virtual reality, robotics, and blockchain are all technologies that have the potential to revolutionize the development of SCs. Simulated environments provide a platform for cities to test and analyze new technologies and systems before they are implemented in the real world. Digital twins provide a virtual representation of a physical system, allowing for real-time monitoring and analysis. The metaverse is a virtual world that exists alongside the physical world, offering new opportunities for collaboration and innovation. Virtual reality and robotics offer new possibilities for training, simulation, and automation in SCs. Blockchain provides a secure and decentralized platform for the management and exchange of data, providing a foundation for the development of new and innovative SC systems. The development and implementation of these technologies in SCs is an exciting and rapidly evolving field, offering endless opportunities for innovation and progress.
- Cloud platforms: City platforms, cloud computing, cloud storage, edge computing, hybrid data storage, IaaS (infrastructure as a service), and PaaS (platform as a service) play critical roles in the development of SCs. City platforms provide a unified platform for the management of SC systems, such as traffic management, energy management, and public safety systems. Cloud computing and cloud storage provide scalable and flexible solutions for the storage and processing of large amounts of data generated by SC systems [13,14]. Edge computing enables the processing of data at the edge of the network, reducing latency and improving response times. Hybrid data storage combines the benefits of both cloud and edge computing, providing a flexible and scalable solution for data storage and processing. IaaS and PaaS provide the infrastructure and platform for the development and deployment of SC systems, respectively. These technologies provide a foundation for the development of new and innovative SCs, leading to a smarter and more efficient future.
- Internet of Things: IoT, machine-to-machine (M2M) communication, networked devices, and sensing are the actors in the development of SCs. IoT provides the backbone for the interconnectedness of SCs, such as traffic management, energy management, and public safety systems. M2M communication enables the seamless exchange of data between different devices and systems, providing a foundation for the efficient functioning of SCs. Networked devices, such as sensors and actuators, provide the data necessary for data-driven decision-making in SCs. Sensing, in particular, plays a crucial role in the collection and analysis of data, providing real-time information on a wide range of metrics, such as traffic flow, energy usage, and environmental conditions.

2.2. Resources Management

Achieving a certain number of elements that identify an SC necessarily involves the use and processing of a large amount of data. The coexistence of heterogeneous technologies, characterized by the presence of different radio access technologies (RATs), has consequently increased the demand for multimedia content and continuous amendments of network conditions. In this context, being able to select the best network solution has become crucial for guaranteeing a high quality of service (QoS). The operator's limited network resources, where several access technologies coexist (e.g., 4G long-term evolution LTE, LTE advanced, and IEEE 802.11), need to be managed and shared in the best possible way. Load balancing is a prominent solution, dynamically scheduling the spatial varied traffic between cells, with the objective of avoiding traffic blocking in highly congested areas, leveraging the utilization of unused resources in decongested areas. Recently, several works in the literature have proposed the exploitation of load balancing for heterogeneous networks. The load balancing for multimedia streaming over the heterogeneous network algorithm, named adaptive real-time multi-user access network selection (ARMANS), is proposed in ref. [15]. Information such as traffic topology, service requests, and real-time traffic types dynamically identify the best candidate network. Thanks to a new priority-based approach, ARMANS is also able to reallocate resources in order to offset satisfaction, taking into account the priority, level of requested services, and characteristics of devices and applications. The need to consider energy consumption led the authors to develop an energy-aware device-oriented video delivery algorithm (E-ARMANS) [16], which leverages both traffic load and energy conservation, striving primarily to maintain high-quality standards for video content delivery. Adaptive real-time approaches have received a great deal of attention since it is critical to provide optimized solutions for media users within a SC. It is important to develop algorithms that take into account several factors for decision criteria, such as the network and user profile, the applications required, and the profile of the device used. These parameters are the input to a multiplicative exponential weighting (MEW) [17] approach that manages the access network selection.

To provide a high-quality experience for users using heterogeneous services, a solution to the complex problem of selecting the appropriate network medium for each type of user service is needed. In ref. [18], the authors proposed a network traffic type-based differentiated reputation (TYDER), a system that is able to discriminate the data delivery process according to the type, taking into account reputation in the context of traffic type requirements to improve delivery performance. Four traffic categories (i.e., gaming, browsing, video, and IoT) were considered for comparative tests, demonstrating how TYDER outperforms the classic solution in terms of all main performance metrics.

In the multimedia-based IoT (M-IoT), smart heterogeneous multimedia objects are allowed to collaborate together and with other internet-connected objects to simplify multimedia services and applications that are globally available to users. Nowadays, solutions performing access network selection for heterogeneous devices do not consider reputations related to a network in a specific instant. In ref. [19], the M-IoT ReMIoT architecture based on network reputation is introduced to improve the quality of multimedia content distribution. The solution comprises three distinct operational phases. The first phase is multimedia service detection, the second phase is network reputation detection, and finally, the M-IoT network selection. With the advent of 5G, it is possible to develop machine learning (ML) techniques for determining subgroups in order to target certain types of resources and content toward a narrow category of users. Currently, the burden of determining subgroups falls solely on the gNB transmitter node. In ref. [20], the authors developed a technique to relieve the computational burden on the gNB in evaluating the location and mobility of users, with the ultimate goal of determining the optimal modulation and coding scheme (MCS). ML techniques can help gNB establish the network configuration, accelerating the MCS determination and resource allocation to subgroups within 5G technology.

In accordance with sub-grouping techniques, the evolution of user devices, along with the growing use of social media, require the coexistence of on-demand and go-live multimedia contents, and the development of a combined broadcast/unicast distribution model, with efficient wireless access management as a key issue. The dual objectives include optimizing the load balancing between coexisting networks and providing adequate QoS to users. In ref. [21], ALOWGATH (i.e., ALOW + GATH) is presented, a solution that provides the joint use of (i) an additive logarithmic weighting (ALOW) algorithm that is able to combine information, such as the network load, packet delay, received signal strength, user equipment, and user credit budget; (ii) a cooperative game theory (GATH) algorithm to optimize ALOW.

Among the various application scenarios within SCs, smart grids are receiving increasing attention to both the flow of electricity and the flow of information related to the management and control of the electricity supply system. The domain of the International Communication Union (ICT) should not be perceived merely as a simple extension or modernization of electricity system equipment, but represent a fundamental requirement to support the monitoring, operation, and control of the distribution network. Similar to the systems seen above, smart grid monitoring and control require the management of extensive real-time data flow between the controlled equipment and the distribution management system. A dense network of sensors of advanced sensors and measurement systems as well as a communication network infrastructure are essential. In ref. [22], two different strategies for power grid monitoring and control are compared: an LTE-based centralized management approach and a 5G-based distributed management approach. The two types of communication systems are compared by considering their performance during fault management in a smart grid scenario.

2.3. Challenges and Opportunities

The digital transformation sweeping across society and the economy is a continuously evolving process that has been gathering momentum in recent years. It is driven by the rapid advancement of various technologies, especially AI, and the increasing availability of digital information. The process involves the use of digital technologies to transform existing economic and social structures and to create new opportunities for growth and innovation. An important element of digital transformation is the use of AI to automate and improve processes and services. AI is used to improve the efficiency of public services and optimize the delivery of services. For example, AI-based chatbots are being used to provide customer service to citizens and simplify the process of accessing services. AI can also be used to analyze data to detect fraud and identify potential areas of risk. AI-based algorithms can be used to provide personalized services and products tailored to user needs. The use of AI is also gaining traction in the area of SC solutions. AI can be used to optimize traffic patterns, reduce emissions, and improve public safety. AI can also be used to analyze data from the city's various sensors to create insights and improve decision-making. In addition, AI-based systems can be used to monitor the environment and identify potential pollution sources. Despite all the benefits of SC-related projects, many challenges still pose serious problems when it comes to deployment, due to typical city requirements and differing interpretations of deployment concepts.

1. Public transport: The advantage gained by cities with extensive transportation systems is the result of numerous applications that simplify the experience of users using public transportation systems. Mobile applications enable real-time information management, providing users with solutions and viable alternatives in all those cases where delays may accumulate due to breakdowns, accidents, unforeseen events, or particular events within SCs. A very important role is attributed to IoT sensors installed on existing physical infrastructure, with minimal investment but huge benefits in the management of smart routine maintenance, scheduled in a timely manner and based on the continuous feedback received from IoT sensors. Intelligent transportation systems (ITSs) and the use of digital signage represent inputs for applications that simplify the user experience by providing real-time information about any delays or unforeseen events, enabling travelers to dynamically change their routes. Intensifying the use of IoT sensors by leveraging existing physical infrastructure provides a dual benefit, both for the end user and for the maintenance of monitoring and control facilities.
2. Traffic mitigation: Traffic mitigation and SCs are two closely related topics that are becoming increasingly important in urban planning. SCs are characterized by the use of technology to improve efficiency and reduce environmental impact, while traffic mitigation is the process of reducing traffic congestion and improving safety. Both are important elements of modern urban planning and can be used to create more livable cities. Applications that reduce road congestion are effective tools, especially in cities where public transportation and people driving their own vehicles are the main means of transportation. Car navigators provide a real-time overview of traffic conditions, alert drivers about the estimated time of arrival (ETA), and allow route rescheduling between the origin and destination. One of the most recent challenges involves smart parking apps that minimize search times and harmful emissions by directing drivers directly to available parking spaces.

3. Air quality: SCs use air quality sensors to detect dangerous levels of air pollutants, such as carbon dioxide, sulfur dioxide, ozone, and particulate matter. The sensors can detect small fluctuations in air quality and alert city officials to take action. SCs also use air quality modeling tools to predict potential air quality issues and develop plans to address them. Due to the growing problem of air pollution, several systems can now be used to monitor the air quality index (AQI) in urban areas. For example, in ref. [23], the authors developed smart bus stops, with smart bus shelters operated by a smart bus stop–social virtual object (SBS-SVO). The SVO features sensors to monitor air quality (temperature, humidity, barometer, and PM10) and a sniffer to assess crowding inside the bus. There is also an actuator that controls the screen that displays information to waiting passengers.
4. Solid waste reduction: Solid waste reduction, tracking, payments, and IoT technologies are important elements of modern waste management systems. These technologies can help reduce the amount of waste generated and track it in real time to ensure that it is disposed of properly. Payments are also a key factor in solid waste management, as they help waste reduction and tracking. Finally, IoT technologies can be used to monitor and manage the entire waste management system in real time. Waste tracking is also important for waste management, as it allows us to monitor how waste is disposed of and ensure that it is conducted properly. This can be achieved through GPS tracking or RFID tags, which allow us to monitor waste in real time. This helps reduce the risk of improper disposal and allows us to identify areas where more waste is generated.

SCs are characterized by smart heterogeneous devices cooperating with each other by exchanging regularly low amounts of data in the context of IoT. Lately, the scientific community has focused on the use of the IoT paradigm to allow the exchange of multimedia content. In ref. [24], a new algorithm is presented, enabling the best QoS and load balance in a 5G network context; named, mobility services user virtualization (MISSION) has been introduced, employing cloud computing and broadcasting to better manage the network load, the number of interactions, and energy consumption of user devices.

Another defining aspect of SCs involves true public green spaces, biodiversity, mountain preservation, and coastal erosion monitoring and control. In ref. [25], the authors presented a coastal crowding monitoring system based on the social IoT (SIoT); this is a promising solution that safeguards coasts from the erosion process (mainly due to natural factors, urbanization, and massive tourism) and manages (in a “smart and green” fashion) a large number of tourists. SIoT is a new paradigm that defines a social network between objects (i.e., devices) that are capable of autonomously establishing relationships with other things according to specific rules. In this context, all involved devices in the monitoring system (i.e., cameras, sensors, traffic lights, or smartphones) can collect and exchange information. The proposed system, carried out and installed in Cagliari (Italy), evaluates the occupational state of a beach, considering the crowding level, environmental data (collected by devices installed at specific points of the city), and real-time feedback sent by users, thanks to the use of a specific application.

Similar work involved pedestrian and vehicular mobility monitoring and control. Ever-increasing urbanization represents one of the key aspects in the field of mobility in the study of SCs. The phenomenon related to the flow of people moving within the city is gaining attention. Indeed, the phenomena of road congestion and overcrowded areas are on the rise. In ref. [26], the authors employ tools for the monitoring phase through Wi-Fi-sniffing systems and video cameras to classify vehicles, people, bicycles, and so on. Real-time monitoring allows citizens to know road conditions in advance with a high level of reliability, overcoming the limitations of a single technological system that provides inaccurate monitoring. The goal is to perform a real-time monitoring procedure to improve the lives of citizens by providing advanced knowledge of traffic conditions. The joint use of two technologies overcomes the limitations of using only one technology. Initially, each technology is performed individually, and the results obtained are combined using NNs with a high degree of accuracy.

The SC paradigm plays a primary role in the implementation of sustainable solutions in the field of urban mobility, both public and private. The SIoT paradigm adds a relational connotation between objects typical of human relationships. Objects operate as equals and request/provide information to each other with a view of providing IoT services to users while maintaining their individuality. The social relationship between objects enables the design of solutions to improve the exchange of information between network nodes in terms of security from malicious attacks external to the so-called social network of objects. In this context, a new SIoT solution for the SC is presented in ref. [27]; private and public vehicles, together with pedestrians, are involved in real-time data collection to improve the city's road system in order to suggest new directions and information to citizens to better organize how they experience the city. The developed architecture is equipped with AI, which processes the collected traffic data and, using ML techniques, evaluates the directions and flows taken by vehicles and pedestrians on a daily basis. The combined effect of the large-scale adoption of mobile communications, the recent advent of low-power wide area networks (LPWANs) promoted by the IoT, and the unprecedented diversification of next-generation networked applications offer new opportunities for further advances in wireless communications. The growing demand for reduced energy consumption has enabled the development of innovative solutions and low-power network communication technologies to be jointly deployed in a real-world scenario in an SC environment [28–30].

The use of energy-efficient technologies and communications, along with emerging areas, such as augmented reality (AR) and virtual reality (VR), monitoring attention [31], and improving safety [32], are just some of the challenges facing emerging technologies in delivering new services to citizens. In ref. [33], the authors propose a multi-hop communication solution (e2McH) that performs energy-efficient multi-hop communications over LPWAN, via narrowband technologies. The push for more energy-efficient networks, where receiver systems cannot be installed, has necessitated the development and testing of single- and multi-hop configurations, demonstrating potential energy savings of up to 15%. Multimedia applications in SCs provide users with innovative sensory experiences, for example, for the fruition of cultural heritage based on imaging [34]. They have recently been joined by multisensory experiences; that is, providing users with realistic multimedia content. In this way, the user's sense of immersive reality can be enhanced by adding multiple sensory effects to conventional media through the stimulation of five senses (i.e., taste, sight, touch, smell, and hearing). In refs. [35,36], for example, a study was conducted on smart homes; it can be replicated in other SC contexts. In addition to high-quality audio-video content, additional effects were provided by exploiting traditional devices (e.g., air conditioning, lights, etc.), equipped with appropriate smart features, as opposed to ad hoc devices often used in other applications, such as gaming systems [37]. The IoT paradigm has been widely adopted to connect smart devices through an IoT-based architecture for delivering multisensory media to users within a home entertainment scenario. Obviously, the synchronization between media and devices defined within the system architecture plays a very important role in terms of the quality of experience (QoE).

3. Evolution of Mobile Networks before 6G

Notably, 3G and 4G wireless technologies were mainly driven by the demand for data services over the internet. The development of 5G was driven by new emerging traffic types and data services, characterized by different requirements and issues to be solved, and an anticipated increase in capacity of up to 1000 times in the next decade on the network side [38]. Radio access, network slicing, and edge computing are three important concepts in the field of telecommunications and networking [39]. Radio access refers to the technology used by wireless devices to connect to a cellular network. This can include technologies such as 3G, 4G, and 5G, and determines the speed and reliability of wireless data transmission. Network slicing is the process of dividing a single physical network into multiple virtual networks, each with its own unique characteristics and requirements. This allows different applications and services to operate independently on the same physical infrastructure, which improves network efficiency and flexibility. Edge computing refers to the practice of processing and analyzing data closer to the source of that data, rather than sending the data to a centralized data center or cloud. This reduces latency and improves the speed of data processing, which is particularly important for applications that require real-time processing, such as autonomous vehicles or industrial automation. Together, these three concepts help drive innovation in the telecommunications industry, enabling the development of new applications and services that require high-speed, low-latency, and highly reliable network connections.

Network operators aim to satisfy the growing traffic demand by deploying cells of various sizes as elements of heterogeneous infrastructures, which need additional intelligence to be operative. The 5G networks are expected to support multiple radio access technologies with overlapping coverage deployed as part of a single multi-radio heterogeneous network, supporting end-to-end network architectures and protocols that seamlessly combine multiple radio access technologies together into a single virtual radio access network (RAN), in a transparent manner to end users [40]. Emerging technologies, such as software-defined networking (SDN) and network function virtualization (NFV) have been proposed for applying intelligence toward 5G communications [41]. SDN has arisen as a reaction to the limitations and intricacies inherent in conventional network architectures. The core concept of SDN involves consolidating authority over network devices within a logically centralized (software) controller, distinct from the data plane. This division between the control and data planes is achieved through an accessible programming interface connecting the data plane switches to the SDN controller. This dissociation empowers the control plane to evolve autonomously from the data plane, facilitating swifter innovation, as software frequently outpaces hardware in terms of innovative velocity. Additionally, the notion of logical centralization holds the potential to streamline network operation and administration, by offering a singular focal point for evaluating the ramifications of managerial actions, with the ability to potentially reject actions that might breach operational constraints. Presently, OpenFlow, the established SDN protocol, hinges on a straightforward match–action paradigm, endowing considerable flexibility, such as in traffic engineering, flow definition, and even in-band network control functionalities [42]. The incorporation of SDN into existing networks gives rise to operational and implementation challenges. Within this context, ref. [43] presents an innovative strategy—denoted as a smart approach—to enhance the performance of dependable and time-critical flows within hybrid SDN-based fog computing (FC) IoT systems (IHSF). The outcomes of the conducted tests demonstrate that the proposed IHSF solution outperforms the pre-existing approach in terms of network observability time, flow disruptions, end-to-end latency, and packet delivery ratio. To enhance communication infrastructures in SCs, the integration of two emerging technologies, FC and SDN, is gaining traction. This combined SDN-based FC architecture aims to meet IoT application needs, emphasizing easy management, scalability, reliability, and low latency. While earlier SDN-based FC traffic approaches considered quality of service (QoS) constraints when computing routes between IoT devices and fog servers, they overlooked link reliability [44].

Initially, several organizations (e.g., the European Telecommunications Standards Institute (ETSI) and the third-generation partnership project (3GPP)) started programs to individuate key technologies for 5G [45–47]. A collective thought was to consider higher spectral efficiency, lower latency, traffic asymmetry, hotspot traffic, and energy efficiency as main requirements [48]. The International Telecommunication Union (ITU) International Mobile Telecommunications (IMT) 2020 focus group, established in May 2015 [49], suggesting potential technological improvements, focusing on support for data rates of up to 20 gigabits per second, the ability to allow massive armies of devices to connect in a small area, and reduced energy consumption [50]. Considering the spectrum use, frequencies below 6 GHz were considered suitable for macro-coverage (i.e., a radius of up to 2 km). For frequencies of up to 30 GHz, about 2.5 GHz could be made available for micro-coverage. Frequencies from 30 to 90 GHz (i.e., visible light) were considered suitable for front-hauling, back-hauling, as well as local deployments (i.e., within a 10 m radius). In this range, about 40 GHz could be allocated for massive machine communications [51].

Flexible adaptation should be a main requirement to allow communication between vehicular devices moving fast and operating at high frequencies. Filter bank-based multi-carrier (FBMC) and universal-filtered multi-carrier (UFMC) were considered as enabling technologies to allow the coexistence of new services performing efficient utilization of narrow frequency bands. Moreover, non-orthogonal multiple access (NOMA) and sparse code multiple access (SCMA) were two other promising methods used to improve spectrum utilization, especially for dense networks and multicast services. Multiple-input multiple-output (MIMO) and beam-forming techniques were strengthened to increase coverage capacity and limit interference, exploiting the coexistence of transmitting and receiving antennas [51]. Another potential solution is the utilization of cell-free massive MIMO (CF mMIMO), which involves multiple wireless access points working together to process coherent signals and serve users collectively. However, achieving both massive connectivity and high SE simultaneously is problematic due to limited pilot resources. To address this issue, ref. [52] proposes a new framework for energy self-sustainability (ESS) Internet of Everything(IoE) networks that decouple user activity detection (UAD) and channel estimation. A further solution is proposed by ref. [53], i.e., a novel framework for ESS IoE networks that decouples UAD from channel estimation. In this approach, a UAD detector based on deep convolutional neural networks (CNNs) is introduced, along with an initial access scheme and a scalable power control policy, enabling the practical and scalable implementation of CF mMIMO.

The 5G network was considered to be heterogeneous, consisting of macrocells along with a large number of low-power nodes. In this context, an industry proposal was made to improve spectral efficiency, combining the LTE standard (i.e., 4G) with Wi-Fi technology, leading to the approval of 3GPP in new projects, to develop new releases (i.e., from release 8 to 14) and interworking between LTE-A and Wi-Fi. This new LTE in an unlicensed band (LTE-U) has the physical layer topology to access the Wi-Fi spectrum, specifically the 5 GHz band. The main side-effect involved the coexistence in a very congested band. In ref. [54], the authors proposed two coexistence models, implementing modifications at the RAN and backbone sites to enable advanced features typical of 5G networks. Device-to-device (D2D) communication, which allows devices to share their radio access connections, emerged as a potential solution to reduce the cost of local service provision and address the rising density of networks. This change was in line with evolving trends in the telecommunications market [55]. Indeed, the centralized architecture of mobile networks required some adjustments to support the growing traffic. For this reason, traffic generated in the RAN was conveyed by serving gateways to packet data network gateways, performing as a gateway between the operator's network and external IP networks. Considering the core, the idea was to route traffic without unnecessary core links, allowing direct communication between devices. Increasing flexibility and adaptation capacity were considered priorities, forecasting that 5G networks would cater to a growing number of heterogeneous devices with different requirements (i.e., IoT). Accordingly, 3GPP started developing solutions for the evolved packet system (EPS) in order to bypass the operator's backhaul and core infrastructure, to allow for a local connection to internet services, preventing locally generated traffic from being rerouted to the core network [56].

Full-duplex systems were indicated as a promising solution in order to provide significantly higher data rates than conventional half-duplex communication systems, reducing the latency by simultaneously receiving feedback signals from the receiver during transmission [48,57]. In parallel, due to increasing global carbon emissions and alarming pollution levels, especially in dense cities all over the world, energy saving was recognized as a primary issue worldwide. The GreenTouch consortium [58], founded in 2010 as an open global research consortium, presented its final results in its "Green Meter" research study [59]. Additionally, the Groupe Speciale Mobile Association (GSMA) set a target to reduce CO_2 emissions per connection by more than 40% by 2020. These fundamental facts have led to the notion of bits-per-joule energy efficiency, which is defined as the amount of information that can be reliably transmitted per joule of consumed energy; it became a key performance indicator for 5G networks [57,60]. In ref. [61], energy efficiency was treated as a performance parameter and design constraint for communication networks; the authors pointed out interesting research directions and highlighted that many technical, regulatory, policy, and business challenges remained to be addressed before the ambitious 1000-fold energy-efficiency improvement goal could be reached.

Considering the percentage of total information and communications technology (ICT) energy consumption (i.e., 25%) [62], 5G was also expected to introduce green communication technologies, taking into account the growing necessity for infrastructure and devices [63]. Several technologies were proposed to improve capacity, coverage, and energy efficiency, such as heterogeneous networks, software-defined cellular networks, and M2M communications [64]. In ref. [65], the authors proposed the utilization of a cognitive network to lease additional spectra outside the licensed cellular bands, being the cognitive radio resource characterized by its potentially broad bandwidth, low transmit power, and low reliability. They showed an energy efficiency-spectrum efficiency trade-off study to provide direct guidelines to the OPEX (operator experience) management of cognitive cellular networks, and proposed different architectures and usage scenarios of cognitive cellular networks. Table 1 summarizes the main features and benefits introduced by 5G.

Table 1. The 5G features and benefits.

5G Features	5G Benefits
Fastest response time	Wide bidirectional bandwidth
High capacity	Unification of radio communications
Connectivity of up to 25 Mbps	Easily integrated with previous generations
Bidirectional, wide bandwidth	Ability to provide uniform and uninterrupted connectivity
Supports private virtual networks	

4. The Role of 5G in Smart Cities

We should note that 5G technologies in SCs play very important roles in several aspects: basic internet, broadband technology, video streaming, high-speed internet, connection to the world, and vertical industries. In ref. [66], the authors discuss the impacts and implications of 5G on ITSs from various dimensions. They present an overview of the technological context and economic benefits of 5G and how the main vertical sectors will be affected in an SC, namely energy, healthcare, manufacturing, entertainment, automotive, and public transportation.

Radio access technologies are the backbone of modern wireless communication systems, enabling high-speed data transmission and reliable connectivity for mobile devices. With the advent of 5G technology and the next generation of cellular networks, radio access technologies are evolving to provide even faster speeds, lower latency, and increased network capacity. One of the key features of 5G is its use of higher-frequency bands, including millimeter wave (mmWave) spectrum, which can provide significantly faster data speeds than previous generations of cellular technology. However, these higher frequencies have shorter ranges and are more susceptible to interference, which requires the use of advanced technologies, like beamforming and massive MIMO to ensure reliable connectivity. Ultra-dense networks (UDNs) are key technological enablers of 5G; however, the densification of small cells from multiple RATs poses challenges to network performance [67]. Therefore, an efficient RAT selection mechanism is necessary to choose the best available technology. In ref. [68], the authors propose a new context-aware radio access technology (CRAT) selection mechanism that considers both user and network contexts to make an appropriate RAT selection. A mathematical model based on the analytical hierarchical process (AHP) and technique for order of preference by similarity to the ideal solution (TOPSIS) was developed, and the proposed CRAT mechanism was implemented and validated in a simulation environment. The CRAT mechanism outperforms the conventional approach in terms of the number of handovers, average network delay, throughput, and packet delivery ratio in SC environments, such as shopping malls and urban areas. The 5G waveform features more flexibility, multiple access support, the ability to co-exist with different waveforms, low latency, and compatibility with massive MIMO and mmWave communications. While orthogonal frequency-division multiplexing (OFDM) has been the dominant technology in many existing standards and is still a favorite for broadband communications in 5G RAN, in ref. [69], the authors explore the merits and shortcomings of OFDM for 5G RAN scenarios, including enhancing waveform characteristics, such as out-of-band leakage and peak-to-average power ratio, as well as methods to reduce the time and frequency redundancies of OFDM, such as cyclic prefixes and pilot signals.

The development of smart communities relies heavily on communication through the IoT. For the IoT to continue to grow rapidly, dependable wireless networks are essential. One solution to this challenge is the use of RAN [15] or cloud RAN (CRAN) [70] in the evolving 5G cellular system, which incorporates cloud computing technology in the radio access network. CRAN provides greater scalability, flexibility, and performance, enabling 5G to connect a vast number of IoT devices that are crucial for SCs. The focus of this research is on reducing latencies in IoT communication by addressing the load balance (LB) problem in CRAN. The study investigates eight practical LB algorithms in a CRAN environment, using actual cellular network traffic characteristics provided by Nokia Research. Results indicate that the simple, lightweight queue-based LB is almost as effective as the much more complex waiting-time-based LB. This research has significant implications for 5G networks and their ability to serve as the backbone of IoT communication in smart communities, as well as for other distributed systems.

Another important aspect of 5G RATs is the concept of network slicing, which allows service providers to create customized virtual networks for different types of applications and services [71]. For example, a network slice could be created specifically for autonomous vehicles, with low-latency connections and high reliability, while another slice could be optimized for streaming video, with high data speeds and large bandwidth allocations. Overall, 5G RATs are expected to enable a wide range of new applications and services, from AR and VR to the IoT and SCs. As the technology continues to evolve and expand, we can expect to see even more innovative uses of wireless communication in the years ahead. The idea behind network slicing is to divide a single physical network into multiple virtual networks, each with its own unique set of characteristics and capabilities. This allows for the more efficient use of network resources, as well as better control and management of network traffic. In the context of IoT, network slicing can be used to automatically allocate network resources based on the specific needs of each device or application. This is particularly important in SCs, where IoT devices are expected to play a significant role in areas such as traffic management, public safety, and environmental monitoring. An automatic network slicing system would be able to dynamically allocate network resources to IoT devices based on their individual requirements, without requiring manual intervention from network administrators [72]. This would enable more efficient use of network resources, as well as better support for a wider range of IoT devices and applications. In ref. [73], the authors suggest the optimization of SCs components for 5G network slicing, also involving the development of a network architecture that can dynamically allocate network resources based on the specific needs of different SC applications and services. This means taking into account the different requirements of each application or service, such as latency, bandwidth, and reliability, and ensuring that the network can allocate resources accordingly. One example of this is the deployment of smart traffic management systems that are optimized for 5G network slicing. These systems would be able to dynamically allocate network resources based on traffic conditions, ensuring that critical information is delivered quickly and efficiently.

Edge computing involves processing data and performing other computational tasks closer to the source of the data, rather than sending them all to a central data center or cloud. This can be achieved using edge devices, which are located closer to the edge of the network and can process data in real time. When combined, edge computing and 5G can provide a powerful platform for creating new applications and services that were previously impossible. For example, real-time video analytics can be performed at the edge of the network using edge devices, with the processed data transmitted over 5G networks. This can enable a wide range of applications, such as remote health monitoring and surveillance. Another example is the use of 5G and edge computing for autonomous vehicles. By processing sensor data and other information at the edge of the network, autonomous vehicles can make real-time decisions, increasing safety and efficiency.

The presence of a cloud in the IoT system of an SC can result in high energy consumption and network delays. To address this, edge computing, which is based on a cloud computing framework, has emerged as a solution that moves computation, storage, and network resources closer to the data source. However, the efficient use of energy while maintaining delay limitations is a critical issue in edge computing when executing tasks generated by IoT systems. In ref. [74], a multi-criteria optimization approach is studied for resource allocation with distributed edge computing in IoT-based SCs. A three-layer network architecture for IoT-based SCs is proposed, and an auctionable approach-based edge resource allocation scheme is presented to ensure efficient resource computation for delay-sensitive tasks. Edge computing offers several benefits [75] in SCs and the IoT, including:

- Reduced latency: Edge computing moves computation and data storage closer to the edge of the network, which reduces latency and provides real-time processing of data. This is particularly important for applications that require real-time processing, such as traffic management, video surveillance, and emergency response systems.
- Improved security: Edge computing can enhance security by enabling data to be processed and stored locally, rather than being transmitted to a central data center or cloud. This reduces the risk of data breaches and other security threats.
- Increased scalability: Edge computing allows for greater scalability by distributing computing and storage resources across multiple edge devices. This enables more efficient use of resources and improves the overall performance of IoT systems and SC services.
- Lower costs: Edge computing can reduce costs by minimizing data transmission and storage requirements. This can be particularly beneficial for organizations operating in remote or underdeveloped areas where internet connectivity may be limited or expensive.
- Enhanced reliability: Edge computing can improve the reliability of IoT systems and SC services by enabling them to function even in the event of network failures or disruptions. This can be critical for applications such as public safety and emergency response.

The virtualization technology proposed in ref. [76] requires security and technology extensions to support a unified view of sliceable and heterogeneous devices and radio technologies such as LTE, 5G, and Wi-Fi. The security of the system is improved by deploying robust compute node authentication, monitoring, and geo-tagging, while wireless connectivity is extended through an innovative multiple RAN controller approach for the management and control of heterogeneous radio resources.

5. 6G—The Emerging New Standard

The 5G of cellular networks has revolutionized the way people communicate and connect together. With its ultra-fast speeds, low latency, and massive connectivity capabilities, 5G has opened up new opportunities for businesses, industries, and consumers alike.

However, as technology continues to evolve, researchers and industry experts are already looking ahead to the next generation of cellular networks, which is 6G.

Several reasons can justify the development of a new wireless technology generation. Firstly, when the run to 5G finishes, all the industries interested in telecommunication business will need a new innovative product to push; they will focus on new methods to offer new services or improve the old ones. At the IEEE Future Directions Committee Meeting [77], within the Industry Advisory Board (IAB), the evolution of wireless systems was discussed, with a focus on 5G; a draft of the 6th generation as a significant evolution of 5G was traced due to its ability to self-aggregate networks of different types, satisfying the requests of resources that will present themselves in a dynamic way.

The mobile network trend (5G) has shifted in its primary goal compared to previous networks; the main goal has shifted from enabling users to connect wirelessly to the internet to enabling huge numbers of users and devices to connect seamlessly to SCs (IoT) by 2020 and beyond [78]. At the World Radiocommunication Conference (WRC) 2015, the main goal was to add an additional spectrum for mobile communications below 6 GHz. However, the massive mobile traffic growth of global mobile traffic cannot be met by adding an additional spectrum band below 6 GHz, as promoted at the 2015 WRC. Therefore, it was decided at the 2019 WRC that additional frequency bands above 6 GHz will be needed to achieve multi-Gbps data rates. Although 6G is still in the early stages of development, it is expected to offer even faster speeds, lower latency, and more advanced capabilities than 5G. Some of the key areas of focus for 6G research include:

- THz frequencies: 6G is expected to utilize higher frequency bands than 5G, including terahertz frequencies, which have the potential to offer even faster data rates and lower latency.
- AI: 6G is expected to integrate AI more deeply into its design, enabling more intelligent network management and a range of new applications and services.
- Quantum computing: 6G is expected to leverage the power of quantum computing to enable new capabilities, such as secure communications and advanced sensing.
- AR and VR: 6G is expected to enable more seamless and immersive AR and VR experiences, enabling new applications in areas such as gaming, education, and healthcare.

While 6G is still several years away from becoming a reality, the groundwork is already being laid for this next generation of cellular networks. As researchers and industry experts continue to push the boundaries of what is possible, we can expect 6G to offer even more exciting opportunities for innovation and growth in the years to come.

The 5G network aims to have a common platform for all radio access technologies (gsm, LTE, Wi-Fi, etc.). In Table 2, a comparison is made between 5G and 6G technologies, considering the main technological and application differences.

Table 2. Comparison between 5G and 6G technologies.

5G	6G
Sub-6GHz band crowded	Ultra-fast connection (THz)
Limited capacity for new type of communications	Fully immersive extended reality (XR) experience and high definition holographic communication
Cellular communications	Cell-free massive MIMO
Infrastructure	Ubiquitous connectivity
Security problems	Quantum communication and Blockchain
Low latency	High reliability and ultra-low latency
Existing algorithms for modeling channel information	Deep learning as solution for improvement

We should note that 6G proposes to integrate 5G with satellite networks (i.e., telecommunications and GPS navigation) in order to reach connection speeds up to 11 Gbps. Nano-antennas will be used for the development of the Internet of Things. Global coverage and high-speed internet connectivity are the main objectives of 6G technology. Moreover, 6G networks will embed planning into the network itself, meaning that the network will become aware of the way it is being used, what is actually required by its users at this specific moment, and what is likely to be required at a later time; it will be able to plan for its evolution by reconfiguring its resources and asking vested parties to provide additional resources, leading to convincing reasons and convincing business plans. Driving trends of emerging 6G are summarized in ref. [79]:

- The convergence of communications, computing, control, localization, and sensing (3CLS): Computing, control, localization, and sensing in addition to current wireless communication.
- Smart reflective surfaces and environments: Driven by smart reflective surfaces that serve as walls, roads, doors, and entire buildings, helping to maintain a line of sight and obtain a quality signal with minimal loss.
- Massive availability of small data: Shifting from centralized big data to massive distributed small data.
- More resource availability (i.e., bits, spectra, and reliability): Higher frequency spectrum (THz), reaching 1 Tb/s.
- Self-sustaining networks: AI to facilitate intelligent wireless networks that are self-sustaining.
- Ubiquitous connectivity that encompasses air, ground, and sea: Integrating the space–air–ground–sea mode to facilitate wireless communications in flying vehicles, XR, brain–computer interface (BCI), and more.

6. 6G for New Smart Cities

As the demand for advanced technological solutions in SCs continues to grow, there are many discussions around the potential for 6G networks to provide the infrastructure needed for these cities of the future. While 5G networks have made significant strides in improving connectivity and supporting the IoT, 6G networks are expected to provide even faster speeds, lower latency, and greater capacity, making them ideal for supporting the complex systems and devices in SCs.

With the help of 6G networks, new SCs could leverage a range of advanced technologies, including autonomous vehicles, smart grids, and remote healthcare. Additionally, 6G networks could support innovative applications, like augmented reality, virtual reality, and immersive gaming experiences, creating new opportunities for businesses and residents in these cities.

However, the development of 6G networks is still in its early stages, and it may take several years before they become widely available. In the meantime, researchers and industry experts continue to explore the potential benefits and use cases for 6G networks in new SC developments. Representative use cases in the context of SCs have been individuated and are presented as follows [80]:

- Intelligent transport and logistics: It is expected that in 2030 and beyond, autonomous vehicles and drones will facilitate the safe, efficient, and eco-friendly movement of people.
- Connected robotics and autonomous systems: Self-driving vehicles, which perceive their surroundings by combining a variety of sensors (e.g., light detection and ranging (LiDAR), radar, GPS, and sonar).
- Global ubiquitous connectivity: Maritime and river applications require network coverage for both the water's surface and the depths below to monitor and manage ecosystems, especially in cities with rivers or ports where resources might be difficult to access.

- Pervasive intelligence: The growing presence of connected equipment, such as robots, smart cars, or drones, will bring out new applications that will require new methods or the updating of computationally intensive AI technologies (e.g., computer vision, simultaneous localization and mapping (SLAM), face and speech recognition, natural language processing, and motion control).

Enabling technologies that are useful for developing these new applications are summarized in Table 3 and illustrated in Figure 1.

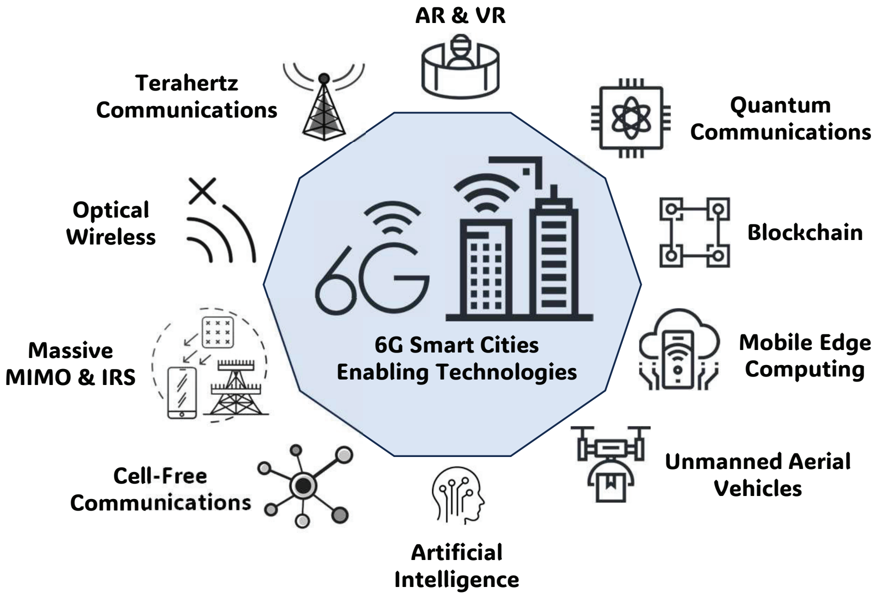

Figure 1. 6G, smart cities, and enabling technologies.

In more detail [81]:

- Terahertz communications: According to the recommendations [82], the 275 GHz–3 THz band range will be assigned to cellular communications and added to the mmWave band (30–300 GHz), potentially increasing more than 11 times the total band capacity. The critical issue of THz interfaces will probably lead to the use of highly-directional antennas.
- AI: AI can reduce the processing delay for communications and improve time-consuming algorithms (e.g., for handover or network selections) [83].
- ML: These techniques can provide solutions for resource management and mobility management challenges in 6G wireless networks, as with other technical challenges, such as resource allocation, task offloading, and handover management [84].
- Massive MIMO and intelligent reflecting surfaces (IRSs): An IRS [85] is a recent hardware technology (also known as a meta-surface) that provides energy-efficient green communication; it consists of many reflecting diode units, reflecting incident electromagnetic signals with an adjustable phase shift.
- Blockchain: It combines a distributed network structure with a consensus mechanism and advanced cryptography, thereby increasing security by eliminating single-point failures. The main weaknesses in 5G are throughput (i.e., 10∼1000 transactions per second) and the interoperability levels between different platforms. New consensus algorithms together with innovative architectures and sharing techniques will reduce these limitations in 6G networks.
- Quantum communication: The emerging paradigm of quantum computing [86] is considered one of the main enablers of 6G, improving its security by using a quantum key based on the quantum no-cloning theorem and uncertainty principle. Data are encoded in the quantum state using photons or quantum particles and cannot be accessed or cloned without tampering with them due to the quantum principles.

Moreover, quantum communication improves throughput thanks to the superposition inherent in qubits.

- Cell-free communication: Conventional cellular and orthogonal communications will be shifted toward cell-free and non-orthogonal communications. Users will be able to move from one network to another network, choosing and selecting the best one automatically (i.e., between the available communication technologies), solving issues related to handover failures and delays, data losses, and the ping-pong effect prevalent in cellular networks.
- Unmanned aerial vehicles: UAVs carry onboard base stations (BSs) to offer cellular connectivity; they have specific features, such as easy deployment, strong line-of-sight links, and degrees of freedom with controlled mobility. UAVs are valuable during emergencies (e.g., natural disasters).
- Mobile edge computing (MEC): Due to the distributed massive cloud applications, mobility-enhanced edge computing (MEEC) has become a crucial part of 6G technology [87]; it addresses challenges in cloud-based scenarios, where the long-distance transmission of data from end devices and edge servers to the cloud incur great latency and security risks and consume a great amount of bandwidth.
- Optical wireless: This technology will be extensively used in several applications, such as vehicle-to-everything (V2X) communication and underwater optical wireless communications, providing very high data rates and low latency. LiDAR [88] is a promising technology for very high-resolution 3D mapping in 6G communications. Also, microLED technologies and spatial multiplexing techniques will be mature and cost-effective in 2026 [81].
- Free-space optical (FSO) communications: Allow for ultra-fast data links that can be applied in a variety of 6G applications, such as heterogeneous networks with enormous connectivity and wireless backhaul for cellular systems [89].
- AR and VR: 6G is expected to enable more seamless and immersive AR and VR experiences, enabling new applications in areas such as vehicular communications and SC security.
- Energy harvesting: The massive growth of devices and data traffic is leading to great energy demands for 6G; energy harvesting is a promising technology used to mitigate the dilemma between the high energy demands and limited battery capacities [90,91].
- Low-orbit satellite: With the rapid development of satellite communication technologies, the requirements for 6G can be satisfied by incorporating space-based and ground-based cellular networks [92]. Low-orbit satellite constellations play a crucial role for space-ground interconnections, ensuring full-coverage broadband services for ground users.

7. 6G-Enabled Smart Cities

One of the key concepts of 6G-enabled SCs regards the integration of advanced communication technology, specifically 6G networks, into the development and management of SCs. An SC utilizes various digital technologies and data-driven solutions to enhance the quality of life for its residents, improve infrastructure efficiency, and promote sustainable development. Moreover, 6G networks can facilitate the development of intelligent infrastructure, such as connected sensors and devices, enabling better monitoring and management of urban resources. This includes smart waste management, optimization of water and energy usage, and intelligent urban planning based on data analytics. Furthermore, 6G-enabled SCs are expected to promote inclusivity and improve the quality of life of citizens by enabling better access to services, such as e-healthcare, online education, and digital governance platforms.

In this section, 6G-enabled SC solutions proposed in the literature are briefly described and grouped into subsections, considering fundamental enabling technologies summarized in Table 3 and use cases. Table 4, at the end of the section, summarizes the correspondence between enabling technologies for SCs in 6G and the works in the literature that describe their use.

Table 3. The 6G enabling technologies for SCs.

Technology	Short Description
Terahertz Communications (THz)	THz waves refer to frequencies 0.1–10 THz with the corresponding wavelengths in the 0.03–3 mm range
Artificial Intelligence (AI)	AI for automatization enabling the transformation from cognitive radio to intelligent radio also improving the transport of real-time data
Massive MIMO (M-MIMO)	5G massive MIMO technology will converge toward IRS in 6G wireless systems that is massive MIMO 2.0
Blockchain (BC)	Perfect technology to manage massive data in future communication systems with improved privacy and security, scalability, interoperability, and reliability
Quantum communication (QC)	Emerging paradigm of quantum computing able to improve its security by using a quantum key based on the quantum no-cloning theorem and uncertainty principle
Cell-free communications(CFC)	Users will be able to move from a network to another choosing and selecting the best one automatically solving issues related to handover failures delays and similar side effects
UAVs	BSs on board to provide cellular connectivity, with specific features as easy deployment of strong line-of-sight links, and degrees of freedom with controlled mobility
Mobile edge computing (MEC)	Able to solve challenges where the long-distance transmission of data from end devices or edge servers to the cloud incurs great latency and security risks
Optical wireless (OW)	These communication technologies will provide very high data rates and low latencies
Augmented/virtual reality (AR/VR)	These technologies will enable new immersive applications and services

7.1. Terahertz Communications

In ref. [93], the authors assert that 6G needs AI-enabled optimization. Traditional approaches are characterized by prior knowledge and statistical analysis but are ineffective due to the elapsed time from the analysis to the decision-making [94]. AI-enabled 6G network protocols and mechanisms, with their employed self-learning ML and deep learning (DL), algorithms are proposed in order to solve several issues in networking.

The concept of futuristic SCs and the role of 6G network technology in their development are discussed in ref. [95], highlighting the need for dense and AI-centric cities, as well as the requirement for massive device connectivity and data traffic. A 6G network is seen as the solution for these futuristic cities, offering high bandwidth and low latency using terahertz waves. However, the short-range and atmospheric attenuation of terahertz waves present challenges to the 6G network. The study proposed a conceptual terrestrial network architecture called the nested Bee Hive, designed to address the needs of futuristic SCs. Simulations using different pathfinding algorithms have evaluated the performance of this architecture and established the dynamics of communication in a 6G environment.

Table 4. The 6G enabling technologies for SCs in the literature.

	THz	AI	M-MIMO	BC	QC	UAVs	MEC	OW	VR/AR
[93]	x	x	x	x	x		x		
[95]	x	x	x						
[96]	x		x						
[97]	x								
[98]	x								
[99–103]		x							
[104]		x							
[105]		x							
[106]		x	x						
[107]			x						
[108]				x		x			
[109]		x		x					
[110]		x		x					
[111]		x		x					
[112]		x		x					
[113]		x		x					
[114]					x				
[115]					x				
[116]		x			x				
[117]	x	x			x			x	
[118]						x			
[119]						x			
[120]		x				x			
[121]						x			
[122]						x			
[123]							x		
[124]							x		
[125]							x		
[126]							x		
[127]							x		
[128]							x		
[129]							x		
[130]							x		
[131]									x
[132]									x

Ref. [96] suggests overcoming the limitations of current THz antennas and IRS by only considering single-carrier modulation with a small array scale through the use of ultra-massive MIMO. The THz links are subject to high-loss connectivity. In ref. [97], the authors propose a cost-effective method to dynamically optimize the transmission path using reconfigurable intelligent surfaces (RISs), constructed by embedding active elements into passive metasurfaces, proposing metasurfaces with tunable functions, such as pixel-level amplitude modulation and wide-range phase coverage for beam steering. The utilization of ITSs and autonomous driving in the 6G era heavily relies on the exchange of massive amounts of information with ultra-wide bandwidth, high reliability, and low latency to ensure safety and provide a seamless experience. However, signals in high-frequency bands, such as millimeter wave (mmWave) and THz, can encounter obstacles that hinder their propagation. To tackle this issue, IRSs have garnered significant attention due to their ability to intelligently reflect signals and alter their propagation directions, thereby creating smart radio environments. IRSs offer advantages, such as easy deployment and cost-effectiveness, making them promising technologies for ground and aerial vehicular networks. They can amplify signal strength, bolster physical layer security, and enhance positioning accuracy [98].

7.2. Artificial Intelligence

Adaptive radio communications are technologies that have been around under various forms, such as the cognitive radio concept, for the past 20 years. The next step, the transformation to intelligent radio, can be supported in the 6G context by using advanced AI algorithms, in order to dynamically adapt radio communications to a specific radio environment.

As the data traffic grows in SCs, different modulation methods are being employed in communication systems for efficient and effective data transmission. Modulation recognition is crucial in signal demodulation and decoding, especially in applications such as interference identification, signal recognition, spectrum monitoring, and threat assessment. For instance, methods such as convolutional neural networks (CNNs) and recurrent neural networks (RNNs) for modulation recognition over additive white Gaussian noise and Rayleigh fading channels were presented in ref. [99]. A CNN-based federated learning approach was proposed in ref. [100], enabling differential privacy for modulation recognition in order to assure the privacy and security of transmitted data.

Apart from the previously presented modulation classification techniques, traffic classification into different classes is another technique to ensure the QoS, enable pricing control, improve resource management, and improve the security of SC applications. In ref. [101], the authors proposed a Tree-RNN to classify network traffic into 12 different classes, thanks to a tree structure that divides the large classification problem into smaller ones, with each class represented by a tree node. Ref. [102] describes a hybrid RNN and CNN-based network to classify traffic from IoT devices and services. CNN layers extract complex network traffic features automatically from the input data, eliminating the feature selection process used in classical ML.

Channel estimation is the process of estimating the characteristics of the communication channel to recover the transmitted information from the channel effect. In ref. [93], a DL-based channel estimation process is presented, where the signal, along with pilot signals, is transmitted. The effects of the channel on the pilot signals are determined, and DL then estimates the channel attributes using the interpolated channel. In ref. [103], a deep neural network (DNN)-based approach for channel estimation and symbol detection in an OFDM system is proposed. With offline training using OFDM samples generated from different information sequences under distinct channel conditions, the obtained model is used to recover the transmitted information without estimating the channel characteristics.

The automotive sector represents another highly significant scenario that has the potential for extensive development with the advent of 6G technology. The expansions of IoT, edge computing, and mobile AI have enabled urban authorities to leverage the wealth of data gathered from connected and autonomous vehicles (CAVs). In ref. [104], the authors propose an intelligent hierarchical framework for road infrastructure maintenance that harnesses the advancements in 6G communication technologies, deep learning techniques, and mobile edge AI training methods. The developed framework meets the stringent requirements for training efficient ML applications designed for CAVs and effectively utilizes the expected proliferation of CAVs on future road networks.

