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Enabling Intelligent and Interactive Immersion in Smart Environments

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رب اوزعني ان اشكر نعمتك التي انعمت علي
وعلى والدي وان اعمل صالحا ترضاه

"My Lord, enable me to be grateful for Your favor which
You have bestowed upon me and upon my parents"

Dedication

To my idols ... my parents, for their sacrifice and support.

To my sisters, our angels, with a love that always glows.

To my right-hand man ... my brother, for his concern and help.

To my Grandfather’s peaceful soul.

To my Grandmother’s peaceful soul.

To coffee ... my companions through many long nights of writing.

> “I hated every minute of training, but I said, don't quit, suffer now and live the rest of your life as a champion.” -- Muhammad Ali Clay

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Contents

INDEX OF FIGURES

INDEX OF TABLES

Acronym List

3GPP	3rd generation partnership project
5G	5th generation
6LoWPAN	IPv6 over Low-Power Wireless Personal Area Network
ACK	Acknowledgement
APIs	Application Program Interfaces
Bi2Bi	Bike-To-Bike
BLE	Bluetooth Low Energy
CN	Core Network
CO	Carbon Monoxide
CoAP	Constrained Application Protocol
CSMA/CA	Carrier-sense multiple access with collision avoidance
DLs	Description Logics
DODAG	Destination-Oriented Directed-Acyclic Graphs
EPIC	European Platform for Intelligent Cities
ETL	Extract, Transform, and Load
ETSI	European Telecommunications Standards Institute
EU	European Union
EV	Electric Vehicles
GDPR	General Data Protection Regulation
GEs	Generic Enablers
GO	Geometrical Optics
GTD	Geometrical Theory of Diffraction
ICT	Information and Communication Technologies
IDL	Interface Description Language
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet-Engineering Task Force
IIoT	Industrial Internet of Things
IoT	Internet of Things
IoV	Internet of Vehicles
IPv6	Internet Protocol version 6
i-SCOPE	Interoperable Smart City services through an Open Platform for urban Ecosystems
ISO	International Organization for Standardization
IVN	In-vehicle Network

JSON	JavaScript Object Notation
JSON-LD	JavaScript Object Notation Linked Data
JWT	JSON Web Token
LAN	Local Area Networking
LLC	Logical Link Control
LNSM	Log-Normal Shadowing Model
LoRaWAN	Long-Range Wide-Area Network
LPWAN	Low-Power Wide Area Network
LTE-A	Long-Term Evolution Advanced
LTE-M	Long-Term Evolution Machine Type Communication
M2M	Machine-To-Machine
MAC	Media Access Control
MDGs	Millennium Developments Goals
MIOTY	Massive IoT Operating Technology
MQTT	Message Queue Telemetry Transport
MTU	Transmission Unit
NB-IoT	Narrowband Internet of Things
NGSI	Next-Generation Service Interface
NLoS	Non-Line-of-Sight
NMT	Non-Motorized Transportation
NO2	Nitrogen Dioxide
O3	Ozone
OASIS	Organization for the Advancement of Structured Information Standards
OF	Objective Function
OpenIoT	Open Source cloud solution for Internet of Things
OpenMTC	Open Machine Type Communications
OSI	Open Systems Interconnection
OWL	Web Ontology Language
PHY	Physical Layer
PLMN	Public Land Mobile Network
PSO-ANN.	Particle Swarm Optimization-Artificial Neural Network
QLoS	Quasi-Line-of-Sight
QoL	Quality of Life
QoS	Quality of Services
QR code	Quick Response code

RDF	Resource Description Framework
REST	REpresentational State Transfer
RFID	Radio-Frequency IDentification
RPL	Routing Protocol for Low-Power and Lossy Networks
RSSI	Received Signal Strength Indicator
SCP	Smart City Platform
SCs	Smart Cities
SDGs	Sustainable Development Goals
SDN	Software-Defined Networking
SO2	Sulfur Dioxide
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TTN	The Thing Network
UAVs	Unmanned Aerial Vehicles
UDP	User Datagram Protocol
UN	United Nations
UNAV	University of Navarre
UPNA	Public University of Navarre
V2V	Vehicle-to-Vehicle
V2X	vehicle-to-Anything
V2X	Vehicle-To-Everything
VLCi	Valencia Smart City
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Networks

Abstract

In recent years, the Smart City concept has grown in popularity, and a significant number of cities around the world have adopted smart city strategies. Smart and sustainable cities are an emerging urban development approach due to their immense potential to improve environmental sustainability. The Smart City concept is based on collecting, analyzing, and displaying a large amount of data and information concerning urban systems and subsystems. As time goes by, the capacity of smart cities for generating digital information has grown exponentially. However, this digital information is heterogeneous, massive, collected from different sources, generated in different formats, and in most cases not structured, which exacerbates the situation of extracting valuable knowledge from data. Therefore, it is fundamental to handle the significant volumes of heterogeneous sensed data and to integrate such data along with information and analysis tools into a comprehensive platform. This can ensure the security, efficiency, and performance of the different Smart City tasks. A comprehensive software platform could provide services such as facilities for application development, integration of heterogeneous data sources, deployment, and management to ease the construction of sophisticated Smart Cities' applications. In this context, the work begins with a concise description of the concept of smart city and the technologies involved in it. It addresses the development of an urban data platform along with how to obtain and integrate information from sensors and other data sources, in order to provide aggregated and intelligent views of raw data to support various domains within the city; in our case, smart mobility. The platform architecture is implemented following a five-layer model that considers elements from perception, sensing to data management, processing, and visualization. With the aim of evaluating the efficiency of the developed platform, three different use cases are described and analyzed, which have been implemented in the city of Pamplona, Spain,

as vertical services linked to the platform: intelligent urban mobility-bike handling, bike-2-bike communication, and restricted vehicle access zone control system. Ultimately, this work provides an experiment to assess different long-range wireless communication technologies to enable their implementation within an urban environment.

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From the bottom of my heart... THANKS!!!

Chapter 1

1 Introduction

CITIES are the world's most rapidly expanding type of habitation; nearly 50% of humanity currently lives in cities. The United Nations (UN) projected that 66% of the world population is estimated to be living in cities by 2050 [1]. Most of this urbanization is expected to be occurring in developing, and emerging economies where the infrastructure to support basic societal needs such as clean water, food, energy, and sanitation are currently lacking.

In this era, a large portion of the world’s resources are preoccupied by cities; as a fact in modern world, 75% of the total energy is consumed by the cities [2]. Urban areas account for 67 % of global energy demand and consume 40 % of total global energy. This perpetual energy consumption generates nearly 80% of the greenhouse gases that cause unfathomable adverse effects on the environment [1] [3] [4].

