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Data Transmission Strategies and Radio Resource Allocation for 6 G RAN

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Context. The sixth-generation (6G) mobile communication systems currently under development are the subject of active research and are expected to enter the standardization phase over the next decade, with an initial version anticipated around 2030 by the ITU. It has already inspired numerous research contributions aimed at significant improvements in terms of performance, intelligence, and network flexibility compared to 5G. One of the most interesting aspects of 6G is its use of very high-frequency spectrums, including sub-THz bands and potentially terahertz. These frequencies will enable ultrahigh data rates, but also new challenges in terms of propagation and coverage. To address this, 6G networks should be based on the use of highly directional and adaptive beamforming techniques, which not only allow for beam direction (as in 5G) but also precise 3D spatial beam focusing [1] [2] [3]. This allows for the dynamic focusing of radio resources on specific users/devices in space, thereby improving spectral efficiency and energy utilization.
The Hexa-X-II project, currently underway, describes several critical use cases that define the challenges at the Radio level [4]: extreme data rates, extreme URLLC (Ultra-Reliable Low-Latency Communications), extreme connection density, and extreme coverage are essential. In each of these scenarios, the convergence of artificial intelligence (AI) and detection is considered essential to manage the inherent complexity of 6G radio resource allocation.
The vision of 6G concerning radio issues integrated several aspects:

(i) **Integrated Sensing and Communication (ISAC)** [5] [6], is thus to use the same radio infrastructure for data transmission and radar-type detection, thereby transforming the network into a ubiquitous distributed detection system. This feature will allow the network to detect changes in the environment, track user mobility, and monitor physical phenomena without dedicated detection hardware.
(ii) **The deep integration of Non-Terrestrial Networks (NTN),** particularly low Earth orbit (LEO) satellite constellations. These constellations will complement terrestrial infrastructures to provide global connectivity to massive Machine-to-Machine (M2M) and Machine-to-Gateway ecosystems. In such future heterogeneous deployments, sensor nodes will navigate a complex environment of multi-connectivity, dynamically accessing terrestrial base stations, LoRa gateways, or satellite links, often on shared spectral resources [7][8][9]. This creates a highly stochastic environment where nodes must intelligently exploit multiple communication paths based on real-time network conditions.

Research Objectives. This research aims to design intelligent and adaptive data transmission strategies for distributed sensor networks operating in heterogeneous 6G environments combining terrestrial and satellite connectivity as defined in the well-known *Hexa X-II* European project [10].
A key challenge is to determine **when and through which link data should be transmitted**, based on real-time and predicted conditions such as channel quality, network congestion, energy constraints, and satellite orbital dynamics. This is particularly critical in LEO satellite systems, where fast-moving satellites introduce rapidly changing link conditions, latency variations, and intermittent connectivity. In addition, **Integrated Sensing and Communication (ISAC) functionalities will be explored** to enable the network to exploit sensing information for improving communication decisions.
A particularly relevant application scenario concerns **environmental monitoring and air-quality surveillance in smart and sustainable environments**. In this context, large-scale distributed sensor networks are deployed across urban, suburban, and rural areas to continuously monitor environmental parameters such as pollutant concentrations (e.g., CO_2, NO_2, particulate matter), temperature, humidity, and atmospheric pressure. These sensing devices typically operate under stringent energy and connectivity constraints, requiring efficient and adaptive communication mechanisms. By leveraging the complementary capabilities of terrestrial 6G infrastructures, LoRa-based low-power networks, and LEO satellite connectivity, the system can provide reliable, resilient, and continuous data transmission, including in remote or infrastructure-limited regions. This scenario enables also investigate how radio propagation characteristics may be used to infer environmental conditions, detect anomalies, or anticipate mobility patterns, thereby enhancing transmission efficiency while reducing the need for dense dedicated sensing infrastructures.For example, by using signal propagation characteristics to infer atmospheric conditions or detect pollution-related anomalies, reducing the need for dense physical sensing deployments.
This scenario therefore constitutes an ideal framework for investigating adaptive transmission strategies, intelligent multi-connectivity management, and energy-efficient radio resource allocation mechanisms for future 6G networks. The final goal is to design **adaptive, energy-efficient, and scalable communication strategies** that optimize both data delivery and sensing performance in real-time.