Moreover, 6G—considered the next major transformative technology in the telecommunications industry—is attracting significant attention from academia and businesses. The global COVID-19 pandemic has accelerated the adoption of virtual meetings and live video interactions across various sectors, including healthcare, business, and education.

Federated learning (FL) holds promise as a training approach for achieving pervasive intelligence in future 6G communication systems. However, implementing FL in 6G-enabled edge systems is challenging due to the high energy consumption during decentralized training and the limitations of battery-powered, resource-constrained mobile devices. The accumulation of intensive computations and communication costs from local updates during numerous global rounds has created an energy bottleneck, which is exacerbated when dealing with non-identical and independently distributed data. To address these challenges, FedRelay [105] represents a versatile multi-flow relay learning framework that performs local updates relay-by-relay in the training flow through model propagation, introducing a decentralized relay selection protocol that leverages the diversity of cooperative communication networks.

A CNN-based channel estimation framework for massive MIMO systems is proposed in ref. [106]; it utilizes one-dimensional convolution to process the input data. Ref. [107] presents an assisted IoT-oriented MIMO wireless network system optimized for 6G. This system aims to improve the bit error rate (BER) and capacity to overcome key challenges related to wireless communication.

7.3. Blockchain-Based Solutions

Existing traditional UAV communication methods are insufficient at addressing the high mobility and dynamic characteristics of UAVs, particularly in hostile environments. Therefore, there is a pressing need for an efficient and secure UAV network. Motivated by these factors, ref. [108] presents a comprehensive survey on the architecture, requirements, and use cases of 6G technology in the context of UAV communication. A taxonomy of solutions is proposed based on the applications of UAV communication, and a security solution leveraging blockchain technology and 6G-enabled network connectivity is introduced. A case study illustrating a blockchain-enabled UAV communication system using 6G networks to enhance the security of Industry 4.0 applications is also outlined.

Leveraging blockchain technology for diverse applications in SCs presents significant challenges to the private sector, public sector, and government entities. Providing improved and optimal services to the citizens is complex. Blockchain technology offers a solution for implementing effective policies, fostering trust among policymakers, and reducing data storage costs while ensuring data security. Its decentralized nature provides enhanced security, enabling anyone to verify records. Trust plays a crucial role in financial transactions and other dealings, and blockchain facilitates the restoration and maintenance of trust through its transparent system, allowing people to verify and monitor policy processes. This concept holds particular importance in the realm of banking, which significantly impacts individuals' lives. Furthermore, the advent of 6G will revolutionize remote communication through the utilization of AI [109]. In ref. [110], the authors investigate the integration of blockchain technology in 6G networks, enabling efficient monitoring and management of resource consumption and sharing. In addition, solutions associated with security and privacy implications in 6G networks are examined, providing valuable insights and directions for future studies on 6G security and privacy. Recognizing the potential paradigm shift and security benefits brought by blockchain, transitioning from a traditional centralized model to a more robust and resilient decentralized model, the authors of [111] propose a multi-tier integrated architecture that combines blockchain and edge computing for 5G and future generations, aimed at addressing security challenges faced by resource-constrained edge devices. Moreover, robust security and privacy measures are necessary for various IoT-enabled industrial applications. The arrival of blockchain technology has revolutionized information sharing by establishing trust on a secure and distributed platform, eliminating the need for third-party authorities [112]. Notably, blockchain technology (BCT) has garnered significant attention due to its ability to address decentralization, transparency, spectrum resource scarcity, privacy, security, interoperability, and confidentiality, as well as its potential in emerging domains, such as industrial IoT (IIoT) and Industry 5.0 applications. The disparity between the requirements for data-intensive disruptive IoT applications and the capabilities of 5G networks has generated a demand for decentralized BCT-based architecture in 6G networks. Ref. [113] presents an extensive survey that explores the integration of blockchain in 6G mobile networks, IoT technologies, and smart industries.

7.4. Quantum Communication

With the world experiencing rapid technological advancements, there has been a substantial increase in the demand for communication that is ultra-reliable, fast, low-power, and secure. Consequently, researchers have taken a keen interest in the emerging field of QC due to its potential to solve complex computations in a robust and efficient manner. It is anticipated that QC can serve as a critical enabler and a powerful catalyst in significantly reducing computing complexities while enhancing the security of sixth-generation (6G) and future communication systems. The study presented in ref. [114] delves into the fundamentals of QC, with the evolution of quantum communication spanning various technologies and applications; the authors specifically focus on quantum key distribution as a promising application for quantum security. Additionally, the authors investigate various parameters and important techniques to optimize the performance of 6G communication in terms of security, computing, and communication efficiency. Potential challenges that QC and quantum communication may encounter in the context of 6G are highlighted, along with future directions for exploration. In ref. [115], the authors focus on exploring the security risks associated with the new 5G paradigm and propose solutions to address them. Specifically, we delve into the role of quantum key distribution as a means to enhance security in the context of 6G. Moreover, the work presented in ref. [116] introduces a novel approach that combines quantum cryptography and CNN for secure communication in SCs. The proposed approach involves the utilization of quantum key distribution (QKD) for the secure key exchange between communicating parties. The key generated through QKD is then employed to encrypt the data using a CNN. This CNN-based encryption adds an extra layer of security to the transmitted data within SCs.

Among the enabling technologies and solutions discussed in ref. [117], we cannot fail to mention quantum optical switching and computing, THz-to-optical conversions, advanced meta-materials for smart radio-optical programmable environments, and AI. This work presents a future application scenario called quantum optical twin, which utilizes the aforementioned quantum optical communication technologies to provide services such as ultra-massive scale communications for connected spaces and ambient intelligence, holographic telepresence, tactile internet, new paradigms of brain–computer interactions, and innovative forms of communication.

7.5. UAVs and Drone-Based Solutions

Another area that is gaining momentum is that of drones and their varied applications for use. The advent of consumer drones, flying ad hoc networks, low-latency 5G, and advancements beyond 5G have significantly accelerated progress in this field. The authors of [118] describe a continuous actor–critic deep Q-learning (ACDQL) strategy to solve the location optimization problem of UAV-BSs in the presence of mobile endpoints, extending the action space of the reinforcement learning (RL) algorithm from discrete to continuous. In detail, a scheme for the dynamic positioning of a UAV-BS in the case of user mobility is proposed, overcoming previous works presented in the literature, which considered fixed locations for the ground endpoints. The proposed reward function aims to keep the

UAV-BS inside the boundaries of the area of interest, and it also intends to maximize the users' sum data rate.

In ref. [119], the authors propose implementing the Consumer Internet of Drone Things (CIoDT) framework, which facilitates the transfer of emergency messages between smart grid systems and power sources, and ensures reliable network connectivity during a disaster. To achieve this, a realistic mobility model was developed, and an edge-enabled opportunistic MQTT message transfer mechanism was implemented. Additionally, a dedicated network slice was devised to assess routing performance, achieving a message delivery probability of about 0.99 in the quality of service level 2 (QoS2) and an end-to-end latency of 1.19 s in the quality of service level 1 (QoS1). In ref. [120], the authors present a continuous Hopfield neural network (CHNN) algorithm for the optimal link-state protocol (OLSR) routing, which is able to reduce breakage and provide efficient routing services in multiple types of UAVs, which form flying ad hoc networks (FANETs). This is obtained using self-assembled networks to collaborate on complex task-application scenarios, such as SCs. The proposed protocol outperforms the original OLSR protocol in key performance metrics, such as packet delivery rate, control overhead, throughput, and end-to-end delay.

Distributed hash table (DHT)-based routing protocols were initially proposed as valuable solutions in high-mobility cases characterized by frequent changes in the network topology. A novel three-dimensional logical cluster-based DHT routing protocol for mobile ad hoc networks (MANETs) that use logical clustering, as well as an effective replication strategy to reduce the routing overhead and lookup latency introduced by the above problems are proposed in ref. [133]. Ref. [134] proposed a subscriber data management scheme based on the combination of distributed ledger technology (DLT) and DHT technologies for 6G mobile communication systems. Traditional mobile communication systems are structured to serve numerous subscribers simultaneously, following a network-centric design approach. In contrast, this study explores the user-centric design approach, where systems are user-defined, user-configurable, and user-controllable. This approach allows for personalized network services tailored to each user. In ref. [135], the authors introduce a new user-centric network (UCN) architecture that outlines core design principles, relevant network components, and procedures. The UCN architecture employs DLT and DHT for distributed implementation, fostering customization, autonomous data control, and privacy protection.

With their affordability and the ability to integrate transmitters, cameras, and sensors, UAVs have the potential to serve as flying IoT devices, seamlessly connecting with their surroundings and offering enhanced mobility within the network. In ref. [121], an overview of the advantageous applications of UAVs in SCs, particularly in the realm of ITS, while emphasizing the key challenges that may arise, is presented. Additionally, the integration of various AI techniques enhances data delivery through global communication, thereby improving operational performance. Despite being in the early stages, UAV-enabled IoE applications hold immense potential for enhancing 6G networks. This paper investigates the recent advancements in methods and mechanisms that enable UAVs to support IoE. It explores the current trends in IoT convergence toward smarter IoE, while also addressing challenges and risks associated with the Internet of Everything [122].

7.6. Vehicular and Mobile Solutions

As presented in the previous section, MEC could solve challenges where transmitting data over long distances from end devices or edge servers to the cloud incurs great latency and security risks. In ref. [123], the authors analyze how MEC should improve applications and services, even in an SC environment. In contrast to cloud computing, edge computing provides a distributed computing platform for services, computation, and storing. MEC may decrease latency to lower levels and improve storage capability in devices with minimal processing capabilities, thanks to the growing use of smart systems. The incompatibility of various technology in cities is one of the most serious problems. In a scenario where MEC is used, a high number of connected devices might negatively impact the network speed, but they can be useful in identifying abnormal occurrences thanks to user-generated material and the right algorithms.

On the path to 6G, the advancing digitalization of buildings and SCs is becoming increasingly impactful [124]. To economically integrate renewable energy into buildings and SCs, the concept of energy storage and supply based on energy management must be emphasized. There has been a shift in political views; they now recognize the importance of energy efficiency in buildings given their considerable share (35%) of greenhouse gas emissions from final energy consumption. The authors highlight the potential of future mobile communication standards, such as 5G beyond and 6G, in providing specialized solutions for building digitization in edge clouds. The advent of 6G will revolutionize how we communicate and manage billions of interconnected devices in our digital future, spanning from macro- to micro- to nanoscales. Beyond providing lightning-fast connectivity, 6G has the potential to significantly enhance healthcare systems, transportation, logistics, safety measures, privacy, and more. It will enable the rapid processing, storage, and visualization of massive amounts of data, exploring the impact of 5G and 6G technologies on the advancement of SCs that are characterized by their intellect and perceptiveness [136].

The utilization of a microcell structure, employing carrier frequencies significantly higher than current 5G cellular networks, will present substantial challenges to the advancement of cellular communication in future generations. Specifically, the reliable operation of communication systems supporting critical services can be greatly impacted by factors like variations in vehicle velocity, rain-induced attenuation, and depolarization. The inclusion of eCall emergency systems—as a mandatory requirement in motor vehicles sold throughout the European Union since 2018—poses significant challenges to the development of 6G in emergency management, particularly due to the high occurrence of road accidents during heavy rainfall. To address the pressing need for assessing the reliability of 6G-based emergency management systems in SCs, in ref. [125], the authors thoroughly examine the technical aspects of designing and implementing vehicle-to-infrastructure (V2I) communication systems. The aim is to optimize reliability in an SC environment, considering the coexistence of both 5G and 6G network backbones. The main objectives outlined in ref. [126] focus on efficiently monitoring the intricate road environment in SC transportation using cutting-edge 6G digital twins (DTs). The aim is to perceive the complex road conditions within SC traffic, with a specific focus on vehicular networks (VNs) as the research subject. The study explores the potential for multi-sensor collaboration and fusion technology within the network to meet the active control requirements of intelligent vehicles. A segmentation network called C-LNet, which combines LiDAR and camera data, is proposed. C-LNet utilizes a double encoder–single decoder structure, with separate encoders extracting image and LiDAR features. By synchronizing LiDAR point cloud data and image data in the sensor space, the heterogeneous data are effectively unified. Additionally, a multiscale feature fusion-based method is designed to handle multimodal information related to vehicle collaboration. In ref. [127], the development of SCs relies on key solutions, such as 5G, IoT, automotive advancements, energy systems, high-speed digital capabilities, AI, data analytics, satellite communication, optics, and cyber-security. The integration of these systems and resources allows for the merging of mobility, communications, energy, water management, monitoring/control, performance management, predictability, and forecasting. Moreover, 6G enables the rapid sensing, processing, control, and human experience of vast amounts of data. The work aims to analyze the advantages and requirements of 6G technology and its potential impact on the development of smart, intelligent, and advanced cities. The potential of 6G joint communication and sensing (JCAS) in driving innovations and SC services highlights the use of wireless networks and millimeter-wave frequencies for perceptive radio networks and channel-based sensing [128]. The proposed concept focuses on operating in the mm-Wave beam space and measuring inter-cell links to enable more accurate spatial sensory activity monitoring. A simulation-based case study on vehicle detection and classification demonstrates the feasibility of the 6G-driven concept.

The enhancements offer new service potentials, including recognizing the trajectory of passing road users.

In current computing systems, like edge computing and cloud computing, many emerging applications and practical scenarios are either unavailable or only partially implemented. This limitation has sparked interest in developing a comprehensive computing paradigm in both academia and industry. However, there is a gap in the existing research, with limited studies on the systematic design and review of such a comprehensive computing paradigm. To bridge this gap, this study introduces a new concept called aerial computing, which combines aerial radio access networks and edge computing. In ref. [129], the authors propose a novel comprehensive computing architecture composed of low-altitude computing (LAC), high-altitude computing (HAC), and satellite computing platforms, along with conventional computing systems. Aerial computing offers several desirable attributes, including global computing service, improved mobility, increased scalability and availability, and simultaneity. The study also explores key technologies that enable aerial computing, such as energy refilling, edge computing, network software, frequency spectra, multi-access techniques, AI, and big data. It discusses various vertical domain applications, such as SCs, smart vehicles, smart factories, and smart grids, which can benefit from aerial computing.

Among the different sectors, emergency services play a crucial role in the realization of future SCs. In this regard, firefighting stands out as a vital component for ensuring security and safety. However, effective firefighting necessitates ultra-reliable and low-latency communications, enabling firefighters to receive real-time guidance through the utilization of distributed sensors, robots, and other technologies. In this context, in ref. [130], the research focuses on the application of edge micro-data centers (EMDCs) to enhance fire prediction and management. A novel three-stage architecture is proposed. The initial stage involves predicting and classifying the occurrence of fires based on sensor data available at the EMDC. The second stage focuses on confirming the fire occurrence using a CNN classification model. Once the fire occurrence has been confirmed, the final stage involves notifying the tenants and streaming a 360-degree monitoring video to the nearby fire station after processing at the EMDC.

7.7. Augmented and Virtual Reality

The use of AR and VR technologies in the context of vehicular technologies in SCs will also benefit from the new features of 6G networks. In the SC context, vehicles are expected to use local (V2V) and global V2X communications to allow for safe, more efficient, and more comfortable driving, since the vehicle will be able to recognize dangerous situations preemptively, even if these are out of visual range due to a bend, or with other vehicles ahead [131]. For example, in ref. [132], the following situation is presented: Vehicles are moving—one behind the other—when suddenly, a pedestrian crosses the road in front of the first car. The first vehicle camera detects the situation and shares the image of the pedestrian with the vehicle behind it. The vehicle processes the information and shows a visual alert on the windshield along with the image of the pedestrian in AR. This use case requires high reliability, availability, low latency, and a high data rate, all of which can be assured by employing 6G communication techniques [131].

8. Real Implementation of Smart Cities

While there is presently no universally established set of guidelines for delineating a smart city, it is generally acknowledged that, globally, there are over 140 intelligent urban centers at the moment; this number is swiftly growing [137].

According to the latest smart city (SC) index, London has consistently risen in recent years and it currently holds the leading position [137]. London has introduced numerous progressive initiatives for smart cities, exemplified by the Connect London program, which oversees the development of an advanced 5G network and comprehensive fiber-optic coverage in the city [138]. Additionally, London has equipped its iconic lampposts with an array of sensors and electric vehicle charging points. Given the city's substantial investments in artificial intelligence (AI), Internet of Things (IoT), and emerging 6G technology, these innovative solutions are expected to advance even further.

Barcelona is another prime example of a smart city. It has implemented a vast grid of LED lampposts outfitted with sensors. These sensors oversee traffic flow, air quality, pedestrian movement, and noise levels, and possess the capability to dim or deactivate lights as necessary. In addition, the city has introduced intelligent waste bins outfitted with vacuums that draw trash underground, reducing unpleasant odors, and cutting down the frequency of collection truck journeys. Oslo showcases another instance of smart sensor deployment. The Oslo Smart Street Lighting initiative encompasses the entire city and aims to enhance the efficiency of the street lighting network. Oslo has consolidated its street-lighting into a unified network that is accessible remotely through internet-based applications. This system permits managing and monitoring lighting levels, and adjusting light intensity based on seasonal variations and specific requirements, thereby further optimizing energy consumption across the city. The incorporation of 20,000 intelligent streetlights in Oslo has resulted in an impressive overall energy reduction of almost 70% [139].

Singapore holds a prominent position among the leading smart cities in Asia. With the initiation of its Smart Nation initiative in 2014, Singapore has introduced an extensive array of intelligent technologies. Notably, contactless payment technology has been widely integrated into streamline movements and payment processes for the approximately 7.5 million individuals using public transportation in Singapore. In response to the challenges posed by an aging population, a digital health system was implemented, which not only normalized video consultations but also introduced wearable Internet of Things (IoT) devices for patient monitoring. This multifaceted approach serves to alleviate the pressures associated with an aging demographic [139].

Seoul is notably regarded as the most advanced city in terms of harnessing big data. By gathering and analyzing urban patterns, encompassing factors like traffic flow, speed, and air quality through an array of sensors and closed-circuit television installations distributed throughout the city, Seoul has laid a robust foundation for the development of intelligent infrastructure and services. A specific focus has been directed toward addressing the needs of the city's aging population. An initiative promoting safety for senior citizens living alone was introduced. This initiative involves the utilization of environmental sensors. These sensors detect anomalies, such as prolonged inactivity or unusual temperature, humidity, or lighting conditions. In such cases, the system immediately notifies relevant case workers and emergency services. Moreover, Seoul is exploring the idea of using its data platform to create an AI-powered detective system that can identify potential crime patterns [140]. Additionally, the city is among the pioneers in adopting 5G technology for enhancing mobility and transportation systems [139].

Finally, New York serves as another testament to the adoption of advanced technologies for SCs. Hundreds of smart sensors and technologies have been tested and placed throughout the different districts in New York City as part of its SC pilot program in 2020 [141]. This program gathers data to help manage services (like waste management and collection) more efficiently. New York replaced their old phone booths with smart hubs equipped with contactless technology, Wi-Fi capabilities, as well as online charging stations [140].

9. Challenges and Conclusions

SCs and 6G are technologies that will transform the way we live and work in the near future. However, combining these technologies leads to a series of challenges that have to be addressed. The challenges for SCs include interoperability, data privacy and security, digital divide, and implementation challenges. Interoperability means that SCs rely on a wide range of connected devices and systems; ensuring that these systems can communicate with one another is a major challenge. Regarding data privacy and security, we can see that SCs generate vast amounts of data, much of which are sensitive and personal. To maintain public trust, it is crucial to ensure that these data are stored and processed securely. In agreement with the digital divide, SC technology is expensive and not accessible to everyone, leading to a digital divide between those who can afford it and those who cannot. Lastly, implementing SC technology requires a significant investment in infrastructure and resources, which can be challenging for some cities.

The challenges of 6G cover different areas, such as technical hurdles, spectrum availability, costs, security, and regulatory challenges. In fact, 6G will require new infrastructure and technology, which may be difficult to develop and deploy. Moreover, 6G will require a significant amount of spectrum availability, which may not be the case in some regions; developing and deploying 6G will be expensive, and there may be concerns about the cost of accessing 6G services. As with any new technology, there may be security concerns with 6G that must be addressed to ensure the safety and privacy of users. Finally, the development and deployment of 6G will require cooperation between governments and private industries, and there may be regulatory hurdles that need to be overcome. Achieving global coverage with 6G will also require international cooperation and coordination. Frequency allocation and network standards will need to be agreed upon and implemented globally, which could be challenging given the competing interests of different countries and network providers. One of the main challenges of global coverage with 6G is the need for a significant infrastructure upgrade. The 6G networks will require many more base stations and transceivers than the current 5G networks to provide adequate coverage, which will require significant investments by network providers and governments. Another challenge of global 6G coverage is the allocation of frequency bands. While 6G networks will likely use higher frequency bands than 5G networks, these frequencies have shorter wavelengths, which means they are more susceptible to attenuation by obstacles such as buildings and trees. This could require additional infrastructure investments to ensure that 6G signals can penetrate obstacles and provide adequate coverage.

SCs rely heavily on advanced telecommunication technologies to support the development of innovative solutions for public services, transportation, energy management, and other applications. Considering this, 6G networks are expected to play a crucial role in enabling the next generation of SCs by providing faster data transfer speeds, lower latency, and increased connectivity. Some potential use cases for 6G in SCs include enhanced mobility, remote healthcare, smart energy management, and public safety. Moreover, 6G networks can support real-time data transfers, enabling advanced driver-assistance systems and autonomous vehicles to communicate seamlessly with one another and SC infrastructure. In addition, 6G networks can facilitate remote healthcare services, including telemedicine, remote patient monitoring, and virtual consultations. One of the aspects that is becoming more prominent is represented by smart energy management, where 6G networks can help power smart grids by enabling the real-time monitoring and control of energy consumption, facilitating the integration of renewable energy sources, and improving energy efficiency. Finally, public safety in SCs can be improved by employing 6G networks to support advanced surveillance systems, emergency response services, and disaster management, by providing fast and reliable communication channels. Overall, 6G networks have the potential to transform how cities function by providing faster, more reliable, and more efficient connectivity, supporting a wide range of SC applications.

This survey tackles all the aforementioned challenges and topics and provides an extensive overview of the published scientific work for each particular topic. Specifically, we concentrated on papers examining SCs in the context of 6G, building on the foundation set by the existing 5G standard and its inherent limitations. We extended the survey beyond the mere delineation of the 6G standard, delving into the potential applications that this emerging standard promises to bring to the SC realm.

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Abbreviations

Acronym	**Description**
6G	Sixth-Generation
5G	Fifth-Generation
IoT	Internet of Things
SC	Smart City
AI	Artificial Intelligence
IaaS	Infrastructure as a Service
PaaS	Platform as a Service
M2M	Machine to Machine
RAT	Radio Access Technology
LTE	Long-Term Evolution
QoS	Quality of Service
ARMANS	Adaptive Real-time Multi-user Access Network Selection
E-ARMANS	Energy-aware ARMANS
TYDER	Network Traffic Type-based Differentiated Reputation
M-IoT	Multimedia-based IoT
ML	Machine Learning
MCS	Modulation and Coding Scheme
ALOW	Additive Logarithmic Weighting
GATH	Game Theory
ITU	International Telecommunication Union
ITS	Intelligent Transportation Systems
ETA	Estimated Time of Arrival
AQI	Air Quality Index
SBS-SVO	Smart Bus Stop–Social Virtual Object
MISSION	Mobility Services User Virtualization
SIoT	Social IoT
LPWANs	Low-Power Wide Area Networks
AR	Augmented Reality
VR	Virtual Reality
e2McH	Multi-Hop Communication Solution
QoE	Quality of Experience
RAN	Radio Access Network
SDN	Software-Defined Networking
NFV	Network Function Virtualization
ITU	International Telecommunication Union
IMT	International Mobile Telecommunications
FBMC	Filter Bank-based Multi-Carrier
UFMC	Universal-Filtered Multi-Carrier
NOMA	Non-Orthogonal Multiple Access
SCMA	Sparse Code Multiple Access
MIMO	Multiple-Input Multiple-Output
CF-mMIMO	Cell-Free massive MIMO
ESS	Energy Self-Sustainability
UAD	User Activity Detection
D2D	Device to Device
EPS	Evolved Packet System
GSMA	Groupe Speciale Mobile Association
ICT	Information and Communications Technology
OPEX	Operator Experience
UDN	Ultra-dense Network

CRAT	Context-aware Radio Access Technology
AHP	Analytical Hierarchical Process
TOPOSIS	Technique for Order of Preference by Similarity to Ideal Solution
OFDM	Orthogonal Frequency-Division Multiplexing
CRAN	Cloud RAN
LB	Load Balance
IAB	Industry Advisory Board
WRC	World Radiocommunication Conference
3CLS	Control Localization and Sensing
BCI	Brain–Computer Interface
LiDAR	Light Detection and Ranging
SLAM	Simultaneous Localization and Mapping
UAV	Unmanned Aerial Vehicle
BS	Base Station
MEC	Mobile Edge Computing
MEEC	Mobility-Enhanced Edge Computing
V2X	Vehicle-to-Everything
FSO	Free-Space Optical
BC	Blockchain
QC	Quantum Communication
CFC	Cell Free Communication
OW	Optical Wireless
DL	Deep Learning
IRS	Intelligent Reflecting Surface
RIS	Reconfigurable Intelligent Surface
mmWave	Millimeter Wave
CNNs	Convolutional Neural Networks
RNNs	Recurrent Neural Networks
DNN	Deep Neural Network
CAV	Connected and Autonomous Vehicle
BCT	BC Technology
QKD	Quantum Key Distribution
ACDQL	Actor–Critic Deep Q-Learning
RL	Reinforcement Learning
CIoDT	Consumer Internet of Drone Things
CHNN	Continuous Hopfield Neural Network
OLSR	Optimal Link-State Protocol
FANETs	Flying ad hoc Networks
V2I	Vehicle-to-Infrastructure
DT	Digital Twin
VN	Vehicular Network
LAC	Low-Altitude Computing
HAC	High-Altitude Computing
EMDC	Edge Micro Data Center
V2V	Vehicle-to-Vehicle

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A QoE Model for Mulsemedia TV in a Smart Home Environment

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***Abstract*—The provision to the users of realistic media contents is one of the main goals of future media services. The sense of reality perceived by the user can be enhanced by adding various sensorial effects to the conventional audio-visual content, through the stimulation of the five senses stimulation (sight, hearing, touch, smell and taste), the so-called multi-sensorial media (mulsemedia). To deliver the additional effects within a smart home (SH) environment, custom devices (e.g., air conditioning, lights) providing opportune smart features, are preferred to ad-hoc devices, often deployed in a specific context such as for example in gaming consoles. In the present study, a prototype for a mulsemedia TV application, implemented in a real smart home scenario, allowed the authors to assess the user's Quality of Experience (QoE) through test measurement campaign. The impact of specific sensory effects (i.e., light, airflow, vibration) on the user experience regarding the enhancement of sense of reality, annoyance, and intensity of the effects was investigated through subjective assessment. The need for multi sensorial QoE models is an important challenge for future research in this field, considering the time and cost of subjective quality assessments. Therefore, based on the subjective assessment results, this paper instantiates and validates a parametric QoE model for multi-sensorial TV in a SH scenario which indicates the relationship between the quality of audiovisual contents and user-perceived QoE for sensory effects applications.**

***Index Terms*—Quality of experience, sensory effects, multi sensorial media, particle swarm optimization, smart home.**

I. Introduction

PROVIDING to the users multimedia content together with sensory effects is one of the main features of future media services, called multi-sensorial media [1], [2]. The user's viewing experience is enhanced by adding various sensorial effects to traditional media contents, triggering all human senses (i.e., smell, taste, hearing, touch, and sight). The Moving Picture Experts Group (MPEG) created a standard in 2007 to integrate user experiences with sensory effects, which include video and audio with effects like airflow, light, vibration, and temperature. The standard, called RoSE (Representation of Sensory Effects), was merged later in 2008 with the MPEG-V standard to allow the annotation of audio-visual content with sensory effects [3]. The multimedia render is used to reproduce audiovisual contents, the sensory effects renders are employed to enable the stimulation of the remaining human senses [4], [5], [6], [7]. For instance, the vibration feature of a mobile phone and ventilation, heating, cooling systems can be employed to trigger the haptic sensation. The olfactory system can be triggered by vaporizer devices [5], and finally lighting fixtures can be used to stimulate the visual system. Enhancing the sense of reality and the strength of emotions can be seen as the primary reasons of adding effects to audio-visual contents, to achieve better viewing experience [8], [9], [10], [11]. Most of the rendering devices for sensory effects in mulsemedia applications are using short range wireless communication standards (i.e., Bluetooth, WiFi, ZigBee,) to connect and render the effects, having as main disadvantage the used architecture. In most of the cases, this architecture is developed only for specific devices, a serious disadvantage in terms of manageability, scalability, and inclusion with a home entertainment system. To overcome these limitations, the authors proposed a different method to connect the sensory effects rendering devices relying on a typical Internet of Things (IoT) architecture [24].

In recent years, the ability of sensors and actuators to communicate and make a global cyber-physical world, gained extensive interest from the Information and Communication Technology (ICT) community. The Smart Home (SH) and Smart Living concepts have expanded, including devices already existing in the home environment [12], [13], [15]. The development of SH applications has been mainly based on the IoT paradigm which was an important part of this scenario's evolution, at pace with the constant evolution of short-range wireless communication.

Adding sensory effects to the multimedia content brings new challenges to the assessment of the Quality of Experience (QoE) for audio-visual contents. The assessment of the users' QoE can be performed via subjective tests, to obtain a Mean Opinion Score (MOS), requiring firm procedures to certify the validity of the results. Sensory effects have a fundamental importance on user's QoE in multi sensorial media applications.

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An SDR-Based Satellite Gateway for Internet of Remote Things (IoRT) Applications

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ABSTRACT Internet-of-Things (IoT) represents a breakthrough for the current ICT market. In many IoT applications, sensors and actuators are distributed over very wide areas, sometimes not reached by terrestrial networks. In such scenarios, the satellite plays a significant role. In this paper, a Software-Defined Radio (SDR) - based satellite gateway for Internet-of-Remote-Things (IoRT) is proposed. The use of SDR allows to decrease equipment cost and provides higher flexibility. The proposed architecture has been implemented by using a standalone SDR platform and Commercial Off-The-Shelf (COTS) modules for covering the main terrestrial IoT standards. Extensive proof-of-concept results are presented and discussed. Uplink and downlink tests showed the correct functionality implementation and transmitted signal generation, while the integration tests allowed to assess the reliability of the end-to-end information processing. Reconfigurability tests confirmed the capability of the gateway of dynamically updating in real-time its protocol settings. The overall test results showed the validity of the proposed SDR-based gateway for IoRT applications.

INDEX TERMS Internet of Remote Things (IoRT), satellite networking, software-defined radio (SDR).

I. INTRODUCTION

In these last ten years, a second revolution in Internet technology has grown around the concept of Internet of Things (IoT) [1]. In the past decades, Internet had become the paradigm of the "global network of the people", where the information content has always been generated by the intellectual efforts of Internet users and driven by their communication needs. IoT is based on a totally different paradigm: in the IoT, instead of manned content producers, smart objects can autonomously process and communicate data and interact among themselves and with the surrounding environment. The application fields of such a revolutionary technology are very wide and range from public safety, intelligent transportation systems, energy management, healthcare, industrial automation, to domotics, retail, etc. As stated in [2], satellite communications may potentially play an important role in IoT. Indeed, smart objects are often remote or dispersed over wide geographical areas or they are inaccessible. Such a situation is referred in [2] as Internet of *Remote* Things (IoRT). In this framework, satellite communication could offer a broadband cost-effective solution for the interconnection of networks of smart objects with the rest of the world. A valuable example is shown in [3], where IoRT supported by satellite backhaul is studied in the framework of video transmission from remote geographical areas involved in emergency situations. In another work [4], the use of two most common Machine-to-Machine (M2M) and IoT protocol stacks, namely: Message Queueing Telemetry Transport (MQTT) and Constrained Application Protocol (CoAP) is tested on a satellite random channel, based on the DVB-RCS2 standard.

In this paper, we tackle the issues of satellite connectivity for IoRT from a different viewpoint. The variety of communication standards, which are currently used for IoT and M2M applications, makes it very difficult to have a single device able to act as gateway. On the satellite side, the hardware cost of a gateway could be significantly lowered considering

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a SDR implementation. From the IoRT system side, the SDR implementation of the gateway can provide a high degree of flexibility in dynamically operating multiple wireless interfaces, especially combined with the plethora of terrestrial communication standards.

The main goal of the paper is to present and assess the hardware implementation of the SDR-based gateway for IoRT, along with its operational characteristics. The analysis of the proposed hardware/software architecture is performed at ''proof-of-concept'' level, without open-field testing that would require the presence of an operational satellite link.

The proposed and tested SDR gateway can find application in heterogeneous distributed IoRT scenarios, where a plethora of sparse devices, transmitting information using different protocols and standards over wide areas, is considered. At the best of our knowledge, the state-of-the-art SDR-based solutions for IoT do not tackle such kind of long-range and sparse multi-standard scenarios, being mainly focused on providing connectivity among devices operating in dense areas of limited extension.

The paper can be regarded as an evolution of three prior papers, in particular [5], [6], and [7]. These papers presented in sequence: the initial proposed architecture [5], the implementation of the terrestrial interface [6] and part of the implementation of the satellite interface [7]. This work presents, together with the complete implementation of the IoRT gateway, the performed tests for the terrestrial and the satellite interfaces, the overall tests and the final results of the entire project.

The paper is structured as follows: section II will discuss the state-of-the-art framework and highlight the novel contribution provided by our work. Section III will describe the architecture of the proposed SDR-based IoRT gateway, while Section IV will be devoted at illustrating the hardware/software implementation of the gateway itself. In-lab testing and proof-of-concept results will be shown in Section V. Finally, Section VI will draw the conclusions.

II. BACKGROUND AND INNOVATION

As shown in Fig. 1, the present work can be regarded as the intersection of a threefold state-of-the-art framework that can be summarized as: M2M/IoT communications over satellite links, SDR for satellite communications, and SDR for IoT.

A. M2M/IoT COMMUNICATIONS OVER SATELLITE LINKS

Some recent publications have dealt with the design of satellite systems for IoT. In [8], Qu *et. al* propose an architecture of a Low Earth Orbit (LEO) satellite constellation-based IoT network, discussing, among the others, aspects of efficient spectrum allocation, heterogeneous networks compatibility and routing protocols. In such a perspective, the authors of [9] showed that the Iridium Short Burst Data (SBD) network is one of the technologies best-suited for long-range IoT communications, with the implementation and testing of a hybrid Iridium-LoraWAN prototype. Another work dealing with transmission aspects for IoT-satellite connections is [10], where ultra-narrowband waveforms, based on Chirp Spread Spectrum (CSS) are designed for direct access of IoT to GEO satellites. In some recent contributions, performance evaluation and optimization of the IoT application protocols in the perspective of future integration of M2M with satellite networks are analyzed in detail [11], [12]. TCP performance of satellite M2M applications is investigated in [13] for random access links, when Contention Resolution Slotted (CRS) ALOHA protocol is used for managing the multiple access. In order to increase the spectral efficiency of satellite-based IoT systems, a novel forward link multiplexed scheme is presented in [14], where the signals of different users can be simultaneously transmitted over the satellite link using the same frequency by means of constellation coding. Finally, an interesting application of satellite-based IoRT is shown in [15], where the IoT sensors are located inside a flying aircraft and a satellite provides the backhaul both with aircraft manufacturers and airline operators.

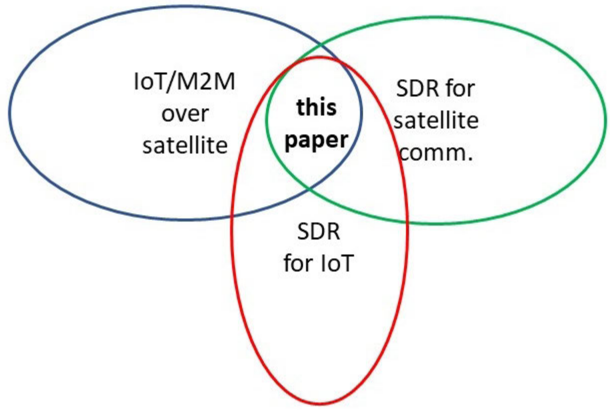

FIGURE 1. State-of-the-art framework of the present paper.

B. SDR FOR SATELLITE COMMUNICATIONS

Due to their flexibility, SDRs can provide a major contribution to the improvement of satellite communications. Through the use of Field Programmable Gate Arrays (FPGAs) and other dedicated processors, SDRs offer great versatility, that enables them to be used with multiple bands and modulation techniques, without requiring any change to hardware components. In such a framework, Digdarsini *et. al.* present in [16] a FPGA-based automatic modulation recognizer that uses the wavelet transform for identifying PSK, FSK and QAM signals. The authors of [17] have implemented a satellite negotiator devoted at ensuring the interoperability between different satellite missions, characterized by different transmission protocols. Another work worth of citation is [18], where an SDR-based reprogrammable Very Small Aperture Terminal (VSAT) terminal is proposed in order to restore multi-modal connectivity in emergency situations. Many recent works consider small satellites and CubeSats as valuable space platforms for the satellite SDR technology deployment. For example, the authors of [19] explore the SDR architecture in order to support the detection of multiple signals coming from multiple CubeSats in parallel. In other related works, the main focus is on the use of very low-cost COTS hardware components and open source software tools in order to enable satellite experiments also for students and researchers working in small labs [20], [21].

The SDR technology can be used for designing and implementing ground stations or user terminals. In [22] a multimodal VSAT unit capable of communicating both through LTE or Wireless LAN (WLAN) terrestrial links, as well as through satellite links is presented. A similar hybrid radio access system (i.e. a system that provides both satellite and terrestrial connectivity) is showcased in [23]. It consists of combining terrestrial Long Term Evolution (LTE) networks used in urban areas with co-channel satellite LTE cells for low populated areas.

C. SDR FOR IoT

The literature about SDR for IoT applications has become richer and richer in these last years. Some examples of related works are reported in the following. In [24], Schadhauser, Robert and Hueberger propose an SDR-based autonomous base station for low-power wide area sensor networks. Ma, Zeng and Sun proposed in [25] a multi-function radar for human body detection in human-centric IoT applications. Software radio is used in [26] in order to implement and test an IEEE 802.15.4k transceiver for low-energy critical infrastructure monitoring. In the same framework, it is worth citing [27], where the standard LTE-based R13 downlink transmission for IoT has been implemented and tested with SDR and USRP boards. Smartphones with SDR capabilities are considered in [28] to overcome the IoT language barriers, while a low-power basedband processor is designed in [29] to effectively support SDR usage in IoT applications. The security aspects of device-to-device communications are considered in [30], where a SDR platform is used to implement a cryptographic mechanism. Another work related to IoT security is [31], where SDR is used to assess the vulnerability in IoT devices to RF jamming attacks and to implement appropriate mitigation strategies. Other works deal with the combination of SDR techniques with Network Function Virtualization (NFV) in order to support multiple programmable air interfaces on top of one radio frequency (RF) front-end [32] and to provide the abstraction of the entire IoT stack to heterogeneous, generic, IoT devices [33].

D. NOVEL CONTRIBUTION OF THE PAPER

Considering the aforesaid state-of-the-art framework, the present work contains some significant innovation points. First of all, the published contributions about M2M/IoT communications on satellite links mostly concern with testing and optimization of terrestrial M2M/IoT protocol stacks in satellite-based IoRT configurations and/or on the study of efficient PHY-layer transmission solutions for direct connection of IoT devices with satellites. At the best of our knowledge, the study and the development of a multi-standard satellite gateway has not yet been addressed. Furthermore, satellite-based SDR applications are mostly focused on the deployment of re-programmable payloads, multi-modal ground stations and terminals and re-configurable links, but never considered the use of SDR for implementing a re-programmable multi-modal satellite gateway for IoRT. In the field of SDR for IoT, the examples found in the literature are focused on software implementation and testing of IoT transmission standards, analysis and mitigation of security threats, implementation of specific signal processing tasks, and, in few cases, implementation of autonomous terrestrial gateways, like in [24], but never on the design, implementation and test of re-configurable satellite infrastructures for IoRT. For this reason, we consider our work a clear step-ahead with respect to the state-of-the-art. In the last years, more IoT and M2M devices already have means to deliver directly IP or MQTT data, but especially for the IoRT field these options are not feasible, and even if they were, there is still the need of the satellite interface.

Also, the state-of-the-art analysis revealed that even though SDR-based solutions are starting to make their way into the market, there are not mature satellite gateway products capable of providing support for the main protocols currently used in M2M and IoRT applications. Hence, the originality of the present paper resides in the functionality of the proposed gateway, as a standalone embedded platform which can handle data from both the terrestrial and satellite sides.

Another novelty of the presented approach is the compactness of the platform, implemented on a low cost, battery-powered device. The use of an SDR-based approach ensures also the necessary flexibility for covering the future developments of IoT standards and applications, that could be implemented easily on the computational platform through the available reconfigurability mechanisms.

III. REQUIREMENTS FOR THE SDR-BASED IoRT GATEWAY

A. TERRESTRIAL INTERFACE

IoRT applications are based on low-power radio communications and need a gateway to connect with the external environment. The backbone of this type of systems is represented by data protocols and communication technologies capable to seamlessly integrate thousands of nodes, while ensuring a reliable data transfer. They operate at different levels of the protocol stack, the most important in this context being data link, network and session level (see table 1).

A key aspect for achieving the goal of covering most of the presented protocols and standards, is the use of a SDR platform as it provides both multi-protocol access for receiving data from different smart devices and the part of directing / transferring satellite traffic.

To ensure multi-protocol access for terrestrial interface of the gateway, two approaches are available:

- implementation of the IoRT protocols on the FPGA of the SDR platform;
- use of COTS modules.

TABLE 1. Different layer protocols used in IoT applications.

ISO Layer		Protocol standard
Session		MQTT, SMQTT, CoRE, DDS, XMPP, CoAP
Network	Encapsulation	6LowPAN, 6TiSCH, 6Lo, Thread
	Routing	RPL, CORPL, CARP
Data link		Wi-Fi, BLE, Z-Wave, ZigBee, 3G/LTE, NFC, LoRaWan

The first approach (implementation in FPGA) has the main advantage that it eliminates the need to use external devices, but significantly increases the complexity of implementation. Depending on the protocol that is intended to be implemented, the requirements regarding the FPGA's capabilities and performance can significantly increase, leading to a higher hardware cost for the SDR gateway. Also, another potential risk may be the inability of the SDR platform to host all the required protocols, due to the imposed constraints that directly affect the platform's performance. The second approach reduces significantly the complexity of implementation by using COTS modules for the desired protocol. The aspects to be addressed here are the interface with the SDR platform and also the additional hardware costs of the COTS modules themselves.

In the specific case of our gateway, based on the aforementioned considerations, combined with the subsequent analysis of the existing SDR platforms [6], the COTS implementation was preferred due to its extended flexibility, low cost and modularity.

B. SATELLITE INTERFACE

The IoRT networks are generally characterized by the existence of a large number of low-power, small sized terminals that share the resources available in very dynamic traffic conditions. In particular, on the return link (ground station to the satellite), users are expected to generate short, bursty traffic with extended periods of inactivity, therefore asynchronous random access schemes are being preferred, to the detriment of the high-cost synchronous ones. The absence of the synchronization mechanism simplifies the deployment and activation of the terminals. The key requirements for choosing an efficient access scheme are:

- high aggregate throughput with very low transmission probability of packets;
- effective support of small packages with very low transmission cycle;
- minimum signaling overhead;
- low EIRP (Effective Isotropic Radiated Power) needs;
- robustness against the energy imbalance of the received packets;
- accessible complexity.

Although the requirements listed above are particularly relevant for the intended satellite messaging system, they may also have general applicability for satellite narrowband mobile communications systems. An important step of our work was dedicated to the investigation and identification of the radio interfaces that best fit the IoRT message transmission needs.

1) UPLINK

The generic requirements of the uplink link for IoRT applications imply low data rates and an elevated number of nodes accessing the transmission resources in short bursts, leading to the necessity of the use of simple, uncoordinated and random access based medium access (MAC) protocols.

Starting from an initial comparative study, extended with our own considerations we concluded in [7] that the most suitable uplink radio interface for the use of M2M and IoT applications would be S-MIM (S - Band Interactive Mobile Multimedia). The E-SSA access mechanism offers the highest MAC throughput and robustness to power imbalance, while allowing for full-time asynchronous packet transmission over time and the lowest EIRP requirements.

2) DOWNLINK

For the downlink, based on our initial requirements analysis [5] the most suitable radio interface would be DVB-S2 [34]. Following the study of the specific standard, we came to the conclusion that DVB-S2X would be even more suitable to M2M/IoT message forwarding requirements [7]. DVB-S2X is an extension of DVB-S2 specifications that promotes additional technologies and features. DVB-S2X uses the LDPC (Low Density Parity Check) Forward Error Correction (FEC) scheme proven and strong in combination with Broadcast Control Channel (BCH) FEC as the external code but introduces additional features, which fulfill the M2M/IoT Forward link requirements [35].

C. GATEWAY ARCHITECTURE

The requirements identified in the previous sections, led us to the specific design of the gateway architecture. The main specific requirements to be satisfied by the architecture are: i) to support or to be able to embed M2M and IoT standards and communication technologies, and ii) to have an embedded architecture with overall low complexity, which can assure portability and flexibility together with reprogrammability and reconfigurability in the framework of a non-proprietary programming environment (Linux, GNU Radio). Also, the system has to ensure adequate FPGA capacity for running complex protocol stacks, large RF bandwidth, MIMO capabilities, interfacing capabilities (AXI, I2C, USB, IP) with external components, embedded GPS module or GPS interface capabilities, reduced power consumption and a low price tag. The envisioned architecture is depicted in Fig. 2 and is based on the computational platform that links the satellite communication with the IoRT one. The FPGA-based platform is also responsible for the implementation of the protocol stack of the most common communication standards

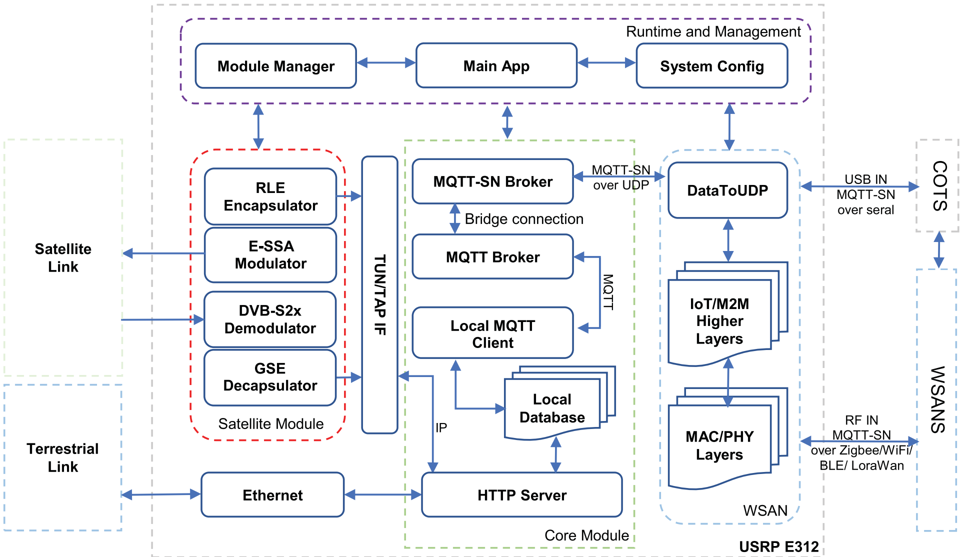

FIGURE 2. Architecture of the proposed IoRT gateway.

for IoT and M2M applications and for the general baseband – RF bidirectional conversion. On the software side, a modular design was adopted to ensure a high degree of reconfigurability and flexibility. Each main feature/functionality has a designated module which can be replaced or updated as needed either before deployment or remotely while the system is in the field.

The central part of the generic architecture is the MQTT broker, part of the Core Module, that acts as a universal transport mean between the terrestrial and the satellite side. The broker is connected to a local database and to a HTTP server. The data to be sent in the database is organized by communication protocol, node id and node type (e.g.temperature, humidity, etc.). All the data present in the database will be sent via the satellite interface to la cache server.

Towards the satellite interfaces (Satellite Module) the communication is done using IP packets, while towards the terrestrial side, inside the Wireless Sensor and Actuator Network (WSAN) module the packets are UDP. The proposed architecture leaves space for both the satellite and the terrestrial interfaces to be implemented as FPGA code or by using external COTS modules connected through the interfacing capabilities of the gateway.

The Runtime and Management module is responsible for the management and the update for all building blocks.

IV. SDR IMPLEMENTATION OF THE IoRT GATEWAY

A. SDR PLATFORM

In order to implement the envisioned architecture of the satellite gateway, several SDR platforms have been taken into consideration. Price, computational power, power consumption, use of non-proprietary development environments and the ability to run autonomously without the aid of an external computational platform were the main factors taken into consideration for the choice of the SDR platform. In [5] a thorough analysis was performed on the SDR platforms available on the market that are compliant with the previously drawn requirements. Based on this analysis, a portable, stand-alone SDR platform was chosen: the USRP E312 comes with a 2×2 MIMO transceiver able to cover bands from 70 MHz to 6 GHz, a Xilinx Zynq 7020 SoC, a dual-core ARM CPU and an Open Embedded Linux OS which offers the support and flexibility needed for custom software development. A 3200 mAh on-board rechargeable battery allows a high degree of autonomy, with more than 2 hours of battery life.

B. IMPLEMENTATION OF THE TERRESTRIAL INTERFACE

As interconnecting satellites with WSANs is best achieved via indirect access - each sensor and actuator communicates with the satellite through a gateway node – and given the fact that an interface which allows third party applications to collect sensor data via terrestrial WAN links is also an important requirement, the terrestrial side of the satellite gateway becomes a key architectural element which enables data pass through between short range wireless communication protocols and traditional terrestrial/satellite networks. For this, the gateway has to offer support for a rigorous set of requirements, the most important being: communication management, security and authentication, data aggregation, protocol translation and power management. As one of the main objectives to be achieved is the capability of communicating with M2M/IoT applications by using the most common wireless protocols and transmission standards, the SDR-based terrestrial gateway offers support for the following communication standards: LoRaWan, BLE, IEEE 802.11 and ZigBee IEEE 802.15.4.