In anticipation of this rapid growth in urbanization and the impending ecological impacts, the United Nations has established ‘The 2030 Sustainable Development Agenda’, listing 17 Sustainable Development Goals (SDGs) and 169 targets for the period 2015–2030 [5][6][7][8]. Among the 17 goals, the first seven goals (No poverty; Zero hunger; Good health and well-being; Quality education; gender equality; Clean water and sanitation; Affordable and clean energy) are an extension of United Nation’s Millennium Developments Goals (MDGs); the other newly introduced goals cover inclusiveness (Decent work and economic growth; Industry, innovation, and infrastructure; Reduce inequality) and sustainability and urbanization (Sustainable cities and communities; Responsible consumption and production; Climate action; Life under water; Life on land; Peace, justice, and strong institutions; Partnership for the goals) [9]. Together, these SDGs aim to end poverty, protect the planet, and ensure peace and prosperity for all.

In a related context, the "The World in 2050" report presents six key transformations needed to achieve the SDGs in a manageable way, based on the major drivers of societal change, including human capacity, consumption and production, decarburization, and the digital revolution [10]. These are:

1. Sustainable development is a societal challenge rather than an environmental one. Human capacity needs to be substantially improved through healthcare and education – leading to higher incomes and better environmental decisions.
2. The need to reduce demand and adopt a circular economic approach, allowing us to do more with fewer resources – responsible consumption and production cut across several other transitions.
3. The energy system could be decarbonized around 2050 through the use of energy efficiency, more renewable, and electrification.
4. Increasing agricultural productivity and reducing meat consumption is necessary to ensure that everyone has access to nutritious food and clean water while also safeguarding the ecosystem and the oceans.
5. Smart cities: Transforming our settlement patterns will benefit the world population and the environment, such as through decent housing, high connectivity and "smart" infrastructure.

6. The digital revolution requires science, technology, and innovation to support sustainable development. It is unclear how the Information Technology revolution will be used in the future – society may choose to continue present trends or may decide to assert societal control over them.

Figure 1.1 summarizes six key transformations needed to achieve the SDGs.

Figure 1.1: six key transformations needed to achieve the SDGs (Source:[10]).

In the field of urban development, sustainability has long been regarded as the prevailing paradigm. Urban sustainability principles have guided urban and metropolitan development to achieve higher social, economic, and environmental sustainability standards. The primary objectives are to reduce urban carbon footprint and greenhouse gas emissions by concentrating on resource and energy usage throughout the construction, operation, and maintenance of the built environment in cities. The goals implicitly guided practical measures in energy conservation, energy efficiency, and renewable energy generation, which are all three aspects of 100% renewable energy generation. Sustainability played a major role in the emergence of cities.

Sustainable development of urban areas is a key challenge for the future. It is necessary to introduce new, efficient, and user-friendly technologies and services, in particular in the areas of transport, energy, and information and communication technologies (ICT). It is essential to apply integrated solutions in terms of research and development of advanced technological solutions and deployment.

Although urban sustainability principles are important, they are insufficient to assist cities in preparing for a future transition to achieve sustainable development and become smart sustainable cities. It will require the use of information and ICT and other methods to enhance the quality of life, the efficiency of city operation, and service delivery. ICT can help to improve energy efficiency in buildings, transportation, and street lighting, among other things. It could also make integrating locally generated renewable energy into the power grid easier. More importantly, to encourage citizens to make more efficient and supportive use of municipal resources.

The majority of smart city proposals consist of four main attributes i.e., sustainability, Quality of Life (QoL), urbanization, and smartness [2][11]. Few sub-attributes are concerned under each attribute, as illustrated in Figure 1.2. Pollution and waste, infrastructure and governance, energy and climate change, economics, social issues, and health are the sub-attributes that come under sustainability. The ability of a city to uphold the balance of the eco system in all aspects, while serving and performing city operations is known as the sustainability. The emotional and financial well-being of urban citizens indicates the QoL improvement. Urbanization attribute focuses on infrastructural, technological, governing aspects of the transformation from rural environment to urban environment, and economical. The smartness is defined as the desire to improve the social, environmental, and economic benchmarks of the city and its inhabitants.

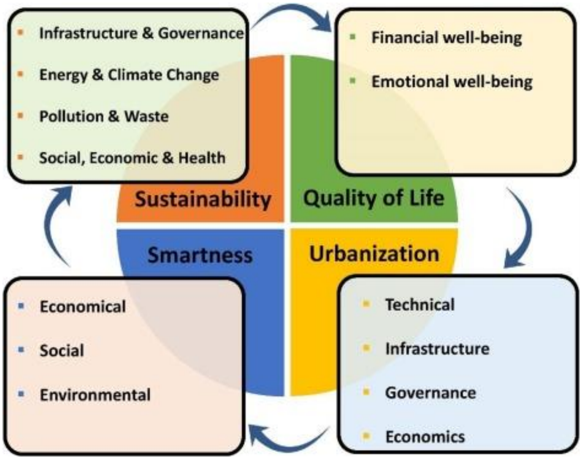


Figure 1.2: Main attributes of a Smart City (Source: [11]).

The European Commission launched the Smart Cities (SCs) strategy under the Horizon 2020 research and innovation program to support initiatives that represent an advance in the sustainability of its cities [12]. Horizon 2020 is the biggest ever EU Research and Innovation programme with approximately €80 billion of funding available over 7 years (2014 to 2020) – not to mention the private investment that this money will attract. It promises more breakthroughs, discoveries, and world-firsts by carrying great ideas from the lab to the market. The main aim of this project is to assist the use of smart urban technologies through bringing cities together, businesses, and citizens to exhibit business' models and solutions that can be leveled up and reproduced. This would result in having smarter and more sustainable ecosystem. The city of Pamplona (Spain) [13], is one of seven European cities (Tampere (Finland), Trento (Italy) - Lighthouse cities, which they will serve as a basis prior to developing the replication strategy suitable for other cities termed as "follower cities"; Cluj-Napoca (Romania), Derry (Ireland), Kozani (Greece), and Litomerice (Czech Republic)) taking part in the STARDUST project; which is one of the seventeen Smart Cities and Communities Lighthouse projects [14]. The challenges that the city of

Pamplona prioritized are related to sustainability, mobility, and energy, which may not be that important in other cities. The collaboration provides valuable experiences, including testing and validation technical solutions, innovative business models, and delivers blueprints that can be replicated in other European cities, and supports cities in their transformation into smart cities. In this way, Pamplona cans avoid investing in costly and expensive platform development from scratch. Furthermore, Pamplona cans obtain a complete review of the strengths and weaknesses of the available technologies that used by other cities in the STARDUST project.

