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HABILITATION THESIS

- abstract -

From Cognitive Radio to Quality of Experience: Reconfigurability and Convergence in Telecommunications

Domain: Electronic Engineering, Telecommunications and Information Technologies

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This habilitation thesis summarizes the research activity of the author over the past 20 years, describing the main scientific achievements obtained in the field, throughout 4 chapters illustrating the evolution of the author's experience during the university activity after the PhD graduation. Each chapter ends with the results obtained in the specific research field.

The four chapters of this thesis trace a coherent and progressive scientific journey: starting from the theoretical foundations of Cognitive Radio and the practical challenges of spectrum management, the work evolves systematically through Software-Defined Radio platforms, Internet of Things ecosystems, Smart Home and HbbTV applications, Smart Cities and 6G communications, culminating in the frontier domain of Extended XR Reality and multisensory immersive media. This progression reflects not merely a chronological sequence of research topics, but a deeply integrated scientific vision: wireless communications, pervasive connectivity, urban intelligence and user-centred immersive experience are all facets of the same profound technological transformation that has characterised recent years.

The common thread connecting all four chapters is the principle of reconfigurability: from hardware-level spectral agility in SDR, through protocol-level adaptability in IoT gateways, to network-level programmability in 5G/6G architectures, and to multisensory XR systems.

1. Chapter 1 - From Cognitive Radio to SDR: Dynamic Spectrum Management

The first chapter of the thesis focuses on the fundamental problem of spectral efficiency in wireless communications, addressed through the Cognitive Radio (CR) paradigm and its practical implementations on Software-Defined Radio (SDR) platforms. The primary motivation is the inefficiency of static spectrum utilisation: initial studies showing that a lage part of allocated spectrum remains unused at any given moment, justifying the need for dynamic and opportunistic spectrum access.

The chapter analyses in depth the spectrum sensing techniques, including energy detection, cyclostationary feature detection and wavelet-based techniques for spectrum occupancy identification, and presents CR system architectures, with emphasis on the cognitive cycle (observe, orient, plan, decide, act) and primary user protection mechanisms. Particular attention is given to TV White Spaces (TVWS) as the first large-scale application of CR, including FCC/Ofcom regulations and the IEEE 802.22 standard for rural broadband networks.

Personal Contributions - Chapter 1

- Development of a wavelet-based spectrum sensing algorithm capable of identifying spectrum edges and detecting primary user signals (DVB-T2, LTE) with high sensitivity at low SNR, validated on a SDR platform.
- Design and implementation of a systems for dynamic spectrum access management, integrating exponential backoff mechanisms and adaptive primary user protection.
- Field measurement campaigns for spectrum occupancy characterisation in indoor environments (university buildings, offices), providing empirical data for calibrating propagation models used in CR systems.
- Technical reports on the protection of DVB-T2 and IEEE 802.22 signals against interference generated by secondary users, with experimentally validated protection margin proposals.
- Analysis of interference generated by 802.11p (vehicular) systems in adjacent bands and evaluation of the impact on co-located CR systems, with mitigation technique proposals.

2. Chapter 2 — From SDR to IoT, Smart Home and HbbTV: Connected Platforms and Quality of Experience

The second chapter illustrates the transition from reconfigurable SDR platforms to Internet of Things ecosystems and intelligent multimedia applications. The chapter demonstrates how the reconfigurability principle from CR transfers to protocol and service level in IoT architectures, generating new connectivity paradigms for the residential environment and media content distribution.

IoRT (Internet of Remote Things) gateway architectures with satellite connectivity for areas without terrestrial coverage are analysed, along with multi-rate modulation techniques for LMS (Land Mobile Satellite) channels, D2D (Device-to-Device) feedback mechanisms for radio resource optimisation, and QoE assessment models for mulsemedia systems in the Smart Home environment. An extended section is dedicated to the HbbTV (Hybrid Broadcast Broadband TV) platform and implicit QoE assessment methods through eye gaze and facial expression analysis.

Personal Contributions - Chapter 2

- Design of an IoRT gateway with satellite connectivity for IoT extension in rural and isolated areas, integrating MQTT and CoAP protocols with adaptation to satellite channel characteristics (latency, bit error).
- Implementation of a D2D feedback mechanism for reducing signalling overhead in dense cellular networks, with experimental evaluation of the spectral efficiency gain.
- Construction of a QoE model for mulsemedia TV systems in the Smart Home environment, based on a PSO (Particle Swarm Optimization) algorithm for calibrating the contribution weights of each sensory modality to globally perceived quality.
- QoE assessment for HbbTV systems through eye gaze and facial expression analysis as implicit predictors of user engagement and satisfaction — an original contribution to the non-intrusive QoE assessment methodology.

3. Chapter 3 — From Smart Home to Smart Cities and 6G: Distributed Architectures and Next-Generation Connectivity

The third chapter extends the perspective from the residential to the urban level, analysing the convergence between the Social Internet of Things (SIoT) paradigm, Smart Cities infrastructures and next-generation communication technologies (5G/6G). The chapter demonstrates how the lessons learned in designing residential IoT systems scale to the urban level, generating distributed architectures capable of orchestrating thousands of heterogeneous devices in complex public spaces.