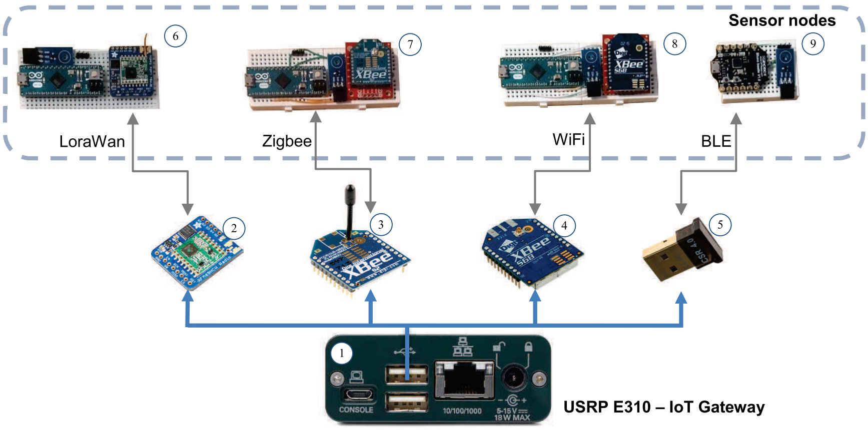

FIGURE 3. Modular hardware scheme of the terrestrial side of the IoRT gateway.

The hardware components adopted for implementing the terrestrial side of the satellite gateway are depicted in Fig. 3 and listed as follows:

- Xbee S6B Wi-Fi (figure 3 – item 4)
- Adafruit RFM95W LoRaWan (figure 3 – item 2)
- CSR 4.0 BLE (figure 3 – item 5)
- Xbee S2 Zigbee (figure 3 – item 3)

The sensor nodes layer consists of four nodes, each able to gather information from various types of sensors (temperature, humidity, pressure, gas etc.), send data to the gateway and perform actions received from the gateway (i.e. relay/actuator control). The LoRaWan, ZigBee and Wi-Fi sensor nodes consist of an Arduino Micro board, a LM50 temperature sensor and the corresponding COTS module. For the BLE sensor node a Beetle BLE board with an integrated BLE module was used. All the modules are connected via the USB ports of the SDR platform.

To ensure the end-to-end device-to-device or device-to-user communication between the satellite and terrestrial interfaces, the MQTT/MQTT-SN (Sensor Networks) protocol [29] has been used. This data protocol has been specifically designed for constrained environments requiring low bandwidth consumption and good performance. The gateway acts as a broker which classifies the data received from the publishers into topics and relays it onward to the interested subscribers, independent of the communication protocols involved. The sensor nodes act as publishers for passing sensor data to the gateway as well as subscribers for receiving commands from the gateway. The UDP protocol is used internally as a payload bridge between WSAN layer and the internal MQTT-SN broker. The packet recovery in case of lost/erroneous packets is handled at the WSAN protocol level and at the MQTT-SN level by properly selecting the quality of service (QoS). In case of the presented architecture, the QoS level is set to 1 which ensures that the sender stores the message until it gets a PUBACK packet from the receiver that acknowledges receipt of the message.

Furthermore, still using GNU Radio we have implemented a multi-band spectrum sensing procedure for detecting wireless activity in the RF bands specific for each considered short-range terrestrial communication standard. The results of the spectrum sensing procedure are returned to the user interface, in order to allow the user to decide for the use of one or more of the aforementioned standards. Both the software implementation of the protocol stacks and the sensing procedure are making use of the RF interface of the USRP E312 platform, capable to cover the terrestrial RF bands used for wireless sensor networks (i.e. 433 MHz, 860 MHz, 2.4 GHz). The user interface of the gateway [6] allows the coordination of an initial spectrum sensing and packet sniffing and the activation of one or more communication standards for the connection with the IoT end devices via the COTS modules.

C. IMPLEMENTATION OF THE SATELLITE INTERFACE

1) UPLINK

The implementation of the E-SSA modulator has been completed using the GNU Radio software package in the FPGA of the USRP E312 platform, using as starting point the block diagram of in Fig 4. In order to ensure the data transport service, the following functions have been implemented:

- error detection mechanisms on the transport channel and reporting to the higher levels;
- FEC (forward error correction) coding;
- matching the rate of the transport channel to the physical channel;
- transport channel mapping to the physical data channel;
- power allocation and combination of physical channels;
- modulation and spreading on the physical channels;
- time and frequency synchronization (bit, chip, burst);
- RF processing.

The Random Access Channel (RACH) is the only data transport channel, characterized by a limited length of the data burst. Two possible dimensions of the length of the RACH burst (total number of bits), namely 1920 and 3600 bits, are supported, matching the rate achieved after the FEC coding. There are two physical channels, the PDCH (Physical Data Channel) used for the RACH data burst and the PCCH (Physical Control Channel), used for physical level

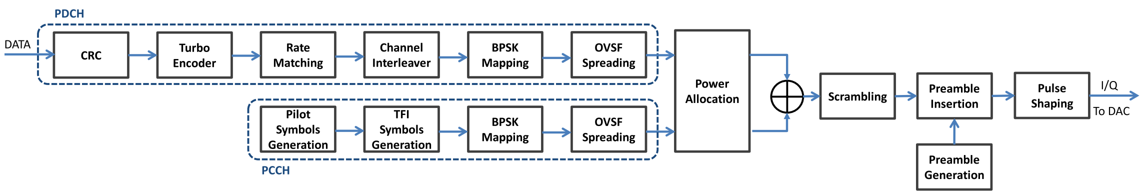

FIGURE 4. Block diagram of the E-SSA modulator.

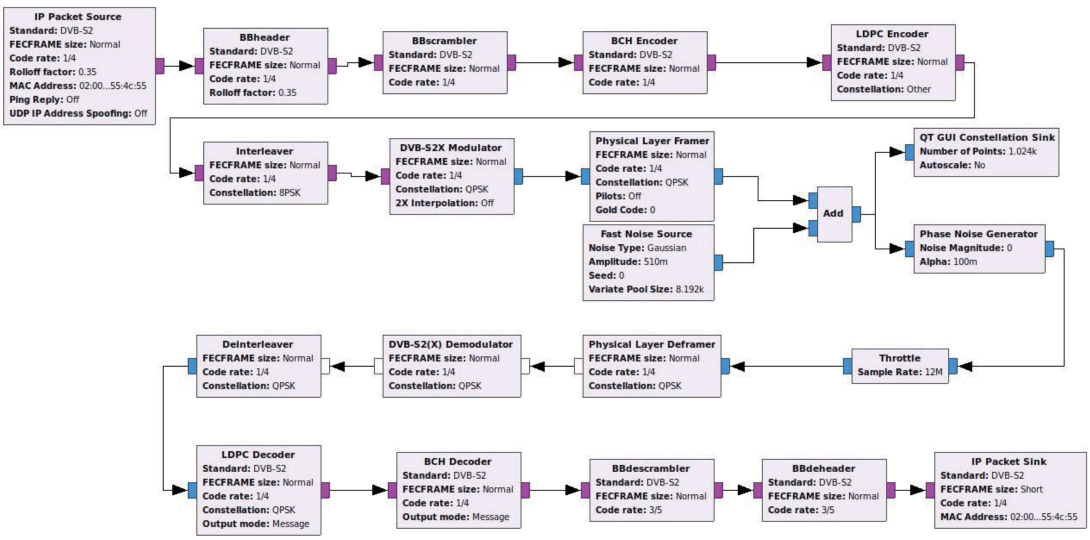

FIGURE 5. GRC flowgraph of the DVB-S2X modulation-demodulation chain.

signaling information. PDCH and PCCH are multiplexed to form an uplink burst (ULB - Up-Link Burst), before which preamble is inserted. The physical level signaling includes the transmission of a TFI (Transport Format Indication) to the receiving party. The UPB is multiplexed I-Q using two Walsh OVSF (Orthogonal Variable Spreading Factor) sequences [36], as in the case of W-CDMA 3GPP. The PDCH and the associated control channel have a burst length multiple of the W-CDMA 3GPP frame period, i.e., 10ms. The purpose of the PCCH is also similar to that of W-CDMA 3GPP. In particular, it allows for a robust estimation of the channel even in difficult channel transmission conditions, ensuring the possibility of transmitting physical level signals that inform the receiver about the burst format without forcing its blind detection. In this respect, the four possible lengths of PDCH / PCCH are associated with two possible signal data rates for after FEC coding, 15 kBaud (corresponding to the information bit rate 5 kbit/s) and 30 kBaud (information bit rate 10 kbit/s) and three possible message lengths (300, 600 and 1200 bits). The power allocation is performed by weighting and combining the physical channels, considering indeed the frame length. The power is controlled by 4 bits in the SSA configuration table that indicate the voltage gain of the control channel PCCH relatively to the data channel PDCH.

The CPU usage of the code implementing the uplink of the gateway was evaluated varying the previously mentioned parameters, i.e. signal data rate and message length. The CPU load remained steady at 42% regardless of the variation of both parameters.

2) DOWNLINK

As it can be seen in Fig. 5, a complete DVB-S2X modulation - demodulation chain has been implemented in the FPGA of the SDR platform using GNU Radio software. Their combined implementation is motivated by the need to validate the developed demodulator scheme. The Physical Layer (PL) Deframer block provides the de-scrambling part at the physical level, the frame synchronization and the PL header decoding in order to automatically determine the constellation and coding parameters according to ETSI EN 302 307-1 section 5.5. The output of this block provides an XFECFRAME type frame. The adopted implementation offered us the possibility of manually selecting the constellation and the coding parameters mainly to carry out tests, the actual implementation being in full accordance with the specifications of the standard.

The DVB-S2X demodulator receives at the input a XFECFRAME and ensures the constellation-bit mapping. The I/Q sequences are mapped into parallel sequences, depending on the chosen constellation, and then converted to FECFRAME frames (a sequence of 64.800 bits for normal FECFRAME, or 16.200 bits for a short FECFRAME) and supplied at the output. In the case of 8PSK, 16APSK and

```
{
  api_end_point: "api_end_point_string",
  body: {
    topic: "topic_string",
    value: "value_string"
  }
}
```

```
{
  api_end_point: "/api/sensor_ctrl",
  body: {
    topic: "0/255/F002",
    value: "measureOncePerHour"
  }
}
```

FIGURE 6. Basic structure of JSON control message (left side) and data message (right side).

32APSK, the frames supplied by the DVB-S2X Demodulator are also passed through the Deinterleaver block. The frames are subsequently supplied to the LDPC and BCH Decoder blocks for correction and detection of residual errors, and a BBFRAME (Base Band Frame) frame is generated at the output. The implementation of these blocks was carried out in accordance with ETSI EN 302 307-1 section 5.3.1 to 5.3.3. The de-randomization section of the BBFRAME framework processes the header and create the data flow (payload) through the BBdescrambler and BBdeheader blocks. The resulting bitstream, encapsulated in accordance with the GSE (Generic Stream Encapsulation) protocol, is provided to the IP Sink block for processing and conversion into IP packets, which are then transmitted to a TUN virtual interface.

3) ModCod SELECTION

In order to determine the optimal MODCOD for the proposed architecture, the following aspects must be considered based on the prevoiusly analysed requirements:

- the requirements regarding the bit rate required to send the control messages to WSAN;
- the minimum band to be allocated so as to ensure the transmission at the determined bit rate;
- ensuring the requirements regarding power consumption (as low as possible);
- reduced use of computational resources (limited).

The bit rate required for control messages is determined by the structure and size of the messages. Fig. 6 shows the basic structure, in JSON format, of a control message (left side), and an example of an actual message to be transmitted to the gateway to adapt the measurement frequency to an hourly WSAN node identified by the "F002" ID (right side). The message size from the previous example is 86 bytes. Based on the current implementation, we determined the maximum size of the control message to be 158 bytes. Considering the analysis of the requirements for any further development, but also future optimizations of the message structure, we concluded that a maximum size of 500 bytes provides the necessary requirements.

Due to the small size of the control packages, a net rate of 500 kbps is sufficient to meet the system requirements. Therefore, the optimal options would be:

- MODCOD 1 - QPSK, 1/4 FEC, 400 kSym/s;
- MODCOD 2 - 8PSK, 3/5 FEC, 400 kSym/s.

Both MODCODs provide a sufficient net data rate, and the occupied band is relatively similar, whereas MODCOD 1 allows the use of a higher FEC and requires less computational resources. Following the analysis, MODCOD 1 was chosen as the optimal variant for our system.

Regarding the symbol rate, an analysis has been performed to determine the optimum rate based on the time required for the frame lock, i.e., the time between the control message is transmitted and the moment it is received and the computational resources used. Fig. 7 provides more details about the average frame lock time as well as the average time difference between the time a control message was transmitted to the transmitter's TAP interface and the time it was received from the receiver's TAP interface. An inversely proportional dependence of these values can be observed relative to the symbol rate, the best results being obviously obtained at a symbol rate of 800 kbps.

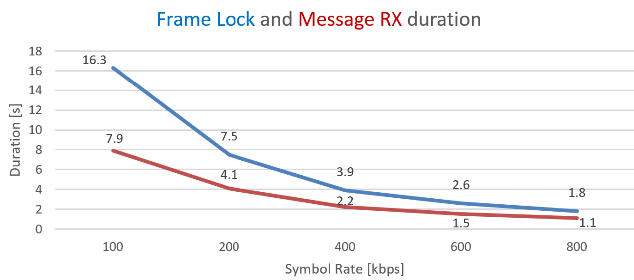

FIGURE 7. Average frame lock time vs. symbol rate for the SDR-implemented DVB-S2X transceiver.

Fig. 8 shows the average level of CPU utilization relative to the symbol rate. A directly proportional dependency to the symbol rate can be seen, the best results being obtained at a symbol rate of 100 kbps. Therefore, the 400 kbps symbol rate is the optimal value ensuring both acceptable duration and relatively low CPU use.

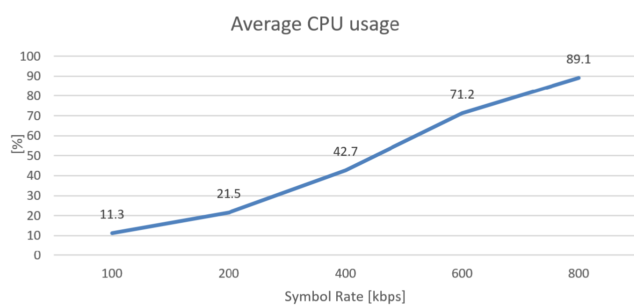

FIGURE 8. Average CPU usage vs. symbol rate for the SDR-implemented DVB-S2X transceiver.

Re-assuming, form the implementation of the up- and downlink satellite interfaces, we can conclude positive on the feasibility of the software implementation with a maximum of 82% of the CPU usage (39.3% for the uplink and 42.7% for the downlink), leaving enough capacity for the implementation of the remaining software blocks from Fig. 2. The overall CPU occupation confirms also the necessity to implement the terrestrial side using COTS modules and not the SDR's FPGA.

D. RECONFIGURABILITY

Reconfigurability is one of the key aspects of the proposed architecture, for which we defined a set of mechanisms which enables satellite and terrestrial link reconfiguration, both remotely and on site, via its Runtime and Management module. The reconfigurability mechanism is illustrated in Fig. 9. The data link can be, as previously stated, a satellite or a terrestrial one.

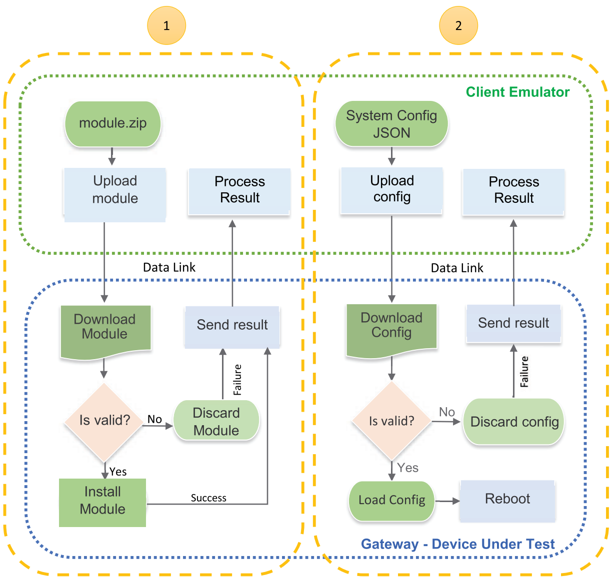

FIGURE 9. **Reconfigurability Mechanism.**

Upon startup, the System Config component is queried and the current configuration is retrieved. Depending on the values provided, the following are selected: uplink/downlink protocols, uplink/downlink frequencies, (active) IoT protocols. Based on the selection, the corresponding modules are loaded and initialized. For example, if in the current configuration DBV-S2X is set as the downlink protocol, the DVB-S2X Demodulator will be loaded and initialized. The configuration can be adapted on site, by manually overwriting the configuration file available at the System Config component, or remotely by pushing the configuration file via the satellite link. After each configuration change a system reboot is required, as depicted on the right side (2) of Fig. 9. Uploading new modules or updating the currently existing ones is also supported (both remotely and on site). A new module may be required for ensuring support for a different uplink/downlink protocol or for adding an FPGA base implementation for an IoT protocol which was previously supported via a COTS module. In both cases, the module implementation (e.g. a zip file) can be pushed via the satellite link and installed on the Gateway device. The Gateway will load and use the newly added module, only after explicitly adapting the system configuration as defined above and graphically described on the left side (1) of Fig. 9. The proposed system offers fallback mechanisms as well: if the system cannot be started after a configuration change, it will automatically fallback to the last known configuration. If a new module was uploaded and set as the one which shall be used or in case of an uplink/downlink protocol change, the system will fall back to the last used module/protocol if no data is received via the satellite link after a fallback timeout defined in the System Config component.

E. SECURITY

The security issues which can arise are the unauthorized access to the gateway and the deployment of malicious software during the reconfiguration phase. The satellite access to the gateway is granted via a web interface (Fig. 10) which implements a credential-based access and allows connections only for a restricted set of IPs. All the payloads are Triple DES (Data Encryption Standard) encrypted. The software upgrades via satellite were initially performed through HTTPS over GSE, but the SSL/TLS handshake procedure caused additional delay. Therefore, we opted for plain HTTP over GSE with the payloads encrypted using the Triple DES symmetric-key mechanism. The same access mechanism is applied in case of terrestrial link access. Furthermore, in this case, access is also allowed via a direct MQTT connection as long as valid credentials (username and password) are provided.

F. COSTS AND SIZE

One of the main goals of the present work is to build a low-cost and compact gateway. These requirements have been taken into consideration when selecting the USRP platform and when opting for a COTS implementation of the terrestrial side communication. The overall hardware costs of the gateway, including the COTS modules, are around 3500 €. These costs do not include the costs of up- and down-converters, amplifiers, satellite dishes and other equipment necessary to connect to the satellite, as the present paper is intended to be a proof of concept and does not present a commercial prototype. As for the size of the proposed gateway, the ETTUS E312 platform has a small form factor, that can be fit, together with the COTS modules and a 3200 mAh battery in a case 140 X 80 X 50 mm. External power supplies and the GPS antenna are not included.

V. IN-LAB TESTING RESULTS

For the up- and downlink in-lab tests, we set up the system presented in Fig. 11. The test transmitter and receiver are implemented in the FPGAs of two identical SDR USRP E312 platforms. The first SDR platform runs the GNU Radio implementation of a DVB-S2X transmitter and of an E-SSA receiver. Its RF part is connected through a coaxial cable with 50 ohm impedance and a 30 dB attenuator to the device

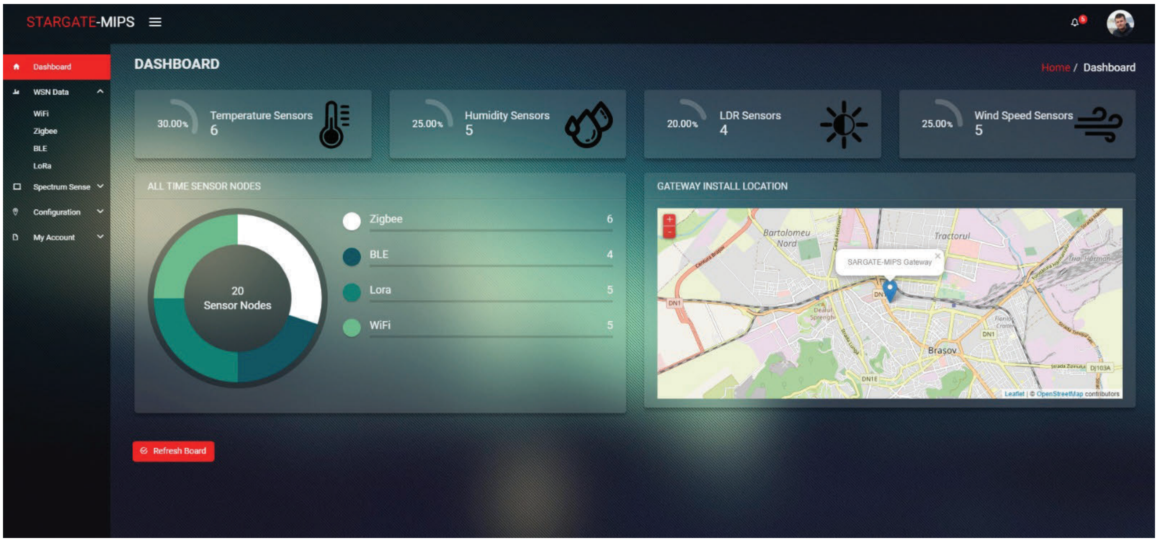

FIGURE 10. User Interface.

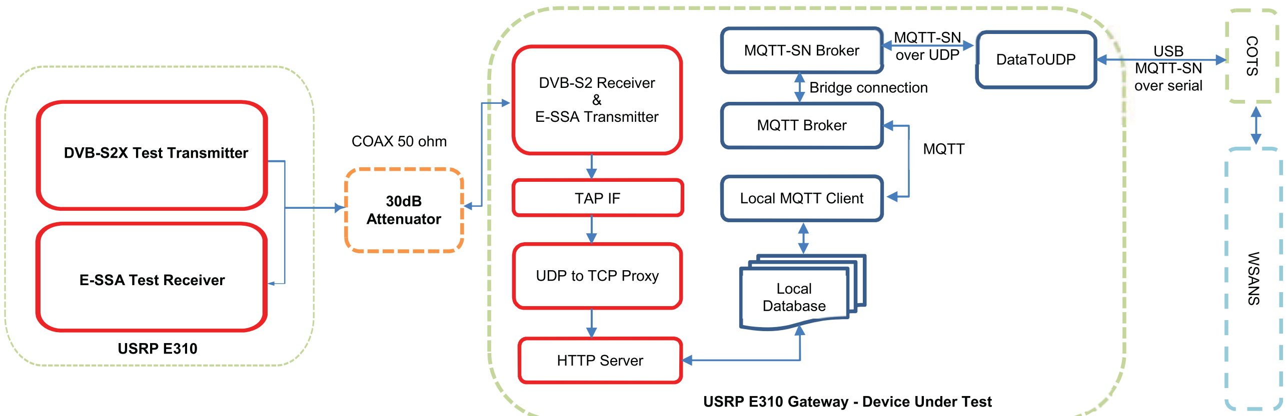

FIGURE 11. In-lab system testing setup.

under test, i.e. the gateway prototype embedded on the second USRP platform, as depicted in Fig. 11.

A. UPLINK TESTS

For the validation of the functionality of the E-SSA modulator, considering the capabilities of the used USRP platform, we opted for the use of the L Band, with a center frequency of 1.2 GHz. By doing this, we avoided for the beginning to use up- and downconverters to the Ka / Ku band, for better assessing the behavior of the generated waveform. A constant payload for the PDCH channel was used, with following characteristics: bit rate 5 kbps, symbol rate 15 ksps and a spreading factor of 16. The chip rate is 240 ksps and the roll of factor for the pulse shaping block is 0.22. The uplink transmitted signal spectrum was evaluated using a Tektronix Vector Signal Analyzer and can be viewed in Fig. 12.

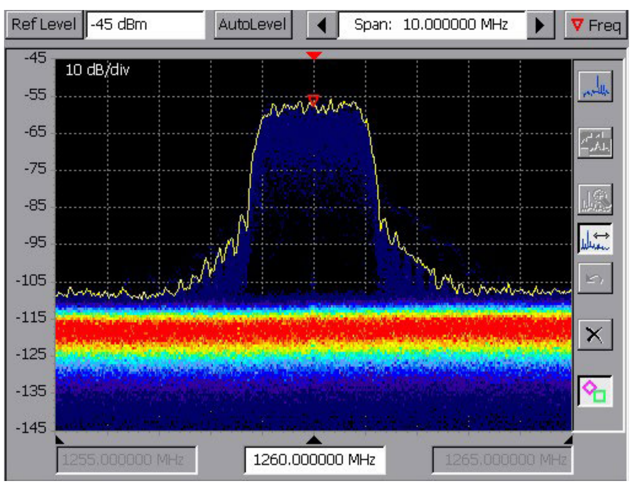

FIGURE 12. Transmitted signal spectrum visualized with a signal analyzer.

B. DOWNLINK TESTS

For validation of compliance with DVB-S2X standard, but also for performance evaluation, a number of automatic tests have been implemented. The components of the automatic test system, shown in Fig. 13, can be listed as follows:

- data generator controllable by the test application;

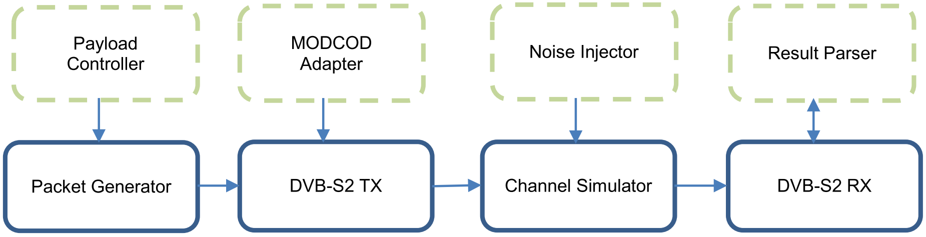

FIGURE 13. **DVB-S2X downlink system components.**

- DVB-S2X transmitter with a dedicated module that allows the automatic modification of MODCODs;
- channel simulator with noise injector (for performance tests);
- the DVB-S2X receiver implemented in section C, with integrated status check modules at different key points (necessary to compare the status of the component blocks at key times with a number of expected predefined states).

The downlink tests permitted us to assess the correct functionality of the entire downlink chain, starting form the constellation of the received signal up to the decoding of the transmitted data (Fig. 14) according to the DVB-S2X standard. Besides adding AWGN noise to the channel we performed also phase noise and adjacent channel interference (ACI) measurements. For the phase noise measurements we used components of the TOPCOM library written in C++. The threshold for the reception was the QEF (Quasi Error Free) requirement as defined in the DVB-S2X standard as the ratio between the useful FECFRAMEs correctly received and those affected by errors, after forward error correction FER $= 10^{-5}$ [37]. The same reception threshold was used when testing the ACI by generating more DVB-S2X carriers in 4 adjacent channels. The ACI was generated using an Agilent N5182A MXG RF Vector Signal Generator instead of the second USRP platform.

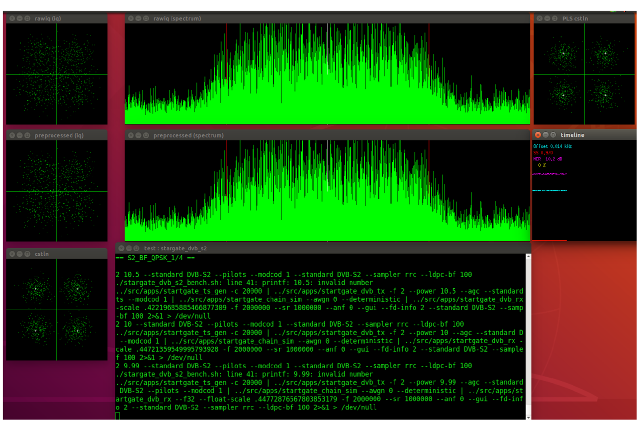

FIGURE 14. **DVB-S2X downlink tests.**

All reception tests were validated also with a DVB-S2X compliant DekTek DTU-315 board.

C. INTEGRATION TESTS

The integration tests verify the functioning of the interconnected internal processing modules, providing performance information based on a test architecture depicted in Fig. 15.

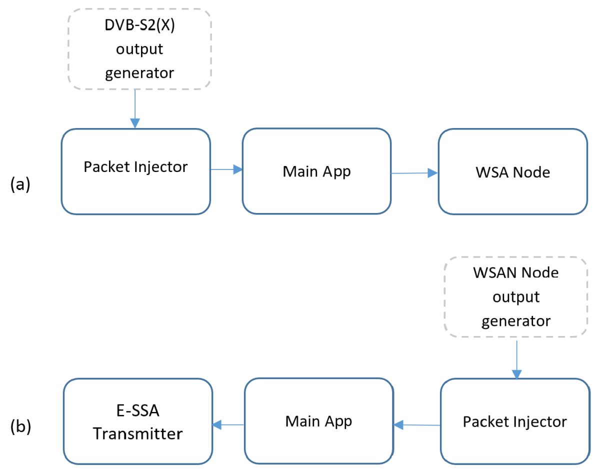

FIGURE 15. **Integration test architecture.**

The test results of the integration tests allowed the evaluation of the end-to-end processing latency of the gateway, the average value being 121 ms for 1000 data packets transmitted. This value increases to 688 ms if there are other packet requests in the processing queue. The higher value of processing time is motivated by the serial processing of requests. Therefore, if other requests are received (e.g. a request to return the data recorded by a sensor) when a control package is received (request to change the operating parameters of a particular WSAN), they will be processed first the requests already present after which the control package will be processed. The serial processing is sped up through a multi-threading implementation that was adopted to ensure parallel processing of client requests and data provided from WSAN (if at the time the application processes a request from a client, a WSAN node transmits data, they will be processed at the same time).

D. RECONFIGURABILITY TESTS

To ensure that the reconfigurability mechanisms are fully functional, a set of manual tests were performed. The focus was on uploading a new satellite module which would offer support for a different set of uplink/downlink protocols. As the modulator and demodulator implementations were already available for both DVB-S2X and E-SSA protocols, a protocol swap test scenario was defined and executed. First, the DVB-S2X receiver and the E-SSA transmitter were loaded on the first USRP. Then, the zip files containing the DVB-S2X Test transmitter and the E-SSA Test receiver were transmitted via the coax link to the device under test (Fig. 11). When the confirmation was received, that the modules were successfully installed, a new System Config file was sent to the device under test in which DVB-S2X was set as uplink protocol and E-SSA as downlink protocol. While the device under test was rebooting, the first USRP was reconfigured to use the E-SSA transmitter and the DVB-S2X receiver. After the reboot was completed, a control message was sent via the DVB-S2X uplink. It was observed that the sensor node reacted accordingly and that a confirmation message was received via the E-SSA downlink.

As for the timing, an overall reconfiguration performed with the new module available locally, took up to 10 seconds (including the time required for the configuration file to be sent over the satellite link). In case of a satellite link protocol reconfiguration, the overall duration was longer, especially for the case when the module for the desired satellite communication protocol was not available on the gateway. In this case the time required to upload the new module has to be taken into consideration. For example uploading a new module with a size of 1.5 Mb over a DVB-S2X link with MODCOD 1 (QPSK, 1/4 FEC, 400 kSym/s) selected will add an average of 6 seconds to the overall duration. Adding the installation time, configuration change and system reboot resulted in an overall duration of up to 25 seconds.

E. UNIT TESTS

The last functional tests performed were the unit tests which are needed to verify the proper implementation and functioning of the individual modules. We integrated the implemented software code both for the up- and downlink parts with the GitLab Continuous Integration / Continuous Development (CI / CD) environment and defined a suite of 70 automatic tests covering the key points of the component modules. The integration with the CI / CD environment ensured the automatic execution of the tests whenever a change in the source code takes place. A picture of the tested prototype, together with the WSAN nodes is presented in Fig. 16. We also tested the system with 20 real, physical nodes, and simulated a maximum workload with 5.000 nodes.

F. POWER CONSUMPTION

The power consumption of the gateway varies much as a function of the data that has to be translated from the terrestrial side to the satellite side and vice-versa. The gateway's consumption varies between 3 and 6 W depending on the performed tasks, reaching its maximum when simultaneously decoding the incoming signal and encoding and transmitting the outgoing signal. On top of this value, we need to add the COTS module with the highest power consumption, i.e. the WiFi module which has a maximum power rating of 1 W. adding all the variables, the mean power consumption is 4W and the maximum power rating is 7W. On the chosen Ettus USRP E312 platform with on-board 3200 mAh battery, that lead to an minimum autonomy of 2 hours.

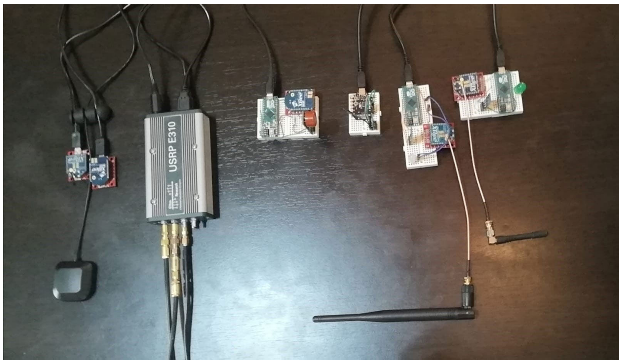

FIGURE 16. Gateway Prototype together with WSAN nodes.

VI. CONCLUSIONS

This paper presents a solution for satellite connectivity for IoRT applications, implemented on a single device that acts as a gateway between the terrestrial and the satellite sides. The main goal of the adopted implementation was to significantly lower the hardware and implementation costs, while assuring a high degree of re-configurability by using SDR technologies. Based on an initial requirements analysis, a generic architecture was conceived and subsequently implemented using a standalone SDR platform and COTS modules for covering the main terrestrial IoRT standards. To lower the implementation cost, the satellite up- and downlink was written in the FPGA of the SDR platform, leading to an overall CPU occupation of 82%. This left enough space for the programming of the control interface, local databases, HTTP server, MQTT brokers and all the other necessary software modules. The memory and CPU constraints of the chosen SDR platform led us to the use of COTS modules connected to the gateway by means of the serial USB interface for the terrestrial side.

The in-lab testing of the entire gateway validated the chosen architecture and the solutions used for its implementation on a low-cost, standalone SDR platform. Although preliminary and still in the "proof-of-concept" stage, the achieved results confirmed the correct and effective SDR-based implementation of the gateway functionalities and fully demonstrated the reconfiguration capabilities of the proposed architecture. The integration tests confirmed the reliability of the end-to-end information processing performed by the gateway in real-time. Finally, the unit tests validated the implementation and the functioning of the single SDR modules. To sum up, the proposed SDR-based IoRT gateway architecture can represent an interesting, innovative, prototypical realization that can be further on upgraded for future open-field testing, where a real satellite will actually support the remote connection. Future work will include the optimisation of the developed solution for reducing the occupation of the FPGA area and also for minimizing the overall delay. Other future work will include tests on the implementation using the new ETTUS E320 board and, alternatively, last generation SoC (System on Chip) devices combined with dedicated RF hardware, in order to lower the implementation costs even more.

ACKNOWLEDGMENT

The research activities presented in this paper fall within the field of interest of the IEEE AESS Technical Panel on Glue Technologies for Space Systems.

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In state of the art of mulsemedia assessments, ad-hoc systems were used rendering the effects. In [4], [9] and [11], a gaming console equipped with two fans and a vibrating bar was used to render haptic effects and the wind flow. The video was displayed on a 24" PC monitor and two loudspeakers with integrated RGB LED lights delivered the visual effects.

Yuan et al. deployed in [8] and [10] a software-controlled USB fan for airflow effect rendering, a scent dispenser with four types of scents as the olfaction renderer, and a vibrating vest from TN Games [16] for haptic effect.

The drawback of this kind of approach is the need for complete communication architecture to control the rendering devices, with obvious challenges regarding scalability and manageability. The main current approach for QoE evaluation is to map the Quality of Service (QoS) to QoE [17], [18] or to derive the QoE from the audio-visual services [19], [20], not taking into consideration any of the additional sensory effects. Another approach is based on the exponential interdependency between QoS and QoE (IQX hypothesis) [21]. This hypothesis is formulated with QoE and QoS parameters as an exponential function: if the satisfaction level decreases, the disturbance level increases. An exponential function was used because even a small disturbance can drastically decrease the satisfaction. In [22], another QoE model is introduced using a triple user characterization model, taking three dimensions into account: first, the sensorial quality represented by the content quality (i.e., sharpness, brightness, blurriness, number of artifacts, etc.); second is the perceptual quality that characterizes the amount of knowledge a user may acquire; finally, the emotional quality depicts the satisfaction in terms of emotional experience. This model mainly addresses adaptation and presentation issues and does not deal with the sensory effects.

The Pseudo Subjective Quality Assessment (PSQA) [23], is a hybrid approach between subjective and objective evaluations. The subjective assessment results are used to train a learning tool that computes the relationship between the parameters that are generating the video sequences distortion and the perceived quality.

The need for multi-sensorial media QoE models is an important challenge for the current and future research, since evaluating multi-sensorial media QoE using subjective methods is a task consuming significant time and generating supplementary costs. In our previous work [24] we examined the feasibility of an approach based on the IoT concept to render multi-sensorial media sequences in a real SH environment. A cloud-based IoT architecture was implemented using home custom devices.

This paper proposes a novel non-linear parametric model suitable for the estimation of QoE for mulsemedia TV applications. The proposed model can be used to predict the enhancement produced by adding sensory effects to conventional services and plan for mulsemedia delivery as new advanced service. Non-Linear Regression (NLR) [25] is used for the model validation. NLR models are usually employed when the relation between predictor and response has a particular functional form, depending on one or more unknown model parameters. The proposed model for the parameter estimation is based on the Particle Swarm Optimization (PSO) method, proved to be efficient for the optimization of non-linear problems [26], [27].

The remainder of the paper is structured as follows: Section II gives information on implementation and provides details on the experimental set-up used to assess the QoE. The QoE model is presented in Section III. The parameters estimation is discussed in Section IV, while the obtained results are presented in Section V. Final conclusions are drawn in Section VI.

II. Experimental Set-Up

The experimental set-up was based on the Recommendation of ITU-T P.913 [28]. The tests for the subjective assessment were conducted in the QoE lab of the University of Cagliari [29]. The lab, which is $4 \times 4 \times 2.70$ m (l $\times$ w $\times$ h), was furnished with a large sofa and parquet floor as shown in Fig. 2(a) to simulate as close as possible the feeling of a typical living room. For the implementation of the whole SH scenario, we employed a cloud IoT platform called Lysis [30], where the effects rendering devices are implemented as Virtual Objects (VOs) [31]. The overall architecture of the platform, organized on four layers [24], is presented in Fig. 1.

The bottom layer is the physical one, built of objects with Internet access. For this specific application scenario, these objects are electronic devices with processing capabilities and integrated peripherals (i.e., smartphones), or single board computers (SBCs) with switching capabilities (i.e., Arduino, or Raspberry Pi), able to manage the renderers. The physical layer links with the upper layers by means of standard communication methods (i.e., wireless or wired) and data protocols (i.e., HTTP and MQTT).

The Virtualization Layer is based on the concept of the virtual object (VO), as the digital counterpart of the real-world entity (RWOs). The VOs represent the RWOs in terms of semantic description and functionalities and have two interfaces, allowing on one side the VO to communicate with the aggregation layer, while on the other side representing the access point to the lower layer RWOs. For this specific architecture, the virtualization layer is implemented as a software driver installed on the RWOs.

The Aggregation Layer is responsible for combining data generated by one or more VOs, ensuring a high level of re-usability. The uppermost layer of the adopted architecture is the Application Layer, where user applications are used for the final data processing and presentation.

A. Test Equipment

The hardware deployed to implement the system consists of the following components, each one in charge for a specific sensory effect. The hardware was explained in detail in [24], here are briefly the main components and features of the set-up.

- An air conditioner (AC) wall split [32] employed as airflow effects renderer, controlled by an Arduino MEGA 2560 fitted out with an IR transmitter;
- A smart light system [33] (Philips Hue) placed behind the TV to emulate their integration with TV frame. The

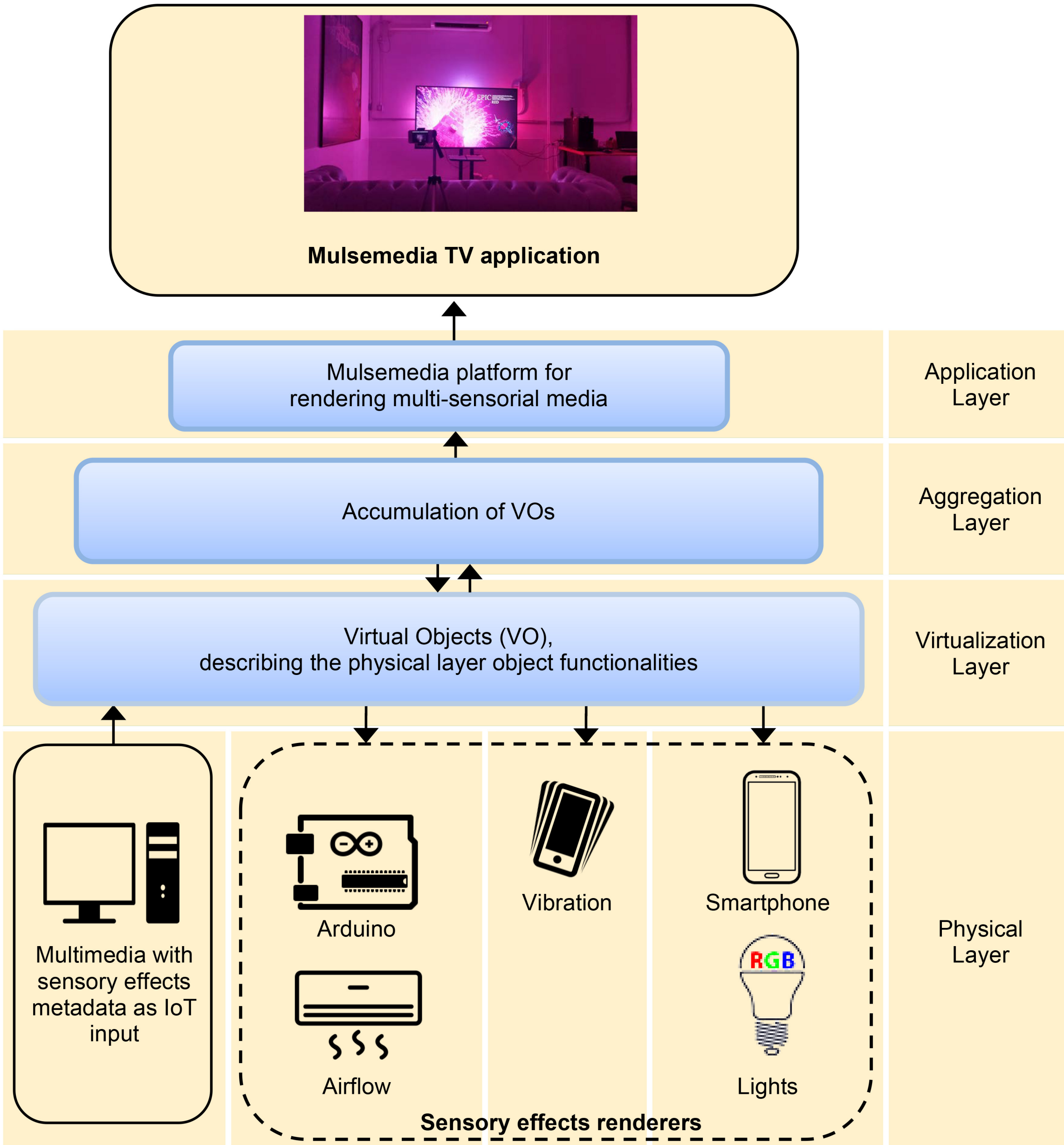


Fig. 1. Mulsemedia IoT architecture.

light effects are automatically extracted using an application running on a smartphone wirelessly connected to the lights. The smartphone is placed in front of the smart TV, performing real-time light effects extraction. The room was completely darkened during the tests;

- The display is a 60″ SAMSUNG TV UHD 4K Flat Smart TV. The distance between sofa and display is 1,86 m, representing 2.5 times the screen's height;
- The haptic effect is generated by the vibration feature of a smartphone. The test cohort held the phone in their hand, in their pockets, or placed beside them on the sofa;
- The media renderer is a multimedia PC connected through a HDMI cable to the TV, running the video content annotated with the sensory effects.

We took into consideration that the air flow effect strongly depends on the distance between the AC fan and the sofa. Literature studies revealed that haptic media can be presented with a delay up to 1 second behind the video content to be acceptable for most of the users [38]. We calculated the delay in the activation time of the AC fan in order not to impair the overall QoE. and released the airflow 5 seconds before the video content [39] to achieve an acceptable QoE level.

B. Subjects

The assessment cohort was based on 40 participants from various backgrounds (30 males and 10 females) with ages between 22 and 50 years (45% between 20 and 30 years, 35% between 30 and 40 years, 20% between 40 and 50 years), and an average age of 31. Only one assessor participated in a similar assessment. Information regarding

(a) (b)

Fig. 2. Test environment (a) QoE lab (b) Test environment during the assessment.

to participants education, age, gender, and occupation was collected.

C. Methodology

The Absolute Category Rating (ACR) method [28] was adopted for this assessment. We based the rating scale used is on the Likert scale as defined by the ITU-T Rec. P.913, with 5 levels labelled as: bad, poor, fair, good, and excellent. Each participant was seated on the sofa in front of the AC situated on the wall above the smart TV (Fig. 2a). The video test sequences, with a duration between 21 and 32 seconds, were shown in a random sequence, interleaved with a sequence of 5 seconds of grey screen, to allow the assessors to rate the previous sequences. Furthermore, in our assessment the duration of the sequences was increased to more than the 10 seconds defined by the ACR method, in order to accommodate multiple sensory effects.

In the first part of the assessment, the participant was orally briefed on the assessment procedures and the rating scale. To reduce the total number of sessions, two participants per session were. Fig. 2(b), shows the test environment used during the subjective assessment. The entire subjective evaluation had a duration of approximatively 20 minutes.

D. Mulsemedia Video Sequences

The participants had to watch 40 multi-sensorial video sequences from the sensory effect dataset [35] downloaded from Sensory Experience Lab [36], coupled with three additional sensory effects: light (L), airflow (A) and vibration (V). Effects were also combined, creating seven different test cases: L, A, V, $L + A$, $L + V$, $A + V$, $L + A + V$. Each video sequence was also presented without any sensory effects.

The L effect can be extracted in an automated manner directly from the video content as previously described. The V and A effects cannot be extracted in real-time, so they had to be a-priori annotated to each video sequence using the SEVino video annotation tool [37], as illustrated in Fig. 3. The

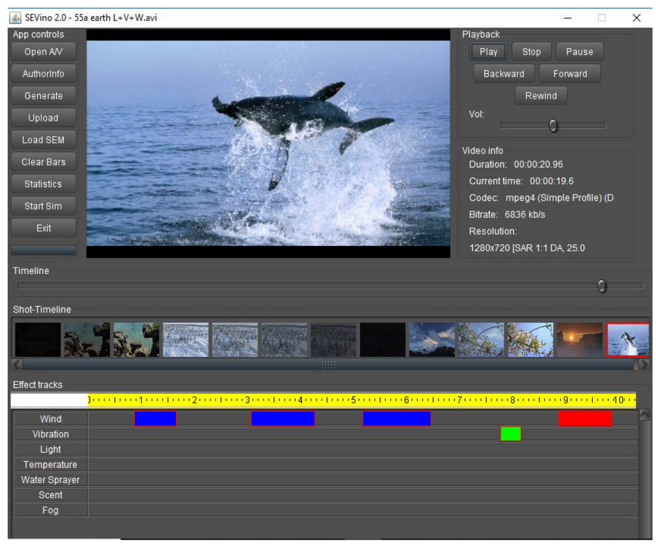


Fig. 3. Video annotation tool (SEVino).

PlaySEM SE and SER software packages [38] are deployed for video playback and effects rendering.

Fig. 4 shows a snapshot from each video sequence (2012, Berrecloth, Bridgestone, Earth, and Pastranas). The video sequences were chosen from more categories such as sports, action, documentary and commercial. Table I gives an overview for each mulsemedia sequence in terms of resolution, bitrates, duration, category, and the video scenario.

E. Questionnaire

The participants were asked to describe their multi-sensorial experience after viewing all the multi-sensorial sequences. The questionnaire comprised questions related to the participants' perception of mulsemedia. Participants were asked to rate their response, to investigate the impact of multi-sensorial media in terms of:

- improvement of the overall sense of reality;
- the impact of annoyance of each sensory effect on the user experience;

Fig. 4. Snapshot from each video sequence (a) 2012 (b) Berrecloth (c) Bridgestone (d) Earth (e) Pastranas.

TABLE I
VIDEO SEQUENCES LIST

Video Sequence	Resolution	Bit-rate (Kbit/sec)	Category	Duration (sec)	Effect	Scenario
2012	1280x720	2186	Action	30	L,A,V	earthquake, tornado
Earth	1280x720	4116	Documentary	21	L,A,V	wind, animal jump
Berrecloth	1280x720	3552	Sport	32	L,A,V	downhill cycling on rocks
Bridgestone	1280x720	2421	Commercial	30	L,A,V	windy weather, car moving
Pastranas	1280x720	2619	Sport	32	L,A,V	rally

- the impact of the intensity of each sensory effect on the user experience;
- the impact of sensory effects on user enjoyment.

III. QoE Model for Mulsemedia Applications

As stated in the introduction, the topic of mulsemedia QoE models is currently a challenging topic, due to the time and cost of subjective quality assessments.

We propose here the following model for QoE for mulsemedia TV applications in a smart home environment:

$$Q_oE_{Muls} = Q_oE_{Mult} * \delta * exp\left(\sum w_i * b_i\right) \tag{1}$$

where Q_OE_{Mult} is the multimedia QoE, (i.e., the audio and video content quality), w_i is the weighting factor for each sensory effect (i.e., light, vibration, or airflow), b_i is a boolean variable used to indicate the presence or not of the sensory effect, and δ is for tuning. The model is validated using the subjective assessment data (MOS). In our assessment, three sensory effects were used: light (L), airflow (A) and vibration (V); the effects were also combined. This model appears as a good compromise between accuracy and complexity.

The specificity of this work is that the effects renderers are deployed in a SH environment using only custom devices. These SH devices are connected to the IoT hence are accessible and can be added to the smart TV to enable a multi-sensorial experience.