The STARDUST project aims to develop urban solutions and integrate the domains of buildings, mobility, and efficient energy in order to pave the way towards a low carbon, highly efficient, intelligent, and citizen-oriented cities. through ICT as illustrated in Figure 1.3. The aim to be achieved is to test and validate these solutions allowing their rapid implementation in the market.

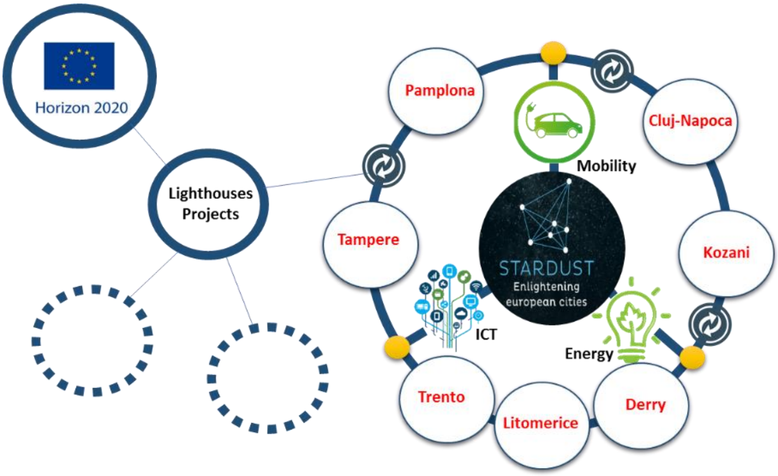


Figure 1.3: Stardust project key elements.

The STARDUST project demonstrates how the proper integration of these actions, jointly with other non-technical measures, can provide an effective platform for encouraging citizen participation. Through a revolutionary productive model based on eco-innovation technologies, sharing information from different inputs and citizen collaboration would improve citizens' quality of life while improving local economies. In this perspective, the transformation of public transport towards more sustainable vehicles is a significant feature to improve, among others, air quality and noise pollution in cities.

Different definitions in the literature have been used to define SCs considering various aspects and perspectives. Harrison et al. [15], have proposed a popular definition states that a SC connects physical, social, business, and ICT infrastructure to uplift the intelligence of the city.

Wang et al. [16], Zanella et al. [17], Belissent et al. [18], and Ianuale et al. [19], have developed a comprehensive definition states that SCs are urban areas that use ICTs to support several metropolitan areas and services, such as governance, to develop a supportive process for urban planning and mobility, which aims not only to provide on-demand services, but also to adapt some services and an environment that deals with pollution and energy efficiency issues.

Kondepudi et al. [20], have sat another comprehensive definition states that SC is defined as an advanced modern city that utilizes ICT and other technologies to improve QoL, competitiveness, operational efficacy of urban services, while ensuring the resource availability for present and future generations in terms of social, economic, and environmental aspects.

The functional definition to SC is a " integrated system of systems" or “fusion of functional systems”, that incorporates a set of smart systems, including smart transportation and mobility, smart lighting systems, smart building and automation systems, water treatment and supply, security and access control systems, disaster and emergency management systems, smart grids, and renewable energy, the urban agenda (cultural and leisure activities...), the tourist offer and even more; to enhance performance efficiency of regular city operations and quality of services (QoS) provided to urban citizens as shown in Figure 1.4.

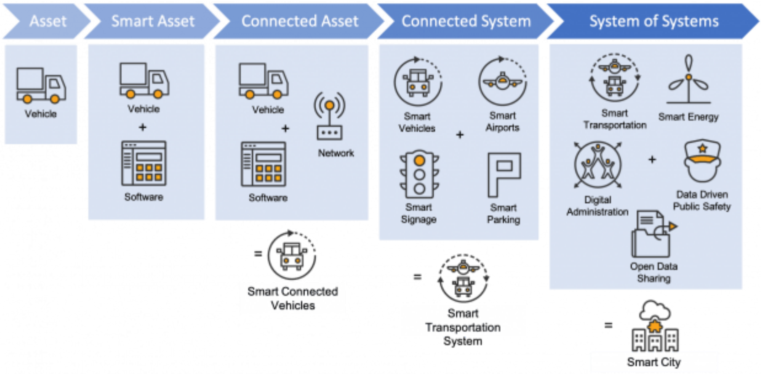


Figure 1.4: Smart city system of systems(Source: [21]).

The utmost goal of initial SC is to enhance the QoL of urban citizens by reducing the contradiction between demand and supply in various functionalities [17]. In order to accommodate QoL demands and fulfill the intense needs of urbanization, modern SCs focus on sustainable and efficient solutions for energy management, transportation, health care, governance, and many other areas [22].

SCs aim to improve the use of public resources, improve the QoS provided to residents, reduce government operational expenditure, and involve citizens in the smooth operation and efficiency of their city. The SCs which are built on top of wide-ranging Internet of Things (IoT) systems, are rapidly expanding around the world and offer an excellent opportunity in a variety of cross-domain sectors [23].

IoT is defined as a network of heterogeneous, Internet-connected physical objects, including devices, sensors, actuators or systems ("things/objects") that can be remotely accessed over the Internet, collect and exchange information ("data") that can be analyzed and aggregated to monitor, maintain, and improve processes to deliver products and solutions (“services”) to consumers [17]. IoT is a representation of the physical world that enables both physical and virtual interaction between devices and users [24]. IoT-enabled applications are rapidly being developed in many domains, such as energy management, building management, waste management, traffic control, mobility, health care, assisted living, and many others. Therefore, the IoT is considered a key enabler for smart and sustainable cities [25][26][27]. In Chapter 2, we provide a comprehensive vision of the IoT, and the technologies involved in it.

In fact, most cities have the basic requirements to become SCs such as, ICT infrastructure, and IoT applications, but the difference between them is the degree/grade of intelligence/smartness that they seek to reach, and the problems/challenges that each city is trying to find solutions to. Even though the SC concept is widely accepted and practically implemented in the real world, the high-speed development and adaptation of the IoT applications in SC domains have resulted in the emergence of heterogeneous IoT architectures, standards, middle-wares, and applications. This heterogeneity (from hardware to application level) is a challenge that needs to be highlighted in order to ensure seamless harmony between the various SC domains, allowing effective data exchange between them, thereby achieving greater efficiency in the services provided by these domains.