The following topics are treated in detail: SIoT interaction models (object-to-object relationships based on ownership, co-location, co-mobility and social proximity), 5G SA network architectures with URLLC and mMTC profiles for Smart City applications, 5G vs. 6G comparisons in terms of latency, connection density and energy efficiency, Non-Terrestrial Network (NTN/LEO) technologies for ubiquitous connectivity, and urban data governance frameworks (GDPR, European data framework).

Personal Contributions — Chapter 3

- Design and implementation of an IoT system for smart tourism (2017), integrating environmental sensors, localisation and cultural information into a mobile platform for visitors.
- Publication of a reference article in IEEE Access (2020) on SIoT-based tourist services, proposing an object-to-object interaction model for adaptive cultural guidance, cited in the international literature.
- Preparation of a comprehensive survey (Sensors, 2023) on 6G architectures for Smart Cities, comparatively analysing candidate technologies (Terahertz, RIS, AI-native networking) and the specific requirements of urban applications (traffic, energy, public health).

4. Chapter 4 — From 5G/6G to Hybrid Extended Reality: Immersive, Multisensory and Distributed Media

The final chapter of the thesis marks the convergence of all previous research threads into a frontier domain: Hybrid Extended Reality (Hybrid XR). While the first three chapters progressively built the technological infrastructure — agile spectrum access, IoT connectivity, urban intelligence — the fourth chapter places the user at the centre of the system, exploring how these technologies converge to create immersive, multisensory and geographically distributed experiences.

The chapter analyses the evolution from multimedia to mulsemedia (MPEG-V standard, 2008), the role of 5G SA networks with URLLC profile in reducing end-to-end latency below the critical 30 ms threshold for Networked Music Performance (NMP) applications, the communication protocol ecosystem (MQTT, CoAP, WebRTC, RTP/SRTP, WebSocket, QUIC/MoQ) with comparative analysis of latency–reliability trade-offs, and compression standards for volumetric content (V3C, V-PCC, G-PCC, MIV, VVC, MPEG-DASH). An extensive taxonomy of QoE assessment methods for XR systems covers subjective, objective, hybrid and implicit methods, with dedicated discussion of cybersickness and co-presence.

The personal contributions are developed within the European Horizon EU HEAT — Hybrid Extended Reality project (2024–2027), coordinated together with partners from universities and research institutes in Cagliari, Dublin and Barcelona.

Personal Contributions — Chapter 4

- Publication of the HEAT project positioning paper: “Toward Interactive and Distributed Hybrid Extended Reality Experiences”, defining the conceptual framework of distributed and interactive XR architectures.
- Design of a real-time audio-video streaming architecture with bidirectional audience feedback, based on WebRTC, Unity 3D and spatial audio, with experimental evaluation of round-trip latencies and jitter for audio codecs.
- Development of a multisensory olfactory synchronisation system with audio content for remote spectators of a distributed live concert, using automatic speech recognition (Vosk ASR) and MQTT communication for real-time triggering of scent and wind effects.

- Design of the EmoLoop architecture — a bidirectional affective interaction system between audience and performers, fusing multimodal biosignals into a deep learning-based emotion recognition pipeline, translating audience affective states into live stagecraft control parameters in real time — awarded Best Poster at IEEE IS2 2025.
- Contributions to QoE assessment for HbbTV systems through eye gaze and facial expression analysis, which underpin the implicit assessment methodology subsequently applied in XR scenarios.

5. Conclusions

The thesis presents a coherent and progressive academic research activity conducted over nearly two decades. Starting from the problem of spectral efficiency in wireless communications — addressed through Cognitive Radio techniques and SDR platforms — the research evolved systematically towards IoT ecosystems and intelligent multimedia applications, escalated to the urban level through SIoT and Smart Cities paradigms, and ultimately converged towards the frontier domain of Hybrid Extended Reality and multisensory immersive media.

The author's main original contributions cover: wavelet-based spectrum sensing algorithms; PSO-validated QoE models for mulsemedia systems; SIoT architectures for smart tourism; reference surveys on 6G and Smart Cities; XR concert architectures with real-time audio-video streaming and bidirectional feedback; multisensory olfactory synchronisation systems; and the EmoLoop architecture for affective interaction in live performance environments. These contributions are materialised in over 30 publications in prestigious international journals and conferences, in Horizon EU European and national projects.

The natural directions for the evolution of the research activity target: (i) the integration of AI-native networking (6G) with real-time multisensory orchestration for XR platforms scalable to large audiences; (ii) the development of QoE-aware adaptive streaming systems, using physiological feedback (eye gaze, EDA, HRV) as real-time control signals for mulsemedia personalisation; and (iii) the standardisation of open control interfaces for sensory IoT devices in XR environments, building on the W3C WoT and MPEG-V foundations towards unified Hybrid XR platform architectures.