IV. Model Parameter Estimation Using Particle Swarm Optimization

This section describes the implementation of PSO to estimate the optimal values of the parameters in the proposed model. The PSO is a self-adaptive search optimization technique, consisting of a set of solutions (particles) called population. Each solution is characterised by a set of parameters and can be represented by a point in a multidimensional space [26].

Initially, based on preliminary tests, we defined the swarm size p (i.e., number of particles = 20), and the maximum number of iterations, $t\_max = 200$. The independent variables V, L, and A represent vibration, light, and airflow effects, and the dependent variable y represent the Q_OE_{Muls}, whereas the outcome of the PSO will be the MOS. In the proposed model the influence of the independent variables (i.e., effects) on the dependent variable (Q_OE_{Muls}), is represented by the coefficients w_L, w_A, w_V. The position of each particle and its velocity within the swarm are denoted by y_j, and v_j, respectively, where the index j is the particle number. For each particle at the 1^{st} iteration ($k = 1$), the initial values of velocity $v_j{}^1$, weights $w_{Lj}{}^1$, $w_{Aj}{}^1$, $w_{Vj}{}^1$ and position $y_j{}^1$ are randomly selected. Particles are moved iteratively to find the new position in the search space dimension.For each of the k iterations the fitness value f_j is calculated as the difference between the previous and the current position. Then, the best location

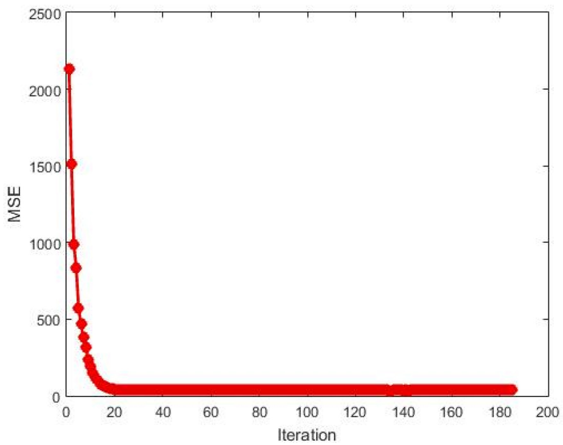


Fig. 5. The convergence of MSE for the PSO algorithm.

visited by each particle ($pbest_j{}^k$), and the best position in the whole swarm ($gbest^k$) is determined. Therefore, if the value of $f_j{}^k$ is greater than the biggest f_j ($pbest_j{}^k$) in history, then it is used as the new $pbest_j{}^k$, the particle with the best fitness value achieved among all particles in the swarm is selected as the $gbest^k$. Particles update their velocity based on the following equation [43]:

$$v_j^{k+1} = I * v_j^k + c_1 * r_1 * \left(pbest_j^k - y_j^k\right) + c_2 * r_2 * \left(gbest^k - y_j^k\right) \quad (2)$$

where $v_j{}^k$ and $v_j{}^{k+1}$ are the current and updated particle's velocity, I is the inertia weight which is a constant $= 0.02$ based on preliminary tests, r_1 and r_2 are random variables in [0,1], c_1 (self-confidence factor) and c_2 (swarm-confidence factor) are constants values equal to 2 as recommended by [43] and [44].

The cognitive component term $pbest_j{}^k$-$y_j{}^k$, represents the best solution found by each particle. The social component term $gbest^k$- $y_j{}^k$ is referred to the best solution in the whole swarm.

At the iteration $k + 1$, the weights $w_{i,j}{}^k$ are updated for each particle, where $i\epsilon\{$vibration (V), light (L), and airflow $(A)\}$. The new updated weights values $w_{i,j}{}^{k+1}$ are calculated using to the following equation:

$$w_{i,j}^{k+1} = w_{i,j}^k + v_j^{k+1}, \ j = 1, \ldots, p \quad (3)$$

Then, for each particle the new updated weights $w_{i,j}{}^{k+1}$ from equation (3) are substituted in (1) to compute the new position $y_j{}^{k+1}$. Each individual particle keeps searching for the individual and global best position based on updating the velocities. This process continues until the optimal parameter values of the proposed model are achieved or the maximum iteration number t_max is reached. The process of the PSO algorithm is summarized in Algorithm 1. To ensure the algorithm achieve convergence preliminary tests on the PSO had been run, the final convergence of the model presented in Fig. 5.

The estimated parameters value (the weights w_i) for the proposed model are shown in equation (4).

$$Q_oE_{Muls} = Q_oE_{Mult} * exp(0.117 * b_L + 0.049 * b_A + 0.074 * b_V) \quad (4)$$

Algorithm 1 PSO Algorithm

```
Inputs:
    Dataset((Lm, Am, Vm), y),    test cases(m:1 → 7)
Initialize:
    p, t_max, c1, c2, and I
for j : 1 → N do
    Initialize:
        y_j^1, v_j^1, w_Lj^1, w_Aj^1, w_Vj^1
end for
while optimum parameter values or t_max is not attained do
    for j : 1 → N do
        K : 1 → t_max
        compute y_j^k
        compute f_j^k
        if f_j^k < f_j^(k-1) then
            p_bestj^k is set to the current location
        end if
        gbest^k = best particle in the whole swarm
        for j : 1 → N do
            compute v_j^(k+1), w_Lj^(k+1), w_Aj^(k+1), w_Vj^(k+1)
            compute y_j^(k+1)
        end for
    end for
end while
```

In the subjective assessment the Q_OE_{Mult} is assessed by presenting the reference video sequence without sensory effects. In production systems, this may not be possible, so the Q_OE_{Mult} can be assessed from existing QoS models [17], [21], [22], [45] and estimating the Q_OE_{Mult} from QoS parameters [38].

The results of the subjective assessment allowed us to derive a non-linear exponential model for the prediction of the QoE of mulsemedia content for TV applications on smart home scenario.

V. Results

This section analyses the cumulated impact of multi-sensorial media on user experience, by taking into consideration the impact of each sensory effect derived from the post-experiment questions. 8 outliers had been detected from the 40 participants, according to the procedure described in [28] and [29]. Fig. 6 to Fig. 10 show the subjective MOS test results and Confidence Interval CI (95%) for the mulsemedia sequences, with eight different configurations. The following sections analyze the influence of each of the sensory effects on the perceived experience.

A. Impact of the Combined Sensory Effects on User Experience

This section presents the combined impact of mulsemedia on user experience through analysis of the impact that each sensory effect (light L, airflow A, vibration V) has on the user, which had to answer to the following statements:

- if the sensory effects (L, A, V) are annoying.

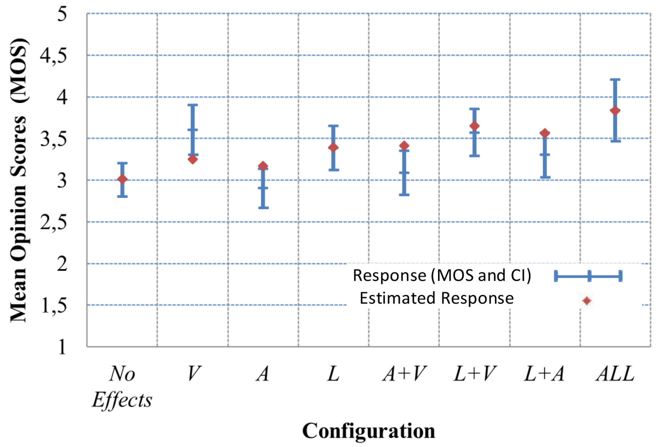


Fig. 6. The model estimated response and the MOS for the action sequence “2012”.

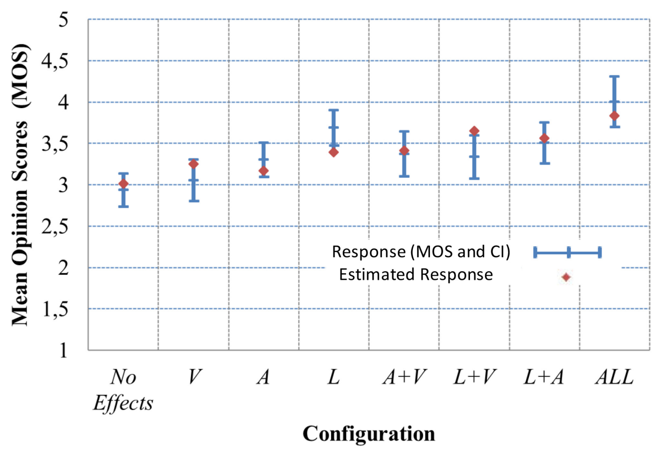


Fig. 7. The model estimated response and the MOS for the documentary sequence “Earth”.

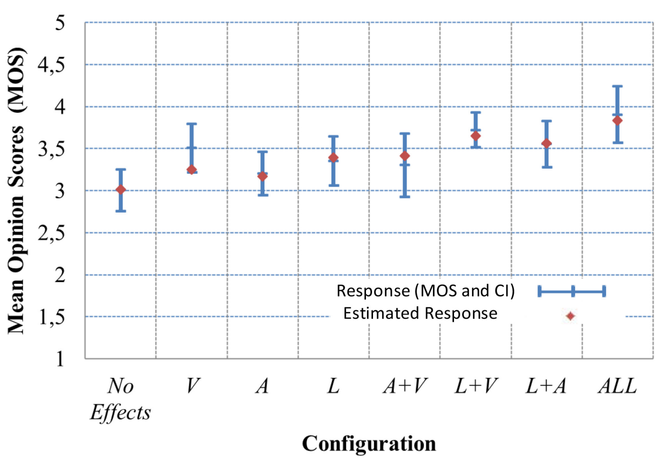


Fig. 8. The model estimated response and the MOS for the sport sequence “Berrecloth”.

- the sensory effects (L, A, V) enhance the sense of reality.
- if the intensity of each sensory effect (L, A, V) is too weak, weak, fine, strong, too strong.
- if the multi-sensorial media is enjoyable.

Each participant watched 40 video sequences from different categories with different configurations. 4 of these

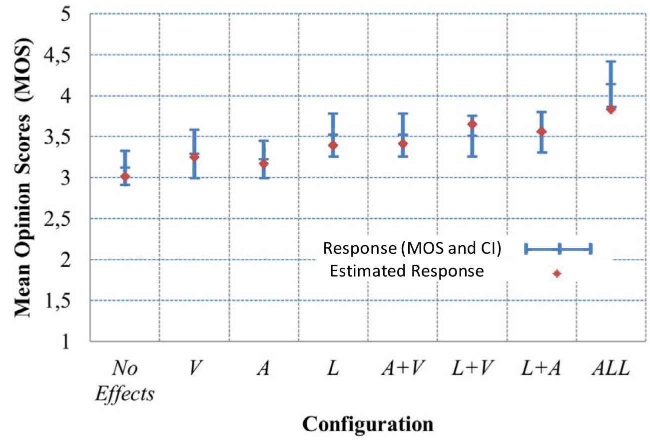


Fig. 9. The model estimated response and the MOS for the commercial sequence “Bridgestone”.

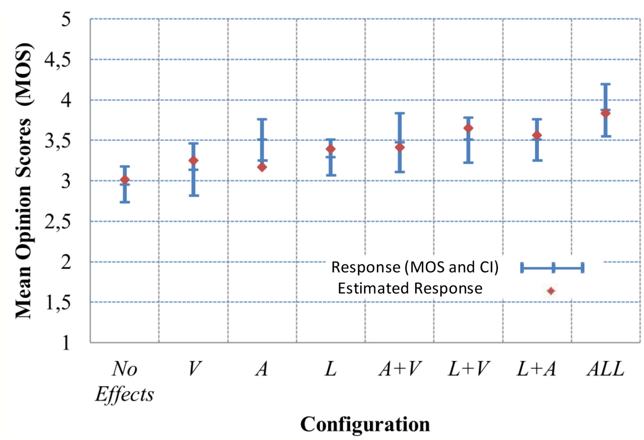


Fig. 10. The model estimated response and the MOS for the sport sequence “Pastranas”.

configurations contain light effects (L, L + A, L + V, L + A + V), 4 configurations with airflow, as well for vibration effect as shown in Fig. 6 to Fig. 10. These figures will be subsequently commented in Section V-B.

1) Impact of the Light Effect on User Experience: The participants were asked to give their opinion regarding the annoyance of light effect, i.e., if the light enhances the sense of reality, and the intensity of the light effect, as shown in Fig. 11. User opinions provided as answers to the questionnaire regarding to the impact of light effect in the experiment gave the following results: 95% of the participants were not annoyed by the light effect, 2.5% had neutral opinion, and 2.5% were annoyed by the light effect. Regarding to the sense of reality, 85% of the participants agreed and strongly agreed that light effect enhances the sense of reality, 10% had neutral opinion, and 5% felt that light effect did not enhance the sense of reality. Finally, the participants opinion about the light intensity during the assessment was the following: 72.5% found the intensity fine, 22.5% felt it was strong, and 5% found it weak-too weak intensity.

2) Impact of the Airflow Effect on User Experience: The influence of the airflow effect on the perceived sense of reality, annoyance, and intensity were collected, and displayed in

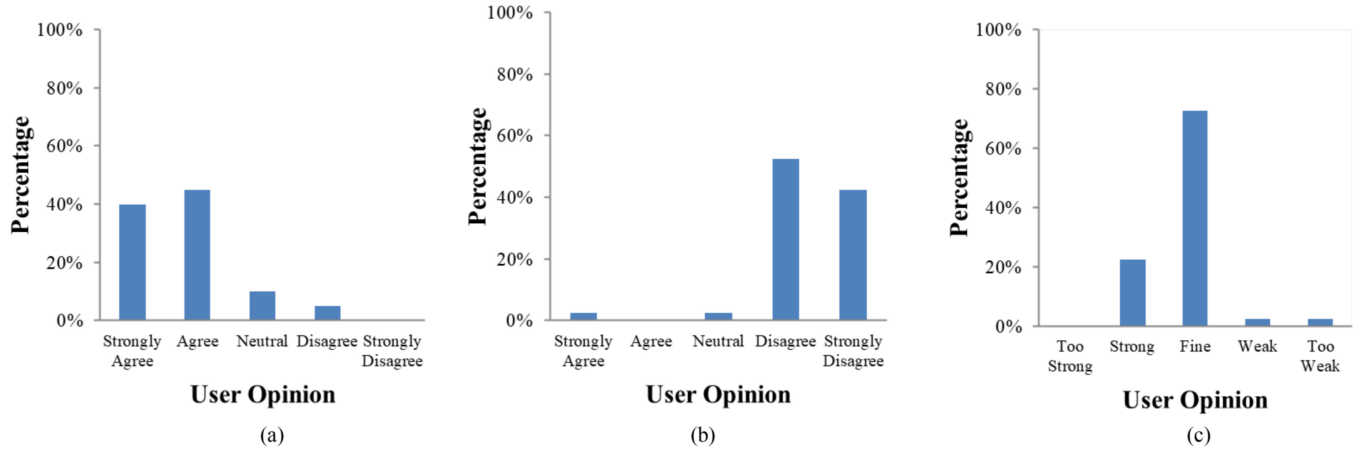


Fig. 11. User response to the impact of light effect (a) Light effect enhances the sense of reality (b) Light effect is annoying (c) The intensity of light effect.

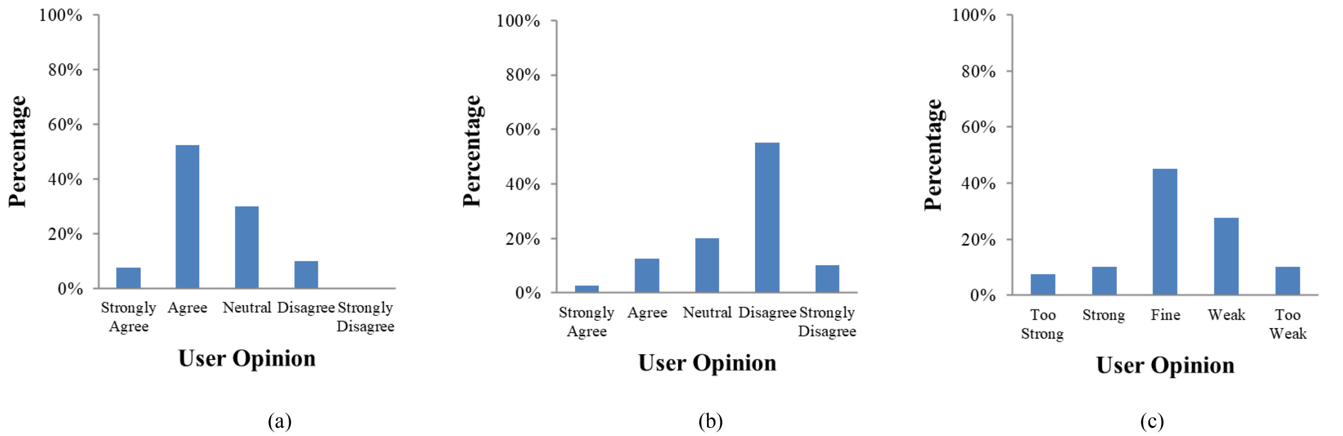


Fig. 12. User response to the impact of airflow effect (a) Airflow effect enhances the sense of reality (b) Airflow effect is annoying (c) The intensity of airflow effect.

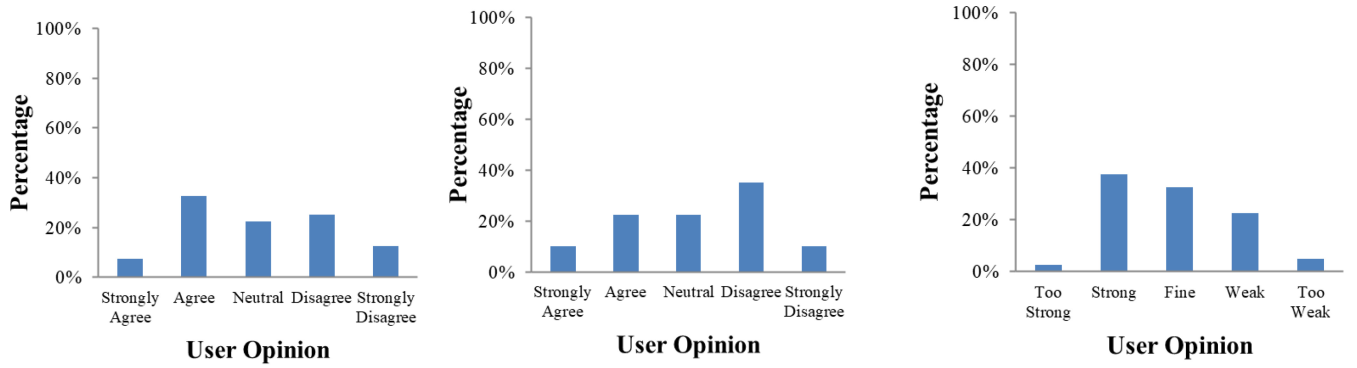
Fig. 12. The majority of the participant (60%) felt that the airflow enhances the sense of reality, 30% had neutral opinion, and 10% did not feel the any enhancement. The response to the annoyance of the airflow effect indicates that 65% of the participants were not annoyed, 20% had neutral opinion, and 15% were annoyed by the airflow effect.

The impact of airflow intensity on user experience was the following: 45% of the participants felt the intensity to be fine, 17.5% found "strong" as too strong, and 37.5% found the intensity "weak" as being too weak.

3) Impact of Vibration Effect on User Experience: User opinions regarding the impact of vibration effect are shown in Fig. 13. Most of the participants (40%) agreed and strongly agreed that the vibration effect enhances the sense of reality, 22.5% had neutral opinion, and 37.5% disagreed. Regarding to the annoyance of vibration effect, 45% of the participants did not consider the vibration as annoying, 22.5% expressed a neutral opinion, and 32.5% found it annoying. The users' opinion on the vibration intensity indicates that 40% found "strong" as too strong, 32.5% felt it as fine, and 27.5% felt it too weak.

4) User Enjoyment and Satisfaction: User enjoyment is important to indicate the quality of experience. The results from the study presented in [10] showed that 70% of the assessors consider haptic and airflow effects enhance user enjoyment levels. In our assessment, results obtained from the question "I enjoyed multi-sensory experience" indicated that 80% enjoyed the multi-sensorial media, 12.5% had a neutral opinion, and 7.5% did not enjoy the mulsemedia experience (Fig. 14). The impact of the effect type on quality of experience variation is shown in Fig. 15, which can be considered as an improved impact compared to the state-of-the-art study [39] as shown in Fig. 16, in which sensory effects renderers are ad-hoc devices. The main disadvantage of these applications is the architecture used for controlling the renders, developed only for specific devices. The results from our assessment reveal that each effect has a higher impact on user opinion, the same for the combination of all effect together. In an SH environment, the user preferences can be saved by the IoT architecture, and the devices settings can be adjusted accordingly, to improve the user experiences through delivering personalized services and increasing user enjoyment and satisfaction level.

The estimated responses by the model for all the sequences are shown in Fig. 6 to Fig. 10. Most of the responses are inside the confidence interval (95%) of the subjective quality evaluation. The model response is also close to the average of the MOS. The MOS without sensory effects is lower



(a) (b) (c)

Fig. 13. User response to the impact of vibration effect (a) Vibration effect enhances the sense of reality (b) Vibration effect is annoying (c) The intensity of vibration effect.

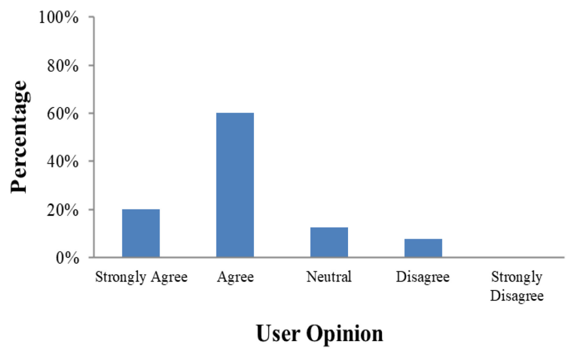


Fig. 14. Percentage of user enjoyment.

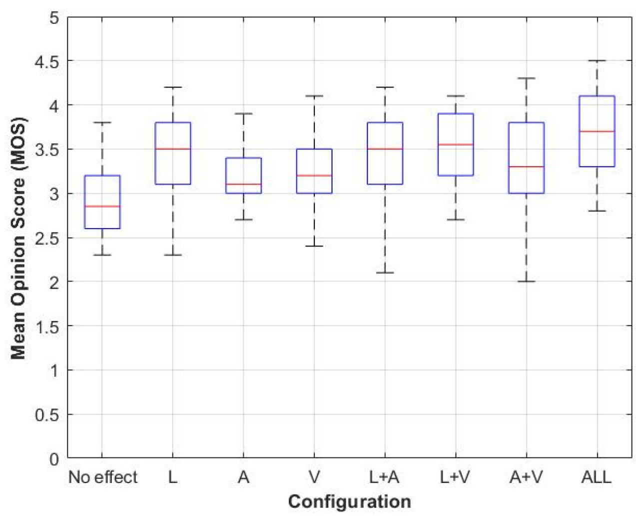


Fig. 15. MOS response and the impact of each effect on the response.

than the MOS with sensory effects in all configurations for all video sequences. The sensory effects impact on the MOS varies based on the category and contents of the sequence. For example, in the "action" category, the vibration effects were the most appreciated effect by users. For "documentary" and "commercial" categories, light was the most preferred effect. For the "sport" category, the vibration effect was the one with the highest impact, specifically for the "Berrecloth" sequence, containing scenes downhill bicycle rides. On the other hand,

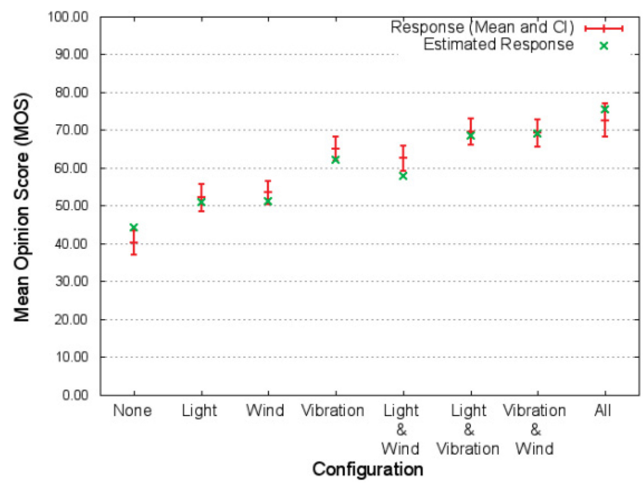


Fig. 16. MOS response and estimated response from user study [39].

for the "sport" sequence "Pastranas", the airflow effect was the preferred effect by users. The impact of the combinations of sensory effects ($L + A$, $L + V$, $V + W$) is either lower than or equal to the impact of an individual sensory effect, though the combination of all effects together has the highest impact on the MOS.

The relatively low MOS score (3) for the case where no effect is added can be motivated by the fact that the order of presentation of the sequences was random, and therefore the sequences with no impairments could have been evaluated after the ones with effects and the evaluators have considered an overall MOS lower, considering positively the multisensory effects to the overall QoE and thus reducing the MOS of the sequences with no effects.

The proposed model performance compared to other mulsemedia QoE models performance [39], [40]. The performance comparison is in terms of means square error (MSE) for two different empirical dataset MOS from two different subjective assessments. Fig. 17. Shows the MSE of the proposed model compared to the other models using the subjective assessment data MOS from our assessment, the proposed nonlinear (exponential) model allows obtaining an improvement of 11.83% compared to the power model presented in [40] and 55.27% compared to the linear model proposed in [39].

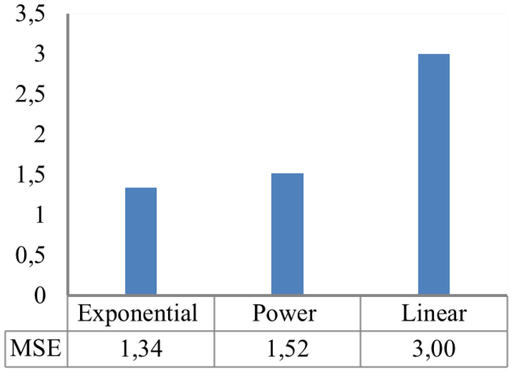


Fig. 17. Models performance comparison in term of MSE using our assessment dataset.

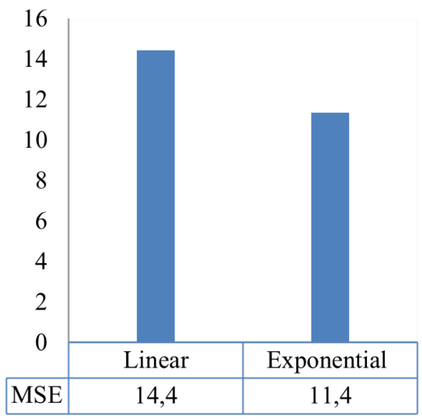


Fig. 18. Model performance comparison in term of MSE using the MOS presented in [39].

Finally, the proposed model performance compared to the linear model [39] performance utilizing the empirical dataset MOS from the subjective assessment presented in [38] is shown in Fig. 18.

B. Validation

Considering the novelty of the proposed QoE model, we repeated the MOS test with a different set of participants in very similar testing conditions at the QoE Laboratory of Transilvania University of Braşov, Romania.

The laboratory has similar dimensions, and, to closely replicate the conditions from the initial training phase, we used the same screen size for the TV set and same distance from the couch to the screen and to the AC fan.

A number of 43 participants have been invited to this assessment (14 females and 29 males), between 20–60 years old, (50% between 20 and 30 years, 35% between 30 and 40 years, and 15% between 40 and 60 years), with the average age 28 years. None of the assessor participated in a similar assessment campaign.

The background of the participants was mixed, being composed in a balanced manner from both technical students and researchers (from the Department of Electronics and Computers) and humanist students and researchers (from the Departments of Social Sciences).

In this case, 6 outliers where identified (<14%). A further analysis, on the outliers in both measurement campaigns show that the majority of them were older people (> 45 years). This is in line with the reduction of the percentage of outliers in this second test assessment procedure, where the percentage of older assessors was reduced. It seems that the multisensorial feature is more shocking for older people that have reacted out of the statistical mean and variance of the rest of the population. The result obtained in this validation phase were very similar in terms of measured MOS, falling into the confidence interval (95% just like in the training phase) as to confirm the effectiveness of the proposed model.

VI. Conclusion

This paper presents the results of the subjective assessment conducted for mulsemedia TV applications in a SH scenario with real custom devices (e.g., air conditioning, lights, etc.). The impact of light, vibration, and airflow effects on user experience was analyzed in terms of enhancement of the sense of reality, impact of annoyance, user response to the intensity of the effects, and user overall enjoyment. Most of the participants (80%) enjoyed the mulsemedia experience with the three effects. Furthermore, most of the assessors (85% for light effect, 60% for airflow, and 40% for vibration effect) felt that sensory effects enhance the sense of reality. 95% of the participants did not experience any annoyance because of the light effects, 65% for airflow, and 45% for vibration effects. In addition, results show that users globally assess the intensity of the sensory effect during the assessment as fine (72.5% for light effect, 45% for airflow, and 32.5% for vibration).

A parametric QoE non-linear model for mulsemedia in a SH scenario has been instantiated and validated in a real SH environment, through two MOS assessment campaigns. The proposed model considers the number of effects and their impact on the QoE and has been instantiated with three sensory effects (light, airflow, and vibration), with further effects that can be added without changing the model. The subjective assessment results applied to the audiovisual sequences, selected from the category action, sport, documentary, and commercial, will reduce the need to conduct further subjective quality assessments to assess how the model performs in other categories. As for the result achieved, the proposed model can provide satisfactory accuracy in the estimation of the QoE on mulsemedia applications and can enhance the estimation accuracy compared to the models currently presented in the literature.

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From Things to Services: A Social IoT Approach for Tourist Service Management

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ABSTRACT In the context of Internet of Things (IoT), the cooperation and synergy between varied and disparate communicating objects is strained by trustworthiness, confidentiality and interoperability concerns. These restrictions can limit the development of IoT-based applications especially considering the emergent boost in the number of communicating objects and their growing itinerant nature in a collective service context. A new perspective arises with the paradigm of Social Internet of Things (SIoT), that relies on the implementation of semi-independent communicating objects with cooperation assessed by social relations and social feed-back. In this article, we present the development and expansion of the IoT concept towards SIoT in the context of the interactions between tourist services as communicating objects. As a proof-of-concept we propose a composition of services as virtualized social objects and the interaction between them, by taking into consideration the balance, trustworthiness, cooperation and synergy of services. Furthermore we present a solution to integrate also accessibility in SIoT services. The presented concept is presented using a demonstrator build for tourist services.

INDEX TERMS Enhanced accessibility in SIoT, socially active virtual services, services as virtual objects, socially aware trustworthiness, the social Internet of Things, tourist service management.

I. INTRODUCTION

The advancements in communication technology has been dramatic in the last decade. The increase of data traffic and sharing has changed the scenario where beside humans also objects have been allowed to be part of the play. The Internet of Things (IoT) concedes any device which can be uniquely recognized to interact with a user. The interactions and connections between the devices and their users can be largely intricate [1], requiring new concepts for the management, trustworthiness and the interaction hierarchy [2]. The new ''social'' paradigm added to the IoT (Social IoT - SIoT) concept means applying a social structure to the things by mapping natural social links to the digital space. In this perspective, data science become fundamental to enable reliable communications for trusted and secure data sharing.

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The social cooperation among people follows the interaction among them and defines the connection that unites them. The type of connection mirrors the social link among the interlocutors, and the strength of kinship that binds them. It can strongly influence the nature of their interactions [4]. The SIoT allows devices to exploit the social interactions and links among humans to achieve reliable navigability. The SIoT can be expanded beyond the original IoT boundaries, to extend the benefit of the paradigm as to include, besides things, also services, creating an extended applicability in social strategy for highly effective mobile marketing [3]. In the service scenario of SIoT, the end user does not intervene in the process of things, but only gets the service it needs at the end of the chain, the intermediate steps being taken away from the organizational complexity [5]. The potential applications can be extended to all areas, such as environmental management, inventory, home automation, surveillance, tourist services and so on [6], [7].

The interest for the advancement of the knowledge of the developed service models lies in the use of the SIoT paradigm that was so far aimed only at the modeling of physical objects through virtualization, identifying social relations, oriented to services to their virtualization and their dynamic composition based on rules of social interaction [8]. The main novelty of the present paper consists in the translation of the Social IoT paradigm from things to services, enabling the services to exploit social links and interactions of humans so as to achieve reliable feedback and navigability. As far as the author's knowledge, this approach is new in the SIoT theme, and simulations or implementations are not yet covered by scientific studies. By putting services in a social relationship, the SIoT paradigm can change orientation, from an approach focused on the objects on which the most recent studies and implementations have been concentrated, to an approach oriented towards the application the and user.

An interesting application field for the SIoT paradigm can be the management of tourism and cultural heritage, which nowadays is still anchored to a traditional approach that has consequences on the mobility and travel sector, in consideration of the change in habits towards a growing independence of the tourist, with increasingly "social" and "digital" behaviors [9]. To overcome these problems, a SIoT approach can be adopted to allow tourist and cultural heritage services to interact dynamically with the end users. The "social" concept, promoted among others by Twitter, Facebook and Instagram, applied to tourist services, would allow these services to become intelligent, cooperating social entities, capable of interacting with each other and with end users using the now daily rules of "digital friendship" [10]. Using these forms of socialization, the relationships between services can evolve towards autonomous structures that maximize the benefits in terms of research and filtering, managing their reliability and the data on which they are based [11].

The main objective of this paper is to create the models and methodologies for cooperative services based on the concept of social interaction between users and services and between the services themselves. These models and methodologies are based on the SIoT paradigm and the related interaction methods, extended from the world of objects to that of services [12].

The specific objectives of this work are the enhancement of service trustworthiness, composition and social interaction and the development of a demonstrator on a SIoT platform for the dynamic composition of services for the tourist and cultural heritage sector. The paper is structured as follows: section II presents the related work and introduces also the concept of services as virtual objects, section III describes the architecture used for the dynamic composition of services, while section IV discusses the parameters for the trustworthiness of the services. Section V is dedicated to the implementation of the demonstrator and section VI draws the conclusions and presents the future work to be done.

II. RELATED WORK

The myriad of smartphones, with their increasing capabilities, boosted up and complemented by the new 5G networks, can boost applications in many domains, allowing enhanced correlation between the user surrounding context and the applications based on the context-awareness in smart systems [13].

In [14] Kasnesis *et al.* introduced the use of smart software agents in order to enable SIoT in the Cloud and to define smart objects profile and life cycle using semantic rules and embedded descriptive files. SIoT applications come with some intrinsic problems in terms of navigability, search response time and link selection [15]. The latter SIoT problem is tackled in [16] using algorithms that follows the key properties of navigability in so-called "Small World" networks for enhancing object navigability in the SIoT by restricting the number of connections for objects. Another approach for enhancing navigability is an enhanced information searching algorithm for SIoT [17] inspired on information searching algorithms from drone networks [18]. Within this context, the authors of [19] investigate the search of suitable friendships and requested services in the SIoT world without human involvement, so typical for an SIoT scenario.

The evolution of cooperative services and the social interaction between users have in a certain sense "opened the borders" also from a tourism point of view: travelers have now the possibility to choose the destination in advance, to study the best solution according to their journey type (transportation means, choice of accommodation, food, entertainment, etc.) thanks also to the experiences of others and, at the end of the experience, to provide their opinion [20] as a feedback. Digital platforms for tourism such as Tripadvisor and Booking classify tourist facilities based on the reviews of their users, providing their clients with a parameter for assessing the reliability of the requested service.

Following the same principles, Wise *et al.* are presenting a concept of developing smart tourism destinations and its potential for smart cities and are outlining the need to integrate social media and content marketing concepts in the emerging smart tourism paradigm [21].

The willingness to share information by tourists and their "social" vein is most of the times misaligned with the reduced knowledge or even unawareness by the tourist service providers (especially the institutionalized ones) of the benefits that a certain type of networking could bring in terms of visibility [22]. Diversification based on demand and on different categories of users would open new market segments that could also guarantee benefits in terms of seasonal adjustment of demand. End-user satisfaction inevitably passes through the quality of the service offered and for this reason the service provider must always be present, competent and available, and to ensure that he is active also in a "social" key [23].

Forging direct relationships with end users is the first step in involving users in the destination promotion process. In this

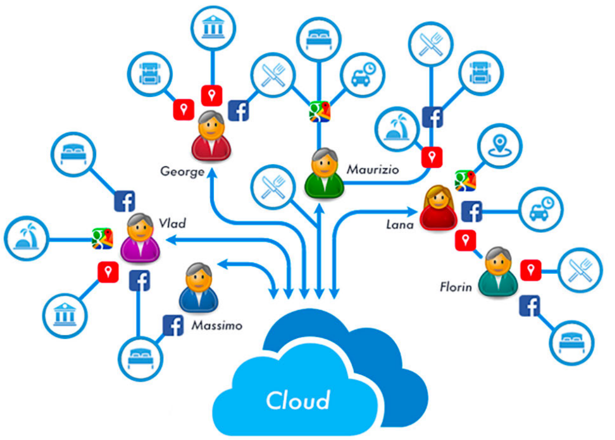


FIGURE 1. Diagram of SIoT architecture.

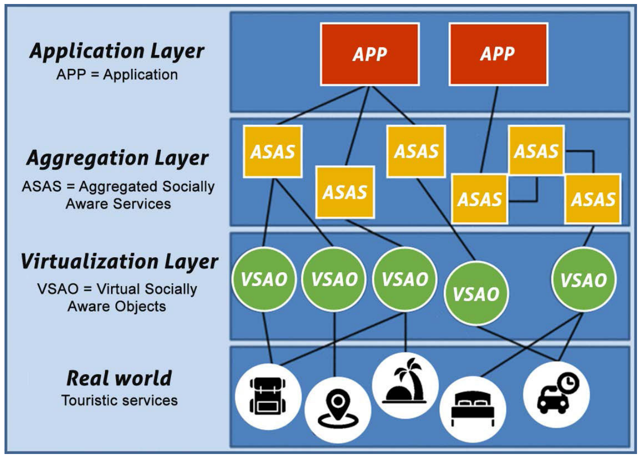


FIGURE 2. Functional levels of the proposed architecture: Real World, Virtualization, Aggregation and Application.

direction, a wide range of frameworks and digital implementation of the SIoT concepts have been recently proposed to strengthen the sustainable mobility in tourism development based on proactive participation of tourists, local citizens and city administration to enhance safety, reduce fraud and the lack of feed-back and availability of proper information about resources and tourist attractions [24], [25].

Despite the evolution in this field, the synergies between the various tourist services are still weak and unable to exploit the vast possibilities offered by the new technologies. The management of tourism and especially cultural heritage is in fact anchored to a traditional approach, based on the dissemination of information in both printed and digital form, but which generally does not allow exploiting all the new applications available for mobile devices and, above all, does not take into account the greater information content that could be generated by the sharing and interaction between end users [26].

Therefore the need emerges for a new, transversal approach based on technological innovation for the distribution of tourist services. Furthermore, technological innovation could also permeate the cultural heritage sector, a primary source for tourism, where, however, the obsolescence of supply models compared to private tourism makes the development path more tortuous and complicated.

III. ARCHITECTURE

The SIoT architecture for the dynamic composition of services is composed of 4 functional levels: the lower level is formed by real-world services, which are digitized in the level of virtualization above. This second level consists of Virtual Socially Aware Objects (VSAO) that represent the abstraction of a real world service in terms of functionality and contextual information [27]. The third level, aggregation, is responsible for combining one or more VSAOs in order to create entities with increased functionalities called Aggregated Socially Aware Services (ASAS) that can inherit all or part of the functionalities of the VSAOs from which they are composed. The last level is the application level where the macro services for users are composed [28]. By macro service we mean a service formed by the composition of the services provided by the ASAS and represents the service as perceived by the user. The social behavior in virtual socially aware objects is implemented through the Socially Aware Parameters (SAP) extending the functionality of the VSAO with enhanced trustworthiness and management [29].

The presented architecture allows the abstraction of real world services as virtualized objects that can be combined, once registered on the platform, in a static or dynamic manner using models of social relations and socially aware parameters. The "social" functions of the platform can be used both for the composition of new entities, and for the smart interaction between various VSAOs through trustworthiness and recommendation mechanisms.

By modeling tourism services and cultural assets as VSAOs, it is possible to study the relationships between services and their evolution towards autonomous structures that maximize the benefits in terms of search, management and exploitation of the data on which they are based [30]. In doing so, tourism services may be able to interact socially with users and among themselves in an enhanced and smart, socially aware manner.

IV. SOCIALLY AWARE TRUSTWORTHINESS

A. ESTABLISHING SOCIAL INTERACTIONS

Establishing social interactions requires new capabilities attached to communicating objects and services which go beyond the common capabilities of the classic objects [31]. One object needs first to choose the nature of the connection and the trustworthiness that it will build with others in order to subsequently interact according to a social relational paradigm. Hence, we introduce a hierarchy of Socially Aware, Geographical and Service Quality parameters that will allow the virtualized services to choose an appropriate type of relation according to these parameters [32].

Similar to the world of human beings, relationship types can influence social interplay between communicating objects mainly at the levels reliability and of trust between participants. A known object with which we have had more interactions so far is more trustworthy than an foreign object, with which there has never been any interaction.

Also, again in an analog manner to the human world, the connections inside a family create a high degree of confidence among its representatives, as opposed to a connection among colleagues or persons with no connection between them. The more powerful the connection between individuals, the stronger the cooperation between individuals and the higher the levels of trust and management [33].

Based on the aforementioned social considerations, we propose a new metric for characterisation of services, specifically designed for tourist services, called Trustworthiness Coefficient (TC). The formula of the proposed TC includes one geographical parameter (Distance), three socially aware parameters (Rating, Like and Check-in) and one service quality parameter (Content):

$$TC = (D * \alpha)+[(R * \beta)+(L * \gamma)+(Ch * \delta)]+(C * \epsilon) \tag{1}$$

where *D, R, L, Ch, C* are parameters and α, β, γ, δ and ϵ are variables whose value depends on the implementation type (will be detailed in section C).

B. PARAMETERS

The establishment of a relationship with a certain level of trustworthiness relies primarily upon on the attributes and values of the virtualized object, to which are added distinctive types of parameters. These parameters are characterized by the scope and purpose for the realization of its activities.

- *Distance (D):*
  The distance is the geographical parameter in our algorithm and can be associated with a pair or a clusters of services in order to express different types of itineraries. The service cost metric can be defined according to a geographic area, an operating environment or an application, using various methods, from the Haversine formula to an API based algorithm like Google's Distance Matrix API. The distance variable can be calculated as a mathematical sum or as a decision tree as shown below:

$$D = \begin{cases} 1.0 & \text{if} < 100\,metres \\ 0.9 & \text{if} > 100\,metres\, \& < 500\,metres \\ \ldots & \\ 0.1 & \text{if} > 10000\,metres \end{cases} \tag{2}$$

  In the presented demonstrator the trustworthiness coefficient is used for tourist services, especially for the purpose of recommendation, therefore next to the socially aware and service quality parameters, which will be presented next, Distance is a necessary geographical parameter to create the aimed recommendations ranking. In the area we have used, the parameter changes its weight in a chosen range from 100 meters to 10 km, but depending on the desired geographical area, it can be modified as appropriate.
- *Rating (R):*
  The rating, a socially aware parameter, is defined in a comparative manner based on performance, characteristic or quality. Depending on who carries out a rating in a crowdsensing context, a distinction is made between internal and external ratings: ratings can be gathered external from third party social media platforms or socially aggregated hyperlinks, or internal as integrated in proprietary systems. Transformation tables provide a comparison of the various rating methods and clusters used by different platforms. In our case, this scale includes 6 rating levels and the rating class assigned to a rating object is the result of the consolidation of individual trustworthiness criteria. Equation (3) presents the formula which evaluates the rating of a service using for example the Google Places API:

$$R = \begin{cases} 1.0 & \text{if} = 5\,stars \\ 0.8 & \text{if} = 4\,stars \\ 0.6 & \text{if} = 3\,stars \\ 0.4 & \text{if} = 2\,stars \\ 0.2 & \text{if} = 1\,stars \\ 0 & \text{if} = 0\,stars \end{cases} \tag{3}$$

  The Rating parameter can be calculated in a similar manner by considering also other rating mechanisms typical for other online platforms such as Tripadvisor or Booking.com.
- *Like (L):*
  With a Like, users of social networks express that they like something or support something (the so-called "liking" mechanism). In many social platform, visitors are given the opportunity to "like" other people's posts via certain buttons. The types of application vary between the option of just casting a positive vote (e.g. on Instagram) or giving a favorable or disapproving rating (e.g. on YouTube). This socially aware parameter can be integrated in the calculation of our TC coefficient coming from well-known social platforms such as Facebook, a decentralized social platform such as Friendica, or as a proprietary function in a custom software.
  For the implementation and computing of the like parameter in this demonstrator we used the Facebook API offered as an open source instrument in the Facebook Developer Tool, which provides the option to analyze and operate social relations between users at the first and second level (e.g. friend or friend-of-a-friend):

$$L = \begin{cases} 1.0 & \text{if} = 100\,Likes\,from\,direct\,friends \\ 0.8 & \text{if} = 100\,Likes\,from\,friends\,of\ \ friends \\ \ldots & \\ 0.2 & \text{if} = 2\,Likes\,from\,direct\,friends \\ 0 & \text{if} = 2\,Likes\,from\,friends\,of\ \ friends \end{cases} \tag{4}$$

As it can be seen in the above formula, the parameter has a higher value for first-hand likes coming from friends, as opposed to the ones arriving from the friends of friends.

- *Check-In (Ch):*
The Check-In is the third socially aware parameter used for the social trustworthiness management. Some social networks allow their users to "check-in" to a real location, telling friends or other users where they are. Check-In takes place via a mobile app on a smartphone, or a custom progressive web application [34]. The basis is the localisation of the user via the integrated GPS of the used device. The operators of the social networks evaluate the actions and in particular the "check-ins" of their users in order to offer individual customer profile suggestions or recommendations. In our approach these transactions carried out by the users are continuously stored in the data processing system and used for user relationship management purposes.

$$Ch = Value \quad \text{if} \quad Friends > F \quad \text{in} \quad Time \tag{5}$$

where:
$Value = 0$ or 1, $F =$ Integer (number of friends) that checked in a certain *Time* interval (expressed in hours). The structure of the check-in parameter is presented in equation 5. The parameter is calculated by our demonstrator using the Facebook API and taking into account the time of the day when the check-in was performed. For example, in our formula we took into account the minimum value $Ch = 0$ if no friend checked in at the specified location and the maximum $Ch = 1$ if 10 friends checked in in the last 10 hours. We chose these values for demonstration purposes depending on the size of the geographical area in which we tested the demonstrator. The number of these constants can vary depending on the area in which it is desired to implement it. For example, in a relatively large city the number of check-ins in a location in a short time will be higher than the number of check-ins in an area where the population density is lower. The *Ch* parameter influences the trustworthiness coefficient positively only if the check-ins of friends are detected, if those are absent and $Ch = 0$, it will be considered null in the formula and will not negatively influence the coefficient.

- *Content (C):*
For characterising the content of a service we can take into consideration both quantitative (e.g. photos) and qualitative (e.g. website, phone) factors. The "Photos" parameter has been chosen as a quantitative parameter, assuming that more pictures of a service implies greater care and an increased level of information, whereas for example the "Website" parameter is considered a qualitative parameter due to the effort submitted for the creation of a web page, thus assuming that the service offered is of higher quality. Each parameter has different weights in the coefficient depending on the importance of each one for the implementation type.
Below is presented the content parameter formula based on the usage of the Google Places API.

$$C = (C_1\,(0.2 * F) * 0.45) + (C_2 * 0.30) + (C_3 * 0.25) \tag{6}$$

where

$$C_1 = from\,0\,to\ 1,\ each\,photo\ F\ counts\,0.2$$
$$C_2 = boolean,\ existence\,of\ \ website$$
$$C_3 = boolean,\ existence\,of\ \ phone\,number$$

C_1 is a parameter that takes values from 0 to 1: 0 (if no picture is present in the Google Places API), 0.2 (if 1 picture is present), 0.4 (for 2 pictures), 0.6 (3 pictures), 0.8 (4 pictures) and 1 (if 5 or more pictures are present). C_2 and C_3 can take the value 0 or 1 if the website and the contact phone are present or not.
In the worst case, if the location does not have any picture, website or phone number, we assume that it does not offer a high quality service and C wa value of 0, if instead a location has both website and contact number, as well as at least 5 images then $Ch = 1$ (maximum value) considering that it is a location that has been taken care of in terms of interaction with tourists and offer valuable services and the level of trust is high.

VARIABLE	CIRCUIT	A to B
α	0	0.35
β	0.30	0.20
γ	0.25	0.15
δ	0.25	0.15
ε	0.20	0.15

FIGURE 3. Touristic itinerary: circuit versus A-to-B route.

C. VARIABLES

In order to compute the Trustworthiness Coefficient (TC) presented above, each parameter has an associated variable that actually represents a weight depending on the implementation type of the desired itinerary. Thus we defined the following weights: α for Distance (D), β for Rating (R), γ for Like (L), δ for Check-In (Ch) and ϵ for Content (C).

As a use case of tourist implementation of the TC we have chosen two types of itineraries, one from a point A to a point B, thus creating a path with a starting point and a final one, and as an alternative a circuit type itinerary, where the user will return at the end to the point of departure. The value of the parameters for the two cases is different because each type of implementation has its own representative features.

The weights of each associated parameter were chosen experimentally depending on the type of circuit and the geographical area. Based on the type of tourist service and the region in which these weights are applied, they may have values that can be modified and adapted according to the local particularities.

D. ACCESSIBILITY AS ENHANCED VALUE

Another sore point of tourist services concerns promotion policies, too generalist and not oriented to the needs of the demand: new categories of potential tourists, such as the elderly and disabled, that would be willing to travel in case the service offers are in line with their particular requests [35] are in most cases not taken into consideration [36]. The diversification in function of different categories of users would open new market segments that could guarantee significant benefits. This could be accomplished by merging data, as well as its subsequent analysis and purpose-based evaluation [37].

The principle of development in our solution is in fact the versatility, so that whatever the field of application, the rules that will determine the accessible trustworthiness social relations between services, applications, users and any other social element of the system considered, will generally be the same. Regardless of the type of relationship, both horizontal and vertical [38], there is always a layer of social relations and socially aware parameters integrated with the accessible trustworthiness dictated by the same model developed within the project and integrated on the platform [39].