To overcome these challenges, SCs need to figure out how to use the advanced technologies gathered under the IoT umbrella to subsidize synchronization between the three elements of SCs: 1)"objects", 2) "data", and 3) "services" [28][29][30], as shown in Figure 1.5.

- **Objects**: The "objects" in the IoT system consist of enormous devices such as sensors, cars, thermostats, industrial robots, tablets, and smartphones. These devices could be connected anytime and wherever. They have a high degree of heterogeneity in terms of the communication resources of devices, protocols, technologies, and hardware, which leads to different types and formats of data depending on the purpose for which they are used. The “objects” represent IoT integration of the physical with virtual systems.
- **Data**: The “data” in the IoT system is heterogeneous, massive,

collected from different sources, generated in different formats, and in most cases not structured, which exacerbates the situation as shown in Figure 1.5. Therefore, the highly dynamic nature of SC requires sophisticated, advanced insights that are data-driven, flexible, and adaptable to harmoniously cope with the highly dynamic heterogeneous environment and decentralized intelligence for the management of multi-agent systems.

- **Services**: that provide customizable and scalable value propositions to observe the dynamic environment, support application development, informed decision-making and provide effective services accordingly. These services cover fields such as transportation (smart road Networks, connected vehicles, and smart public transport), public utilities (smart electricity, water, and gas distribution), education, health and social care, public safety.

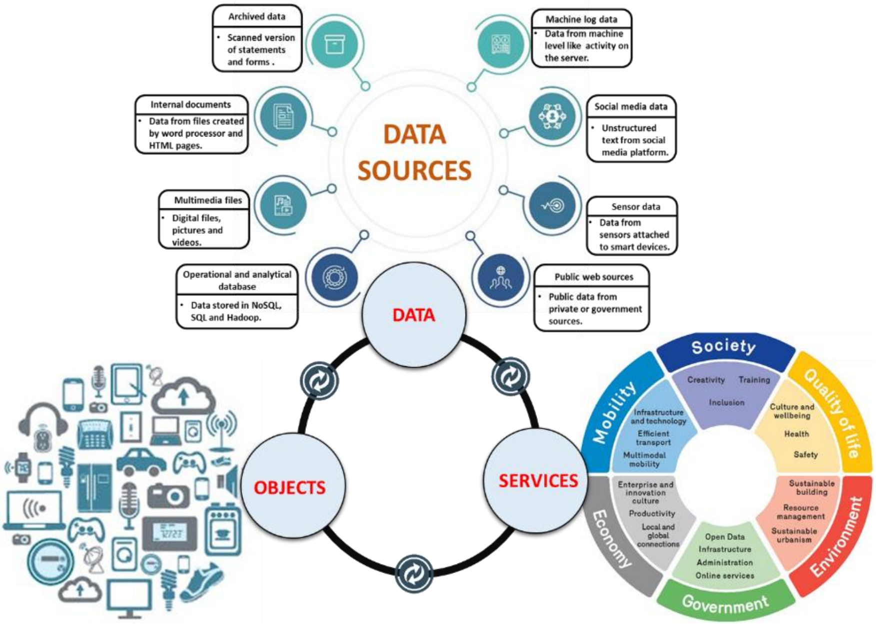


Figure 1.5: Three elements of SCs (Source: Author, [31], [32], and [33]).

On the other hand, the systems that control and operate today's cities and communities typically function mainly in a siloed manner, with little or no connectivity to other systems, as shown in Figure 1.6.

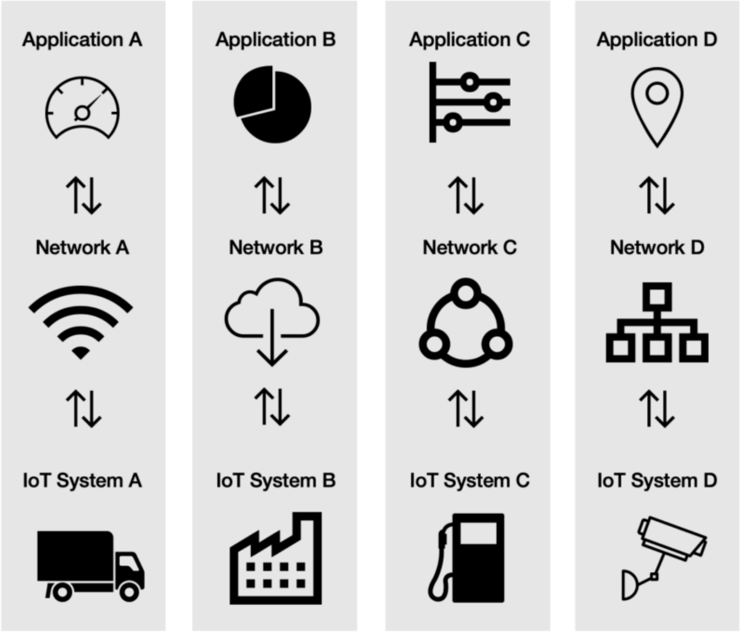


Figure 1.6: Siloed IoT Applications (Source: [34]).

Cities do not function in such a siloed fashion. The occurrence of an event in one system can affect the occurrence of an event in another system throughout the city. Drainage and flood control systems can impact both emergency management and traffic management systems. The power systems in the city have a critical impact on almost every role. When power usage peaks on hot days, how may a city use its energy management systems, intelligent building controls, or lighting controls to reduce peak load? By monitoring and analyzing the usage of city assets, the government can adequately distribute the assets to improve operational efficiencies.

Basic services provided by the underlying software infrastructure are required to integrate these domains into a complete and consistent solution. Figure 1.7 shows the smart domains for Smart Cities.

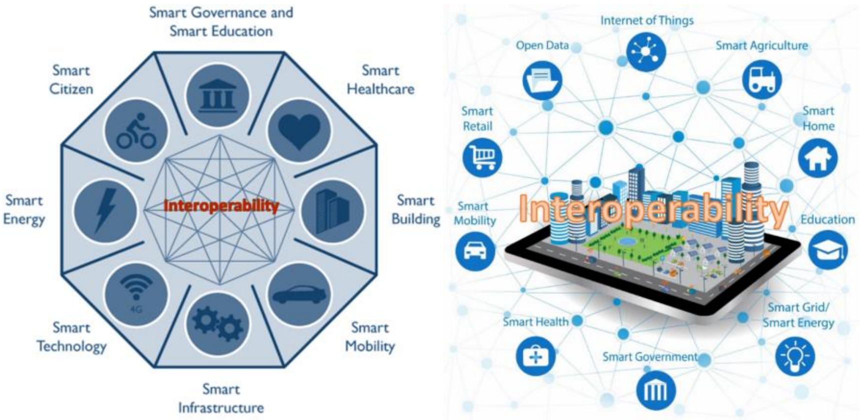


Figure 1.7: Smart domains for Smart Cities (Source: Author and [35]).