This PhD will investigate:
- **Dynamic link selection policies** for choosing between terrestrial (5G/6G), Long-Range (LoRa) based networks, and satellite links.
- **AI-driven predictive models** to anticipate channel variations, traffic demand, and mobility patterns of both nodes and satellites.
- **Radio resource allocation strategies** that consider spatial interference, beam overlap, and network congestion in dense deployments.

- **Data-aware transmission strategies**, where sensor data may be transmitted, aggregated, compressed, or even predicted at the network edge depending on context.
- **Exploitation of ISAC capabilities**, where sensing information is used to enhance communication decisions, such as detecting environmental conditions or mobility patterns that influence transmission strategy selection.

Methodology and Validation. The proposed transmission and radio resource allocation mechanisms will be designed, implemented, and validated through a combination of analytical modeling, simulation, and experimental evaluation. The research will rely on advanced 6G-oriented simulation and emulation platforms, including OpenAirInterface (OAI), network simulators, and LoRa-based experimental infrastructures. Performance will be assessed in terms of latency, throughput, energy efficiency, link reliability, and sensing accuracy under realistic mobility and traffic models.
In particular, both USPN and AUSLP (Autonomous University of San Luis Potosi, Mexico) provide complementary experimental platforms that will support real-world implementation and validation activities: USPN hosts a LoRa experimental infrastructure, while UASLP operates a LoRaWAN platform dedicated to IoT and large-scale wireless communication experiments. These platforms will enable the evaluation of the proposed mechanisms under realistic deployment conditions and heterogeneous communication scenarios integrating terrestrial and low-power wide-area network technologies.

Proposed Timeline:
1- State of the Art and Scientific Positioning. Comprehensive literature review on 6G RAN architectures, NTN integration, ISAC, AI-native communication systems, and adaptive radio resource management. Analysis and synthesis of emerging 6G protocols, standards, and Hexa-X-II use cases. Identification of scientific challenges and definition of research objectives.
2- Simulation and Experimental Platform Setup. Installation and configuration of simulation and emulation tools. Deployment and experimentation with OpenAirInterface (OAI) and LoRa-based communication platforms. Integration of terrestrial and non-terrestrial communication models.
3- Data Collection and System Characterization. Collection of communication and sensing datasets under realistic operating conditions. Measurement and analysis of network behavior, traffic dynamics, channel variability, and mobility patterns. Modeling of heterogeneous network conditions and LEO satellite dynamics.
4- AI Modeling and Optimization Mechanisms. Development of predictive AI models for channel estimation, mobility prediction, and traffic forecasting. Design of adaptive transmission strategies and intelligent radio resource allocation algorithms. Integration of ISAC-aware optimization mechanisms and multi-connectivity management strategies.
5- Validation, Performance Evaluation, and Dissemination. Performance evaluation and comparative analysis of the proposed solutions. Optimization and refinement of algorithms under realistic 6G scenarios. Preparation of scientific publications, conference papers, and thesis manuscript writing.

Keywords: 6G, ISAC, LEO satellites, resource allocation, AI-driven networks, heterogeneous networks, LoRa, M2M communications, traffic modeling, environmental monitoring, air quality sensing, edge intelligence.
Requirements: Master's degree in a relevant field (Telecommunications, Computer Engineering, Electrical Engineering, or similar) with solid foundation in communication networks (WiFi, LoRa, 4G/5G/6G concepts). Good understanding of 3GPP cellular systems Programming skills in Python, MATLAB, and/or C/C++ **.** Strong background in probability, signal processing, and traffic modeling. Familiarity with Unix/Linux environments

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