The formula below illustrates the proposed Accessible Trustworthiness Coefficient (ATC), including the previously introduced TC and a new parameter, Accessibility (A):

$$ATC = (TC * 0.45) + (A * 0.55) \tag{7}$$

The Accessibility (A) parameter was introduced to ensure a reliable amount of trustworthiness for people with different degree of disabilities who are in need of assistive technology or features in order to take advantage of the offered services:

$$A = \begin{cases} 1.0 & \text{if } \textit{has full equipment for the disabled} \\ 0.7 & \text{if } \textit{has 70\% equipment for the disabled} \\ \ldots & \\ 0 & \text{if } \textit{has no equipment for the disabled} \end{cases} \tag{8}$$

V. PRIVACY ASPECTS

All technologies based on big data must deal with the legislation dedicated to the circulation of information. The biggest problem arises when the information being processed is data related to real persons. In SIoT, the large amounts of data that is exchanged concerning the services offered to people might include user data or user behaviors. The risk is very high because the behavioral patterns of each human person could be concentrated in larger databases and used for illicit purposes [40]. To avoid these problems The European Parliament adopted precise rules which are contained in the Reg. (UE) 2016/679 (in short GDPR) [41] and which were already tacked by the European Union (EU) years before. Article 25 of the GDPR provides a general obligation to be respected when designing goods or services: this rule is called ''data protection by design and by default''. According to this rule, a preliminary study on the project to be developed is always necessary in order to identify whether personal data is involved and, if so, to apply the rules to guarantee the rights contained in art. 5.1 of the GDPR: lawfulness, limited purposes, minimization, accuracy, limitation of conservation, integrity and confidentiality. With GDPR, privacy becomes a design constraint and, as a result, protection measures must be implemented by default. The architecture and the demonstrator presented in this paper are based on the interactions between online services, consequently it was subject to a preliminary analysis in compliance with the ''data protection by design and by default'' rule. The first aspect considered was related to the type of information processed, in order to understand if it personal data or not. This detail is fundamental, because the presence or absence of personal data [42] is the determining element to understand if the GDPR is applied. This first analysis revealed the possible presence of personal data only in the initial phase, i.e. in the phase in which the analysed services make available information related to the identity of real persons. However, this type of information is not collected by our platform. All the collected data does not require connection to a specific person: e.g. we gather information on how many (and not which) people have been satisfied with a given service; a score is attributed based on the relationships between people but without know their identity. At this point it was necessary to understand if the dissociation between identity and information takes place definitively (anonymisation) or if it is possible to have a connection between them again (pseudonymisation). Our preliminary analysis has revealed that the proposed demonstrator is based on an anonymisation process, because, after collection from the original database, the data definitively loses any connection with the identity of the person. Furthermore, not all the data sources used make available information on the identity of people. Many of them are already anonymised. This first result would have been sufficient to exclude any subsequent step of the ''data protection by design and by default'' evaluation. Despite this, we preferred a very cautious approach because we are aware that even from the intersection of anonymous data it is sometimes possible to deduce the personal identities. For this reason, in compliance with art. 32 GDPR, we have applied every appropriate measure to prevent this risk. The legal aspects of our project are not limited to personal data but concern all types, even non-personal ones. Their rules are contained in Reg. (EU) 2018/1807 [43], which uniformly regulates the free circulation of non-personal data within the European Union and which represents the first concrete step towards the elimination of territorial barriers that hinder the development of data-based technologies such as IoT.

VI. IMPLEMENTATION

In order to prove the functionality of the previously presented approach for modelling services as social object, we developed a demonstrator specifically for tourist and cultural heritage services. The architecture of the demonstrator is presented in figure 4.

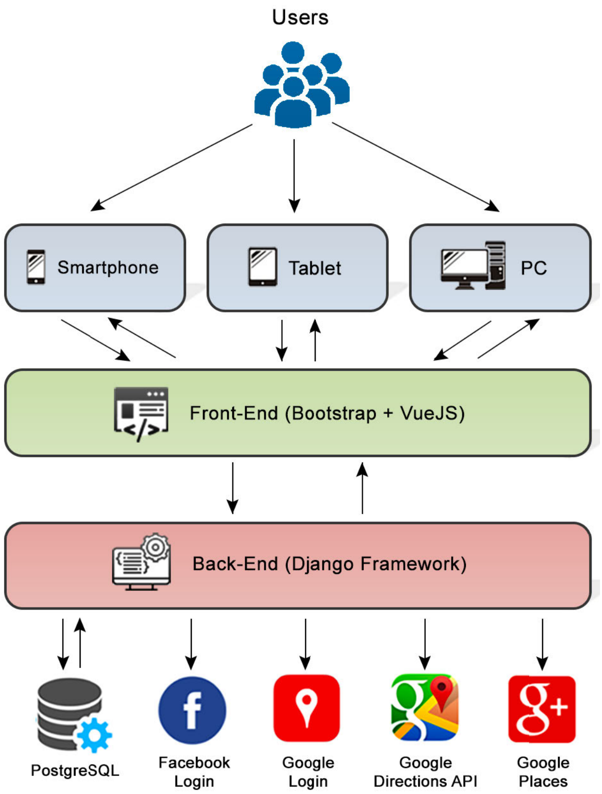


FIGURE 4. Layered architecture of the demonstrator.

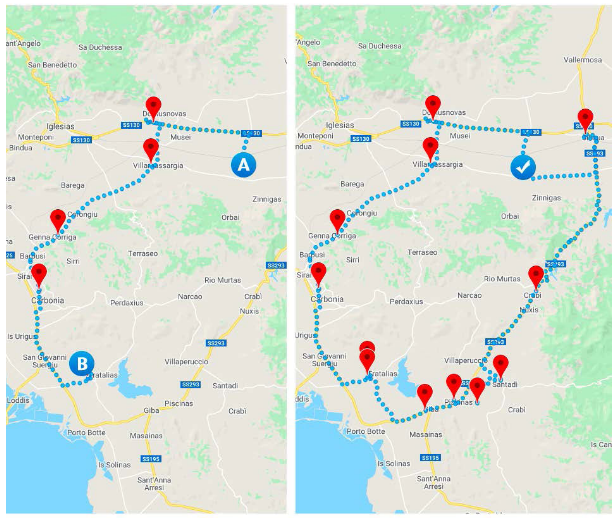


FIGURE 5. A to B itinerary (left) and a circuit type itinerary (right).

It is composed by a front-end application and a back-end engine developed in the Django Framework, interacting with a PostgreSQL, a complete object-based Database Management System (DBMS) released with a free license (BSD License style) Database. Django is a free and open source web application framework written in Python. The use of Python Virtualenv is necessary to isolate the configuration of multiple Python / Django projects residing on the same server. To make server setup as simple as possible, Docker was used, an open source platform that automates the deployment of applications within software containers. The server resides on Amazon Web Services (AWS). The main technologies used in the Front-End are: HTML, CSS, Javascript, jQuery, Bootstrap and VueJS.

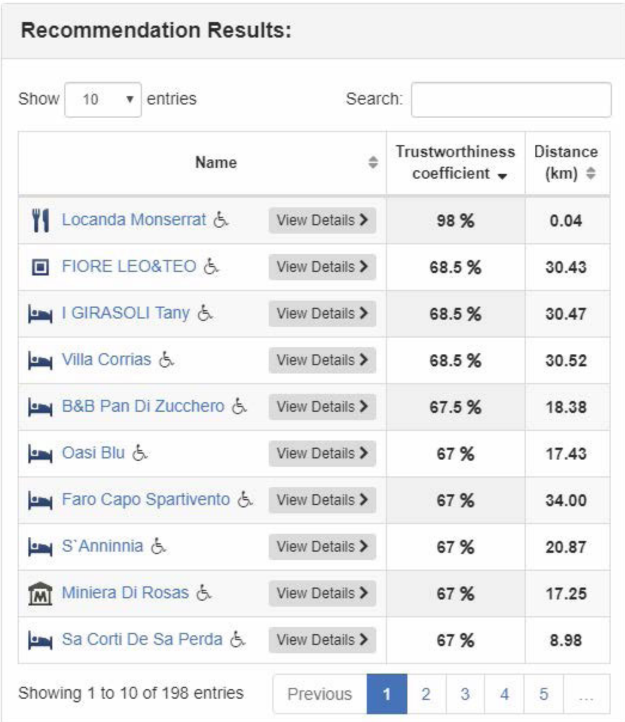
The first step in the development of the demonstrator was to build up the database. We concentrated on a limited geographical area, situated in the south-west of Sardinia (Italy), a region known as Sulcis - Iglesiente that can be seen in figures 5 and 7. We inserted, starting from a regional open database, a number of 1500 entries composed of tourist services (i.e., hotels, restaurants, beaches, lodges, etc.) and cultural heritage attractions (i.e. museums, archaeological sites, churches) and started to populate these entries with the information found on the web, using well known platforms such as Google Places, Tripadvisor and Booking. The data was retrieved in a semi-automatic manner, by means of Python scripts and subsequently manually checking the results for consistency. Once the services defined as database entries, we abstracted them to objects, and started to construct a social group composed by one initial object and the objects with which it has interacted, enriched by the types of relationships and corresponding levels of trust. The social group is renewed from a log timestamp of interactions of the object that stores each of its interactions. We are using a formalization and a parametrisation of the basis of interaction (socially aware parameters), allowing objects to determine their behavior during interactions [44], [45].

The demonstrator is built with a social login, feature that allows each user to access the platform through their Google and Facebook profile. Furthermore, in addition to accessing the platform with social accounts, it is possible to register with personal credentials through the registration module. The Social Functionality in the demonstrator is referred to those services that can be used by the user who accesses the platform: once logged in, the user can declare its appreciation by clicking on the "Like" button, or communicate that he is visiting the structure at that moment by clicking on the "Check-In" button.

These two features are important for those who use the Login through Facebook, because social friends can see how many of them have interacted with the same structure. Calculation of a recommended route can be done in two ways, one from a point A to a point B, thus creating a route with a starting and an ending point, and alternatively a circuit-type itinerary, in which the user will return eventually to the starting point, as presented in figure 5. The type of relationship between the communicating services abstracted as objects reflects the degree of connection between them, and reference to the level of trust in their relationships [46].

The relations between the services allows the diffusion of the geographical, socially aware and service quality parameters in the community of objects.

The prioritization of the hierarchy of objects (shown in figure 6) is done by using the TC and ATC coefficients, which can be associated with the value added and the impor-



Recommendation Results:

Show 10 entries Search:

Name		Trustworthiness coefficient	Distance (km)
Locanda Monserrat	View Details	98 %	0.04
FIORE LEO&TEO	View Details	68.5 %	30.43
I GIRASOLI Tany	View Details	68.5 %	30.47
Villa Corrias	View Details	68.5 %	30.52
B&B Pan Di Zucchero	View Details	67.5 %	18.38
Oasi Blu	View Details	67 %	17.43
Faro Capo Spartivento	View Details	67 %	34.00
S'Anninnia	View Details	67 %	20.87
Miniera Di Rosas	View Details	67 %	17.25
Sa Corti De Sa Perda	View Details	67 %	8.98

Showing 1 to 10 of 198 entries Previous 1 2 3 4 5 …

FIGURE 6. Prioritization of the hierarchy of objects in an A to B itinerary.

tance of the reliability and trustworthiness. Recommended results can be filtered using a search input, and the number of results for each page is configurable. For easier navigation, only a summary of the results in the table are displayed in the first phase. If a user wants to view more details about one or more services, he can click on the ''View Details'' button, so that a detailed list of information will be displayed through the ''Accordion'' module of the jQueryUI library.

When the logged in user has already decided to make a trip from one city to another, or wants to plan one, the web platform prepares the possibility of calculating an itinerary that includes parking in some structures or in any case of the slight deviations from the path already chosen, based on the values provided by the TC or ATC for each structure. ATC (Accessible Trustworthiness Coefficient) is used only when the accessibility filter is enabled by the user, by default the filter is disabled and only TC (Trustworthiness Coefficient) will be used to display the recommendations hierarchy. The Google Directions API was used for the implementation. For example when the itinerary is of type A to B, in our demonstrator we considered the weight of the distance parameter as 0.35 to calculate the Trustworthiness Coefficient for displaying the recommendation results. In the front end view of the application for the purpose of informing the user we display both the coefficient and the distance in tabular mode using the jQuery DataTables plugin, through which the user can sort the results according to the desired parameter (column): Name, Trustworthiness Coefficient or Distance. Figure 7 shows the evaluation of a tourist itinerary based on the reliability coefficient with the accessibility filter enabled.

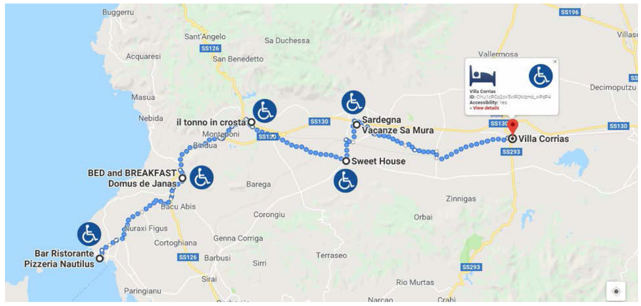


FIGURE 7. Touristic itinerary based on the trustworthiness coefficient with the accessibility filter enabled.

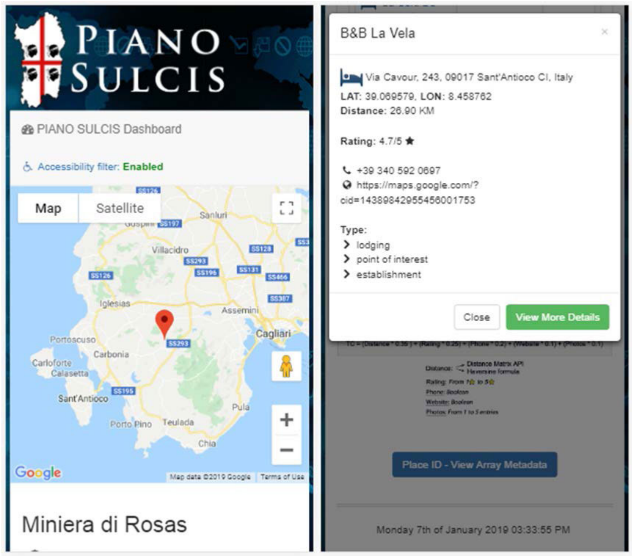


FIGURE 8. Demonstrator front-end view on a smartphone.

The demonstrator application was developed using the content to terminal adaptation and responsiveness paradigms and is thus compatible with all modern devices on various resolutions and operating systems from smartphones up to 4K [47]. The figures 8 and 9 illustrate the the front-end view of the demonstrator on a smartphone and on a laptop.

The demonstrator has custom profiles, in which the user can select which parameter is most important to him, for example: Distance (D), Rating (R), Content (C), Accessibility (A) etc. Depending on the profile selected, the variables for each parameter change their value, the Trustworthiness Coefficient (TC) thus changing it's value according to the user's necessity.

Most of the problems and challenges encountered during the implementation and the validation of the demonstrator were related to the lack of ''open'' data regarding the structures of the Sulcis - Iglesiente that we used. We used data provided by Google Places which, after an initial automatic script-based collection operation, were corrected by hand to avoid further problems once the data is entered into the database. We have also been able to obtain other data from tripadvisor.com partially using web scraping techniques and

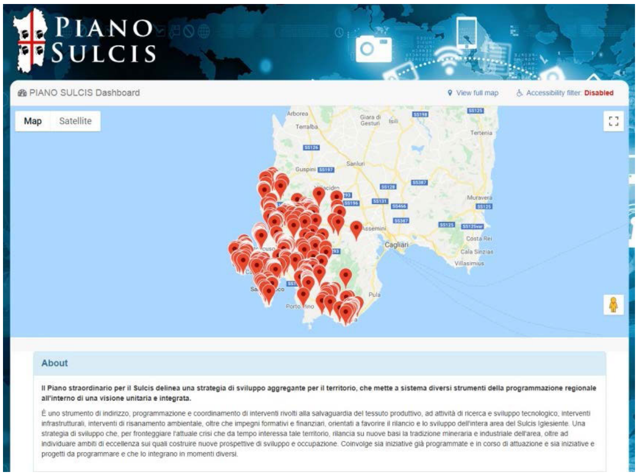


FIGURE 9. Demonstrator front-end view on a laptop.

partially manually, since there is no API type interface to be able to interface automatically via script.

The lack of data was important in the case of facilities and services for the disabled, where information was very scarce. Google Places only provide a Boolean value for this parameter, while the other portals such as Tripadvisor, Booking, etc. provide some specific data, but not directly interpretable, for which further manual classification was required.

The research carried out shows the lack of a classification standard for the disabled of tourist facilities and services. A regional investigation in this sense may be appropriate to allow, at least for the new structures and services registered at the regional level, to specify in an unambiguous way what types of services are available for disabled and elderly people.

VII. CONCLUSION AND FUTURE WORK

The new Social Internet of Things paradigm (SIoT) proposes a new perception on the cooperation and synergy among objects which build up the Internet of Things (IoT). Its intent is to imitate human social behaviors, in order to apply them to connected virtual objects and to deliver new, improved results in the cooperation and transactions between services entities of smart systems.

In this article, we present a new concept in the SIoT and the aspects of social relations, transposed to tourist services as communicating objects. We propose a new architecture of a communicative virtual socially aware objects (VSAO), which allows to manage the social ties between objects, through principles of interaction and trustworthiness. Through interaction paradigms such as crowdsensing of service between objects we improve the evaluation of services and improved management of tourism and cultural heritage. The proposed model of social interaction is based on a relational model involving 3 types of parameters: geographical, socially aware and service quality enhancing the concepts of trustworthiness and accessible trustworthiness, which can open new research topics for the future of SIoT.

The main result of the research activity within this project was the modeling and definition of tourism services as part of a typical SIoT architecture. Using these models, services can be identified and composed in a dynamic manner, thus creating new aggregated services. By introducing the accesibility parameter, weextended the intital scope of the application, enabling access for people with disabilities or special needs.

The services provide rules and metrics of reliability and quality that affect their characterization using typical indicators for SIoT architectures such as Quality of Experience and Trustworthiness enabling access through the use of assistive technology. Even though the developed demonstrator is dedicated to tourist services, conceptually the developed Trustworthiness Coefficient (TC) and the subsequent Accessible Trustworthiness Coefficient (ATC) can be extended in a wide range of economic and industrial spheres as well as in the non-profit area. The future work will be concentrated to employ an additional machine learning layer to the relational model. The new layer will be used to build a logical interpretation of the processed data, to check for deviations from expected trustworthiness, predict upcoming links and social relations between objects and determine trends in social ties.

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Review

When Social Networks Meet D2D Communications: A Survey

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Abstract: In the last few years, one of the main characteristics of the current technological development is the constantly increasing need for data exchange among various types of devices, both mobile and fixed. Within this context, the direct communications between devices has the potential to create new, location-based peer-to-peer applications and services, as well as to help offload traffic from the congested traditional cellular networks. The main hurdles for this kind of Device to Device (D2D) communications are throughput, spectral efficiency, latency and fairness. Most of these hurdles can be overcome by the use of the new Social IoT (SIoT) paradigm, of things and people involved together in the network, guided autonomously by social relationships following the rules set by their owners. This paper aims to investigate the state of the art of socially-driven D2D communications. Upon an initial analysis, we perform an in-deep literature investigation of the main directions in which social ties can improve D2D communication, draw conclusions and identify the research topics left open.

Keywords: D2D communication; social; IoT; 5G

1. Introduction

The constantly increasing demand for local data services at increased data rates has led to the development of the D2D (Device to Device) communication paradigm that enables the direct communication of nearby mobile users without the advent of a higher level controller. The obvious advantages of this kind of communication are higher throughput and enhanced data rate, lower latency, fairness, improved spectral efficiency, and lower energy consumption [1]. These advantages are based on several technical challenges, including relay discovery and peer selection, communication mode selection, spectral resource allocation, interference coordination and management, channel allocation, and upgrade of existing infrastructures.

The novel D2D communication approaches have resulted in the last few years in innovative network architectures and applications that redefine the current state-of-the-art with respect to wireless connectivity, next generation cellular communications (e.g., 5G), Internet of Things (IoT), and also vehicle-to-vehicle (V2V) communications [2].

In the past few years, the idea of the convergence between D2D communications and social networks started to attract increased attention of the scientific community, which started to apply features from the social networking for increasing the performance of D2D communication. The most important social features that can be applied to the D2D communications are the social communities, social links and the concept of centrality. The quick success and vast diffusion of social networks, through platforms such as Twitter, Facebook and Instagram, generated vast amounts of data about the structure and dynamics of social networks encouraging researchers from various research areas to transversally apply "sociality" to their works [3].

However, the role of sociality is still not clear. Most of the currently published papers make use of social attributes coming from ties among persons. Nevertheless, the idea of things networked together with people has led to the Social IoT (SIoT) concept [4], where objects are able to establish social relationships autonomously, based on rules imposed by their owners. The resulting social network of objects is able to deliver a faster service and information discovery, by scanning a network of "friend" objects and is also able to manage in a more consistent way the received information.

Social networking for D2D communication refers to finding and exploiting the interaction patterns between the users, both people and objects, of the social network, to enhance the efficiency of the D2D networks based on proximity information.

The research on the combination between social-enabled networking and D2D communication is still at the beginning, therefore the most important research directions currently need to be identified and addressed. The aim of the present survey is to explore and understand the benefits of the integration of social-awareness with D2D communication to offer a clear picture of the current scientific efforts in this field. The survey identifies the key topics of D2D communication that can benefit from the social-enabled networking, and, for each of these topics, creates a taxonomy of the identified applications.

The paper is structured as follows: Section 2 gives a concise overview of the D2D concept through the lens of social networks and social ties and identifies the key issues to be investigated. In Section 3, the actual investigation is performed for three distinct issues, cataloging the current research efforts and highlighting the key social concepts that can be used to enhance the performance of D2D networks. Finally, in Section 4, the lessons learned from the performed surveys are put together to draw the final conclusions in Section 5.

2. System Description

As mentioned in the introduction, D2D communications were initially introduced to benefit from [2]:

- the proximity of devices for assuring higher bitrates, lower delays and reduced power consumption;
- the reuse of resources by simultaneously allowing both D2D direct-link communications and "infrastructured" communications (e.g., cellular or WiFi); and
- the use of a single link rather than involving resources for both an up- and a downlink.

The concepts of social networking can help in finding solutions and improvement for D2D communications in the communication domain where devices can help or be assisted before accessing a network or before starting a D2D communication and in the social domain where devices can create a social network governed by social relationships and events. Considering these two main domains, the following three key issues can be investigated:

- Relay discovery and peer selection: The efficiency of a D2D communication is mainly related to the neighbor discovery process that is necessary prior to the effective direct communication. Peer selection can be time and energy consuming if network support is not available.
- Communication mode selection: A device can select either an established transmission channel respecting the procedures and constraints of the used network infrastructure, or a D2D communication. Involving all the devices to take this decision can improve data transmission capacity and resource utilization.

- Spectrum resource allocation and management: D2D communications use the same spectrum resource and air interfaces as normal, structured communications. To use these resources more efficiently, D2D communications may be performed for example by reusing the same frequency channels, involving decision and scheduling methods for spectrum sharing.

A schematic representation of a D2D communication environment, containing both the social and communication domains, is depicted in Figure 1. The previously identified key issues are inserted in the lower half of the schematic representation. It has to be said that, although identified, these three key issues cannot be clearly divided from the social point of view, considering the fact that some social concepts can interfere simultaneously with more than one issue.

The next section presents each of these three keys topics in terms of the solutions and algorithms proposed to improve D2D communications performance based on the social components.

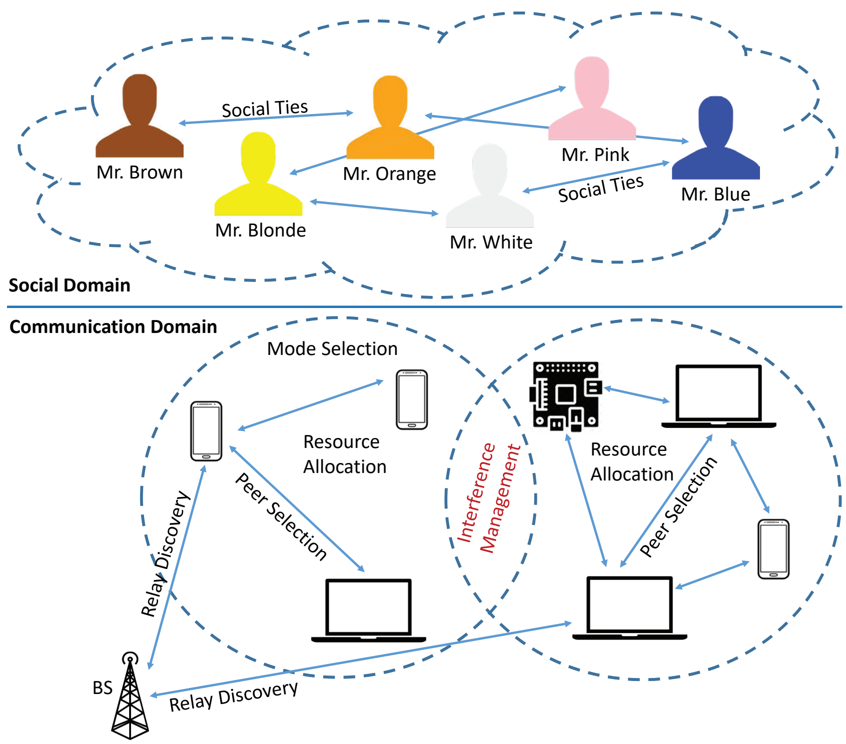

Figure 1. System design.

3. How Social Ties Can Improve D2D Communications

3.1. Relay Discovery and Peer Selection

When a device wishes to establish a D2D communication, the network and/or the source user equipment (UE) has to find which are the possible peers that can be used as a relay by a peer selection procedure [5,6]. In the last five years, a social-aware approach has boosted the development of this procedure, such as the work proposed in [7], where the relay is selected according to the concept that two friends can serve as the feasible relay for each other, which is called the reciprocal cycles concept.

Concepts of social networking are also used in [8], where devices are aggregated in clusters based on human social ties; the cluster head, which has to act as the relay to communicate with the Base Station (BS), is then selected based on the centrality degree of the devices. A similar approach is proposed in [9], where social ties are used as incentives to enable D2D communication, where the stronger is the tie between two peers, the higher is the probability to select them as a relay.

In 2017, the authors of [10] introduced another perspective of social networks: they used attributes related to the service, such as the interaction information among the users and their contact history, to assess the reliability of the other users, as well as considered social attributes, i.e., users' interests and their relative importance, to create dynamic clusters for the users with communication demand and then help them to select their neighbors. Recently, Du et al. [11] analyzed and suggested different mechanism on how to use the social features to optimize the network performance. In particular, they considered social features from the network perspective, such as the centrality of the devices, i.e., the devices' frequency of forwarding data to other devices, and social features from the user perspective, where they relied on the credit, i.e., that the devices social relation is built based on trade for data forwarding, and reputation, i.e., the quality of forwarding or relaying a service.

In particular, the contribution of the social features has been applied to the two main challenges in the selection of a relay among the peer devices, namely the mobility of the devices and the selection of trustworthy peers [2].

One of the biggest problem in traditional peer selection schemes is related to the lack of information regarding the location of other peers to which they send beacons or other probing mechanisms. Usually, this problem is solved through mobility patterns, which predict the position of the devices; however, the mobility of the nodes can be highly variable and then such approaches suffer from accuracy issues: to this, social networking information, which is less variable than node mobility, can improve the reliability in the discovery of a peer for D2D communication, which is willing to relay the content.

In this regard, Zhang et al. [12] and Wang et al. [13] proposed the most recent attempts to take into account social features in D2D communication to foresee a user position. The creation of the link is based on the interaction histories between two users, while at the same time considering information regarding the channel status and the user contact model. A further step in solving the mobility issue through social contribution for D2D communication was given by Zhang et al. [14]. The authors pointed out how connectivity among users is highly intermittent due to the user mobility, leading to the degradation of the QoS (Quality of Service), while social relations are usually stable over time. Social networks are therefore split between offline ones, which only reflect social relations, and online ones, which are a subgroup of offline social networks and consider external influence from media or friends. The authors' goal was to combine both social networks in order to improve traffic offload when selecting a peer in D2D communications.

Peer selection is usually performed through one of the following two approaches: ad-hoc, where the discovery is made in a distributed way by the devices themselves through the transmission of periodic beacons, and network-controlled, in which a central unit assists the device in the discovery of D2D candidates.

The ad-hoc approach is the most sensible to the mobility issue and it has seen the highest number of contributions from researchers. Zhang et al. [15] suggested the first social approach by exploiting social network characteristics to assist the ad-hoc peer selection. Their goal was to increase the beaconing rate only for a subset of nodes, thus leading to an increase in the detection of their peers. To do this, they first divided the D2D users into communities based on their social features and then selected the nodes with the highest centrality as the subset of nodes. Similarly, the work in [16] proposes a distributed solution for peer selection considering social relationships among users and a dynamic scenario where all users are mobile with the aim to maximize the data rate transmitted to the BS. This idea is based on the work proposed in [17], which shows how two people who share a common friend and have close connection times with him/her have a higher probability to have a similar movement trajectory and therefore are likely to meet and can act as a relay for each other.

All the above-mentioned works are based on the idea that users can only belong to one community at a time. However, due to the multitude of social attributes and interests of people, it is reasonable to assume that a user can belong to more than one community. This is the starting point of the work in [18], which detects overlapping communities and designs a neighbor discovery method for the ad-hoc network approach: the solution identifies the beacon detection rates by dynamically estimating the roles of a user, who belongs to various overlapping communities, to enhance D2D communications both intra and inter-community.

Regarding the network assisted approaches, the authors of [19] proposed a centralized solution based on a coalition formation game to solve the relay discovery problem. Their goal was to push forward the trust and reciprocity derived from social aspects in the D2D communication domain. Similarly, in [20], to improve the stability of D2D communications in a mobile environment, the relay discovery is based on the type of relationship shared between a potential relay and the end user and the relay's centrality.

The second problem that drives the research for social D2D communication is tied to the relay reliability. Due to the spreading of several wireless devices on the market, especially considering configurable smart ones, choosing wireless terminals as temporary relays may bring data integrity and privacy leakage concerns, thus the selection procedure of trustworthy peers is particularly important for D2D communications.

Several papers study how to exploit social relationships among peers to establish a higher degree of trustworthiness during D2D communications. In particular, in [21], the authors used the social trust levels among nodes to derive a stop-wait approach for the selection of the relay, while, in [22], the goal is to minimize the end-to-end content delivery delay, thus the relay is chosen using both social trust and the propagation link. Social trust is analyzed thoroughly in [23], where the authors studied the objects' behavior in a 5G scenario to build a reliable system: when a device has to upload content, it selects the relay based on the trustworthiness of its peers. The trust metric is constructed based on the sociality among the devices. Another example is presented in [24], where the authors used a trustworthy social-communication graph to improve the capacity gain and data rate of the D2D communication. Recently, Militano et al. [25] introduced the concept of sociality to identify the presence of malicious node in a network by making use of the concepts of reliability and reputation to model the level of trust among the devices involved in a D2D transmission. Similarly, the authors in [26] proposed a coalition formation game to enhance content uploading services through an opportunistic hop-by-hop forwarding scheme based on the trust of each hop.

However, even if in its infancy, the research towards social networking concepts applied to D2D communications is progressing really quickly, so that some real applications can already be found. In this context, one of the first applications proposed is SoCast [27], which is a video multiCast system that uses social-aware D2D communications. Among the main features of SoCast, the system considers an incentive for the user cooperating in the communication based on the social ties between peers, which is a similar feature to [7] where the relay discovery is based on the concept of reciprocal cycles.

Finally, Nitti et al. [28] proposed an innovative approach for D2D communications applied to a real indoor environment, based on a Social IoT (SIoT) architecture [4] able to involve all participating objects in a twofold procedure, gathering both Quality of Service (QoS) and spectrum sensing data and weighting the received information using a social trustworthiness algorithm.

Figure 2 shows our classification tree for the peer selection approaches based on the two main issues addressed in this context, namely mobility and trust, with the root of the tree aggregating general works applying social concept to the topic.

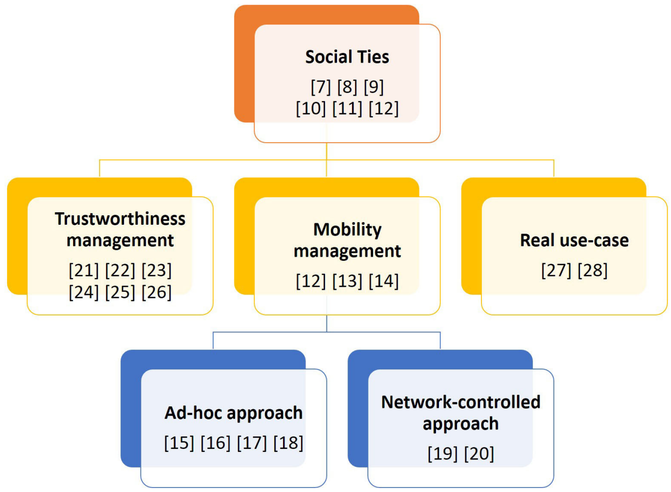

Figure 2. Classification tree.

3.2. Communication Mode Selection

During the initial procedure for the socially aware device-to-device (D2D) networks, the decision-making of the transmission mode is a fundamental issue. The choice to select D2D mode or cellular mode for communication is a daunting work in D2D underlaying cellular networks. Communication between two participants, in cellular mode, can only be done via the BS even though both parties of the associated call are in the immediate vicinity. In D2D mode, data packets are transmitted via a direct connection between the user equipments (UEs). Because D2D communication normally uses the same air interface as cellular communication, a UE can only operate simultaneously in D2D or cellular mode [29]. The decision of D2D or cellular communication mode determines, in D2D-enabled cellular networks, the mode selection issue for UEs. A UE needs to establish neighboring UEs as D2D candidates, before mode selection, and perceive their possible service [8]. Given the randomness and variability of content location, the limited transmission and storage capacity of devices, and the coexistence of selfish and altruistic user behaviors, it is important to understand how to promote effective collaboration and how to adapt applicants to content providers to achieve all the benefits of D2D content sharing [30].

Principally, when the D2D, base-station-to-device (B2D) and novel multi-D2D sharing modes exist together, the concern of content sharing mode selection operates the prevalent aspect in this specific matching [31]. Wu et al. [32] presented the concept of socially aware rate, which blends the link rate with the social selfishness from the social knowledge to achieve the effective cooperation together with the physical link quality. Additionally, the sharing mode selection issue based on social awareness is designed as a maximum weighted mixed matching problem, which can be algorithmically diminished to a transposable interest issue subject to a matroid constraint. In [32], the authors developed a framework based on a best-effort distributed algorithm that exhibits possible choice of numerous computational ramifications and estimation rates to satisfy the varied practical demands.

After the mode selection process, the network operator has to allocate the radio resources like frequency bands, time slots, and to transmit the D2D and cellular links, respectively. Those issues of nearby UE detection, wireless resource allocation and communication mode selection are coupled with each other, and are always connected with level loading over a network, the user-level behaviors and channel conditions, thus delivering new challenges for cellular networks [33]. Recent studies have identified that, by using the cellular resources in a D2D communication underlaying cellular system, UEs can determine to transfer data over their serving BSs, or to communicate with each other via direct links [15,34]. By achieving the awareness of the instantaneous network load, potential D2D pairs and channel conditions, the system can choose the best mode, assign the resources and handle interference efficiently, to recognize the proximity, reuse and hop gains delivered by D2D communication [35,36]. Mode selection relies on the awareness and recognition of the intercell interference, channel condition, and network load. Thus, managing the community structure information can facilitate the discovery of the aforementioned three physical parameters to make the mode selection decision accurately and quickly for the user [37].

Li et al. [38] presented a solution to increase the data transmission volume from all the BSs to all the UEs. To better monitor the channel condition, the system generally has to examine security and privacy concerns. The social tie information can be analyzed as a way to conclude the trust between two peers, because the transmission power of a tie can be associated to the reliability of the channel between two nodes. Hence, in the D2D communication system, managing the data and knowledge of social ties in resource allocation can be used not only to achieve higher throughput distinguished to an architecture that is non-socially-aware but also enhanced security and privacy [39].

To bypass possible network congestion, the resource allocation and mode selection processes could be aware also of the community bridges. Particularly, the resource allocation modules need to allocate more resources to the users of the bridge, as long as the mode selection module has to deliver high preference for cellular communication to bridge peers. The bridge user detection algorithms, bridge-aware resource allocation and mode selection schemes have the potential to enhance and increase the global coverage and throughput of the D2D communication underlaying cellular network [38].

An interesting idea for autonomous mode selection was presented by Kumbhar et al. [24] who combined relay discovery schemes and communication graph to establish social relationships (social graph). The solution, called Reliable Relay, also includes a self-governing archetype, Social D2D (S-D2D), by adding trust factors in mode selection schemes. Performance observation and interpretation suggest that the proposed Reliable Relay scheme increases capacity gain and data rate with imperceptible delay.

On another research topic, Hoeyhtyae et al. [40] presented a study of power-efficient transmission mode selection for social-aware D2D communications in future networks aiming at integrating WiFi and LTE air interfaces seamlessly. Various smartphones have diverse power profiles and thus the optimization method should take this information into account. Power consumption models for LTE and WiFi interfaces commonly have a static part just for being active and a linear rate-dependent part. In the most recent models, the static part is clearly the dominating factor, because the increase in the data rate increases the power consumption lightly, as demonstrated in [40]. Hence, it is suggested that a heterogeneous mobile social network tries to minimize the number of active interfaces to save power. It would be beneficial if the smartphones could be developed so that the static part in power consumption would be close to zero and otherwise the communication based consumption would be a linear function of the bit-rate for a given distance. This would enable better optimization of transmission power for distinctive scenarios and schemes.

When social connections among users are exploited in a way that fairness is ensured, the awareness of social characteristics could be advantageous also for the Quality of Service (QoS) of D2D cooperative communication. The communication mode selection and peer selection problem arise, at the D2D cooperative network creation stage, as users suitable to engage in D2D cooperation must be identified. However, in practice, the users' hesitation to cooperate by allowing access to their equipment to others or granting the distribution of their own data among other devices, can still create difficulty in D2D communication [41].

Huynh et al. [42] introduced a socially aware energy efficiency optimization solution for D2D communications in 5G networks, in which the energy efficiency optimization issue is answered for optimal channel mode selection and optimal transmission powers allocated to each mobile user (MU) in order to boost the energy efficiency, by making use of adaptive genetic algorithm. Thus, the increasing of social networks (e.g., Twitter, Facebook, etc.) can give favorable opportunities to develop and enhance the performance of D2D communications in 5G networks.

Figure 3 presents an overview on the current research directions for the communication mode selection, with an overview of the references for each specific direction.

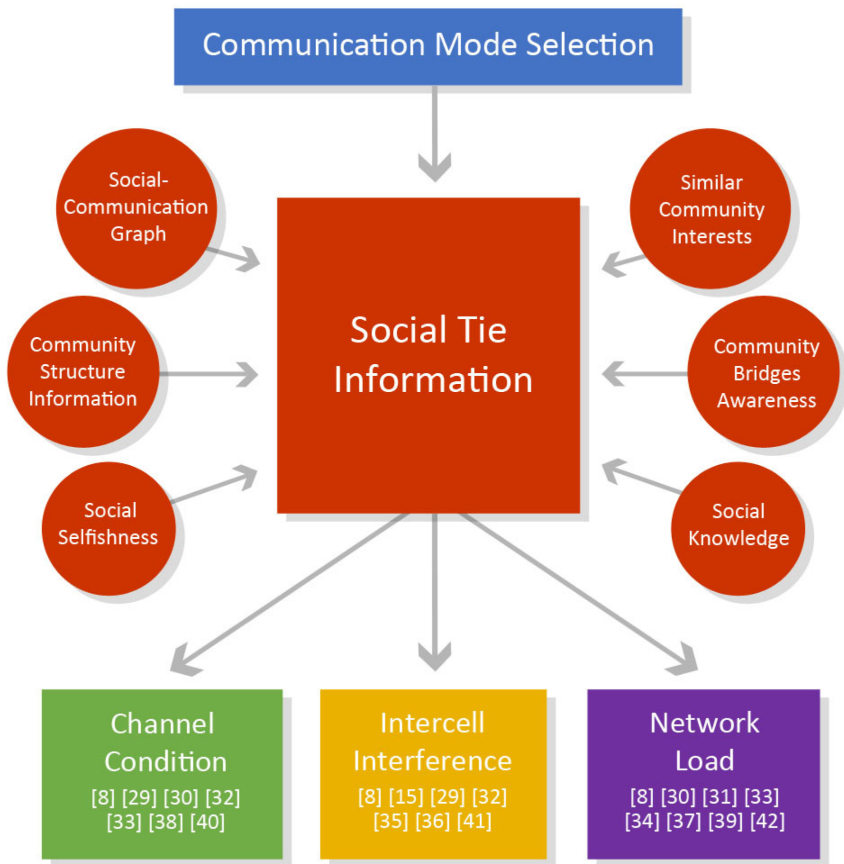

Figure 3. Enhancing the mode selection decision using social tie information.

In conclusion, the communication mode selection can include various social ties to be used for managing channel condition, intercell interference and network load, based on the following social concepts: similar community interests, community bridges awareness, social knowledge, social selfishness, social-communication graph and community structure information.

3.3. Spectrum Resource Allocation and Management

In this section, all significant works concerning resource allocation and optimization issues for D2D communications are shortly described. Some of these can be grouped considering similar approaches, methods or algorithms. Six main key requisites to design social-aware resource allocation and optimization for D2D communication were identified [43]:

- Social-aware metrics: Considering the high variability of social-aware D2D communications both in time and in the type of applications and relationships between users, allocation mechanisms need to assure dynamic generalization and adaptation.

- Scheduling: Dynamic scheduling algorithms are crucial to improve resource allocation evaluating the resources necessary to set the users' application demands and assigning them.
- Resource Heterogeneity: It is in terms of device spectrum diversities (e.g., time variance of the spectrum and features of channels) and capabilities (e.g., throughput, energy, and interfaces helpful for transmission).
- Resource Optimization: These kinds of mechanisms can assure the usage of the available resources in a better way, meeting the required service level accordingly.
- Estimation Accuracy: Social interaction between devices needs to carefully manage the monitoring of social-aware D2D links.
- Privacy: It is crucial to be assured by enabling device protection and social information protection (e.g., encrypting data and deploying a rigid policies concerning access personal information).

We start our analysis from the social-aware metrics, for which Li et al. [38] proposed in 2014 a social-aware enhanced D2D communication system to find solutions to the main D2D communications issues, such as mode selection, interference control, and allocation of resources. Resources (i.e., transmission power, frequencies, and channel conditions) need to be efficiently managed to preserve D2D and cellular communications from mutual interference because interference level is essential to assure the closeness and reuse. Another example is the work in [44], where the authors applied the social relationships among the objects to enable an efficient and trustworthy spectrum utilization in a cognitive radio scenario. In [45], an advance of the Bayesian theory is exploited to achieve the social ties between devices that are offline in mobile networks based on their social activities. The authors described a method to learn relationships using a coalitional graph game: the number of served users grows according with their popularity. Zhao et al. [46] presented a game theory model to improve the serviceability perceived by D2D users of a social group. The main objective was to find the Nash Equilibrium (NE) of the maximization game performing a distributed allocation of resources. Both D2D and mobile users are characterized by an utility function based on social features. The way of structuring the game makes the equilibrium complicated to be always reached. In [47], the authors formulated the distributed power and subcarrier allocation problem in a D2D content dissemination system as an evolutionary game. A new algorithm for global search was carried out to obtain the evolutionary equilibrium considering the predicted contact duration to limit computation complexity and data exchange. The eNB studies the framework of the social network examining the related platform (e.g., Facebook and Twitter) to calculate social trajectory similarities and to send them to D2D users. Successively, D2D users choose transmission adjustment and calculate their services in a random way and send their reports to eNB. Thanks to these information, the eNB can select the average utility in order to broadcast it to all D2D links. In this way, D2D links are able to evaluate and decide for utility changing until the game equilibrium achievement. In [48], an optimal social-community aware resource allocation (OSRA) algorithm for D2D communication is developed for limiting the duration of D2D communications taking advantage of users' social characteristics. The solution shows a centralized nature that allows a reduction of data transmissions but overloads the BS. In [8], the authors faced the increasing storage space problem, proposing to let the distributed file caches be exploited by cellular networks, replacing cellular links with local D2D links in order to decrease mobile traffic and to improve spectrum utilization. While a D2D device is caching information desired by several adjacent UEs, a procedure to create a cluster for multicast communications can start [48]. The bandwidth is dedicated to the cluster head. The proposed Social Aware-D2D (SA-D2D) scheme allows a cluster head to perform in an asynchronous way to exchange information using the same spectrum, guaranteeing goodness of transferred videos. To do this, two approaches were presented: a half duplex (HD) and a full-duplex (FD) approaches. A half-duplex approach in which two orthogonal time stages are needed [49]. In the first one, considering a cluster, all UEs can obtain information transmitted by the

BS over the mobile downlink. Successively, the cluster head is able to multicast data to the other UEs over direct D2D links inside the cluster. With the full-duplex approach, a cluster head communicates on the same frequency band in a simultaneous way (i.e., transmission and reception), but it must use two different antennas (i.e., one for transmission and one for reception). Both self-interference and co-channel interferences can be mitigated using existing methods [50,51].

In the literature, several works propose solutions to cope with the scheduling issues. In [52], data exchange is studied in terms of inter-community and intra-community data forwarding. Neighbor users (i.e., physically close) can have very different social relationships and this information can be used to influence short connections, also leading to an underutilization of resources. For this reason, a cooperative approach can help users in considering both social and physical attributes, to select the optimal way to cooperate for reducing delay. Both a coalition game and the concerns of users are used to divide them into fog communities, leading to a new, highly scalable network architecture. In [27], the authors presented a distributed algorithm based on a coalition game to obtain clients grouping for video content multicast distribution in a cooperative way. A resource allocation module was carried out to improve BS management of D2D links in order to maximize utilization of resources. The service delivery is based on the restoration of video frames. In this context, the BS take decisions on resource allocation according to the received requested from each group, not needing to previously know the video features and the social relationships between clients. In the implementation of multicast dissemination, the interference can be managed with Base Station and Access Point control, as proposed in [53]. Efficient scheduling and radio resource allocation can be improved using network information (e.g., channel condition, potential D2D pairs, etc.) increasing both signal overhead and, at the same time, efficiency of local data dissemination.

Resource heterogeneity is another challenging line for social-aware communications. In [54], a two-step coalition game was developed to efficiently allocate resources to D2D communications considering uplink channels of a cellular network. The evaluation of the proposed framework was performed in real human traces and random networks showing its effectiveness achieving a substantial improvement in performance compared to systems that do not provide resource management based on community aware methods. A time-varying social-aware resource allocation for D2D communication has been proposed in [55], based on the Auto-Regressive Integrated Moving Average (ARIMA) model with the call records. Social community is analyzed to obtain an utility function for a potential game. The authors demonstrated that the new algorithm reaches NE, improving the total utility of the system and increasing system capacity. In [22], several new relaying strategies are presented and described. For example, the relay discovery strategy allows multiple relay nodes to choose the best pair of source and destination channels, introducing a feedback procedure used by the destination to give information about the transmission. Full duplex strategy assures higher spectral efficiency but, as a drawback, it shows loop interference and self-interference in the presence of relays with multiple antennas. Instead, half-duplex relays reveals multiplexing losses. Sakr et al. [56] presented an energy-harvesting-based D2D communications system model where the D2D transmitter harvests energy from environment interference and communicates with its D2D corresponding receivers over channels allocated to cellular users. In the device relaying and multicast scenarios, energy harvesting can be taken into account as an efficient incentive mechanisms, due to the possibility for the devices to use the harvested energy to broadcast or multicast local contents instead of their own power [53].

Many algorithms tackle the resource optimization problem. Yu et al. [57] analyzed methods to share resources maximize the throughput in D2D communications performed in cellular networks. In [58], a power optimization framework managing interference from cellular users by proposing a δD-interference limited area control scheme is proposed. In [59], the authors considered peer and service discovery as the first step to start D2D communications. Device relaying and multicast dissemination scenarios are proposed, where devices requesting local traffic can be performed in dedicated portion of band or reusing licensed spectrum. Clearly, in the second case, interference problems need to be carefully managed, even if the spectrum is used more efficiently. In [60], D2D transmissions in downlink OFDMA networks are considered. A two-hop socially-aware method for resource allocation is presented: a device is connected with the base station (i.e., first hop) and can also perform a new communication with another device (i.e., second hop). This solution shows disadvantages when the number of iterations between the first hop and the other devices increases. In [61], the authors modeled D2D communications in terms of sociality finding a new characteristic of link strength, that is the contact time. The contact time was set as a constraint to limit the transmitting time of a D2D communication. Performance of network is influenced by both physical features (e.g., number of user) and social features (i.e., contact time). The sociality-aware scheme improves network throughput thanks to the contact time. In [62], routing algorithms over peer-to-peer (P2P) share enabled multi-hop D2D networks are proposed. D2D users try to download common data from several distributed D2D servers. The Routing scheme with Location-Aware P2P-Share (R-LPS) mechanism is presented: the main objective is to calculate a route passing by or directly through other users. Simulation results demonstrated that, for the generalized case, all the schemes allow improvement in terms of throughput. In [63], a relay node can be helped to increase the spectral efficiency. This method allows choosing the best buffered relay between all destination links, for transmitting data if channel is good or, alternatively, buffer it. In a D2D relay network, one of the mobile devices in a D2D communication device pair is called a relay device, able to perform as a forwarder for the BS in case the perceived quality of the transmission from the BS to the end user is under a satisfying level [20]. In this way, the throughput perceived by a higher number of users can increase, as well as the coverage area of a base station not introducing co-channel interference to devices in other cells [64].