To overcome these challenges and promote the development of SCs, the primary focus should be on the accessibility of objects and services, and to build an architecture that enables multiple information sources to be integrated into a single framework by reusing infrastructure, data, and services [36][37][38][39].

In this sense, overcoming market fragmentation and achieving interoperability between established SC silos through global standards and interworking mechanisms are critical to the successful adoption of smart cities [17][40][41].

A comprehensive software platform could provide such services, including facilities for application development, integration, deployment, and management to ease the construction of sophisticated SCs applications.

A Smart City Platform (SCP) is an open and interoperable system that can securely consume heterogeneous data and events from a wide range of subsystems and data sources throughout the city and deliver meaningful insights and results-oriented recommendations to city managers, partner organizations, and the general public as shown in Figure 1.8.

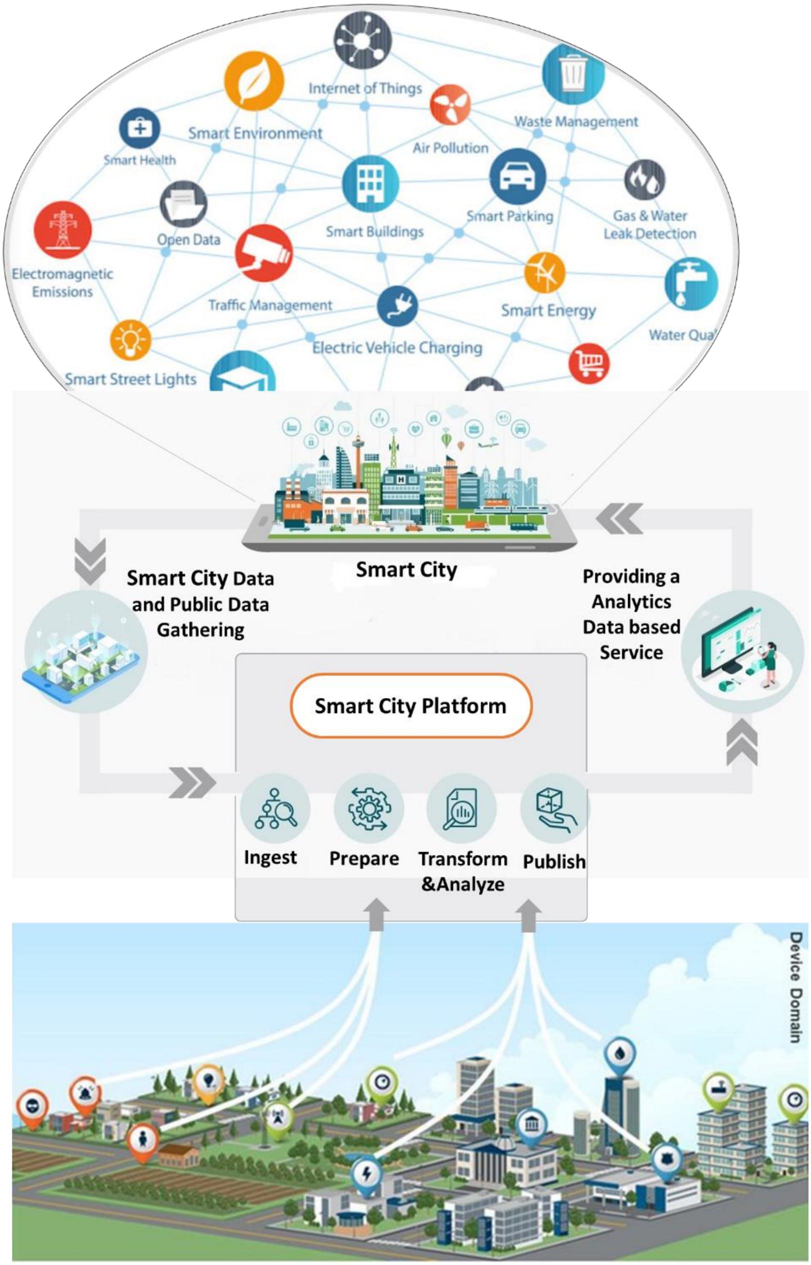


Figure 1.8: Schematic diagram of Smart City Platform (Source: Author, [42], and [43]).

SCP serves to unify data and information from the many-siloed systems. The SCP provides a standard mechanism for visualizing and managing data, and most importantly, optimizes overall city operations. Owner-operators and end-users are beginning to realize the value of unified SCP. The SCP can provide seamless access to data across multiple systems and operating domains to create a harmonious and holistic view of the overall performance and state of the city and its various functions.

However, many challenging issues still need to be addressed before a highly effective platform for SCs can be created, including the following: enabling interoperability between a city’s multiple systems, guaranteeing citizens’ privacy, managing large amounts of data, supporting the required scalability, and dealing with a large variety of sensors.

1.1 Objectives

The motivation of this thesis is to propose an integrated solution to unify siloed smart IoT systems within the city, including smart transportation, smart buildings, environmental sensing, and many more, into a single, open, and interoperable environment; an SCP can securely manage and analyze heterogeneous data across domains and can deliver meaningful insights and outcome-driven recommendations to city managers, partner organizations, and the public. In this sense, the thesis's contribution focuses on the study of the essential requirements, functionalities, information technology infrastructure, ICT, and architecture required for successfully developing such a comprehensive SC ecosystem platform. It provides context for the massive array of data. It turns these data into actionable, contextualized information to achieve better, sustainable outcomes that can be used to reduce energy consumption and operational costs and inform planning and policymaking while improving citizens' overall safety and quality of life. The desired goals of this dissertation are:

- To propose an architecture for a Smart City Ecosystem Platform as a supportive infrastructure in the development of an SC, where people, processes, policies, technology, and other enablers work together to deliver a set of outcomes. It allows the integration of diverse sensors, machines, people, vehicles, and other devices across a wide range of applications and usage circumstances. The interoperability process between the platform and these heterogeneous components will be taken into account to ensure a smooth integration, regardless of data formats or standards, through open standards, open APIs, open documentation, and accessible open data models. Finally, the platform design will ensure reliability, scalability, service quality, security, and compliance.
- To evaluate the enabling networking technologies, protocols, characteristics, and requirements for opportunistic data gathering and data exchange with respect to smart cities applications.
- To provide/introduce intelligent urban mobility solutions to citizens as vertical services linked to the platform, in which all data collected, processed, and related to mobility is provided by the platform in an accessible way for sustainable and intelligent mobility that reduces unnecessary journeys and allows for better use and exploitation of roads.
- To engage citizens and external stakeholders through workshops, co-creation activities, early involvement, hackathons, open data, etc., is an open-ended task (Co-responsibility between citizens and administrations).