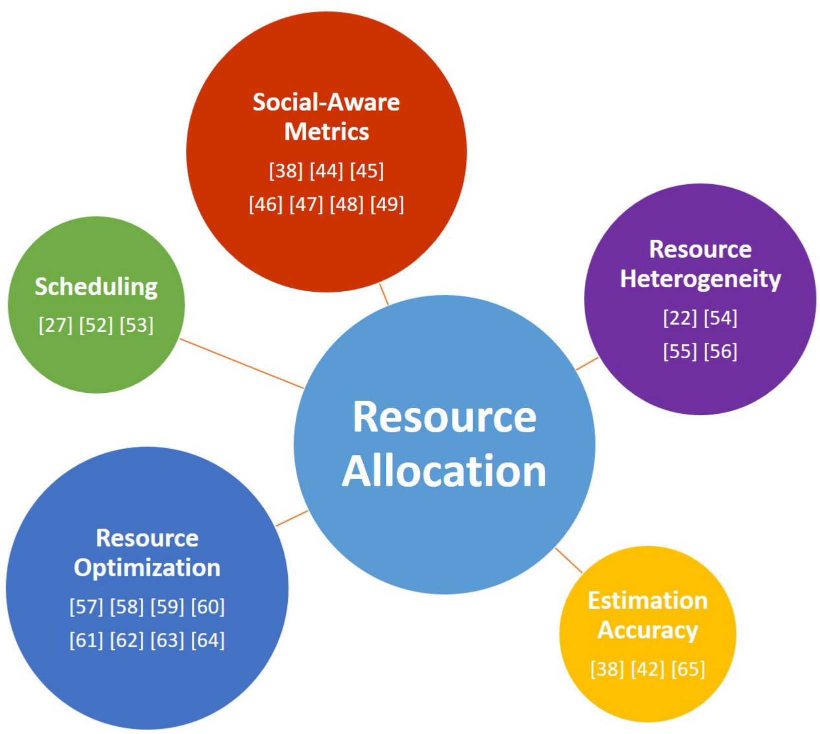

Figure 4. Resource allocation works grouped considering key requirements to design social-aware resource allocation and optimization for D2D communication.

Finally, some works focus on estimation accuracy. In [38], qualitative and quantitative evaluations are performed to assess performance growing by allowing social-aware D2D communication. In [42],

QoE Assessment for IoT-Based Multi Sensorial Media Broadcasting

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***Abstract*—One of the goals of next generation TV broadcast services is to provide realistic media contents to the users. The user's sense of reality can be reinforced by adding to conventional media multiple sensorial effects, through five-sense stimulus (i.e., taste, sight, touch, smell, and hearing). In a smart TV broadcasting context, especially in a home environment, to deliver the additional effects, customary devices (e.g., air conditioning, lights, etc.), provided of opportune smart features, have to be preferred to ad-hoc devices, often deployed in other applications as for example in gaming systems. In this context, a key issue is the interconnection among the smart TV and the customary devices that deliver the additional sensorial effects to the user. In smart home use cases, the Internet of Things (IoT) paradigm has been widely adopted to connect smart devices and this paper presents an IoT-based architecture for multi sensorial media delivery to TV users in a home entertainment scenario. In such a framework, home customary devices, act as smart objects interconnected via IoT network to the smart TV and play a role to implement additional effects to the conventional broadcast TV service. In this paper, the requirements in terms of synchronization between media and devices is analyzed and the architecture of the system is defined accordingly. Furthermore, a prototype is implemented in a real smart home scenario with real customary devices, which allowed a subjective test measurement campaign to assess the quality of experience of the users and the feasibility of the proposed multi sensorial media TV service.**

***Index Terms*—Quality of experience, multi sensorial media, next generation TV, IoT, smart home.**

I. Introduction

During the last decade, the evolution of the TV market has been terrific. Broadcasters have been facing news challenges to cope with an increasing demand of new services from user's side. With the convergence of second-screen adoption and the abundance of real-time news consumption via social channels, the broadcast landscape underwent a major transformation. Viewers have begun to demand highly customized experiences that meet their individual needs.

In short, the evolving needs of the viewer seem to be in the future of broadcast television. In the next years, it is likely that this will become even more evident, with more people demanding customized television experiences through user-generated content and the option of micro bundled packages. To keep up, broadcasters must stay current with the latest innovations to engage with their customers.

Despite the increasing market of handled devices such as smartphones and tablets, and consequent demand of spontaneous access to video content form mobile broadband users, the total minutes watching video per week of traditional home TV is still predominant [1]. The global service providers' offer of advanced whole-home video delivery enables consumers to new services. Over-the-top (OTT) content providers are offering movies and TV shows for either download or direct streaming over the Internet, the type of shows that consumers prefer to watch on a big-screen high definition TV. Within this framework, home entertainment systems have known for the past few years a constant evolution in size and complexity, delivering new levels of experience and adventure to consumers. To adapt to users' need the home entertainment sector developed a true dedicated electronic playground, with large-screen displays, consoles for gaming, audio gear, and docking stations, generally managed through a single remote control giving the complete command to the user. Technology companies have been announcing linkage of TV screens, PCs, video recorders, game consoles, and other electronic devices together in the same home network, allowing the user to share content among these devices. On the other hand, due to the complexity and cost, the home entertainment products reached only a niche of the population. This slow down the evolution of the TV broadcasting services, which are still based on content media not able to exploit all the features that home entertainment systems could provide, being intended for traditional TV services.

Furthermore, in the last years the concept of smart home has gained attention from the information and communication technology (ICT) community. There has been a massive interest in the ability of embedded devices, sensors and actuators to communicate and create a ubiquitous cyber- physical world. Smartness has been extended to customary devices traditionally populating the users' houses, such as domestic appliance, for instance. Finally, today's new technologies enable

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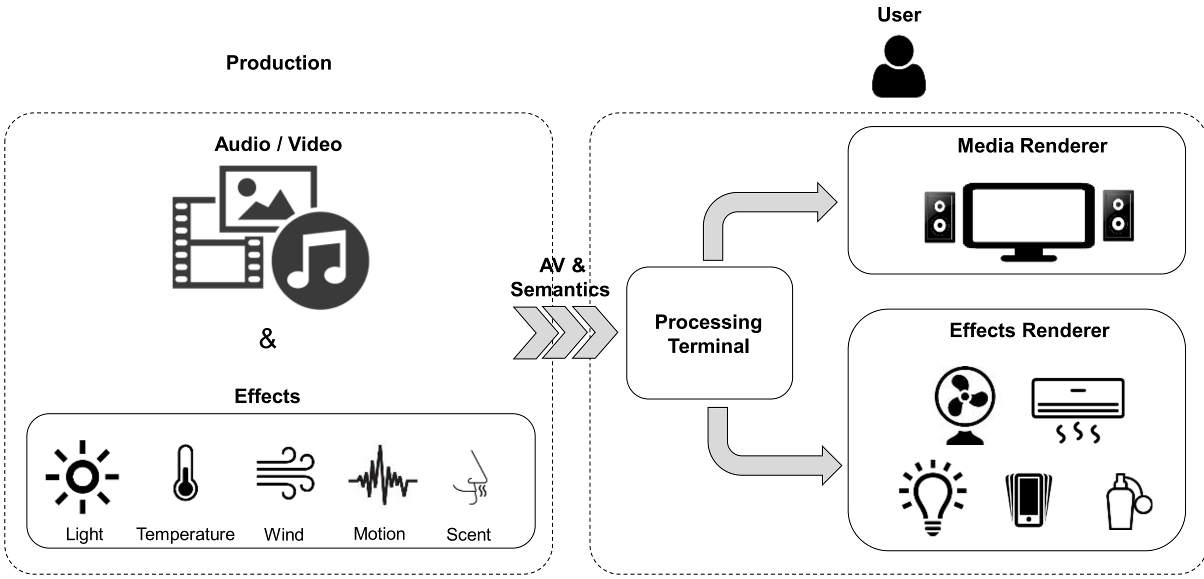

Fig. 1. Multi sensorial media concept.

also the interaction with the residential environment: control of utilities (lighting, heating, ventilation, air-conditioning, automated window treatments, pool and spa controls), control of security (garage and access controls), control of home appliances locally or remotely from a smartphone [2].

A crucial role on the rapid evolution of this scenario has been played by the Internet of Things (IoT) paradigm [3] and by the recent development of short-range mobile communication technologies that together with an improved energy-efficiency are expected to create a pervasive connection of "things" [3]. The drastic increase in the number of smart devices and sensors connected to the IoT has the potential to change how consumers interact with networked technology, including media and entertainment platforms [4], [5]. This represents an interesting opportunity for the entertainment industry to include the growing volume of customer interaction that comes with IoT in order to create more responsive and interactive applications, redefining the level of interaction between entertainment providers and their customers [6], [7]. There is now the condition for the TV service broadcasters to redefine their content and products and have chances to reach also the traditional user who will be more and more immersed in a smart home scenario, surrounded by customary devices able to cooperate and provide enhanced TV experience.

One of the goals of next generation TV broadcast services is to provide realistic media contents to the users. The user's sense of reality can be improved by adding to conventional media multiple sensorial effects, through five-sense stimulus (i.e., taste, sight, touch, smell, and hearing). The main point of adding effects is to give the user the sensation of being part of the multimedia content, so achieving a better user experience. In a smart home environment, to deliver the additional effects, customary devices (e.g., air conditioning, lights, etc.), provided of opportune smart features can be deployed.

Enriching traditional multimedia with additional effects, introduces a number of challenging issues like the assessment of the quality of experience (QoE) for audio-visual sequences enriched with additional sensory effects. QoE evaluation is based on mean opinion score (MOS) subjective tests measurement campaigns [8] and accurate procedures have to be followed to certificate the validity [9], [10].

This paper proposes an IoT architecture to enable multi sensorial media home TV services. For this purpose, to deliver effects, customary home devices jointly participate to the creation of the extended media experiences. The proposed architecture relies on the Cloud IoT platform Lysis [11]. In Lysis the smart TV and the rendering devices, such as remote switches for air conditioning, lighting and vibration are represented as Virtual Objects (VOs) [12]. Micro Engines (MEs) combine and control VOs so that the requirements in terms of synchronization between media and devices are fulfilled. A set-up based on Raspberry Pi computational platforms and Arduino devices enhanced with switching capabilities has been implemented to test the proposed architecture.

According to procedure defined in [9] and [13] a measurement campaign has been then executed on a population of 40 users of various gender, age and instruction, to assess the QoE based on MOS. The goal of the measurements was to evaluate if the common TV users would be positively impressed by the multi sensorial media. Result show that multi sensorial media TV services implemented on home customary devices cooperating through an IoT architecture can be delivered to the users with positive effect to their QoE.

The paper is organized as follows: Section II provides information on multi sensorial media, Section III presents the proposed IoT architecture and gives detail on the implementation. Section IV describes the experimental set up to assess the QoE. Results are discussed in Section V. Finally, Section VI draws the conclusion and suggests future works.

II. Multi Sensorial Media

The concept of receiving sensory effects with audio-visual content is shown in Fig. 1. The processing terminal is responsible for managing the actual media audio-visual resource associated with sensory effect metadata (SEM) in a synchronized way based on the user's setup in terms of both media and sensory effect rendering [14]–[16]. SEM is a description of supplementary effects based on Sensory Effect Description Language (SEDL), which is an XML-based language used to describe sensory effects. Media and effect renders are used to reproduce audio-visual media and supplementary effects that enable the stimulation of senses other than audition and vision [14]–[19]. For example, a mobile phone vibration, fan/ventilator, heater/cooler, can be used to address haptic sensations, whereas vaporizer devices can stimulate the olfactory system [17]. The stimulation of the visual system can be further enhanced using ambient lighting devices. The main point of adding effects is to give the user the sensation of being part of the multimedia content, so as to enhance user's viewing experience by increasing the sense of reality. The sensory effect role on viewing experience and user enjoyment was demonstrated in [19] and [20], where authors show that the viewing experience can be improved by adding effects to the multimedia content. Furthermore, it has been shown that when sensory effects are used emotions like fun, worry, fear, etc. are perceived stronger [21].

Synchronization between sensory effects and video content, when implementing multi sensorial media applications is a challenge for future research, the impact of synchronism between the sensory effects and multimedia content had been investigated by [22]–[25]. According to [25] haptic media could be presented with a delay up to 1s behind the video content in order to be acceptable by most of the users; in contrast airflow media could be released either 5 s ahead of or 3 s behind the video content to achieve the acceptable level. The results in [18] indicate that the time window for releasing a certain scent ranges from about 30 s before to up to 20 s after the content is displayed.

In current implementations of multi sensorial media, the rendering devices are ad-hoc devices connected to relays or other types of electronic switches triggering the action in a direct manner using wireless communication standards such as Bluetooth, WiFi, ZigBee or ZWave. The drawback of such approach relies in the need of developing an entire communication architecture for controlling the rendering devices, with inherent difficulties in terms of scalability and manageability. Most of the few existing commercial devices for multi sensorial media in home entertainment have a proprietary architecture which does not give room for extensions and further development.

Based on these considerations, in this paper we propose a different approach for connecting the rendering devices using a typical cloud-based IoT architecture, presented in the following section.

The specificity of the proposed work is to implement multi-sensorial experience in a smart home environment using only customary devices. In the envisaged smart home scenario, real customary objects, such as the ones used to render the effects, are not connected through a local or ad hoc network, but they "exist" and are accessible in a real world because they are connected to the IoT and at any time can join the smart TV and create a multi-sensorial rendering environment.

III. IoT Architecture and Implementation

A. Architecture

The proposed architecture for multi sensorial media relies on the Cloud IoT platform named Lysis [11], which foresees four layers, as depicted in Fig. 2:

- *Physical Layer:* Cloud implemented, this layer includes objects capable of accessing the Internet, called real world objects (RWOs) due to their direct connection with the physical environment where they sense and act. For this particular scenario, the RWOs are either electronic devices with processing capabilities and integrated peripherals, such as smartphones, or computational platforms equipped with switching capabilities, for example Raspberry Pi or Arduino platforms, able to switch on and off rendering devices. The physical layer communicates with the upper layers using standard wired or wireless communication (e.g., Wi-Fi, Bluetooth, LTE, USB, Gigabit Ethernet etc.) methods and data protocols (i.e., HTTP and MQTT).
- *Virtualization Layer:* For de-coupling the hardware part from the cloud-based software representation, most IoT solutions introduce the virtual object (VO) concept as a digital counterpart of any entity in the real world [23], [24], so that each object in the Physical Layer is represented by a virtualization. The VO is a key part of the overall solution and depicts the RWO in terms of semantic description and functionalities. It is equipped with two interfaces, which allow for a standardized communication procedure: on one side, it enables the VO to communicate with the aggregation layer, while on the other side it represents the access point to the real world, providing the connection with the RWO. For our specific purpose, the virtualization layer is implemented by means of a software driver installed on the RWO, as detailed in the next section.
- *Aggregation Layer:* This layer is responsible for the aggregation of data coming from one or more VOs in order to ensure a high re-usability level. The Micro Engine (ME) is a mash-up of one or more VOs and even other MEs, in charge for getting and processing data from VOs into high-level services requested by the higher layers (application layer).
- *Application Layer:* At this level, user applications are responsible for the final processing and presentation. The deployment and execution of applications is based on the use of one or more MEs.

B. Implementation

For the media renderer the RWO is a high desktop PC connected to the TV via a 4K HDMI cable and connected to the upper layers through Gigabit Ethernet. For the implementation of the multi sensorial effects on the proposed architecture, we rely on home customary devices. Specifically, the devices involved in this architectural implementation are: the fan of

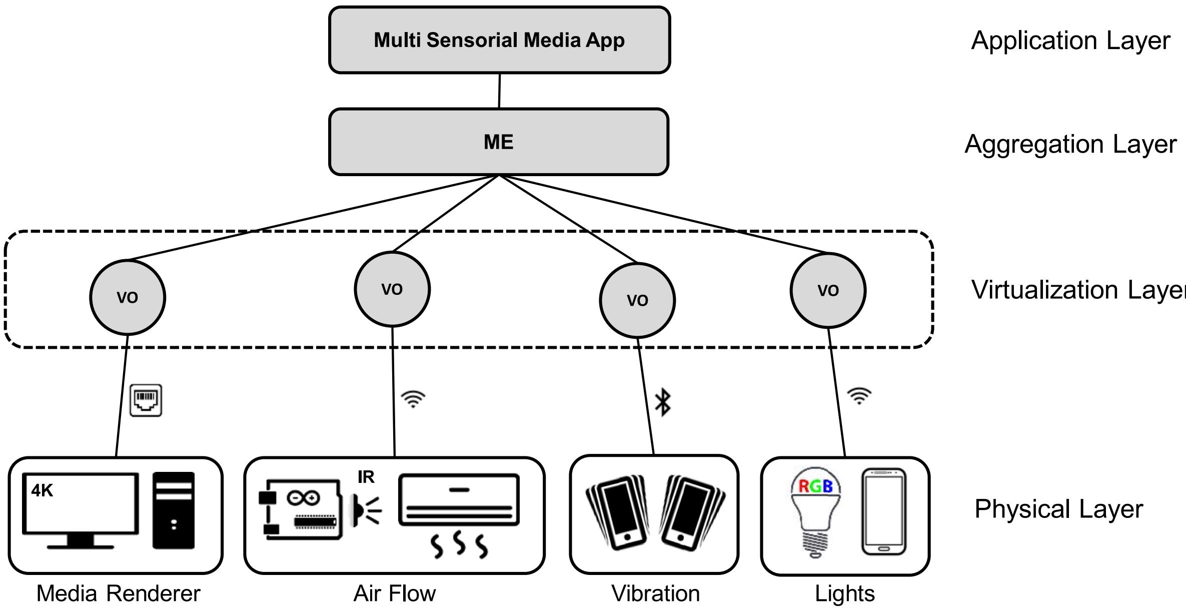

Fig. 2. IoT architecture for multi sensorial media.

an air conditioning (AC) wall-mounted split to reproduce air-flow effects, an RGB smart LED light system with integrated Wi-Fi connection as to the light enhancement effects and the integrated call vibration feature of a set of smartphones to provide haptic effects. The virtualization of the smartphones is done through an application software opportunely developed and running on Android operative system. The AC fan is controlled via an infrared (IR) remote using an Arduino board with an IR shield which represents the system's RWO. The RGB Smart LED lights are connected via WiFi to a smartphone running an application able to automatically extract light effects form the phone camera while placed in front of the TV. In this case the RWO is the smartphone controlling the RGB Smart LED lights. Using a software driver for the Arduino board and an iOS app for the smartphones, we were able to virtualize the RWOs and make them accessible through the virtualization layer (i.e., VOs) to the upper layers of the proposed architecture. This allowed us to have full control of the system and respect the synchronization constraints specified in Section II. The communication with the RWO was implemented using the MQTT data protocol over the various communication standards which assured a low latency, with values lower than 1s for this specific implementation.

The hardware and software deployed to implement the system are presented in Table I.

TABLE I
LIST OF HARDWARE/SOFTWARE DEPLOYED

Item	Description
Samsung Serie 6 JU6800	Professional high-performance 4K monitor with 60-inch diagonal
Haier Model AS09BS4HRA	AC wall split INVERTER technology 9000 btu
Philips hue personal wireless lighting RGB Smart LED	Three RGB smart LED lights
Android/iOS Smartphones	1 iOS to synchronize the RGB smart LED lights with the video sequences by adding related colors 2 Android to generate the haptic effect
Arduino MEGA 2560	Arduino microcontroller equipped with IR and WiFi shields
PlaySEM/SER [26]	PlaySEM SE Video Player PlaySEM SER
Desktop PC	Cpu: Intel Core I7-7700k RAM: 2x16GB 3000MHz Video Board: GTX 1080 Ti 11GB GDDRSX Mother Board Asus ROG Strix 270I Gaming Antec H1200-Pro cooling Corsair CX850M 850 Watt supplier Hard drive: SSD 480 GB

IV. EXPERIMENTAL SET UP

A. Test Environment

The measurement tests have been performed at the QoE Lab of the Department of Electrical and Electronic engineering of the University of Cagliari, Italy. The QoE lab is a 4×4×2.70 m ($l \times w \times h$) separate room furnished with parquet floor, a three seat sofa and equipped with an Haier inverter technology air conditioner wall split [27], a three RGB smart Philips LED lights system [28], a SAMSUNG TV UHD 4K Flat Smart JU6800 Series 6 with a 60-inch diagonal [29] and Wi-Fi internet connection, with the purpose of replicating the living room environment in a smart home scenario.

The setup of the test environment was performed according to ITU-T Recommendation P.911 [30]. Our tests involved two assessors per session, simultaneously rating the test video sequences with multi sensorial effects. The participants sat down in the sofa in front of the air conditioning wall split fan, which is placed above the smart TV at a height of 2.5 m. The monitor has been calibrated before the starting of the test.

A sketch of the setup geometry is shown in Fig. 3. The distance *d* from the monitor is 2.5 times the height H of the video monitor (2.5 H), 186 cm for position 1 and 2 (i.e., angle α $\pm 24°$). Vision angle is referred to the surface normal to center screen angle. Three RGB smart Philips LED lights are placed behind the monitor, to give the feeling that the lights integrated in the frame of the monitor, as shown in Fig. 4(a). The RGB smart Philips LED lights are piloted by a smartphone placed behind the sofa with the camera faced in front of the TV screen as shown in Fig. 4(b). Each assessor is provided with a smartphone with vibration call feature as shown in Fig. 4(c). Fig. 5 shows a real panoramic of the QoE lab setup.

B. Participant Cohort

40 participants (31 males and 9 females) from various backgrounds, between 22–50 years old, with the average age 32 years, had been invited to this assessment; only one participant took part in a similar assessment. For each participant, the following information was asked: age, gender, education, and occupation. Prior to a session, the participants were screened for normal visual acuity on the Snellen chart [31]. A person taking the test covers one eye from 3 meters away, and reads aloud the letters of each row, beginning at the top. The smallest row that can be read accurately indicates the visual acuity in that specific eye. Moreover, the participants were tested through the Ishihara color test [32] to detect color blindness. The Ishihara color test consists of 38 so called pseudo isochromatic plates, each of them showing either a number or some lines. According to what you can see and what not, the test gives feedback of the degree of your red-green color vision deficiency. According to this test, the observer could be "none", "weak", "moderate" or "strong" red-green colorblind. All observers reported normal or corrected-to-normal vision, and had no color vision deficiency.

C. Assessment Procedure

The Single Stimulus Continuous Quality Scale (SSCQS) method as defined by ITU-R Rec. BT.500-13 [33] was used in this assessment, as shown in Fig. 6. In the assessment 30-40 seconds video sequences are shown randomly interleaved with 5 seconds of grey screen used by assessors to rate the video sequences. The SSCQS does not imply the use of reference sequences to be shown to the observers. This is not a limitation in this particular assessment scenario where the aim is to evaluate the delight/annoyance caused by adding multi sensorial effects to conventional TV services. Observers are supposed to be familiar with conventional TV since they experience it daily. The use of SSCQS allowed to reduce the overall time of the assessment for each participant pair to less than 20 minutes, thus avoiding lack of concentration due to user tiredness.

The rating scale used in the assessment is based on MOS as defined in the ITU-T Rec. P.911. The ITU-T Rec. P.911 defines

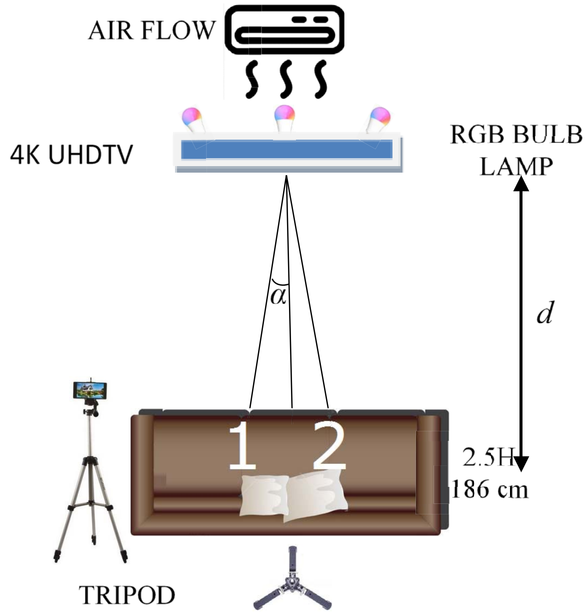

Fig. 3. Setup of the proposed geometry.

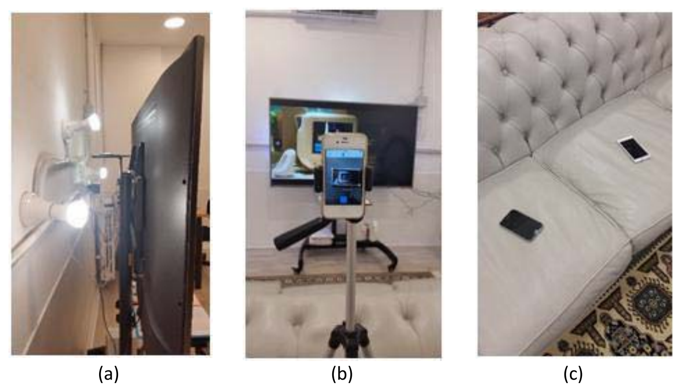

Fig. 4. Equipment used in the assessment (a) RGB smart LED lights (b) Smartphone camera (c) Smartphones.

five-level rating scale as reported in Table II. Each participant in the assessment asked to give his/her quality rating for each video sequences.

The participants watched 10 video sequences at different resolutions and bit-rates enriched with light (L), vibration (V) and air flow (A) sensory effects as described in Section III, hereinafter referred to as multi sensorial sequences. L effects is extracted automatically from the video content as described in Section III, whereas V and A effects are manually annotated to the videos using the sensory effect video annotation tool [34].

The sequences have been selected from the category action, sport, documentary, and commercial. The news category was not included in this assessment, since according to [19] sensory effects have low influence on news category. Table III describes the details of each multi sensorial sequence with the resolution, bit-rates, category, duration, the effects added to the sequence, and the video scenario description. Before the start of the assessment session there

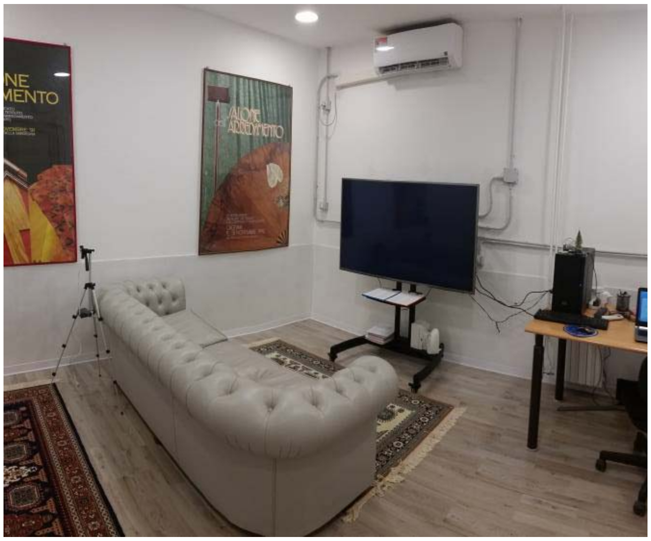

Fig. 5. Panoramic of the test environment.

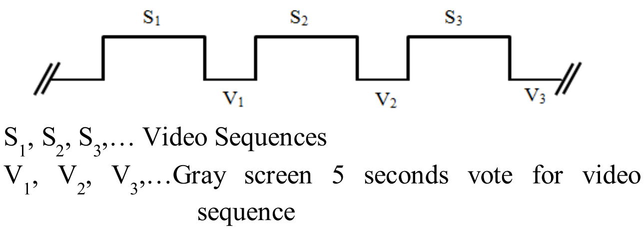

Fig. 6. SSCQS assessment.

was an oral presentation, prepared to make the participants familiar with this type of assessment, and explaining the rating scale.

Each session involved two participants rating the multi sensorial sequences, which allowed reducing the number of sessions required to obtain reliable statistics.

After displaying all the multi sensorial sequences the participants had to answer the post-experiment questions, in which they were asked to comment on their experience regarding to the multi sensorial media. The survey aimed to assess the following:

- improvement in the sense of reality
- if the sensorial effects are distracting
- the grade of delight in the fruition of the multi sensorial media
- the appropriateness of effects timing with the audio-video content
- the impact of each additional sensory effect

The assessment overall time was about 20 minutes for each participant.

V. Results

Of the 40 participants took part in this assessment, 8 outliers had been eliminated according to the procedure described in [33]. The reliability of the ratings given by a subject has been detected by checking the correlation between the average ratings and the *i*-th rating. An

TABLE II
FIVE-LEVEL RATING SCALE

5	Excellent
4	Good
3	Fair
2	Poor
1	Bad

outlier is an observation that appears to deviate markedly from other observation in the sample and may indicate bad data. Evaluators were managed accordingly to the Pearson Correlation Coefficient (PCC). PCC is an index of the strength and direction of a linear relationship between two interval level variables. For PCC$<$0.75 the evaluator is considered as outlier.

A. MOS Ratings

The mean opinion score (MOS) and confidence interval 95% for each multi sensorial sequence are shown in Fig. 7 The participant's ratings for each video is shown in Fig. 8. The ratings in percent of good or better (%GOB) using the values from Good and Excellent, the percent of poor or worse (%POW) using the values from Poor and Bad, and the rest percent (%Rest) for fair are described in Fig. 9. It can be notes as for higher resolution video sequences the perceived quality is higher. This was expected since the sight sense in human being is well known to be predominant. Nonetheless, greater results are achieved sequences showing high dynamic motion in nature environments (e.g., Ice Ski 1, Bridgestone), but the degrades when in similar scenario the subjective view is included (e.g., Ice Ski 2, Berrecloth). This can be justified by the fact that in subjective view sequence the expectation of the observer is higher, and the impact of the effects delivered by the customary devices deployed is perceived as week.

B. Survey Results

The post experiment questions evaluation gave the following results:

- 85% of the participants agree that sensorial effects improve the sense of reality, 10% had neutral opinion, 5% disagree;
- 67.5% of the participants were not distracted by the sensory effects, 17.5% had neutral opinion, 15% were distracted;
- 80% of the participant enjoyed the multi sensorial media, 12.5% had neutral opinion, and 7.5% did not enjoy the multi sensorial media experience.
- 70% of the participants judged appropriate the timing of the sensory effects, 18% had neutral opinion, 12% disagree.

Concerning the sensory effects impact, the results show that its different from a video category to another category. The experiments indicate that additional light effects are more pleasant for the eyes with nature and sports videos than with action videos. This is due to the fact that additional light effects reduce eye strain due

TABLE III
MULTI SENSORIAL SEQUENCES

Video Number	Video Sequence	Resolution	Bit-rate (Kbit/sec)	Category	Duration (sec)	Effects	Scenario
S1	Ice ski 1	1920x1080	15411	Sport	22	L, A	ice skiing
S2	Ice ski 2	1920x1080	14979	Sport	23	L, A, V	subjective view, ice skiing, falling down
S3	Skyfall	3840x2160	12703	Action	33	L, A, V	subway crash, car crash, falling down, wind, gun shots, explosion
S4	Fireworks	3840x2160	10207	Documentary	35	L	different color fireworks
S5	Elysium	3840x1610	11364	Action	40	L, A, V	Car crash, shots, wind, explosion
S6	2012	1280x720	2186	Action	30	L, A, V	earth quick, tornado
S7	Pastranas	1280x720	2619	Sport	32	L, A, V	rally
S8	Berrecloth	1280x720	3552	Sport	32	L, A, V	subjective view, bicycling down the rock cliffs
S9	Earth	1280x720	4116	Documentary	21	L, A, V	wind, animal jump
S10	Bridgestone	1280x720	2421	Commercial	30	L, A, V	windy weather, car moving

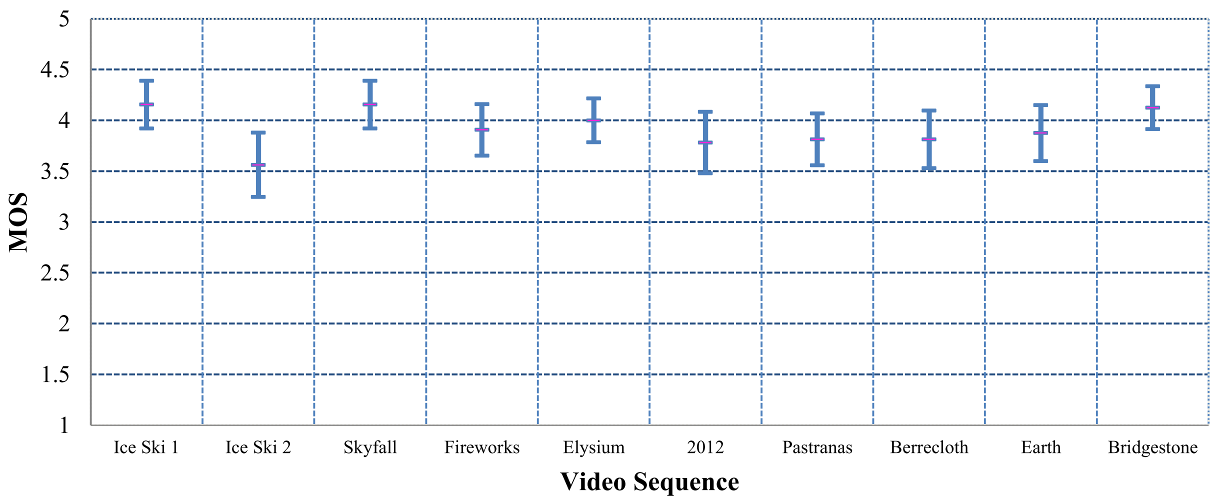

Fig. 7. Mean opinion score and confidence interval.

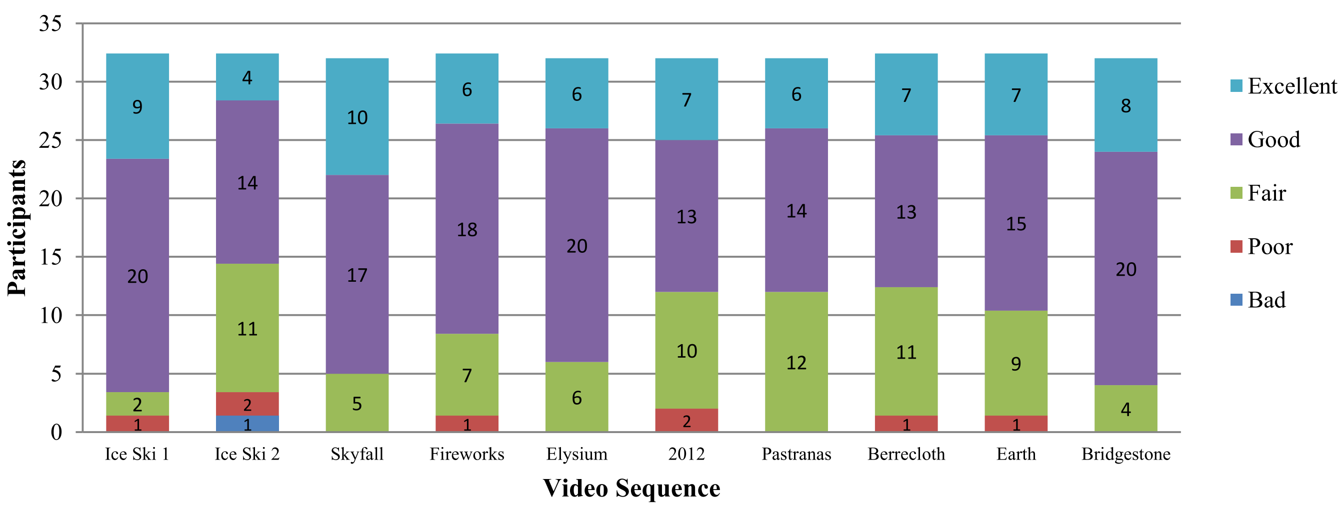

Fig. 8. Ratings.

to a smoother lighting difference between display and background which is more accentuated on high dynamic video sequences.

The majority of participants consider that the air-flow and vibration effects in the multi sensorial media, improve the sense of reality. Also, most

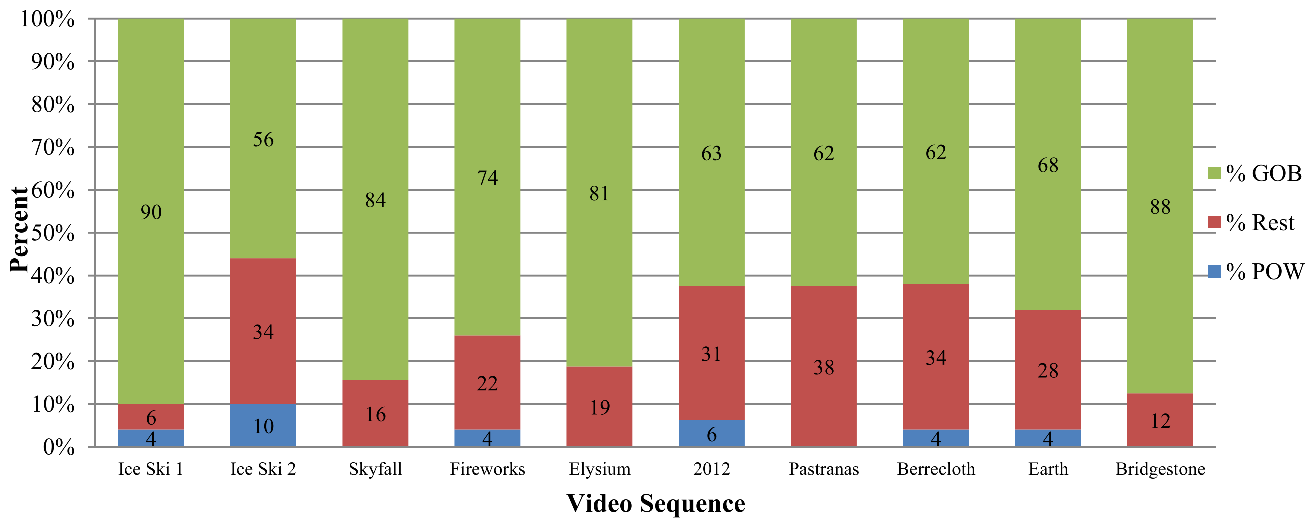

Fig. 9. %GOB and %POW.

participants agree that both effects result in an enjoyable experience.

VI. Conclusion and Future Work

This paper investigated the feasibility of an IoT based approach to reproduce multi sensorial media sequences on a real smart home television scenario. A cloud IoT architecture has been designed and implemented based on home customary devices by respecting the synchronization constraints. A quality of experience assessment campaign has been performed based on subjective tests. The result showed the feasibility of the proposed approach in terms of synchronization constraint, increase of the sense of reality and general overall satisfaction of the users. The IoT solution allows implementing the system in a real smart home scenario without the need to deploy dedicated specific hardware. Furthermore, the IoT approach allows scalability and also the possibility to add customized features to the overall system. In a smart home scenario, the user preferences can be saved by the IoT architecture and the setting of the devices can be adjusted accordingly. This opens new outlooks in the broadcasting area, since it is possible to forecast new services that could be provided to consumers tailored on their experience preferences.

Nonetheless, the QoE assessment tests highlighted some issues that need to be further investigated in future works. The main critical issue derived from the individual comments of the participants concerned the vibration effects delivered by the smartphones which have resulted sometime annoying during the assessment depending on their placement. Participants either held the smartphone in their hand, or placed it in their pockets, or leaning beside them in the sofa. Moreover, most of the participants complained about the limitation of impact of the RGB lights led due to the distance set between the sofa and the TV monitor. It seems that the viewing distance as specified by the ITU-T Recommendation P.911 does not match with the need of the users in case of light enhancement effects. On the other hands the air flow effect strongly depend on the distance between the AC fan and the sofa. It appears evident that different room geometries and more tests have to be performed in order to find the right tradeoff.

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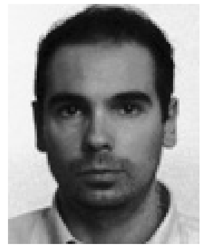

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the energy efficiency optimization (EEO) problem in D2D communications is formulated, analyzing both the social conjunctions and physical interference among mobile users. The starting idea is to allow D2D pairs in sharing spectrum resources of a cellular subscriber to increase spectrum efficiency. An adaptive genetic algorithm is applied to solve this EEO problem to maximize the energy efficiency, while at the same time assuring high system throughput and spectrum efficiency considering QoS constraints. In [65], the authors analyzed a relay-aided D2D network focusing on wireless channels uncertainty in order to provide a stable, optimal, and unique solution. The proposed method is close to the centralized optimal solution, showing a low level of computational complexity.

Actually, it seems that privacy is an open issue and no relevant works have been found in the literature. Similarly, social information protection is a hot topic also considering the growing interest of users in defending their personal data. In fact, in the last two years, legal order started a process to improve laws and fundamental rights all over the world.

In Figure 4, all papers presented in this section are grouped and summarized. The dimension of circles is proportional to the number of found references.

4. Lesson Learned

In the past years, social network concepts have been applied to D2D communications. The convergence between social networks and D2D communication is still in its infancy, however the already available scientific contributions clearly demonstrate that the social contribution is fundamental for the improvement of D2D communications. This section overviews the existing gaps in the research and points out the current challenges that still must be addressed.

Several works use the concept of sociality, however there is no common agreement regarding the origin of such sociality, whether it should be inherited from the social networks of people or created among the devices themselves. Future research should therefore address this difference, since the resulting social networks, among people or things, have different characteristics and can then be more or less useful based on the issue at hand.

Among the issues in which the social concepts have been applied, the relay discovery and peer selection topic has been deeply investigated. In particular, the usefulness of social networks has been proven in helping the devices involved in a D2D communication to select reliable and trustworthy peers as their relays, and identify and avoid any malicious device. Another problem tackled by the research community is the prediction of the user's location: even if the number of papers studying this issue is large, we believe that further studies are needed to assess the contribution of sociality, since until now the benefits of social networks to foresee the user's mobility have only been tested through simulations in very specific scenarios, and the literature is still missing experiments on large, real datasets concerning aspects of people and objects behavior. Finally, researchers should concentrate their efforts to apply these concepts to real use cases, since only a couple of works have tried to explore this territory.

The communication mode selection topic has seen several social concepts applied to it. To achieve the effective cooperation together with assuring the physical link quality, the concept of socially aware rate can be used to blend the link rate with the social selfishness from the social knowledge. The new challenges for cellular networks can be managed and handled using community structure information and user-level behavior, improving the management of the channel condition, the inter-cell interference, and reducing the network load. For this specific topic, we believe that there is the need for more research on real applications and also for the development of more realistic scenarios to identify and establish the distinctness between the test use cases and real use cases using the social knowledge and social selfishness.

Combining relay discovery schemes and communication graph to establish social relationships can be used when social connections among users are exploited in a way that fairness is ensured, enhancing also the Quality of Service with the use of social characteristics.

The perspective of socially aware communication mode selection will probably be emergent and unpredictable, and there is the need to achieve a better understanding of social relationships and of the automatic selection of connections from a group of social characteristics focused on the community structure information and similar community interests.

The resource allocation topic has also been analyzed since the beginning of the social-aware approach. Five metrics are presented to summarize the main challenges faced in the last years by research community to improve resources utilization in order to optimize their management considering the growing demand in terms of number of users and services. The proposed strategies do not match a common thread, even when taking into account the same metric, leading to some interesting result, limited though to a specific network or to a particular algorithm. Many specific solutions can be found in the literature, nevertheless a generally recognized direction for the management and reuse of resources is still missing, so it can be largely considered an open topic. Finally, the literature is still lacking solid works to ensure privacy in social-aware resource allocation, which remains an open issue, especially in light of the introduction of international guidelines such as the General Data Protection Regulation (GDPR) introduced in 2018 [66].

5. Conclusions

In this paper, a comprehensive study of the convergence between social networks and D2D communication found in the literature is presented. The concept was proposed around 5–6 years ago: the number of papers, even if limited, is still relevant when compared to this time frame, showing that this topic clearly represents an emerging trend. We analyzed this convergence under three different aspects: relay discovery and peer selection, communication mode selection, and spectrum resource allocation and management.

The main aims of this survey are to investigate the benefits of the integration of social-awareness with D2D communication, and to give to the reader a clear picture of the current scientific efforts on the D2D "communication domain". From the analyzed papers, it clearly emerges how social networks can improve D2D communications under different aspects. However, the efficiency of the proposed solutions has to be proven with the aid of real use cases.

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Research Article

IoT Architecture for a Sustainable Tourism Application in a Smart City Environment

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In the past few years, the Smart Cities concept has become one of the main driving forces for the urban transition towards a low carbon environment, sustainable economy, and mobility. Tourism, as one of the fastest growing industries, is also an important generator of carbon emissions; therefore, the recently emerging sustainable tourism concept is envisioned as an important part of the Smart Cities paradigm. Within this context, the Internet-of-Things (IoT) concept is the key technological point for the development of smart urban environments through the use of aggregated data, integrated in a single decisional platform. This paper performs the first analysis on the feasibility of the use of an IoT approach and proposes a specific architecture for a sustainable tourism application. The architecture is tailored for the optimisation of the movement of cruise ship tourists in the city of Cagliari (Italy), by taking into consideration factors such as transport information and queue waiting times. A first set of simulations is performed using 67-point of interest, real transportation data, and an optimisation algorithm.

1. Introduction

IoT leads a sweeping cultural change as a huge number of machines, devices, sensors, actuators, and other objects become interconnected to each other and to higher-level systems. Due to the enormous amount of variety of connectable devices and automatically collected data, entirely new services and features can arise, to form the basis of, among other concepts, Smart Cities. IoT and big data are both technology-driven developments leading to scenarios such as the one for the Smart Cities, having the potential to generate enormous market opportunities as well as make citizen lives smarter and more sustainable.

The Smart Cities architectures envisioned or implemented up to date deal mostly with use cases from the following categories: energy, waste disposal, environmental management, and transport. All these use cases can have their needs covered by means of an IoT platform connecting heterogeneous sensing systems with the upper layers dedicated to services and interfaces [1].

Tourism is not only the largest growing industry in the world but it also accounts for 5 to 12% of global greenhouse gas emissions [2]. Therefore, in the context of the passage towards a low carbon environment and sustainable economy, the term sustainable tourism was recently coined and begins to gain acceptance from both sides: tourists on one side and tour operators and the interested territory on the other side.

Without travel there is no tourism, so the concept of sustainable tourism is tightly linked to the concept of sustainable mobility which, for the specific case of an urban environment, can be included in the frame of the Smart Cities paradigm.

Based on these aforementioned concepts, this paper proposes an IoT architecture for a sustainable tourism application in a Smart City scenario. The proposed architecture is tailored for a specific use case: sustainable movement of tourists in the city of Cagliari in Sardinia, Italy.

The paper is structured as follows: Section 2 analyses briefly the key requirements for an IoT architecture operating in a Smart City environment for the specific implementation purpose; Section 3 presents the proposed architecture, while Section 4 is dedicated to the use case description and model, tested in Section 5 through a first series of simulations. Section 6 presents the conclusions and the future work.

2. Key Requirements for an IoT Platform in a Smart City Environment

The emerging Smart City concept has many definitions and implementation approaches. However, as pointed out in the Introduction, from an infrastructural point of view, all Smart Cities have at their core a highly capable ICT system (IoT platform) connected to network of sensors, wired and wireless broadband connectivity, and advanced data analytics that settle the basis for developing intelligent applications and services for citizens [3].

Due to the current lack of fully defined standards for IoT architectures, the key requirements for their usage in a Smart Cities scenario are rather difficult to be defined. The first steps in this direction have been done by the PROBE IT EU-financed project which aimed, among others, at benchmarking IoT deployments and setting guidelines for IoT rollouts for Smart Cities [4]. Based on some of these guidelines, considering other surveys [5–9] and also the requirements fulfilled by some of the existing commercial IoT architectures and platforms [10, 11], we extracted a set of key requirements for IoT platforms operating in a Smart City environment.

The compliance of the architecture proposed in Section 3 with the identified requirements, considering also the first implementation steps, is discussed individually for each one of the requirements.

2.1. Security Requirements. There are already more connected devices than people on the planet, with the estimation that, by 2020, there will be 50 billion connected devices [11]. The inclusion of these devices in IoT platforms means that they will be readable and controllable over the Internet. Poor or misconfigured networks are potentially vulnerable to attacks and IoT environments are no different at all, as they are always connected to the Internet. Therefore, an IoT platform must have strong built in security, which, specifically for the Smart Cities environment and for the chosen application, should have the following key requirements.

(1) End-to-End Security Mechanisms and Data Encryption. Standard-based encryption from the hardware devices to the IoT platform is arguably one of the best deterrents of data theft. Many services encrypt data once it gets to their data centre, but in many ways data is more vulnerable when it is in transit. The challenge for the developer with doing this from end to end is making the entire authentication happen without the user's intervention, so the data is encrypted automatically. For the specific case of the proposed architecture, the critical links are between the real-world objects and the related virtual objects. To ensure a secured connection, the real-world objects exchange keys and IDs with the virtual objects at the association phase, avoiding any other further connection to. All the subsequent connections between the virtual objects and the upper layers are inside the cloud environment that avoids unauthorized access to the users' data.

(2) Flexible, Configurable Access and Authorization Control. Different user types need different levels of access to the data, especially for the specific scenario of live environmental data monitoring such as temperature and humidity. Therefore, an IoT platform should be able to grant to the users of the Smart City environment different access profiles in terms of ownership, security level, visibility, data polling frequency, etc. The virtual objects used in the proposed architecture can have three types of permissions: if "public," the resource can be accessible to everyone without the use of any keys; if "private," the resource can be accessed to the owner key only; if "friend," the resource can be accessed by providing the friend-key known by the friend virtual object.

All the other security requirements can be covered by the cloud environment which will be used to implement the proposed architecture.

2.2. Flexibility. The market for IoT-enabled devices, although in full extension, is still in the early stages of adoption. Developers of the next generation of connected devices and products need to rely on certain flexibility from their software counterparts aggregating their products. For these reasons, an IoT platform should comply with the following flexibility rules.

(1) Networking and Device Agnosticism. Configuration changes should not be limited to writing/changing the driver and data format when a device is added or updated, giving the freedom to hardware developers to constantly develop their products without being limited by predefined settings or compatibility issues.

(2) Device Manageability. Since a large number of smart devices and sensors can be placed geographically at large distances in a Smart Cities environment, the IoT platform must incorporate means to allow the remote management of these devices. This may include remote delivery of operating system patches, profiles, new analytics algorithms, and key management of parameters.

(3) Usage of Open APIs. Smart Cities inherently can generate large data sets originating mainly from networks of devices and sensors. Much of this data remains stored and not analysed mostly because of its unavailability to third party users other than the one intended for the original application. Therefore, as a quintessential element for the Smart Cities environment, the IoT platforms underneath should allow access to common shareable data and as such to become a motor for the development of innovative applications.

The proposed cloud-based architectural approach using virtual objects decoupled from the actual real-world objects allows for the flexibility requirements to be fully implemented.

2.3. Data Requirements. IoT data comes mainly from things but also from users in the form of metadata. Smart Cities

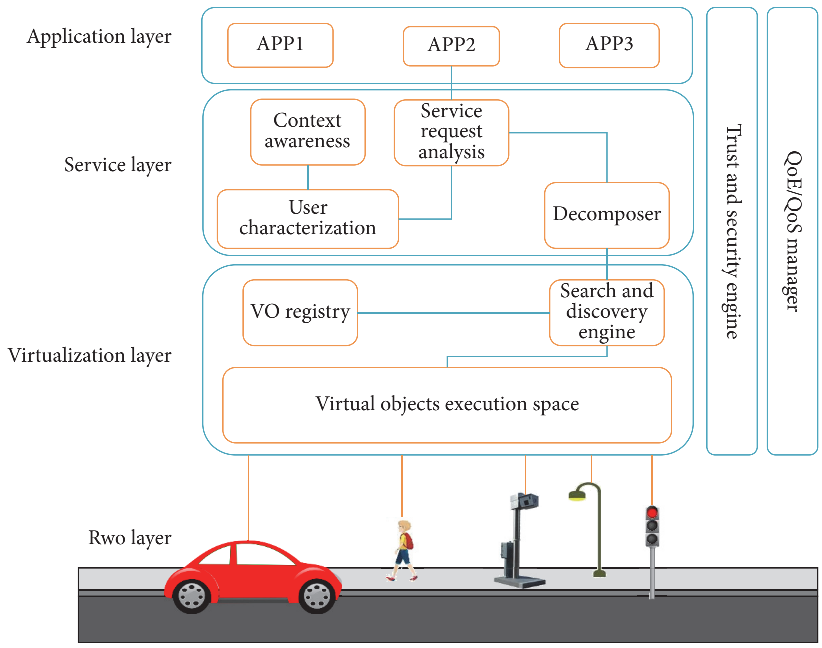

FIGURE 1: Cloud-based IoT architectural solution.

and IoT are more than a remote monitor of incoming data, with the key concept being data intelligence which implies some strict requirements in terms of data [10, 11]:

(1) Flexible Data Definition Tools, Data Virtualization, and Non-SQL Databases. New devices on an IoT platform need to be implicitly easy to define and set up, with no limit on the type of devices. As a consequence, there is no room for the inherent rigidity of SQL databases and the development lag to change the database schemes. The cloud platform to be used for the implementation of the proposed architectures relies on nonrigid SQL databases and flexibility in terms of data definition.

(2) Data Scalability. The data set of an IoT platform in a Smart City environment is predestined to grow on a fast pace, especially when monitoring environmental data, so the platform should have the ability to manage the warehouse of data using culling and archiviation methods, preferably in a fully automated manner. Data scalability for the proposed IoT platform is achieved by using cloud-based implementation.

(3) Component Reusability. In a Smart City environment, even though the incoming data may come from a variety of sources depending on the various application scenarios, the usage of this data is often very similar. Therefore, an IoT platform should allow at a large extent the reuse of the created components with minor adaptations. The proposed solution, through its layered architecture, gives the developers the possibility of building templates of objects and services available also to other uses different from the current one.

3. IoT Architecture for a Sustainable Tourism Application

As mentioned in the Introduction, the goal of our work is to present an IoT architecture for the specific Smart City scenario dedicated to the sustainable management of the tourist flow in the urban environment of Cagliari. To support the deployment of major applications, such as the efficiency of urban operations and services and the sustainable tourism, and to satisfy their quality requirements, an IoT architecture and its implementation as an IoT platform need to be able to address the previously listed requirements. To deal with these stringent requirements, we envision that, through the use of virtualization technologies, every real-world object participating to the Smart City, from smartphones to traffic lights and sensors, is associated with its virtual counterpart in the cloud. Associating a digital counterpart to physical objects is a common practice in the latest IoT research activities [12, 13], since through virtualization the physical devices gain augmented capabilities and are able to [12] (i) fully describe their characteristics with semantic technologies and then be able to interact with other virtual objects; (ii) identify, analyse, and manage the context related to an object surroundings and take decision accordingly; (iii) simplify the search and discovery of services and devices, which continuously join, move, and leave the network.

3.1. Proposed Architecture. The main purpose behind the proposed architecture, shown in Figure 1, is to activate the data-stream from IoT objects when needed. These data-streams are continuously processed to support end-users/ICT applications, with a set of procedures monitoring the context and producing alerts when particular conditions are met.

The proposed IoT platform foresees a four-level architecture: the highest level is the *Application Layer* in which user-oriented macroservices are deployed; the *Service Layer* is responsible for receiving the service requests and mapping them to the atomic services available in the lower layer; this layer is the *Virtualization Layer*, which interfaces directly with the real world and enhances objects' functionalities; the last level is the *Real-World Layer*, containing the real physical devices of the Smart City. Two additional cross-layers are needed to manage the quality requirements of the applications and to ensure that every communication takes place in a trustworthy and secure way, according to the previously listed requirements.

Even if this architecture is at the beginning of its implementation, we are moving towards implementation using Platform as a Service (PaaS) features, since they provide the tools needed to develop, run, and manage web applications, such as the execution containers of web services and related databases for data storage (see the Virtualization Layer subsection).

This approach has manifold motivations: (i) it enables objects to "speak" the same language at virtual level; (ii) it enhances the search and service discovery; (iii) it decouples the service requests and the actual IoT objects which satisfy the request; and (iv) it offers personalized experience to users based on their own needs and traits.

In the following paragraphs, we describe in detail the layers proposed for the architecture.

(1) Application Layer. At this level, user applications are responsible for final processing and presentation of the results. Deployment and execution of application make use of one or more services. An application at this level shows a back-end interface to the underlying layers. Additionally, applications can show a front-end interface so that requests can be triggered by users or by the objects themselves. A user interface is provided for the interaction with the system; however, in this case, the requests need to be translated in a language understandable by the platform.

(2) Service Layer. This layer is responsible for the analysis of the service requests generated by the application in the above layer and to enhance this request with a range of facts concerning the human user, including user context, profile, preferences, and policies. Each service request contains a semantic description of the input and of the desired output.

In particular, the *Service Request Analysis* (SRA) receives the query and asks for the retrieval of the current situation in which the query is performed. Moreover, it must be able to reuse the output of a previous request to respond to requests that present the same inputs and similar user information in order to reduce the burden on the Virtualization Layer and save redundant data requests.

The *user characterization* provides all the information associated with the user or the user's object which made the query. This block comprises cognitive functionalities to build user-related knowledge and act on behalf of the user when needed. This is an important component in our platform because many applications in a Smart City scenario, such as the one for sustainable tourism, are characterized by personal choices: requests coming from different users can have different solutions.

However, user characterization is only related to static user information, so a *Context Awareness* block is needed to detect, recognize, classify, and act upon the particular situation the user is involved in. A tourist looking for a museum to visit can receive different recommendations based on the time of day, the distance from different museums, or the number of people in the queue waiting to visit it.

All the collected information is then forwarded to the *Decomposer*. This block has to decide which atomic tasks (sensing, actuation, and computational) compose the query in order for the Virtualization Layer to be able to search for the right objects through the activation of subqueries.

(3) Virtualization Layer. The Virtualization Layer is where the virtual counterpart of the physical objects, namely, the *virtual objects* (VOs), reside. VOs are digital representations of the service(s) of any entity in the IoT, which are usually described in terms of semantics. VOs are implemented as web services and each of them as a related database for the data storage of the information sent by the physical counterpart.

Moreover, at this layer, the physical objects are enhanced with capabilities which enable them to perform operations otherwise hampered on real objects. Traffic lights, proximity sensors, and road cameras can communicate without any problem at this level even if they all use different communication technologies: simple technologies, such as RFID tags and NFC, can be attached to Points of Interest (POIs) to enhance the visiting experience of tourists by interpreting information about the environment and making choices accordingly, in order to push information to users via smartphones or tablets when necessary [14].

The core of this layer is represented by the *Virtual Object Execution Space* (VOES), where all the instances of VOs run. In fact, whenever a new object is detected, based on the information it provides about its resources and functionalities, it is associated with a new virtual object instance in the VOES. This instance is chosen among the possible VO models from a template repository which matches the physical device information. The VO model includes objects' characteristics; objects' location; resources, services, and quality parameters provided by objects.

Every VO is composed of two parts: on one side, it interfaces with the physical object it is associated with. This way it is possible to introduce a standardized communication procedure between the platform and the extremely variegate set of physical devices, so that the VO can switch among multiple communication channels, such as HTTP (Hypertext Transfer Protocol) or CoAP (Constrained Application Protocol) based on the situations. On the other side, the VO is able to communicate with the other VOs in the VOES through the use of a common semantic.

Thanks to this, heterogeneous objects become interoperable at the virtual level, even if they are not at the real-world level, since all the VOs "speak" the same language regardless of the properties of their physical counterparts. Moreover, since all the data provided by objects are indexed making use of a common language, the discovery of services is simplified.

The metadata about each of the active VOs is maintained in the VO registry, which stores the semantically enriched data that are used for the description of the VOs, in order for them to be available anytime from anywhere.

Whenever the *Search and Discovery Engine* receives a request from the upper layer to find one or more services, this request is matched into VO template names for which VO instances are searched. This module then performs a search in the VO registry in order to discover potentially available and relevant VO instances of the requested VO template names.

(4) Real-World Object Layer. The lowest level of the proposed architecture is made up of real-world objects (RWOs). A RWO can be any entity in the physical domain, human or lifeless, static or mobile, solid or intangible, which is represented in the virtual world through the use of ICT objects. The capabilities and functions of these devices are then described in the Virtualization Layer in terms of sensors, actuators, and resources exposed to the other VOs in the system.

(5) Trust and Security Engine. This layer focuses on the implementation of appropriate security procedures to guarantee reliable communication at every layer. For example, at the Application Layer, it determines the level of access of the apps that generated the requests and grant access accordingly; at the Virtualization Layer, it has to understand how the information provided by the VOs has to be processed in order to ensure that the resources obtained are trustworthy.

(6) QoE/QoS Manager. Quality management is particularly problematic in IoT scenarios due to heterogeneity and mobility issues. The proposed architecture addresses these issues due to the adoption of the VOs; however, a quality manager is still needed to assure that the overall acceptability of applications and services is guaranteed, considering both end-to-end communication requirements (QoS) and the users' expectations (QoE).

4. Use Case

In this section, we analyse how the IoT platform previously described can be used to implement a Smart City scenario specific for the sustainable movement of tourists in the city of Cagliari. The scenario considered in this paper is that of cruise tourists that arrive in Cagliari and have just a few hours to visit the city. The tourists wish to visit some of the city's POIs, in the limited time available before the cruise leaves. For this purpose, we suppose tourists are provided with a smartphone/tablet app where they are able to specify which POIs they wish to visit. The objective is to visit all the desired POIs in the shortest time possible. We detected two main elements that can cause delays to the tourists: (i) choosing the wrong mode of transport to get to the POI and (ii) getting to the POI at the wrong time, when a longer queue time is expected.

For this specific use case, we assume to have sensors placed at each POI's entrance (for those that have one, excluding, e.g., statues, squares), to measure queue waiting time. These sensors, to be physically implemented in the next phase of this work, are virtualized by the Virtualization Layer, so that they are easily interoperable with all the objects that participate to the proposed architecture. Data gathered by the queue sensors is sent to the Service Layer and processed to infer a queue model that associates times of the day to queue waiting times, for the POI under examination. This association is necessary in order to have an estimate queue waiting time at the beginning of the route planning operations.

In our use case, we consider a model based on the mean value of queue waiting times with reference to each time of the day and POI.

Based on the current and expected queue waiting time and on the time needed to get to the POI either by public transport or walking, the optimal route to visit all the selected POIs will be recommended to the tourist.

(1) The Tourist Route Planning Problem. The optimisation problem solved by the application is a typical Travelling Salesman Problem (TSP) [12]: the tourist is given an optimal route where he/she visits each POI only once, minimizing a cost that, in this use case, is considered to be the sum of the time wasted to get to the POI and on the queue.

Given a complete digraph $\mathcal{G}(N, E)$ where N is the set of nodes and E is the set of edges, we associate node $i = 0$ to the tourist starting point and node $i = \{1, \ldots, n\}$ to each POI that the tourist wants to visit. For each edge, we introduce a logical variable $x_{ijk} = \{0, 1\}$ that equals 1 if the tourist goes from POI i to POI j at time step k. Analogously, we introduce a logical variable $y_{ik} = \{0, 1\}$ that equals 1 if the tourist is visiting POI i at time step k.

The cost to get from POI i to POI j at time step k is defined as

$$c_{ijk} = c_{ijk}^{\text{path}} + c_{jk}^{\text{queue}}, \tag{1}$$

where c_{ijk}^{path} is the time needed to go from POI i to POI j at time step k and depends on the mode of transport used; c_{jk}^{queue} is the time spent on the queue at POI j at time step k.

The tourist starts from the starting point $i = 0$. Therefore, it is necessary that

$$y_{00} = 1. \tag{2}$$

Furthermore, the tourist visits each POI exactly once. This is expressed as

$$\sum_{k=1}^{K} y_{ik} = 1 \quad \forall i \in N \setminus \{0\}. \tag{3}$$

Finally, if the tourist visits POI i at time step k, then he/she has to leave it at time step $(k+1)$:

$$\begin{aligned}
&\sum_{j \in N} x_{jik} = y_{ik} \quad \forall i \in N \setminus \{0\},\ k \in \{1, \ldots, K\}, \\
&\sum_{j \in N} x_{ij(k+1)} = y_{ik} \quad \forall i \in N,\ k \in \{0, \ldots, K-1\}.
\end{aligned} \tag{4}$$

Summarizing, the problem to be solved can be formalized as follows:

$$\begin{aligned}
\min \quad & \sum_{i \in N} \sum_{j \in N \setminus \{0\}} \sum_{k=1}^{K} c_{ijk} x_{ijk} \\
\text{s.t.} \quad & y_{00} = 1 \\
& \sum_{k=1}^{K} y_{ik} = 1 \quad \forall i \in N \setminus \{0\} \\
& \sum_{j \in N} x_{jik} = y_{ik} \quad \forall i \in N \setminus \{0\},\ k \in \{1, \ldots, K\} \\
& \sum_{j \in N} x_{ij(k+1)} = y_{ik} \quad \forall i \in N,\ k \in \{0, \ldots, K-1\}.
\end{aligned} \tag{5}$$

The problem described by (5) is a binary programming problem, which can be solved using a branch-and-bound algorithm. This type of problem is NP-hard; that is, its complexity scales exponentially with the number of variables [14]. In our case, the number of variables is given by $|x_{ijk}| + |y_{ik}|$, with $i, j \in N$ and $k = \{1, \ldots, K\}$. Considering that at each time step the tourist visits one of the POIs, $K = N$ time steps are needed to visit all the POIs. Therefore, problem (5) complexity is proportional to $2^{(N^3+N^2)}$. Although it can appear high demanding for the computational resources involved, it has to be noted that this is just an upper bound that is rarely reached. Furthermore, it needs to be considered that the tourist has a limited amount of time to spend in the city, so he/she can only visit a low number of POIs. Nevertheless, should the problem still be considered too complex, heuristic techniques such as genetic algorithms or swarm intelligence may be used for the subsequent implementation of the entire system, planned in the next phase of this work.

The pseudocode of the Tourist Route Planning Problem described in this subsection is provided by Algorithm 1.

```
For i in POI_list then
  For j in POI_list then
    For k in range(1, POI_number) then
      For m in transp_mode_list then
        Retrieve path_time_ijk[m]
      End For
      path_cost[i, j, k] = min(path_time_ijk)
      queue_cost[j, k] = retrieve queue_time_jk
      Compute cost[i, j, k] according to eq. (1)
    End For
  End For
End For
Find all opt_route that solve eq. (5)
If there is more than 1 opt_route then
  Assign opt_route to the one that corresponds to
  the shortest path
End If
```

Algorithm 1: Tourist route planning problem.

5. Simulations

The use case described in Section 4 has been tested by means of a Python code implemented in the Service Layer of the previously presented architecture. We opted for our own implementation using Python and not for the free tools offered by Google Maps and Bing Maps APIs because of the usage limitations of these solutions.

We considered 67 of the main POIs belonging to the city of Cagliari, including churches, museums, monuments, gardens, towers, and historic buildings. Each tourist can select from 2 to 8 POIs, which can be reached either by bus or walking: each transportation mode represents a different cost, expressed in number of minutes.

To test the behaviour of the application, the POIs have been selected randomly from the map. The starting point is set to the port of Cagliari. In order to evaluate the cost to get from one POI to the other, the Google Maps APIs have been used in an initial phase. The queue waiting times c_{ik}^{queue} have been set randomly from 0 to 30 minutes. To compute the right time step k at which the cost value c_{ijk} has to be computed, we also considered the time spent by users at each POI, supposing that they need an average of 45 minutes to visit each POI. The results obtained using the proposed application, called TRAPP hereinafter, have been compared to the following approaches:

(i) Minimization of the time spent to reach the POIs (called MIN PATH), without taking into consideration the time spent on the queue: this is the typical behaviour of common route planning apps that are not enhanced by an IoT platform.

(ii) Moving to the next closest POI using the bus whenever possible (called ONLY BUS): this is the typical behaviour of a tourist who does not feel like walking.

(iii) Walking to the next closest POI (called ONLY WALK): this is the typical behaviour of a tourist who does not feel like wasting time either waiting for the bus or on the wrong bus line or finding the right bus stop.

Figure 2 shows the mean time values of the overall time spent to get to the POIs and on the queue, the only time spent to get to POIs, and the only time spent on the queue, for the four approaches described above, for different numbers of POIs. Focusing on the overall wasted time, TRAPP outperforms all the compared approaches, enabling to save up to 21% with respect to MIN PATH, up to 44% with respect to ONLY BUS, and up to 55% with respect to ONLY WALK.

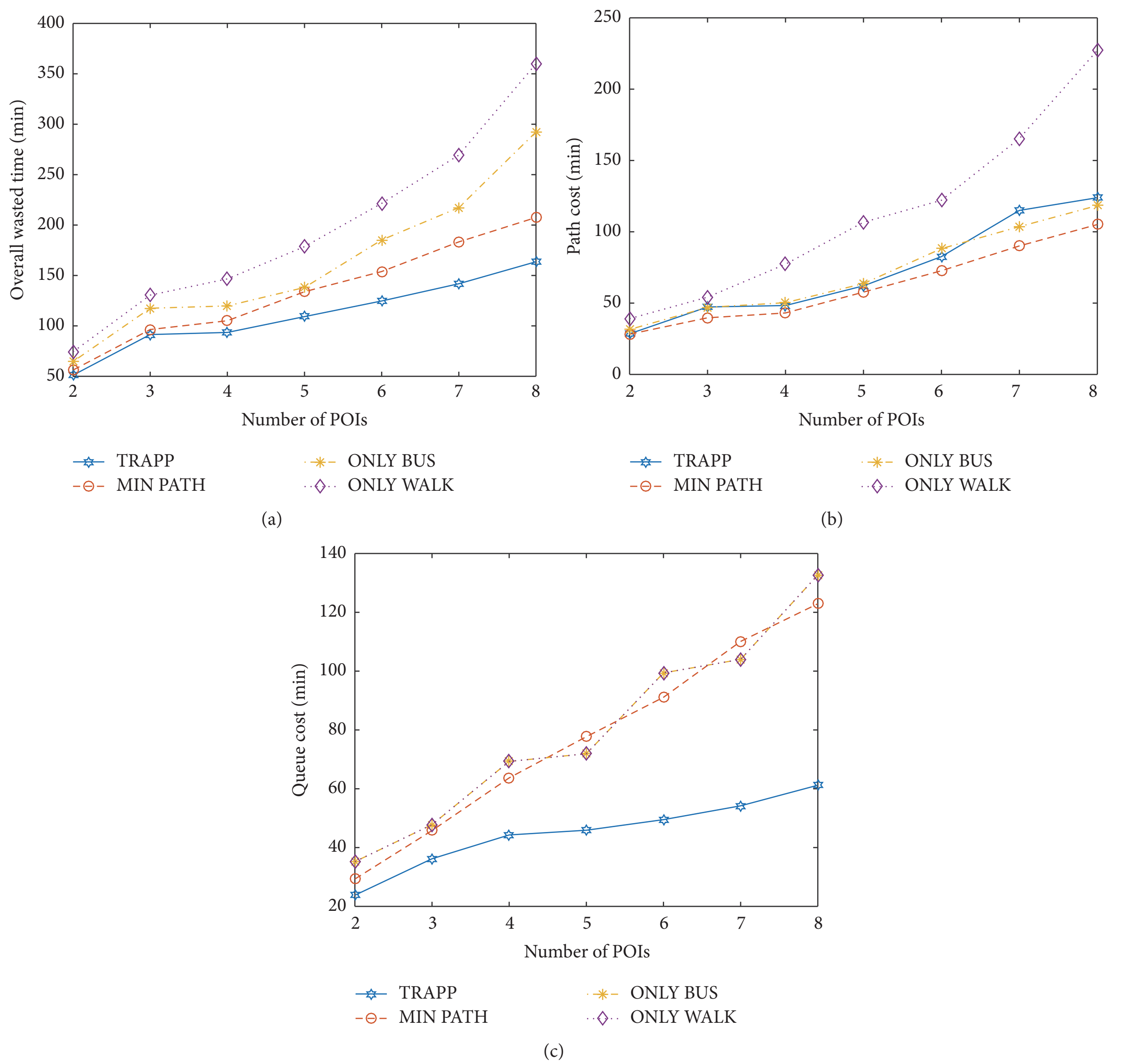

Figure 2: Mean time values for the overall wasted time, path cost, and queue cost for different numbers of POIs.

It has to be noted that, with reference to the queue cost, ONLY BUS and ONLY WALK approaches have the exact same values. This is because in both cases tourists' sequence of visited POIs is the same, as they are moving from one POI to the closest one, but using a different way to reach it.

It is interesting to note that, according to Figure 3, using TRAPP, the tourists' ratio between the distance covered by bus and the total distance is similar to that of MIN PATH when the number of POIs is low, but it gets closer to that of ONLY BUS when the number of POIs considered gets higher. Recall that ONLY BUS ratio is not 100% because it takes into account the distance covered by the tourist to get to bus stops and, in addition to that, sometimes there is no bus line between two POIs. On average, by using TRAPP, the tourist walks 44% of the time.

Cruise tourists usually spend from 6 to 9 hours in Cagliari. Considering this limited amount of time, tourists' satisfaction is higher if they are able to visit all the POIs they have planned to see. Accordingly, we define a satisfaction level given by the ratio between the number of POIs actually visited and the number of POIs that was planned to visit. Figure 4 shows the average tourist satisfaction level of visiting 8 POIs, considering an overall available time of 9 hours, supposing that they spend, on average, 45 minutes to visit each POI.

6. Conclusions

This paper proposes an IoT architecture for a sustainable tourism application in a Smart City scenario. The proposed architecture is tailored for the use case of an application for sustainable tourism. The presented IoT architecture is based

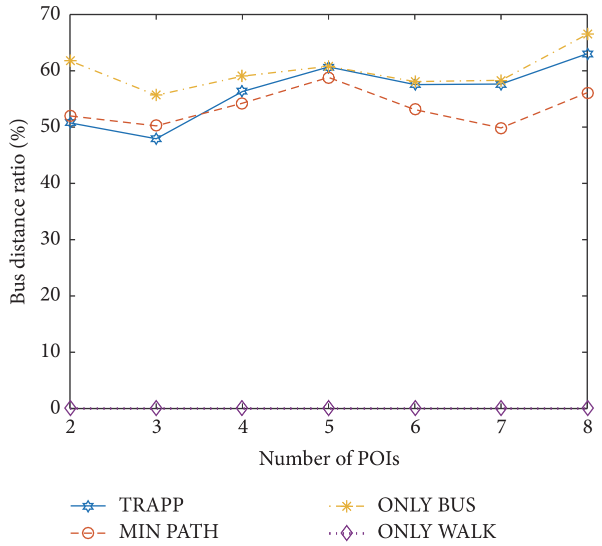

FIGURE 3: Mean percentage of distance covered by bus, with respect to the overall distance covered either by bus or walking.

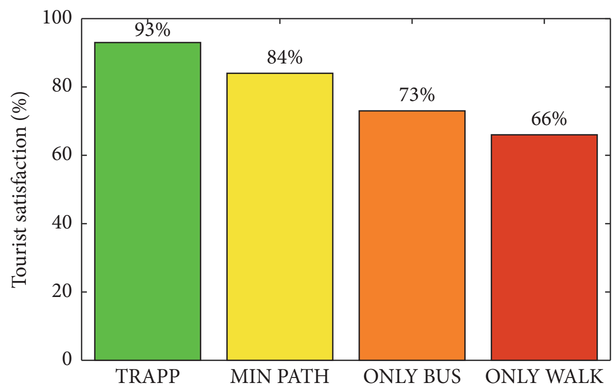

FIGURE 4: Average tourist satisfaction level to visit 8 POIs, for an overall available time of 9 hours.

on a specific set of requirements and can be implemented using a cloud-based IoT platform. The actual implementation is ongoing and is preceded by the proposed implementation of a specific use case for sustainable movement of cruise tourists that arrive by sea in the city of Cagliari, Italy, and have just a few hours to visit the city. The simulation of the presented use case includes a set of 67 POIs, information about the waiting times at the POIs, and transport information (walking and bus times and distances).

The simulation results evaluate the mean time values of the overall wasted time, the time wasted to get to POIs, the time wasted waiting on the queue, the distances covered by bus or walking, and the average tourist satisfaction level. The results showed that, with reference to other approaches, the proposed application enables tourists to save up to 55% of their time, with a satisfaction level up to 27% higher. Furthermore, the distance covered by bus rather than walking is comparable to that of the approach where tourists chose to use bus whenever possible, particularly for higher number of POIs.

Based on these encouraging first results, we already started the implementation of the proposed IoT architecture on a cloud-based IoT platform. The future work includes the completion of the implementation activities, the deployment of the virtual objects, including the queue and traffic sensors, and the introduction of new constraints to improve the Tourist Route Planning Problem (e.g., considering other modes of transport, user profiling, clustering techniques, and different weights of the cost elements of the problem, based on user preferences).

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Interference Issues for VANETs Communications in the TVWS in Urban Environments

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***Abstract* — Within the scenario of the proliferation of smart vehicles, a novel tendency is to exploit the cooperation between vehicles to create vehicular ad-hoc networks (VANETs) using the IEEE 802.11p standard. IEEE 802.11p includes Dedicated Short Range Communications (DSRC) between high-speed vehicles and between the vehicles and the roadside infrastructure in the licensed Intelligent Transportation System (ITS) band at 5.9 GHz. At such frequencies fading problems caused by Doppler effect and/or multipath adversely affect propagation, especially in dense urban environment. To reduce such propagation impairments the use of lower frequencies has been proposed in literature, namely the TV White Spaces (TVWS) in the UHF band. TVWS is the part of the spectrum licensed to broadcasters which is not occupied at a given time in a given geographical area on a non-interfering /non-protected basis with regard to primary services. This work analyses coexistence issues between DVB-T2 broadcasting and IEEE 802.11p transmission in the TVWS. Aim of the study is twofold: to evaluate the protection of DVB-T2 broadcasting services interfered by IEEE 802.11p communications as well as the impact of adjacent DVB-T2 services on IEEE 802.11p communications in the TVWS. The main outcomes of the study are the maximum transmission power level and bandwidth configuration of an 802.11p signal in the adjacent channel (i.e., TVWS) of an active DVB-T2 system whereas protecting the broadcast service, and the error rate curves for each allowed mode of IEEE 802.11p in the TVWS to evaluate the performance of VANETs communications coexisting with DVB-T2 regular services in the licensed TV band.**

***Index Terms*— VANETs, IEEE 802.11p, DVB-T2, interference, TVWS.**

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I. Introduction

Vehicular ad-hoc networks (VANETs) are wireless networks with constantly changing network topology, due to the mobility of the nodes. In this context, a specific standard, the IEEE 802.11p for wireless access in vehicular environments (WAVE), has been designed [1]. IEEE 802.11p enables the 802.11 family (Wi-Fi) [2] to support intelligent transport systems (ITS) allowing the exchange of data between vehicles (V2V) and between vehicles and infrastructure (V2I) in the 5.9 GHz band [3]. Unfortunately, the use of such high frequencies raises fading problems such as the Doppler effect and/or multipath that adversely affect propagation, especially in dense urban environments. To solve this drawback, researchers proposed the use of lower frequency bands [4], considering also that, for frequencies below the GHz, the system would be more robust in real urban traffic conditions due to the less severe impact of fading effects. This frequency range is currently divided mainly between digital terrestrial TV (DTT) broadcast services and cellular mobile services. For the DTT services the frequencies are allocated by a geographical-based planning to ensure reduced interference between adjacent TV channels. This allocation process leaves free channels in each territorial area, the so-called "TV white spaces" (TVWS) [5], which could be used to implement opportunistic ad-hoc short-range and low-power communication systems [6], such as systems based on the IEEE 802.11p standard.

DTT broadcasting worldwide relies on several standards. Among these standards the digital video broadcasting – terrestrial (DVB-T) is widely deployed with over 60 countries that have adopted it. The second-generation DVB-T2 has been already introduced in Europe as an extension of DVB-T, based on the 2009 specifications of the European Telecommunication Standardizations Institute (ETSI) [7].

The tolerance of DVB-T/T2 receivers to adjacent channel interference (ACI) has been quantified [8], revealing that transmission on adjacent channels can cause harmful interference if the output power of the transmission exceeds the maximum received interference

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power tolerable by the receiver. The Electronic Communications Committee (ECC) presented a report to provide technical and operational requirements for secondary unlicensed devices operating in the 470-790MHz frequency band, in order to ensure the protection of the incumbent radio services [9][10].

In this context, this work proposes a coexistence study between VANETs communications based on IEEE 802.11p standard adapted to operate in the TVWS and DTT services based on DVB-T2.

A first measurement series has been carried out to determine the protection levels for DVB-T2 receiver interfered by IEEE 802.11p communication operating in adjacent channel (i.e., TVWS) at varying the carrier frequency for different operation modes of the IEEE 802.11p standard [11]. In particular, the Protection Ratio (PR), that is the minimum value of the signal-to-interference ratio (C/I) required to obtain a specified reception quality under specified conditions at the receiver input [12] has been evaluated.

For these measurements, the reception quality has been quantified using a subjective evaluation criterion: the absence of a picture error for a certain period of time, called picture failure (PF). PF is commonly used as impairment criteria for broadcasting services to determine the signal-to-interference threshold C/I_{th} at which the interfering signal source has degraded the TV reception to an unacceptable quality. TV reception is considered unacceptable in presence of picture break-ups during 30 consecutive seconds of observation period. [13][14][15]. These measurements allowed identifying the maximum transmission power level and bandwidth configuration of a 802.11p device operating in the adjacent channels and within the coverage area of an active DVB-T2 system whereas protecting the DTT service.

A second measurement series completes the coexistence study by reversing the view point, which is analyzing the performance of 802.11p devices operating in TVWS under DTT emissions based on DVB-T2. In particular, the bit error rate (BER) curves in the presence of adjacent DVB-T2 interference have been evaluated for each allowed mode of the IEEE 802.11p standard. For these measurements, to cope with real VANETs communication scenarios characterized by rapidly varying conditions due to changing topology of the networks of moving vehicles, multipath fading and Doppler effects have been considered. In [16] three different statistical distributions have been compared (i.e., Rayleigh, Rician and Lognormal) so as to choose the one causing the highest BER, hence the worst channel conditions. It is shown that the Rayleigh distribution generates the highest BER, while Rician distribution gives BER values between the Rayleigh and log-normal at mobile speeds of 30, 60, and 90 km/h when measured at the same distance. By the light of the above study, in our experiments a Rayleigh channel model has been considered, thus considering the worst condition case. Experiments have been performed under the assumptions of slow and flat fading which can be easily verified for IEEE 802.11p transmission in the TVWS in urban scenarios where the vehicle speeds is limited to 50 km/h.

In this study, the IEEE 802.11p PHY layer has been modeled on the transmitter and receiver side to transmit standard compliant signals in the TVWS, in order to evaluate the BER of the received signal in the presence of adjacent DVB-T2 interference. We tested different configurations of the IEEE 802.11p considering different bit rates, modulation types, and channel bandwidths provided by the standard. For the DVB-T2 signal, the typical settings for the multiple frequency (MFN) and single frequency (SFN) broadcasting networks have been considered.

The study allowed determining the maximum transmission power level and bandwidth configuration of an 802.11p signal in the adjacent channel (i.e., TVWS) of an active DVB-T2 system whereas protecting the broadcast service, as well as the BER curves for each allowed mode of IEEE 802.11p in the TVWS, thus evaluating the performance of VANETs communications coexisting with DVB-T2 regular services in the licensed TV band.

The rest of the paper is organized as follows. Section II describes the IEEE 802.11p physical layer, while section III illustrates the measurement set-up. Section IV describes the measurement methodology. The obtained results are discussed in section V. Finally, section VI presents the conclusions and future work.

II. IEEE 802.11p PHY Layer

The IEEE 802.11p standardization process originates from the allocation of the dedicated short range communications (DSRC) spectrum band in the United States and the effort to define the technology for usage in the DSRC band [17]. The IEEE 802.11p is only a part of a group of standards related to all layers of protocols for DSRC based operations [18]. The IEEE 802.11p standard [19] is a MAC and PHY level standard. For the purposes of the present study the PHY layer has been fully implemented. The PHY layer is conceived to make small changes to the already existing 802.11 PHY, in order to optimize it for its use in vehicular networks. The IEEE 802.11p operates at a frequency of 5.9 GHz. The PHY layer in IEEE 802.11p is the same as in IEEE 802.11a

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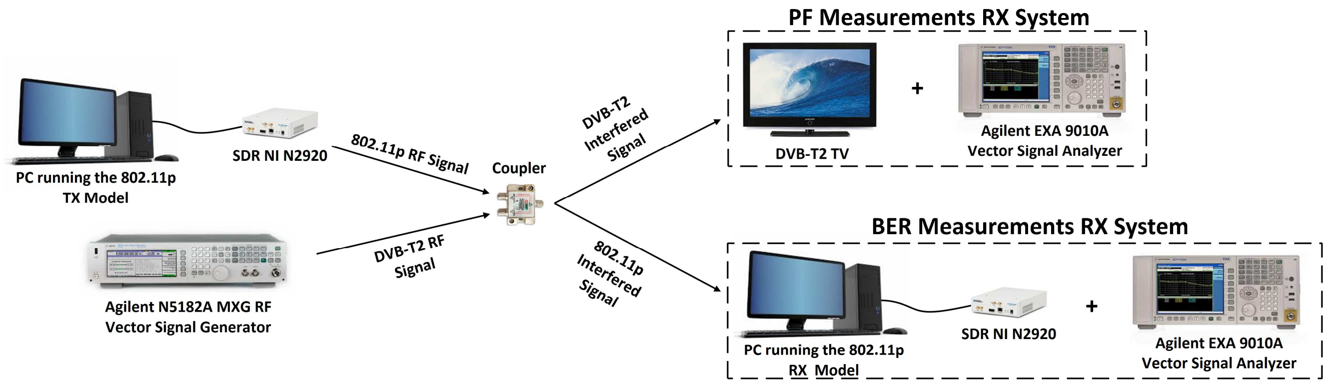

Fig. 1 Measurements Set-up.

except for the different sampling rate. It defines three different modes: 20 MHz, 10 MHz, and 5 MHz. The different modes can be achieved by using reduced clock/sampling rates. IEEE 802.11a usually uses the full-clocked mode with a 20MHz bandwidth. In comparison, IEEE 802.11p usually uses the half-clocked mode with a 10MHz bandwidth and the symbol length is doubled, making the signal more robust against fading.

The 20 MHz mode is optional. The 802.11p signal uses a carrier spacing reduced by half when compared to 802.11a.

In this work the IEEE 802.11p PHY layer has been modeled using Matlab/Simulink software on the transmitter and receiver side in order to transmit a real standard compliant signal and to receive it evaluating the BER after the Viterbi decoder.

A. Transmission Side

The source bits are produced by a binary random generator block. The data is coded using convolutional coding, with a native rate of 1/2 with a constraint length equal to 7. The other code rates can be obtained by puncturing bits. Coded bits are then delivered to an interleaver. The interleaving scheme is defined by two permutations. The first permutation ensures that adjacent bits are modulated onto nonadjacent subcarriers and the second permutation ensures that the adjacent bits are mapped alternatively onto less and more significant bits of the constellation.

In the IEEE 802.11p standard four different types of modulation are used: BPSK, QPSK, 16QAM and 64QAM. The modulation type depends on the desired data rate, ranging from 1.5 to 27 Mbps. Data bits are mapped to subcarriers after modulation. The IEEE 802.11p uses OFDM modulation characterized by 64 sub-carriers (i.e., 1 sample per OFDM subcarrier), of which 48 used for the data, 12 void to reduce interference between adjacent channels and 4 pilot for the channel estimation. After insertion of pilot and guard, an IFFT is operated on them to create the OFDM symbol. A cyclic prefix is added at the beginning of each OFDM symbol. Finally the signal is converted from parallel to serial and prepared for transmission.

The 802.11p PHY layer signal is physically generated using the National Instruments USRP N-2920 Software Defined Radio (SDR) board connected to a PC running the implemented Matlab/Simulink software model.

The most important parameters characterizing the 802.11p signals transmitted during the measurements are shown in Table 1.

TABLE 1
MODULATION SCHEMES AND CODE RATES FOR 802.11P

Data Rates [Mbps]	Modulation Type	Coding Rate	BW [MHz]
1.5	BPSK	1/2	5
3	QPSK	3/4	5
9	16-QAM	2/3	5
13.5	64-QAM	3/4	5
3	BPSK	1/2	10
9	QPSK	3/4	10
18	16-QAM	3/4	10
27	64-QAM	3/4	10

B. Receiver Side

The synchronization of the signal assures that the symbol timing from the input complex waveform is recovered correcting the timing offset. Also, a frequency offset correction is implemented thanks to a frequency offset correction algorithm. Then, the cyclic prefix is removed to each received OFDM symbol and the OFDM

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demodulation is performed. After removal of pilot and guard, each symbol is demodulated.

Data are de-interleaved using a de-interleaver scheme complementary to the algorithm used at the transmission side. For the forward error correction (FEC) a lazy Viterbi decoder algorithm has been implemented: it is a maximum-likelihood convolutional code much faster than the original Viterbi decoder [20].

III. MEASUREMENT SET-UP

The set-up for the measurements is shown in figure 1. The transmission side, a DVB-T2 signal and a IEEE 802.11p signal simultaneously transmitted and combined, is the same for the two measurement series. The DVB-T2 signal is generated using an Agilent N5182 Vector Signal Generator (VSG) and the Agilent Signal Studio Toolkit. Two typical settings for the MFN and SFN broadcasting networks were considered: 8K FFT size, 256QAM modulation, 1/128 guard interval, code rate 3/5, PP7 pilot pattern for MFN networks and 64QAM modulation, 1/16 guard interval, code rate 3/5 and PP4 Pilot Pattern for SFN networks. The 802.11p signal is RF modulated and transmitted using a NI N2920 SDR platform connected to a computer running the transmission Matlab/Simulink model described in section II. The 802.11p signals used for the measurements are of a pulsed nature, which allowed considering the intrinsic time variance for a typical vehicular transmission.

For the PR measurements, the combined RF signal is received both by a DVB-T2 receiver and by the Agilent EXA9010A Vector Signal Analyzer (VSA). The measurements on the power of the two signals (i.e., DVB-T2 and 802.11p) are crosschecked using as reference the VSA.

For the BER measurement series, the 802.11p interfered signal is received both by means of a NI N2920 SDR platform connected to a computer running the reception Matlab/Simulink model described in previous section, and by the Agilent VSA.

IV. MEASUREMENT METHODOLOGY

A. PR Measurements Series

Transmission on adjacent channels can cause harmful interference if the output power of the transmission exceeds the maximum received interference power tolerable by the DTT receiver. The parameter to evaluate this influence is the PR that quantifies the threshold value of the signal-to-interference ratio C/I_{th} required to obtain a specified reception quality under stated conditions at the receiver input [11]. For these measurements, the reception quality was quantified using a subjective evaluation criteria: the absence of PF [13][14][15], during a minimum observation time of 30seconds [14]. In order to evaluate the performance of a DVB-T2 system interfered by 802.11p transmission, PF has been monitored for different bit rates and bandwidths of the IEEE 802.11p standard.

Preliminary measurements have been performed, showing that the set-up conditions are frequency invariant within the UHF band, therefore, without losing generality, the TV channel 44 (i.e., $f_c = 658$ MHz, $B_c = 8$ MHz) has been considered in this study to report the results. The interfering 802.11p signal is transmitted on every adjacent channel starting from the first adjacent channel up to the ninth adjacent channel of the DTT signal on each side of channel 44. In this frequency range, the maximum transmission power levels of a 802.11p signal has been obtained in order to respect the condition for absence of PF for a DVB-T2 receiver. The following test procedure is used to measure the C/I_{th} for all adjacent channels:

1. The sensibility of the tested DVB-T2 receiver is measured with the Agilent VSA finding an average power level of -73 dBm. Thus, the DVB-T2 signal power level C was set to -73 dBm. This can be considered the worst operative case. The DVB-T2 signal power level is measured using the Agilent VSA with effective bandwidth of 7.61 MHz.
2. The 802.11p interfering signal is initially set to a power level of -20 dB below the sensibility of the tested receiver. This power level (i.e., -93 dBm) has been measured with the Agilent VSA.
3. The signal power level of the 802.11p interference is then adjusted at the output of the SDR board. The objective is to find the power level of the 802.11p signal above which the received and decoded TV signal starts to degrade (i.e., PF point).
4. The power level of the interferer is measured in the channel bandwidth of the receiver.
5. The C/I_{th} is calculated from steps 2 to 4.
6. Steps 2 to 5 are repeated for each of the channels from $N - 9$ to $N + 9$.
7. Steps 2 to 6 are repeated for a 802.11p signal characterized by a 10 MHz and a 5 MHz bandwidth, considering all the bit rate values as in the IEEE 802.11p standard.
8. Steps 1 to 7 are repeated for two different configurations (MFN and SFN) of the DVB-T2 signal.

B. BER Measurements Series

In BER measurement series again channel 44 is considered. The transmission frequency of the 802.11p

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signal is set to the central frequency of the first adjacent channel (i.e., $f_c = 666$ MHz). To characterize the Rayleigh fading channel model, the speed of the IEEE 802.11p transmitter and receiver is supposed to be constant during all the measurements: 50 km/h speed has been chosen so as to reproduce the worst channel conditions in VANETs communications in urban environment. Slow and Flat fading assumptions have been verified for every mode of IEEE 802.11p. The distance between IEEE 802.11p transmitter and receiver has been considered constant with a mean value equal to 5 meters, which is a mean distance between two flanked vehicles. The position of the DVB-T2 interferer is fixed.

The following test procedure is used to measure the BER for different bit rates and bandwidths of the IEEE 802.11p systems interfered by a DVB-T2 system operating in the adjacent channels:

1. The transmission power level of the DVB-T2 signal (I) is set to - 60 dBm and is fixed during all the measurement. This value ensures that the TV receiver is working at least 10 dB above the interference free PF threshold;
2. The transmission power level of the 802.11p signal is initially set considering the PR value to respect the condition for the minimum PF level of a DVB-T2 receiver, as calculated in the first measurement series (i.e., in section IV.A);
3. Starting from the level set at point 2, the power level is decreased to evaluate the performance of the IEEE 802.11p receiver, in terms of resilience to the DVB-T2 interference;
4. The RMS power level of the 802.11p signal (C) is measured in the considered channel bandwidth using the Agilent VSA to calculate the corresponding signal to interference C/I ratio;
5. The BER after the Viterbi decoding is evaluated;
6. Steps 2 to 5 are repeated for a 802.11p signal characterized by a 10 MHz and a 5 MHz bandwidth, considering all the bit rate values as specified in the IEEE 802.11p standard.
7. Steps 1 to 6 are repeated for two different configurations (MFN, SFN) of the DVB-T2 signal.

V. Results

In this section the results obtained from the PR and BER measurements are shown.

A. PR Measurements Results

Figures 2 and 3 respectively show the results for different bit rates of a 10 MHz and 5 MHz 802.11p signal interfering a DVB-T2 signal typical for a MFN network configuration.

Figures 4 and 5 respectively show the results for different bit rates of a 10 MHz and 5 MHz 802.11p signal interfering a DVB-T2 signal typical for a SFN network configuration. For the sake of clarity only a subset of the measured curves have been reported, corresponding to equally distributed bit rates in the range allowed by the 10 MHz and 5 MHz modes.

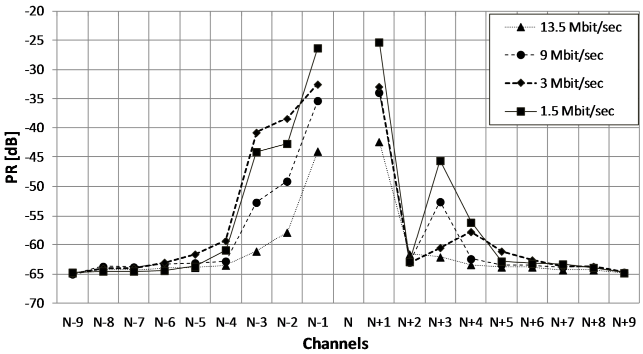

Fig.2 MFN DVB-T2 into 5 MHz 802.11p protection ratio.

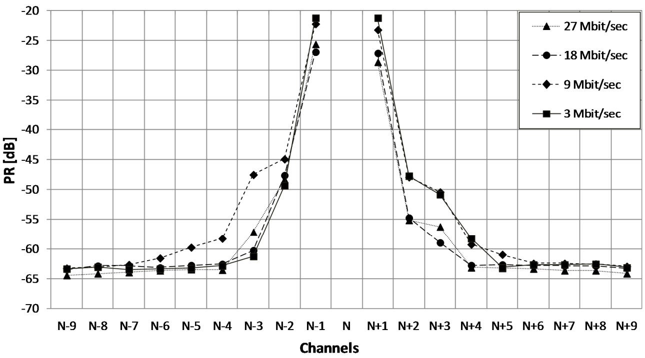

Fig.3 MFN DVB-T2 into 10 MHz 802.11p protection ratio.

By comparing the obtained results it can be noticed that the interference level changes with the bandwidth of the interfering signal. As expected, 5 MHz signals disturb less for all values of bit rate compared to 10 MHz signals both for the MFN and the SFN configuration. A 5 MHz bandwidth signal uses a subcarrier spacing of 78.128kHz while the 10 MHz bandwidth signal has subcarrier spaced at 156.25 kHz thus, producing less interference. Furthermore, it can be noticed that high interference is caused by signals with low bit rates. This criticality can be explained considering the spectral efficiency which is the ratio between the transmission rate offered to the user by a communication system and the bandwidth used for such communication [21]. A system with a higher spectral efficiency shows a more compact spectrum with an average lower power. This effect can be seen comparing two signals only differing for the bit rate, the first one

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having a low bit rate (for example 3 Mbit/s) and the second one characterized by a higher bit-rate (27 Mbit/s). The signal with lower bit rate has an average power level of -65 dB which is superior to that of the signal with a higher bit-rate, which is equal to -80 dB, both values measured with the Agilent VSA for the same transmission schemes. This difference accounts for higher PR for lower bit rates.

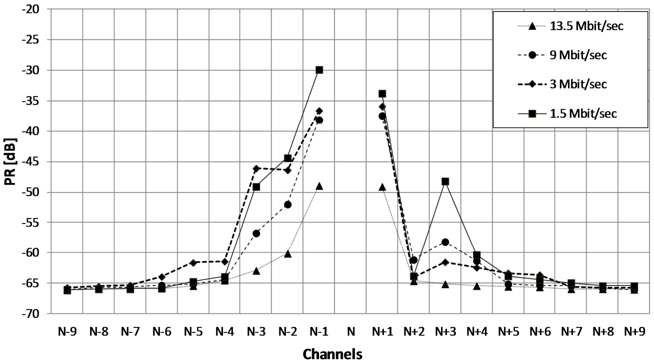

Fig.4 SFN DVB-T2 into 5 MHz 802.11p protection ratio.

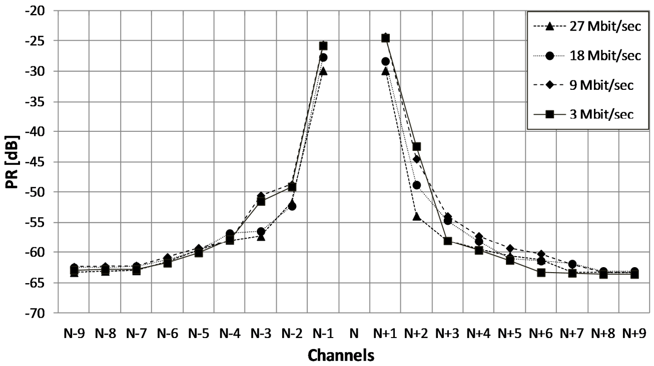

Fig.5 SFN DVB-T2 into 10 MHz 802.11p protection ratio.

Figures 2 and 4 illustrate that an 802.11p signal with 5 MHz bandwidth interferes a DVB-T2 signal over the adjacent channels especially for lower transmission bit rates and in particular in correspondence of the third adjacent channel $(N + 3)$ where this effect is more pronounced. The problem does not occur for higher bit rates for both SFNs and MFNs.

Laboratory measurements on DTT receiver protection ratio values required to ensure adequate reception in the presence of interference from devices transmitting in the TVWS have been carried out for different DTT tuners (i.e., silicon and CAN tuners) in [22][23]. Some of these DTT tuners show a similar undesired effect, depending on the quality of the receivers.

Finally, comparing the curves obtained for the two considered DVB-T2 configurations for MSN and SFN, lower PR values have been obtained for 64QAM type (i.e., SFNs). The curves measured for the 256QAM modulation (i.e., MFNs) type differ up to 5 dB, showing a lower robustness (i.e., higher PR) of the MFNs. These results confirm the outcome of a previous work [24] that provides guidelines to optimize cognitive networks in the TVWS by choosing the parameters that best fit their needs in case of coexistence with DVB-T2 service operation.

B. BER Measurements Results

Figure 6 shows the BER results applying the Viterbi decoder to the received data of an 802.11p signal interfered by a DVB-T2 signal typical for a MFN network configuration, with different bit rates and bandwidths.