A schematic description of the elements analyzed within this work is depicted in Figure 1.9.

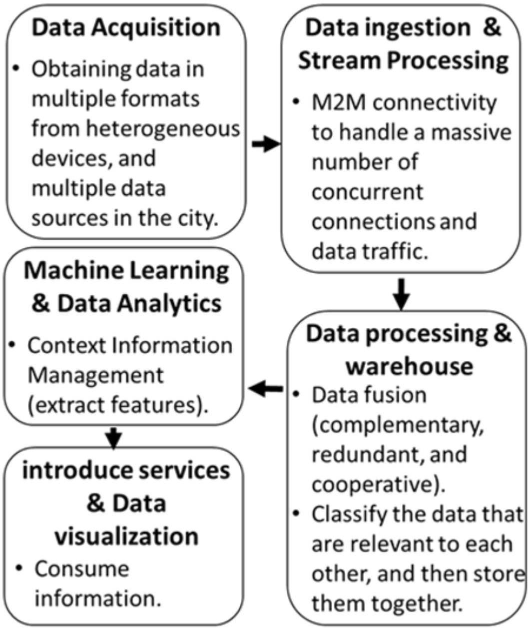


Figure 1.9: Schematic description of the thesis objectives.

1.2 Related work

The advent of the IoT has led to an increasingly broad range of sensors, computing technologies, and services, which has led to many new SCP offerings. We will analyze some of the most relevant contributions in the field of SCPs.

Kazmi et al. [44], have presented a VITAL (Virtualized programmable InTerfAces for innovative cost-effective IoT depLoyments) platform for modeling heterogeneous IoT data streams to overcome the challenge of heterogeneity. The main objective of the VITAL platform is to facilitate the development process of cross-platform and cross-context IoT based applications for smart cities. The VITAL platform uses linked data standards for modelling and accessing data including Resource Description Framework (RDF) as a basic data model, JSON-LD as the data format, and ontologies to specify the data in a formal way. This allows VITAL applications to integrate other data sources in the Web, resulting in a large and varied set of usable data items. The European Platform for Intelligent Cities (EPIC) project proposes a complete IoT Middleware to facilitate the use and management of Wireless Sensor Networks (WSN) [45]. This middleware aims to deal with the heterogeneity, interoperability, scalability, extensibility, and reconfigurability problems in a WSN.

Valencia Smart City (VLCi) [46] is a platform launched in 2014 by the City Council of Valencia, Spain. VLCi arose from the need of improving the efficiency of public services provided by the City Hall and to promote the Valencia innovation environment. Such a platform can provide information based on 350 indicators, including data related to traffic, street lighting, gardens, local police, pollution levels, etc. VLCi supports several types of information such as unstructured, structured, and geo-referenced data coming from citizens' smartphones, sensors scattered throughout the city, and external systems. The platform also allows generating several types of reports, querying, and analyzing data, and visualizing information about the city at real-time through a dashboard. Sanchez et al. [47], have presented the deployment and experimentation the testbed architecture of the IoT experimentation facility being deployed at Santander city, Spain; SmartSantander. The platform is capable of processing a wide range of of information, including data about traffic conditions, temperature, CO2 emissions, humidity, and luminosity. Currently, the project has placed more than 20,000 sensors in the city. With a close concept to the SmartSantander is the Oulo Smart City [48] (Oulu, Northern Finland) and CitySense [49] (Cambridge, USA). UrbanSense [50] is deployed in the city of Porto, Portugal, and collects key environ-mental data from sensors, such as air quality parameters, solar radiation, noise, precipitation and wind speed and direction. City of Things [51] (Antwerp, Belgium), a city-wide open testbed infrastructure, considers the use of LoRa technology to allow experiments at the network, data and user levels. Zanella et al in [17] presented a Padova Smart City project; a proof-of-concept deployment of an IoT island to create a sensor network in the city of Padova, Italy. Using more than 300 sensors, the platform collects environmental data, such as CO2 emissions and air temperature and monitors streetlights. A feature highlighted in this platform is the use of common protocols and data formats to allow interoperability among multiple city systems.

BIG IoT [52] is an EU H2020 project that aims at enabling the emergence of cross-standard, cross-platform, and cross-domain IoT services and applications. Civitas [53] is a middleware that addresses some challenges related to the development of applications for smart cities, such as scalability, heterogeneity, geolocation information, and privacy issues. The platform is composed by several core nodes providing relevant services to the city. A core node can be maintained by either public or private institutions interested in providing services to the city and/or taking advantage of the data produced by it. Civitas also enables entities (citizens, companies, public institutions, etc.) and physical devices to connect to the platform to consume and share information relevant to the city, as well as to combine them with information regarding the physical space of the city. In addition, Civitas supports features such as processing audio and video streams, publish-subscribe based communication and complex events. Vilajosana et al. [54], have proposed a generic and conceptual platform to support heterogeneous smart city applications. All interaction between applications and the platform is performed through APIs based on Web services. The proposed architecture encompasses components representing sensors and actuators, components for real-time data storage and historical data, etc.

Tei and Gurgen [55], have proposed a two-layer architecture to collect data from the WSN and manage the sensors and actuators in the city network. The first layer, "Sensors and Actuators Layer," is responsible for handling data from the WSN. The "IoT Kernel" Layer, the second layer, supervises and monitors the network of sensors and actuators. The work based on ClouT [56]; a collaborative project jointly funded by the

7th Framework Programme of the European Commission and by the National Institute of Information and Communications Technology of Japan.

Elmangoush et al. [57], have presented Open Machine Type Communications (OpenMTC); a Machine-To-Machine (M2M) based communication platform for Smart Cities. Its goal is to enable effective communication among a large number of devices by connecting them to a variety of services. The platform accomplishes this by supporting standard interfaces to many types of devices, real-time data/event processing mechanisms, and easy application development via a software development kit. De Amicis et al. [58], have presented i-SCOPE (Interoperable Smart City services through an Open Platform for urban Ecosystems) is a platform that provides three types of services to SCs including enhancing citizen inclusion and mobility with routing systems and barrier signaling in the city; optimizing energy consumption; and environmental control.