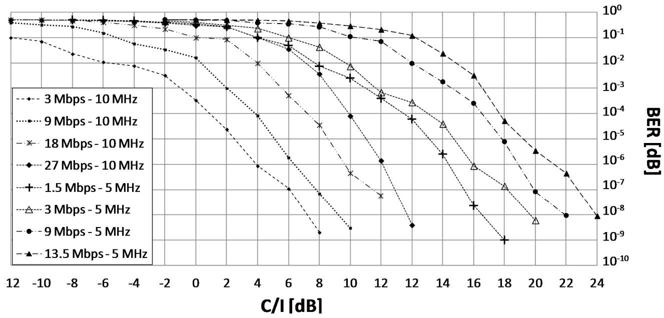

Fig.6 BER evaluation after Viterbi decoder for a 10 MHz and 5 MHz 802.11p signal interfered by a DVB-T2 MFN signal.

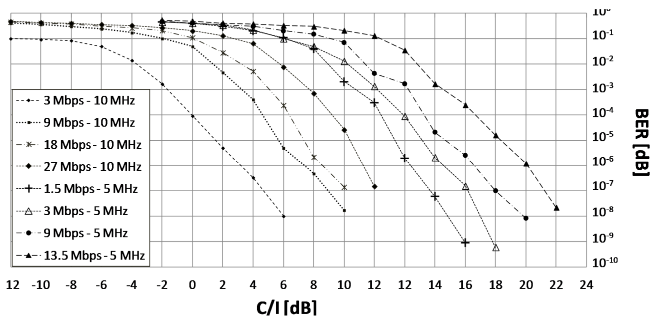

Fig.7 BER evaluation after Viterbi decoder for a 10 MHz and 5 MHz 802.11p signal interfered by a DVB-T2 SFN signal.

The 5MHz signals show higher BER levels compared with the 10MHz signals. This effect is due to the overlapping effect between the 10MHz 802.11p signal and the 8 MHz DVB-T2 signal, which adversely affects the quality of the received signal. Furthermore, the robustness increases with the bit rates. Higher modulation schemes with higher data rates are more robust to DVB-T2 interferences.

Figure 7 shows the BER results applying the Viterbi decoder to the received data of an 802.11p signal

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interfered by a DVB-T2 signal typical for a SFN network configuration, with different bit rates and bandwidths.

The results are similar to those obtained for the MFN case, leading to the same conclusion: 5MHz signals with higher bit rates are more robust to DVB-T2 interferences.

Comparing the curves obtained for the MFN case (figure 6) and for the SFN case (figure 7), it can be seen that the IEEE 802.11p standard is more susceptible to DVB-T2 interferences in a SFN configuration.

VI. Conclusions

This work presents a coexistence study between DVB-T2 broadcasting services and IEEE 802.11p transmissions in the UHF TV channels in urban evironments. A first measurement series allowed assessing the maximum transmission power level of an IEEE 802.11p signal while assuring the integrity of the DTT services for the typical MFN and SFN operation modes of a real DVB-T2 broadcasting network. To assure the protection of the DTT systems the reception quality was quantified assuming the absence of a picture failure during a minimum observation time of 30 seconds.

The results obtained for the investigated DVB-T2 transmission modes suggest that the effect of the 802.11p adjacent interference changes with its configuration. For the tested DVB-T2 receiver the worst operative case has been considered. The 802.11p interfering signal was initially set to a power level of -20 dB below the sensibility of the tested receiver and then adjusted at the output of the SDR board to achieve the required degradation (PF point) of the received and decoded TV signal. The bandwidth and the bit rate were the two monitored parameters.

A 5MHz bandwidth signal disturbs less for all values of bit rate compared to a 10 MHz bandwidth signal both for the MFN and the SFN networks configuration. For a 10 MHz bandwidth signal the most critical cases are for low bit rates. This can be explained considering that the spectral efficiency is high efficiency when using all the bandwidth, leading to a more compact spectrum with increasing bit-rate and a consequent decrease of the disturbance caused to the broadcasting signal.

Comparing the curves obtained for the two considered configurations, it could be noticed that lower protection ratio values have been obtained for 64QAM type. The 5 MHz case shows an undesired effect in correspondence of the third adjacent channel, even more pronounced for low bit rate values, depending on the quality of the receiver.

A second measurement series analyzed the performance of 802.11p devices in the presence of DVB-T2 broadcasting services. The BER of an 802.11p device after a Viterbi decoder has been evaluated in the presence of adjacent DVB-T2 interference. The results show a similar trend for both the SFN and MFN configurations, leading to the conclusion that higher modulation schemes with high data rates are more robust to DVB-T2 interferences. Moreover, the 5 MHz signals show higher BER levels compared with the 10 MHz signals, due to the overlapping effect observed in the 10 MHz case that adversely affects the quality of the received signal.

A further study considering real scenarios characterized by different environment conditions is under planning, so as to assess the results of the present work in real operating conditions.

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EmoLoop: A Bi-Directional System for Emotion-Driven Interaction Between Remote Audiences and Live Performers

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***Abstract*—This paper presents *EmoLoop*, a bi-directional interactive system designed to create real-time emotional feedback loop between performers and a distributed audience during music or theatre events. The proposed system collects emotional data from the audience using different feedback methods, such as EEG signals from wearable headbands, facial expression analysis through VR headsets, and interaction with smartphones. These emotional states, expressed as valence/arousal values or emotion categories, are used to control various parameters of the performance, like spatial audio, lighting, and scenographic elements, both on stage and in virtual environments. EmoLoop also includes a real-time feedback system that gives performers useful cues based on the audience's emotions. Communication between components is managed with protocols like OSC, MQTT, WebSockets, MIDI, and ArtNet to ensure low-latency transmission. The architecture is modular and flexible, and the paper explains its components, integration, and possible use cases. EmoLoop offers a new approach to participatory performance, where emotions play a central role in shaping the artistic experience, in line with current research in the Internet of Sounds (IoS) and Internet of Musical Things (IoMusT).**

***Index Terms*—Internet of Sounds, emotion recognition, audience feedback, immersive audio, VR performance, real-time audio interaction, affective computing, hybrid performance, Open Sound Control, text-to-emotion mapping, sentiment-based synthesis, spatial audio, networked music performance, artistic installations, human-computer interaction in music**

I. INTRODUCTION

The integration of emotion recognition into interactive media and performance arts is gaining relevance as new sensing technologies and machine learning techniques allow deeper audience engagement and adaptive storytelling. Recent work in affective computing has emphasized the potential of emotional feedback loops to influence musical improvisation, virtual environments, and hybrid performances in both artistic and therapeutic settings [1], [2].

EmoLoop introduces a novel architecture that enables real-time, bi-directional interaction between performers and distributed audiences by leveraging *multimodal emotion recognition* and *adaptive media control*. The proposed system intends to integrate a variety of sensing modalities—including facial expression detection, EEG data acquisition, and smartphone-based interactions, to interpret the affective state of audience members and modulate the performance accordingly.

In immersive settings like live concerts or theatrical installations, understanding how emotion manifests in neural, facial, and behavioral patterns is essential to personalize the user experience and enhance presence [3], [4]. Platforms such as Meta Quest and Muse 2 offer real-time access to these biosignals through SDKs and APIs, providing a viable infrastructure for emotion-adaptive systems [5]–[7].

The EmoLoop framework includes: (i) a user emotion detection module that fuses multimodal signals using deep learning technologies, (ii) a mapping engine translating emotional states into real scenographic modulation parameters, and (iii) a real-time feedback channel to performers via audio-visual cues. This modular pipeline enables new forms of audience-performer co-presence, which are especially relevant in hybrid or remote performance contexts as explored in recent studies on networked music and interactive dramaturgy [1], [8]–[10].

This work contributes to a broader research objective: investigating how multimodal emotion sensing can be integrated into live performative ecosystems, shaping expressivity and interaction across physical and virtual spaces. In this first stage, our focus is on designing and implementing the architectural foundation of such a system, defining sensing modalities, communication protocols, and mapping strategies for supporting future evaluative studies. EmoLoop aims to contribute both as a conceptual framework and an operational prototype to address these questions on the *Internet of Sounds (IoS)* and *Internet of Musical Things (IoMusT)* [11] topics.

In addition to affective computing and networked performance research, EmoLoop also aligns with developments in

Technology-Mediated Audience Participation (TMAP) [12], a field that examines how digital, gestural, or sensor-based tools enable audiences to actively influence live performance. Within this spectrum, EmoLoop adopts an affect-driven participation model, where the audience's emotional states modulate the performance rather than serving as explicit inputs.

This paper is structured as follows: Section 2 reviews related work in emotion-driven performance systems, multimodal affective sensing, and networked interaction. Section 3 presents the overall architecture of the EmoLoop system. Section 4 details hardware/software integration and preliminary technical evaluation. Section 5 outlines use-case scenarios. Section 6 discusses the current limitations and future work.

II. Related Work

The EmoLoop system builds upon interdisciplinary research across affective computing, multimodal emotion recognition, immersive performance, and emotion-driven generative systems. This section outlines the specific relevant contributions.

A. Affective Computing and Emotion-Aware Performance

Recent years have seen a growing interest in integrating emotion recognition technologies into performative contexts. Damiano et al. [1] explored strategies for designing affective interaction in live performances, highlighting the narrative and structural implications of emotional modulation. Similarly, Hopkins et al. [10] investigated trust-driven co-creation between audience and performers in interactive musical improvisations, suggesting that affective data can influence performative agency and dramaturgy.

In immersive virtual environments, Lee et al. [3] demonstrated how chat-driven sentiment feedback can enhance shared presence during live VR concerts. Their findings support the use of collective emotion as a modulating signal for scene rendering and audio mixing, which aligns with EmoLoop's real-time feedback architecture.

B. Multimodal Emotion Recognition

Multimodal affect recognition, which combines EEG, facial expression, and interactional data, is central to EmoLoop. Kalansooriya et al. [13] demonstrated EEG-based classification in affective gaming contexts, while Hao et al. [14] proposed a multimodal fusion approach integrating neural and audio features for real-time music emotion recognition.

Recent frameworks such as the Magic XRoom [4] and work by Su et al. [15] stress the importance of combining biosignals across multiple anatomical domains. Meanwhile, Wang et al. [16] examined emotion-triggered scenographic changes in theatrical VR performances, providing a compelling case for fusing emotion and dramaturgy in real-time.

C. Emotion-Driven Generative Systems

Emotion-adaptive systems have been implemented in music recommendation [17], [18], music video emotion tagging [19], and interactive art [20]. Zhang et al. [21] explored deep-learning-based music generation conditioned on emotion, using convolutional and LSTM architectures.

D. Technologies for Real-Time Feedback

Studies such as Colafiglio et al. [7], Kulkarni and Kaur [22] and Geetha et al. [23] provide overviews of real-time emotion recognition pipelines that integrate these technologies. Protocols like Open Sound Control (OSC) [24], ArtNet [25] and MIDI [26] are commonly used in multimedia interaction systems. WebSockets and MQTT are also explored as low-latency control layers in musical contexts [27] and are considered in EmoLoop's planned implementation.

III. System Architecture

EmoLoop advances the IoMusT by integrating audience-side wearable devices as active musical things within a distributed performance network. Through real-time communication protocols like OSC, MQTT, and RTP-MIDI, multimodal biosignals captured from remote users are translated into controllable parameters for sound, lighting, and scenography. This emotional mapping layer extends typical IoMusT interaction models, where control is performer- or instrument-driven, by positioning the audience as an affective source within the same networked ecosystem.

The EmoLoop system is designed as a modular, real-time architecture enabling bi-directional interaction between a live audience and performers by emotion recognition and immersive environment modulation. Figure 1 provides an overview of the architecture. This section details the envisioned system's primary components, organized into five functional modules.

A. Input Devices

1) Meta Quest V3 VR Headset: The Meta Quest V3 provides high-fidelity immersive rendering and captures biosignals via embedded sensors. Eye tracking, IMU, and facial expression data (via infrared camera arrays and Meta Quest SDK) allow real-time acquisition of Facial Expression Activations (FEAs), based on the Facial Action Coding System (FACS) [6]. Recent studies [28] validate the use of these signals for in-VR affect recognition, even under partial occlusion caused by the headset itself.

2) Muse 2 Brain-Sensing Headband: Muse 2 captures EEG signals across frontal and temporal lobes, providing neurophysiological insights into emotional states such as arousal and valence [13]. Integration is supported via the Muse SDK and other open source frameworks, such as BrainFlow and OpenBCI, offering compatibility with existing signal processing pipelines [5], [7], [29].

B. User Emotion Detection Module

This module fuses data from the VR headset and EEG headband. It includes:

- **Preprocessing:** Signal synchronization, noise reduction, and artifact removal across EEG, IMU, and FEAs.
- **Multimodal Emotion Recognition:** Based on deep learning architectures such as the multi-scale attention LSTMs with squeeze-and-excitation (SE) blocks proposed in [5]. Facial expression data is expected to be processed using methods akin to the EfficientNet-B0-based convolutional neural networks exploited in [28].

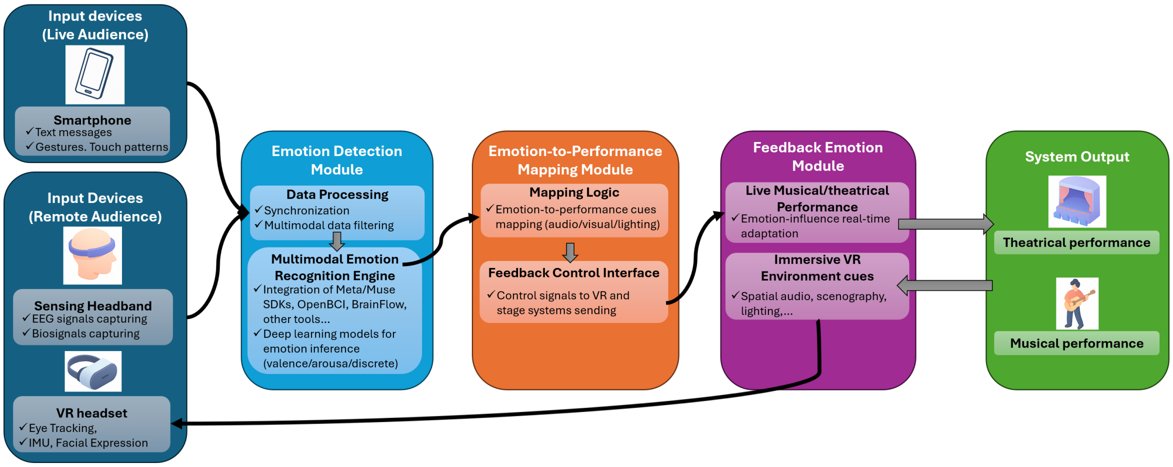

Fig. 1. EmoLoop Architecture

C. Emotion-to-Performance Mapping Module

In this stage, emotion vectors (e.g., valence/arousal, discrete emotion classes) are translated into performance control parameters. Their corresponding control signals are then transmitted on the stage using real-time communication protocols such as ArtNet, MIDI, OSC, and optionally WebSockets or MQTT chosen based on latency requirements and endpoint compatibility [8]. The mapping logic is synced in real-time also in the VR environment (e.g. Unity), using custom plugins and it can include for example:

- Spatial audio modulation (e.g., reverb, panning);
- Dynamic lighting and scenography (e.g., color tone based on collective emotion);
- Scene transitions triggered by the dominant audience feedback.

D. Emotion Feedback Module

Performers receive real-time cues (visual or auditory) reflecting aggregated emotional states of the audience. These could be presented for example via on-stage visual indicators, augmented HUD overlays or audio modulation feedback through in-ear monitors.

The bi-directional link enables co-creative and affect-driven performance modulation, aligning with concepts of participatory dramaturgy [1], [16].

E. System Output

The final output is twofold: (i) immersive VR Experience delivered via VR Headset, adapted to user emotion, (ii) dynamic music/theatre shaped by continuous audience feedback.

This architecture closes the loop between audience perception, emotional response, and performative expression—an innovation grounded in current affective computing frameworks and immersive media interaction.

IV. Implementation and Preliminary Setup

The EmoLoop system is currently under active development, with its modular components designed to support real-time emotional feedback for immersive and interactive performance environments.

A. Hardware Integration and Multimodal Pipeline

The first stage of implementation focuses on establishing a reliable multimodal sensing infrastructure. The Meta Quest V3 headset serves as the primary VR interface and provides streams from built-in eye tracking, inertial measurement unit (IMU), and facial expression sensors. Parallelly, the Muse 2 brain-sensing headband supplies continuous EEG signals representative of user cognitive and affective states.

These data streams are acquired via vendor-specific SDKs, such as Meta Quest SDK for Unity and BrainFlow for Muse, and will be aligned and synchronized in real-time to enable robust cross-modal feature extraction.

B. Software Architecture and Tools

A modular software architecture is being implemented using the following technologies:

- **Unity XR Framework:** for VR scene design, avatar integration, and spatial audio control.
- **Emotion Recognition Engine:** built with PyTorch for EEG and image-based inference pipelines, with plans to integrate multi-scale attention LSTM and EfficientNet-B0-based models [5], [28].
- **Communication Protocols:** Open Sound Control (OSC), MQTT, and MIDI will be evaluated for low-latency message delivery between emotion recognition modules and the VR/performance control subsystems.

C. Preliminary Technical Evaluation

Although a full experimental validation is not yet available, feasibility is corroborated through (i) reference to standard dataset performance, and (ii) simulated latency benchmarks.

For EEG-based recognition, studies on benchmark datasets such as DEAP and AMIGOS report a binary accuracy of around 70% for valence and around 80% for arousal using LSTM-based models. Indeed, Li et al. [30] report 72.06% for valence and 74.12% for arousal on DEAP with a convolutional–recurrent (LSTM) network, while a recent survey [31] summarizes attention-based LSTM-RNN results on AMIGOS of 79.4% and 83.3% for binary classification of valence and arousal, respectively.

Similarly, facial expression recognition in VR settings has been shown to reach accuracies in the 70–82% range even under occlusion using EfficientNet-B0 trained on EmoHeVRDB [6], [28]. These results establish realistic baselines for EmoLoop's emotion detection module.

Latency and jitter analyses from networked performance research and industrial communication studies confirm that, for on-stage feedback where sub-tens-of-milliseconds control is required, OSC over UDP and RTP-MIDI are the most suitable solutions. In [32] and [33] an OSC round-trip performance is reported to be consistently below 10 ms in musical networking contexts, while in [34] is emphasized that RTP-MIDI is designed for real-time musical interaction. By contrast, in hybrid or remote scenarios, WebSockets and MQTT become more viable: empirical evaluations such as [35] show that WebSocket typically remains within 40–90 ms depending on cloud routing, whereas MQTT ranges from 90–130 ms under comparable conditions. These latency bands remain acceptable for non-time-critical feedback and asynchronous control tasks.

Furthermore, previous implementations of multimodal interactive frameworks report end-to-end latencies which aligns with EmoLoop's design goals [11].

V. Artistic Use Case: Emotion-Driven Performance Scenario

To validate the EmoLoop system within a real-world creative context, we envision its deployment in a hybrid musical-theatrical performance scenario, where audience emotion becomes an integral part of the artistic language.

The use case centers around a live immersive concert set in a virtual scenography, where the EmoLoop architecture enables a dynamic feedback loop between audience and performers. Multiple audience members wear the Meta Quest V3 VR headset and the Muse 2 EEG band, exploring different scenes in a shared virtual environment.

Each scene corresponds to a narrative segment with its own musical and visual aesthetics. Emotional states derived from the audience (e.g., valence, arousal, discrete labels) dynamically influence:

- Spatial audio mix (reverb depth, source positioning);
- Ambient lighting and scenographic elements;
- Textural evolution and expressive variations in the music played live.

A. Interaction Mechanism

The emotional vectors inferred from EEG and facial signals are mapped in real-time to audiovisual parameters through the Emotion-to-Performance Mapping Module using OSC/MQTT messages to interface with the Unity environment, where the system updates scene visuals, audio, and stage lighting.

Performers receive simplified visual cues via stage displays or auditory feedback, helping them to modulate dynamics, tempo, or timbral expressions based on the collective emotional feedback of the audience.

B. Role of the Director and Audience Participation

An optional human director can mediate dramaturgy by choosing which user's view is projected onto the holographic screen. Alternatively, the system may automate viewpoint selection using aggregated emotional data or entropy-based metrics. Audience members act as co-creators, since their affective responses shape the evolution of the performance. Currently, emotional inputs are captured individually but fused into a single collective feedback stream for both performers and the immersive environment. Personalized feedback is planned but not yet implemented.

C. Creative Objectives

This scenario explores how emotion-driven interaction can enhance audience immersion, enable performer adaptability and improvisation, and reshape dramaturgical structures by considering emotion as a dynamic variable. By making affective states perceptible and manipulable in real time, EmoLoop supports expressive relationships among musicians, audiences, scenographers, and computational systems. Audience immersion will be evaluated through self-report questionnaires, biosignal and behavioral indicators such as EEG patterns and gaze, and responsiveness to performative modulation. Dramaturgical effects will be assessed through logged scene transitions, performer feedback, and analysis of how emotional triggers influence musical or narrative development. These measures will help determine how the emotional loop increases presence and co-creation across virtual and physical settings.

VI. Conclusion and Future Work

This paper introduces EmoLoop, an interactive framework that enables a bi-directional emotional feedback loop between performers and audiences in immersive musical and theatrical contexts. By combining multimodal emotion recognition from EEG signals, facial expressions, and behavioral cues with real-time performance control, the system supports new forms of affect-based co-creation in hybrid environments.

The architecture relies on wearable sensors such as the Meta Quest V3 and Muse 2, together with emotion inference models and low-latency protocols, to dynamically influence sound, scenography, and spatialization. The work is positioned within Affective Computing, Networked Performance, and Internet of Sounds, offering a feasible model for participatory art.

Future work will focus on finalizing system integration of emotion sensing, VR interaction, and performance control, conducting user studies to assess emotional accuracy and expressiveness, testing scalability in hybrid online–offline setups and co-developing new dramaturgies with artists and designers. The long-term ambition is to connect human affect and computational performance systems, enabling scenarios where emotions do not only inspire but actively shape performances in real time.

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Immersive Application for Real-Time Interactive Music Performances Using Spatial Audio

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***Index Terms*—XR Audio, audio-visual systems, Networked Music Performance, Real-Time Interaction, Quality of Experience, Multimedia Coding.**

***Abstract*—This paper proposes the implementation of an Extended Reality (XR) application that enables real-time streaming of live music concerts, where users equipped with XR headsets can interact with musicians in immersive virtual spaces. Musicians are represented by avatars, each associated with one or more audio tracks captured by a digital mixer. Using spatial audio and real-time interaction mechanisms, the system provides an engaging and dynamic concert experience, simulating the presence of a live audience while offering an user-controlled feedback channel. In the proposed system, multitrack audio streams from the musicians' mixer are transmitted to the XR environment via low-latency streaming protocols. These audio tracks are spatialized in the 3D space using advanced algorithms such as Head-Related Transfer Function (HRTF)-based rendering or Ambisonics within typical 3D game engines (e.g. Unity, Unreal). Each musician's avatar, positioned in the virtual environment, dynamically updates its location and sound directionality relative to the musician's position and orientation. Audience members can interact with musicians in real time by providing audio feedback (e.g. cheering, clapping, singalong), which are reflected on the musician's side by spatialized audio crowd responses.**

I. Introduction

The pandemic conditions witnessed few year ago, pushed a still growing worldwide interest for remote and distributed audio production applications, both at industrial [1], [2], [3] and academic [4], [5], [6] level. Indeed, since 2020, the number of experimental events such as Networked Music Performances (NMP) and live streaming of musical concerts to a remote audience increased exponentially [7], [8], due also to the technological progress of hardware and software technologies supporting NMP [9], [10] (e.g. broadcasting platforms, audio spatial mics, audio routing protocols, 360 and depth cameras, etc.) and higher bandwidth availability [11] (e.g. FTTH, 5G, etc.).

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A. Networked Music Performances

As previously stated, NMP applications have been a real game changer in the past four years, enabling the collaboration in terms of live performances between musicians situated in different geographical locations. The main challenge remains though the level of engagement and audio realism that is still far from the one provided by an in-person performance. Creating a natural and engaging auditory experience in these situations is still a challenging task due to latency, spatial disconnection, and lack of perceptual immersion. Therefore, current research and implementation efforts address the following essential factors: spatial audio, low latency and jitter thresholds to enhance the in-person experience within networked environments.

B. Spatial Audio Techniques

In terms of spatial audio technologies, for the realistic recreation of three-dimensional soundscapes, the HRTF [12] and Ambisonics [13] techniques have recently become prominent in NMP systems. Commercially available systems such as Steam Audio [14] and Resonance Audio [15] deliver the possibility to have real-time spatial rendering that dynamically adapts to user orientation and source positions. The integration of spatial audio into NMP has been discussed in [16], showing how 3D audio increases the sense of presence and immersion for remote performers. Other works implement hardware-optimized solutions, [17] (FPGA-based) and [18] (SOC-based), that look promising for reaching real-time spatial audio rendering with very low computational latency. These systems enable an accurate spatial positioning of audio sources for the musicians, enhancing ensemble synchronization and spatial awareness.

C. Low Latency and Jitter Thresholds

Latency is still the main limitation of NMP systems considering the fact that the perceptual thresholds for

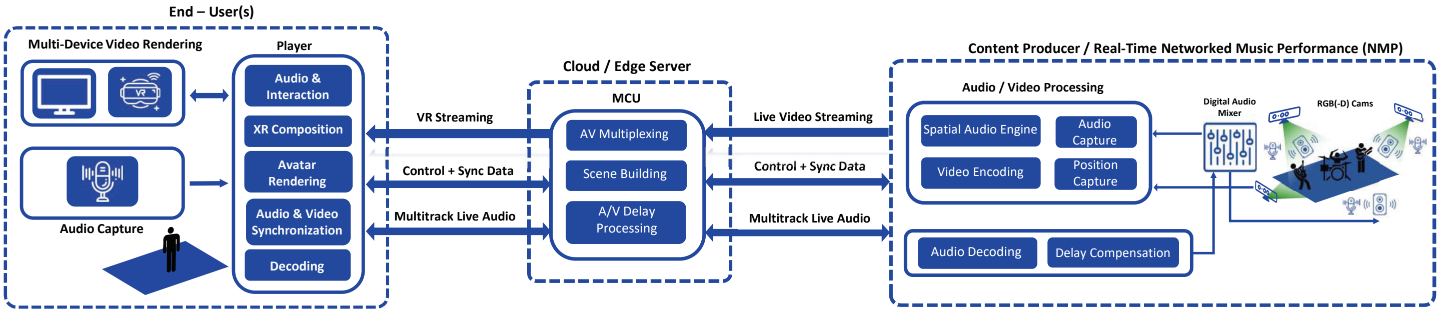

Fig. 1. Proposed Architecture

acceptable delay are around 20–30 ms for musical synchronization [9]. According to [19], this threshold is critical in real-time performances to maintain rhythmic cohesion. Buffer optimization, packet prioritization, and edge computing are some of the strategies explored to minimize latency in audio transmission. State-of-the-art systems like Soundjack [20] and LoLa [21], which allow very low latencies under optimized network conditions, are among the most used for high-performance musical collaboration. Recent developments in the optimization of 5G networks has led to the inclusion of this communication standard for further reducing transmission delays and ensure that quality remains consistent across geographically dispersed musicians [22].

D. Enhancing In-Person Engagement

While NMP systems focus mainly on latency reduction, recent studies and applications go further to replicate the physical and emotional engagement of in-person performances. The use of XR technologies has led to the creation of immersive environments where musicians and audiences can interact visually and aurally. XR concerts like those depicted in [3] and projects like MINERVA [23] aim to demonstrate how real-time spatial audio and visual data can enhance presence and engagement, creating a shared virtual stage for performers. Moreover, systems leveraging depth sensors (e.g., Microsoft® Kinect™ and Intel® RealSense™ LiDAR) dynamically adjust spatial audio rendering based on the musicians' movements and orientations, further bridging the gap between physical and networked performances [16], [18].

This paper aims to introduce and discuss the key aspects behind the design and implementation of immersive applications (AR/VR/XR) that enable real-time streaming of live music concerts, where users equipped with suitable hardware (i.e. Smart TV with in-built camera and mic, PC, smartphone, XR headset) can provide feedback to the musicians through the virtual environment. This research has two main scopes to investigate:

1) the bi-directional feedback mechanisms that maximize the user experience on both sides of the application (end-users hearing and seeing the concert and musicians playing the songs);

2) the real time spatial audio generation approaches based on spatial data.

This paper presents the developed architecture, describes its components and draws the implementation conclusions based on a list of critical challenges, togehter with the performed measurements.

II. Proposed Architecture

A. Architectural Description

The proposed and implemented architecture, depicted in Figure 1, is divided into three main layers: 1) *Content producer/ Real Time NMP*, 2) *Cloud/Edge Server*, 3) *End User(s)*. On the *Content Producer* side, the band performance is live video captured with the aid of an array of at least four RBG-Depth cameras, in our specific case the Intel® RealSense™ LiDAR Camera L515. The RGB data, together with the information related to the depth, are fed to the *Position Capture* block, where the data are preprocessed in real-time in order to generate the complete 3D scene, identifying the position of each musician and allowing the extrapolation of the spatial information which is fed to the *Video Encoding* block and also to the *Spatial Audio Engine* block. The multitrack audio data is captured via microphones or directly form the instrument amplifiers through a *Digital Audio Mixer* (e.g. a Behringer X32 Compact mixer) and fed channel-wise to the *Audio Capture* block. Each channel represents one instrument, the singer's voice being captured also on a separate channel. In case of the drums, where more microphones are used to capture the sound, the different sound sources are mixed down internally on a unique channel and fed as such further to the *Audio Capture* block.

The output of the main *Content Producer/Real-Time NMP* layer consists therefore of the live video data, the depth data, the multitrack live audio data, the control data and the synchronization data.

The *Cloud/Edge Sever* layer implements the necessary mechanisms to synchronize the audio and video data (the *A/V Multiplexing* block) and to build the entire 3D scene (the *Scene Building* block). All the mechanisms are implemented in the cloud, using a micro-services based architecture (e.g. Docker/Kubernetes) and a real-time communication protocol (e.g. WebRTC [24]). The avatars of the musicians are dynamically built in terms of texture and position.

The *End User* layer receives the data from the cloud through the *Decoding* block and builds the 3D scene for the final user, rendering the content for multiple devices, such as 3D headset or 2D screen, by means of the *XR Composition* and the *Avatar Rendering* blocks. The user is interacting with the scene through the rendering device, as follows: for the 3D headset the movement of the user is extrapolated directly by using the data delivered by the headset, while for the 2D screen, the eyegaze of the viewer is analyzed by a 2D camera (dedicated camera or cellular phone), using specific algorithms [25], [26]. The end user's audio is captured by using the 3D headset's or the built-in camera's microphone, correlated with the user's movement in the *Audio-Interaction* block and synchronized by the *Audio-Video Synchronization* block. The user's audio feedback, as a separate audio channel, is subsequently forwarded to the *Cloud/Edge Server* layer where the delay is furthermore compensated by the *A/V Delay Processing* block and then forwarded to the live performance. The position of the user is transmitted as spatial metadata through the *Control+Sync Data* channel.

In the *Content Producer/Real-Time NMP* layer the audio is decoded, the delay is again compensated to overcome network delays and then fed to the *Digital Audio Mixer* as a separate input feedback channel. Based on the spatial metadata, received via the the *Control+Sync Data* channel, the audio feedback is panned by the digital mixer (controlled by the mixer's SDK) and fed to each musician's monitoring line (e.g. monitor loudspeakers or in-ear monitors) to simulate the movement of the user, creating a realistic audience representation also on the musician's side.

B. Architectural Challenges

Keeping latency below acceptable thresholds (e.g. 30 ms) between the two endpoints is one of the key challenges, since this technical condition is essential for reaching real-time interaction and synchronization between performers and audiences. High-latency environments disrupt the flow of bi-directional feedback and diminish the immersive experience. To tackle this, the architecture incorporates low-latency streaming and coding protocols, (e.g. RTP and Opus Codec [27]), which have demonstrated effective real-time transmission capabilities in platforms like JackTrip [28] and LoLa [21]. Additionally, the use of 5G networks and edge computing solutions ensures faster data transmission, minimizing latency for spatial audio and multi-sensory feedback.

Bandwidth and scalability present another challenge, as high-quality spatial audio and volumetric video demand significant bandwidth, especially in large-scale implementations. Object-based audio rendering technologies like MPEG-H 3D Audio [29] and Ambisonics [13] provide scalable solutions, enabling individual sound sources to be dynamically spatialized while maintaining efficient bandwidth usage. For example, Ambisonics can capture 360° soundfields, ensuring that remote listeners perceive audio spatially aligned with visual cues in XR settings. The integration of 5G technology further enhances scalability by offloading processing to edge servers, reducing the computational burden on local devices.

The synchronization of multi-sensory feedback, including audio, visual, and haptic elements, is another technical hurdle. Bi-directional audio feedback systems can further enhance interaction by spatializing audience responses (e.g., clapping and cheering) and transmitting them as real-time cues to performers. Additionally, haptic devices can simulate remote applause or heartbeat feedback, providing a richer sensory connection between participants.

III. Architecture Implementation and Performed Measurements

In order to evaluate the architecture in terms of connection quality for immersive audio applications with ultra-low-latency constraints, we implemented a subset of the entire architecture, concentrating on the audio connection between the content producer and the end-user. A Unity server was set-up in the cloud and fed with four audio tracks audio coming from prerecorded lossless WAV files. On the client side, the end user navigates through the 3D environment of the unity server, where avatars represent the three band members (bass, guitar and vocals and drums). Based on the coordinates of the end user, the different sound sources were 3D mapped to his position in relation to the position of the musicians. Since the network transmission was based on the WebRTC protocol, the WebRTC Internals Chrome tools were used. Two main metrics were used to assess the architecture's behaviour: total round trip time and jitter, supported by the majority of the studied references as the most significant for the NMP applications [30], [31], [32]. For the aforementioned metrics, various codecs were used to which one of them yields the best results. Since the Unity 3D environment was used, the choice felt on the native audio codecs implemented in Unity, namely RED, OPUS e G722. The latter one, even though a codec intended for high-definition voice applications was considered in order to test the influence of a smaller sample- (8 kHz) and bitrate (64 kbps) on the considered metrics.

TABLE I
Jitter and Round Trip Time measures with WebRTC Internals

Metric	OPUS	RED	G722
Jitter (ms)	4.26	3.71	4.02
Total Round Trip Time (ms)	3.68	3.42	4.89

The obtained values are in line with the ones obtained in the literature, but do not take into consideration also other processing delays which are very much depending on the hardware and software installed at the end points. Parallel measures were done on the server's side using Wireshark, yielding much higher values for the round trip time, for example for the OPUS codec a value of 82 ms vs. the 3.68 ms of the WebRTC internals value. The Total Round Trip Time values were obtained for combined audio-video packets, with a video quality set to a resolution of 640 X 480 pixels with 15 frames per second.

IV. Conclusions

The present paper introduces and discusses the key aspects behind the design and implementation of immersive applications (AR/VR/XR) that enable real-time streaming of live music concerts, where users equipped with suitable hardware (i.e. Smart TV with in-built camera and mic, PC, smartphone, XR headset) can interact with musicians in a virtual environment. The study aims to develop innovative feedback loops for audience engagement, such as spatialized applause and dynamic performer-audience interactions. Through the combined use of spatial audio rendering, real-time audio processing, and XR integration, the architecture allows to create an immersive and scalable platform that overcomes latency, bandwidth, and synchronization challenges while fostering bi-directional interaction between performers and audiences, laying the groundwork for a transformative experience in interactive musical experiences, new content delivery and broadcasting-related services.

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Toward Interactive and Distributed Hybrid Extended Reality Experiences

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ABSTRACT

Hybrid Extended reAliTy (HEAT) is a project born to pave the way for the next-generation distributed experiences: being realistically immersed (holo-ported) within real captured omni-directional and navigable hyper-realistic 3D spaces, feeling their atmosphere, and sharing these experiences with others, regardless of their location. This paper gives an overview on how HEAT aims at integrating immersive media technologies such as point cloud/holographic imaging, multi-sensorial media, Social VR in a multi-user, feedback-enabled communication system to provide the construction of compelling context-aware and embodied experiences for innovative hybrid XR applications.

KEYWORDS

XR, holography, multi-sensorial.

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1 INTRODUCTION

Multi-user virtual communication and collaboration solutions have gained popularity during the pandemic, as the traditional "in presence" habits of working/learning/entertaining had to be translated to remote/blended ones. Major limitations associated with such remote/blended approaches are mainly related to two aspects. On one hand, there is an inadequacy of how the classic means of audio-video content dissemination (i.e. PCs, laptops, tablets, TV sets) represent real scenarios. On the other hand, the traditional multimedia content itself (i.e., audio and video) is not adequate enough to reflect the real world. 3D scenarios, dynamic volumetric representation of users, stereoscopic 2D, 180°/360° videos, point cloud/holographic imaging have been considered more suitable candidates to reproduce highly realistic experiences. True realistic contents should also include media with multiple sensorial effects (i.e., multi-sensorial media, also called mulsemedia) aimed at increasing the user's experience through the five senses representation (i.e., taste, sight, touch, smell, and hearing), as the real world is perceived. Mulsemedia has been proposed and tested in several scenarios in which it has been proven to enrich the sense of reality with respect to multimedia (i.e., audio-video) [6]. Furthermore, Virtual Reality (VR) headsets have been proposed to enhance users' immersivity levels, allowing them to experience a seamless and rich integration of heterogeneous media formats. Moreover, social interaction between remote users can now be enabled through shared immersive virtual environments, bringing up a new communication medium termed Social VR [9]. Social VR has rapidly attracted a high interest, magnified by the social distancing measures brought by the worldwide pandemic. Social VR allows multiple distributed users getting together in shared virtual environments to socially interact and collaborate. However, the major issue with the current VR approach is sharing of audio-video content only, relying on synthetic avatars for representing users which makes the social cues complicated to be shared. The potentiality of the above technologies is far from being fully exploited, especially due to the lack of a "system perspective" where the technological integration could really make the difference in enabling true immersion and almost-real interaction based on the effective exchange of social cues and proper rendering of user feedback. A step ahead in this sense has been made in [4], where photo-realistic volumetric user representations (i.e., holograms) are used to allow richer identification of the self and others' representations, as well as richer interaction between the users and the VR environment and among themselves. However, full VR experiences have limited and very specific application scenarios (e.g., virtual training, learning, etc). More often, especially in real-time performance scenarios (e.g., live performance, blended learning), real needs are more for hybrid eXtended Reality (XR) applications [5][10], where remote users can experience a real captured environment through immersive XR, while in presence users can visualise and interact with the holograms of remote users integrated in the real environment through holographic rendering. Such interactive hybrid and multi-sensory scenarios have not been fully considered so far and at least three main issues need addressing:

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(1) How can remote users be brought together by capturing and presenting their 3D holograms in a real in presence environment? That is, how can next-generation multimedia and immersive content be effectively processed and delivered over hybrid XR scenarios using low-complexity and low-cost devices?
(2) How can the real in presence environment (audio-visual and multi-sensory) be realistically 3D captured and presented to remote users?
(3) How can in presence and remote users interact? That is, how can remote users' feedback (e.g., social cues, emotions, ratings, etc.) be conveyed to the in-presence users and vice-versa?

The EU Horizon Europe-funded Hybrid Extended reAliTy (HEAT) project was designed to effectively answer the above questions, paving the way for the next-generation distributed experiences. Its aim is to integrate immersive media technologies such as point cloud/holographic imaging, multi-sensorial media, Social XR in a multi-user, feedback-enabled communication system to provide the construction of compelling context-aware and embodied experiences for innovative hybrid XR applications. The resulting system will aim at facilitating the exploitation of agile 3D data acquisition techniques, such as plenoptic point cloud, enhancing interoperability and performance at reduced costs. Examples of HEAT's envisioned mobile multi-sensor volumetric capture setups are shown in Figure 1. As illustrated, HEAT will create an adaptable and modular communication pipeline embodying either encapsulation of different media from classical audio-video to multi-sensorial to holographic video or a combination of them, providing means for efficient encoding, processing, storage, (real-time) streaming and rendering. Different scenarios set in real-world environments are considered for assessment of enhanced XR user experiences: a blended learning, a modern theatre act, a music festival, and an opera show. The pilot actions will follow all GDPR and ethical recommendations.

2 HEAT INNOVATION

HEAT has been conceived around several major pillars to lay the foundation for a new enhanced-media ecosystem in the context of real multi-user social XR experiences: volumetric capture and reconstruction; adaptive delivery and multimodal integration; XR presentation (XR headsets and holographic displays); multi-sensory experience, and interaction techniques.

On the topic of volumetric capture and reconstruction, HEAT will go beyond the state of the art by providing novel technological solutions to enable the agile volumetric (photo-) realistic real-time capture by using a set of off-the-shelf and low-cost sensors such as the one of mobile consumer devices (e.g., smartphones/tablets, 360°/RGB-D cameras), thus overcoming key challenges like varying resolutions of available sensors, their potential limited mobility, and achieving a (semi-) automatic calibration process. Artificial intelligence (AI) techniques will be investigated to enable fast and agile capture in the wild: opportune machine learning (ML) algorithms will be investigated to train capturing systems to reduce complexity and perform near real-time acquisition and processing. Two aspects will be considered: (i) dynamic (real-time) multi-sensor capture and reconstruction of 3D humans (i.e., remote users and live performers), (ii) offline and near-real-time capture and reconstruction of environments or objects. In addition, HEAT will go beyond the state of the art enabling an effective and strategic integration of heterogeneous content modalities and formats, overcoming challenges not only in terms of performance, but also in terms of storytelling and providing increased feelings of realism and immersion beyond 3DoF+ scenarios, at reduced costs [2].

Multi-sensory technology is one of the latest enhancement techniques for XR technologies. HEAT will investigate the production of content with integrated sensorial effects. The current solutions for adding effects into multimedia content mostly consist of manually inputting tags with the desired effects/scents into a video's timeline. Haptic effects are also usually triggered by specific actions manually performed by users with their avatars. Designing (semi-)automatic solutions to enhance multimedia content with sensorial effects will simplify the addition of such effects to both new and existing content and is expected to enhance viewer experience.

User feedback conveying and rendering is currently one of the critical points of virtual and mixed-mode reality applications, being available only in limited scenarios and with the use of additional hardware such as haptic gloves or vests. In HEAT, together with the industry partners specialised in holographic and multi-sensory technology and with the partners involved as end users, we will develop feasible means of conveying and rendering meaningful user feedback (e.g., social cues, emotions, ratings…) to all involved users in both virtual and mixed modes. Biometric data acquisition (e.g., eyegaze, heartbeat) and AI and ML techniques will be investigated to automatically produce dynamic and accurate feedback. As to Adaptive delivery and multimodal integration, volumetric video brings remarkable challenges in terms of real-time processing and adaptive delivery compared to traditional 2D video, mostly due to the much larger amount of captured data and the recent emergence of such formats. HEAT plans to advance the state-of-the-art in this topic by: (i) devising and adopting novel semantic-, position- and viewport-aware strategies for content encoding and segmentation, exploiting AI-based techniques, like autoencoders, as well as denoising and completion methods; and (ii) exploiting the capabilities of network virtualization and Cloud Continuum (e.g., Edge Computing), to maximise scalability and interoperability, by offloading heavy processing functions from the clients to virtualized in-cloud media processing functions, as preliminarily done in [2].

All the above-mentioned pillars have an impact on the perceived user Quality of Experience (QoE) [3], both at remote and in presence users. Therefore the HEAT project will also focus on better evaluating the user QoE for hybrid XR applications. In particular, noteworthy is the evaluation of the effect of multisensorial content on Quality of Interaction (QoI) [7]. Furthermore, the latest developments in terms of AI algorithms and its use for XR media consumption will be investigated as well as further directions on how to confer intelligence to XR, the so-called Affective Computing, or Artificial Emotional Intelligence [8].

3 ENVISIONED HEAT PLATFORM

To enable the hybrid interactive and immersive multi-sensory XR experiences envisioned in HEAT, innovative media components and

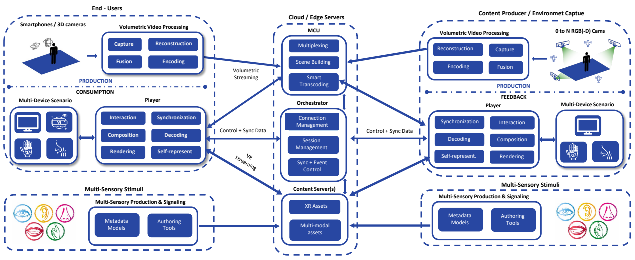

Figure 1: HEAT high-level system architecture

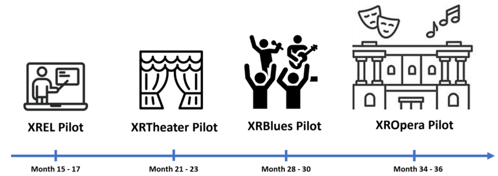

Figure 2: Pilot development timeline

modules need to be developed, evolved, and integrated, re-defining current-day end-to-end media workflows. This involves the specification and development of a modular, elastic and standards-compliant end-to-end platform, integrating:

- Advanced agile heterogeneous multi-sensor capture setups for volumetric media (Point Clouds, NeRF, etc.);
- Authoring tools and well-defined metadata models for the integration of multi-sensory stimuli (haptic, scent);
- Processing and coding for delivering reliable user feedback;
- Low-latency, adaptive and viewport-aware delivery strategies, potentially assisted by cloud computing;
- Orchestration components for signalling sessions and contents, dynamic session management, scene composition, and rich media synchronisation;
- Interaction Engines, including communication and synchronisation features, with interfaces between users, contents, applications and specific output devices for rendering user feedback;
- Rendering capabilities, including heterogeneous consumption devices with their required hardware and software components;
- Strategies to adapt the presentation of contents, based on the available resources (consumption devices, bandwidth, etc.), preferences, interaction patterns, and session and context status, assisted with advanced content- and context-aware QoE models.

These components will be integrated within an end-to-end platform, comprising key parts: Production and Preparation, Orchestration and Distribution, and Consumption and Interaction. A high-level system architecture of the HEAT platform, with its key components and their communication interfaces, is sketched in Figure 2 . Its conception departs from key outcomes of the EU H2020 VR-Together project (coordinated by i2CAT): HoloMIT, a worldwide pioneering platform to enable real-time multi-party real-time holographic communications between remote users [1]. However, its evolved architecture, components and interfaces will be more accurately specified and refined during the project lifetime, based on the selected use cases and derived requirements, and ongoing research findings and associated developments.

As a whole, the HEAT platform will be able to accommodate the multimedia modalities, distribution technologies, interaction modalities, multi-sensory output devices, Internet of Things (IoT) sensors and actuators, and the wide set of heterogeneous consumption devices (e.g., XR headsets, holographic displays, smart wearables etc.) considered in the project. However, a key aspect of the HEAT platform, and of each of its innovative components, is that it will be designed based on standard-compliance and modularity. On the one hand, the platform and its components will be adaptable to interoperate with both state-of-the-art and next-generation broadband workflows. On the other hand, they will be extensible to accommodate additional and/or emerging features not addressed in the project, but that are relevant in the media consumption landscape (e.g., adaptive storytelling based on the audience's feedback, delivery workflows, etc.).

4 APPLICATION SCENARIOS

HEAT will consider four distinct pilot cases as examples for the deployment of the developed technologies in real scenarios. The pilots will be used to validate the applicability and effectiveness of the proposed system through test assessment that will aim at estimating the perceived user's QoE, as well as readiness and acceptability of HEAT contributions. The pilots are listed in ascending order based on their estimated complexity. The timeline for the pilots is depicted in Figure 2.

4.1 XREL Pilot

A lecture, that is a classroom/laboratory environment including a teacher and laboratory equipment will be captured, using volumetric cameras, microphones, and multi-sensory acquisition devices. The whole captured environment (i.e., the live lecture) will be dynamically processed and delivered to the remote students via XR headsets and multi-sensory actuators (i.e., olfaction dispensers, haptic gloves/vests). The remote students will be captured at their site using available devices (e.g., 360°/plenoptic/RGB-D cameras/stereo microphones from smartphones or dedicated cameras), being their hologram tele-ported into the classroom that will be equipped with holographic displays to allow teachers and remote students to socially interact, sharing visual social cues with them.

4.2 XRTheatre Pilot

In a cultural performance of modern theatre, the environment (i.e., scenography, stage and performers) will be captured with volumetric cameras, microphones and multi-sensory acquisition devices. Remote audiences will experience the environment together with the in presence audience, with the use of XR headsets and multi-sensory actuators (i.e., olfaction dispensers, haptic gloves/vests), like being seated in a specific position upon their request. The remote audience will be captured at their site, using available devices (e.g., 360°/plenoptic cameras/stereo microphones from smartphones or dedicated cameras), being their hologram tele-ported in the theatre via 3D holographic displays and/or XR headsets.

4.3 XRBlues Pilot

The performance of a blues/rock band in a club will be captured using volumetric cameras and multi-sensory acquisition devices. Sound will be dynamically captured from the stage mixer and synchronised with the visual part. Remote audience will experience the environment together with the in presence audience, with the use of XR headsets and multi-sensory actuators (e.g., olfaction dispensers, haptic gloves/vests). The remote audience will be captured at their site, using available devices (e.g., 360°/plenoptic cameras/stereo microphones from smartphones or dedicated cameras), and their hologram tele-ported in the club via 3D holographic displays.

4.4 XROpera Pilot

In a cultural performance of opera, the opera scenography and performers will be captured with volumetric cameras, microphones and multi-sensory acquisition devices. Remote audiences will experience the environment together with the in-presence audience, with the use of XR headsets and multi-sensory actuators (i.e., olfaction dispensers, haptic gloves/vests), like being seated in a specific position upon their request. The remote audience will be captured at their site, using available devices (e.g., 360°/plenoptic cameras/stereo microphones from smartphones or dedicated RGB-D cameras), being their hologram tele-ported in the theatre and rendered via 3D holographic displays. In addition, multi-sensory feedback (e.g., haptic, heart bit) from remote users will be acquired and the possibility of dynamically rendering to the performers via wearable devices will be investigated.

5 CONCLUSIONS

In this paper, the ambition of the Hybrid Extended reAliTy (HEAT) project has been presented. HEAT aims at integrating immersive media technologies such as point cloud/holographic imaging, multi-sensorial media, Social VR in a multi-user, feedback- enabled communication system to provide the construction of compelling context-aware and embodied experiences for innovative hybrid XR applications. The project will provide well designed and fully tested scenarios in real-world environments for enhanced XR experiences: a blended learning, a modern theatre act, a music festival and an opera show.

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