ThingWorx [59] is another IoT platform that facilitates the development of Smart City applications and has already been adopted by many corporations. As part of the IoT/cloud convergence, the OpenIoT (Open Source cloud solution for Internet of Things) is an open-source middleware platform that gathers sensor data and uses the cloud computing mechanism to offer Sensing as a Service model [60]. IBM Intelligent Operation Center [61] is a private platform owned by the IBM company, which is located in different cities around the world, such as Rio de Janeiro. It provides an environment with several essential tools that may be adjusted/customized on demand.

As described in thesis goals, this work aims to present a smart city platform to manage the city data and provide customized smart services related to mobility to citizens.

1.3 Thesis Organization

The thesis structure is depicted in Figure 1.10.

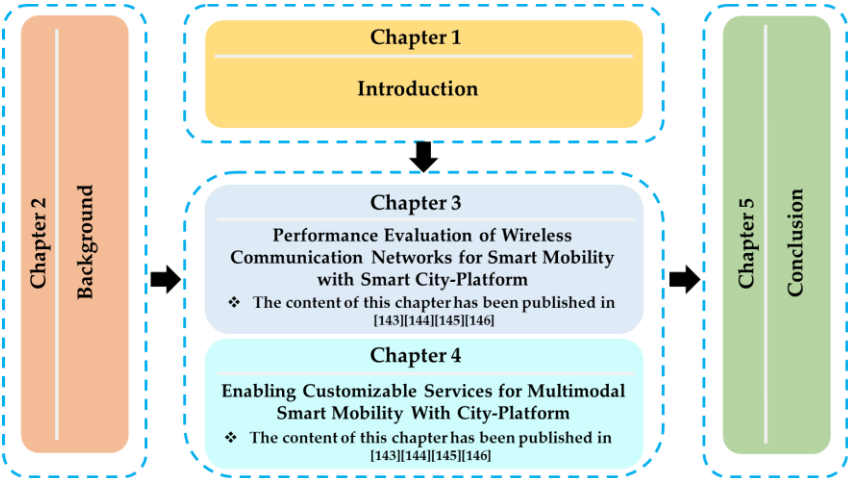


Figure 1.10: Thesis organization.

- The thesis continues with Chapter 2 which provides the reader the required background in technologies, concepts, solutions, and requirements relevant to the smart cities' paradigm requiring IoT.
- Chapter 3 discusses the enabling communication and networking technologies used in smart cities. It also assesses and categorizes the most available and applicable wireless technologies for smart cities. It also highlights the characteristics and requirements of wireless communication protocols for data collection and exchange in smart cities applications.
- Chapter 4 discusses the development and evaluation of an urban data platform as a supportive infrastructure for developing an SC. Several functionalities are addressed, including acquiring information from the environment

through sensors, open data sources, or other alternative sources that meet security and privacy requirements. In order to fulfill interoperability requirements, the data obtained are normalized to the JavaScript Object Notation (JSON) based format and translated from the formats and different protocols of the data source to the platform data models. The prototype platform architecture is implemented following a five-layer model that considers elements from perception, sensing to data management, processing, and visualization. Three different use cases are described, which have been implemented in the city of Pamplona, Spain, as vertical services linked to the platform: intelligent urban mobility-bike handling, bike-2-bike communication, and restricted vehicle access zone control system.

- Finally, Chapter 5 summarizes the work and concludes the thesis.

Chapter 2

2 Background

THIS chapter describes the technical background and the state-of-the-art, which sustains the work in this thesis. The topics covered, begin with the IoT, its current architectural trends, and the IoT protocols used as part of our performance evaluation of the SCP and smart mobility.

2.1 Introduction

IoT is one of the most talked-about and disputed topics in today's ICT, and it is gaining ground rapidly in the scenario of wireless communications. The term IoT was first coined by Kevin Ashton in 1999 in the context of supply chain management [62]. The Auto-ID Labs [63], a global network of academic research laboratories in the field of networked RFID and new sensing technologies, is credited with coining the term "Internet of Things.", and have been targeted to architect the IoT, together with EPCglobal [64]. The basic idea behind this concept is the ubiquitous presence around us of a variety of objects or things – such as sensors, RFID tags, actuators, Smartphones, and so on – that, through unique addressing schemes, are able to interact with one another and collaborate with their neighbors to achieve common goals [65][66].

A radical development of the current Internet into a network of interconnected objects that not only gathers data from the environment (sensing) and interacts with the physical world (actuation/command/control), but also uses existing Internet standards to provide services for information transfer, analysis, applications, and communications.

Atzori et al. [66], have identified that the IoT can be realized in three models—internet-oriented (**middleware**), things-oriented (**sensors**), and semantic-oriented (**knowledge**), as seen in Figure 2.1.

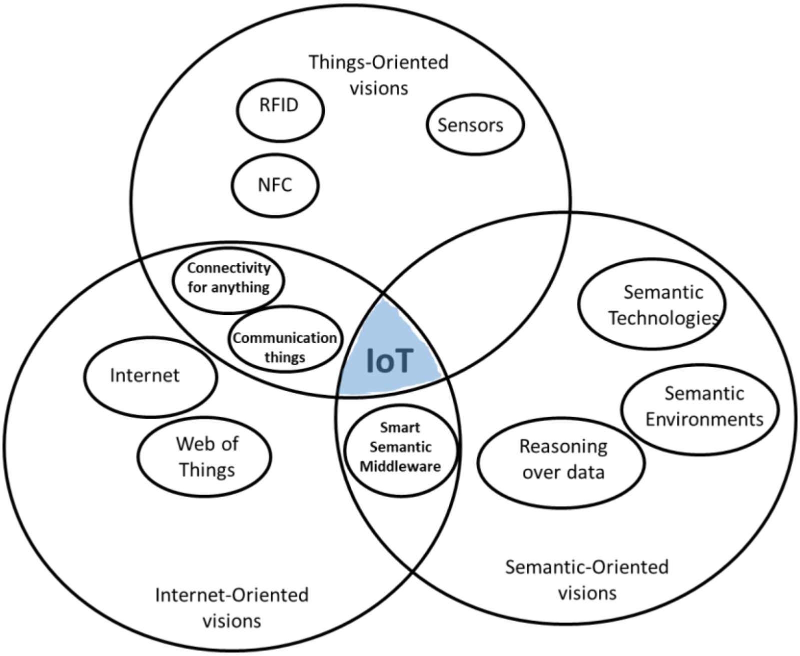


Figure 2.1: Three models of Internet of Things (Source:[66]).

Forrester [18] defined IoT as a smart environment that uses information and communications technologies to make the critical infrastructure components and services of a city's administration, education, healthcare, public safety, real estate, transportation and utilities more aware, interactive, and efficient.

The "Web of Things" is another vision associated with the IoT, in which Web standards are re-used to connect and integrate everyday-life objects containing an embedded device or computer into the Web [67].

So, based on the above, the IoT is a network of heterogeneous, interrelated, and internet-connected of connected things, sensors, actuators, and other smart technologies, that can collect and exchange data via the Internet and allowing for person to- person and object-to-object communication.

2.2 IoT Architecture

The IoT includes an increasing number of smart, interconnected gadgets and sensors that are frequently nonintrusive, transparent, where the communication between these devices, as well as with connected services, should occur at any time and in any location, and it is frequently done wirelessly and autonomously. Services become far more fragmented and sophisticated. As a result, IoT architecture is essential to manage the complexity. In this sense, architecture refers to a framework that specifies the physical components of a network, as well as their functional organization and configuration, operational rules and procedures, and data formats used in its operation. The key qualities of a sustainable IoT ecosystem are functionality, scalability, availability, maintainability, and cost-effectiveness, which are all provided by the IoT architecture.

There is no broadly agreed-upon architecture for the IoT, different researchers have proposed various architectures, and the basic model is a 3-layer architecture consisting of the Application, Network, and Perception Layers [68][69]. The three-layer architecture defines the core concept of the IoT; however, it is insufficient for IoT research because it frequently concentrates on smaller details. The five-layer architecture that additionally includes the Middleware and Business layers considered as the best-proposed architecture of IoT, especially when the project is carried out using a variety of cutting-edge technology and a wide range of applications [69][70]. The five layers are perception, transport, middleware, application, and business layers, as shown in Figure 2.2.

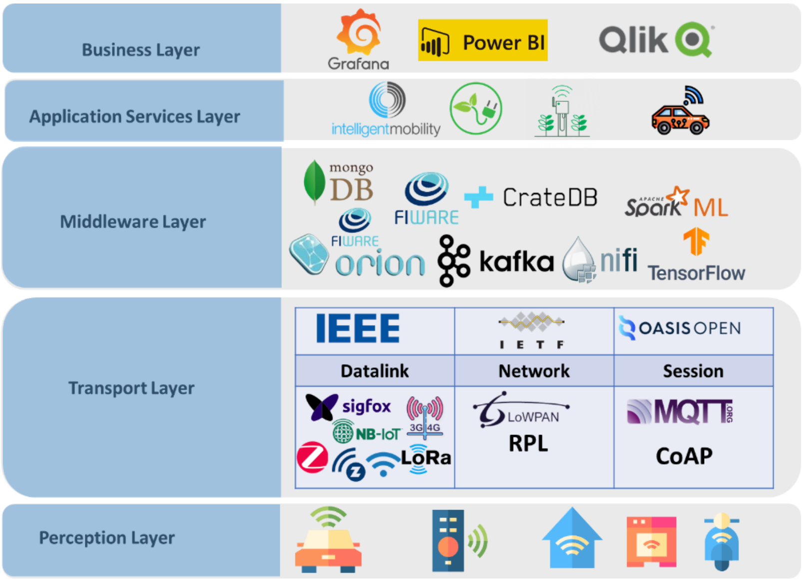


Figure 2.2: IoT layered architecture.

The perception layer is responsible for sensing and gathering information about the environment, and then pass data to another layer so that some actions can be taken based on that information. The network layer is responsible for communication between perception and middleware layer, and for data transmission using networking technologies. The middleware layer is where the data that comes from the network layer is stored, processed and analyzed. The application layer; manages all application processes based on the information obtained from the middleware layer. The business layer; manages the whole IoT system, including applications, business and profit models, and users' privacy. It involves making flowcharts, graphs, analysis of results, and how device can be improved, etc.

We describe next the most important components and architectural elements in the IoT, as described and categorized in the extensive surveys performed by Gubbi et al. [71], Li et al. [72], Atzori et al. [66], Salman et al. [73], Santa et al. [74], Mekki et al. [75], and Al-Fuqaha et al. [76].

2.2.1 Perception layer

The perception layer is the physical layer and exists at the lowest level of the IoT Architecture, which begins with the "things" themselves. The layer consists of different types of sensors (*i.e.* RFID, QR code, Infrared, cameras, etc.) devices. This layer generally in a smart environment scenario cope with overall device management, such as device identification and data gathering by each sort of sensor device. The gathered information can be location, wind speed, temperature, pH level, humidity, air quality, amount of dust in the air, etc. This gathered information transmits through the Network layer for its secure communication toward middleware layer.

2.2.2 Communication/Transmission Layer

The communication layer integrates several layers of the Open Systems Interconnection (OSI) seven-layer model for data networks [73]. The OSI network model is a network model developed by the International Organization for Standardization (ISO) [77]. OSI's functions are divided into seven layers: Physical, Data Link, Network, Transport, Session, Presentation, and Application Layer. Each layer provides unique and redundant protection to address security issues and potential risks related to data intrusion, manipulation, destruction, and so on.

Three of OSI's layers are playing a significant role in communication and data transmission, which are the data link layer, network layer, and session layer:

- **Data link layer**: The data link layer connects IoT elements, either two sensors or a sensor, and a gateway device that connects a set of sensors to the Internet. It aims to provide functional and procedural means to transfer data between network entities, detect, and possibly correct errors in the Physical Layer. The data link layer is divided into two sub-layers based on the architecture used in the IEEE 802 Project (Institute of Electrical and Electronics Engineers): logical link control (LLC) and media access control (MAC) [78]. It defines many wired and wireless local area networking (LAN) technologies, including Ethernet and IEEE 802.11 ("wireless Ethernet" or "Wi-Fi") [79]. IEEE 802 is now the home of several wireless network standardization projects that use its highly successful development system[80].

- **Network Layer**: The Network Layer describes the functions of internetworks. It manages the subnet's functions, deciding which physical path data should take based on network conditions, service priority, and other criteria. It makes the traffic decisions, traffic control, fragmentation, and logical addressing. The Network Layer is also in charge of relaying and routing data across as many concatenated networks as necessary while maintaining the quality-of-service parameters requested by the Transport Layer.
- **Transport/session layers:** The session layer protocols enable messaging among various elements of the IoT communication subsystem and ensures reliable and efficient communication between network devices. The Transport Layer aims to provide transparent transfer of data between end systems. As a result, the upper layers relieve themselves from any concern of not receiving reliable and cost-effective data delivery. It has connection oriented and connectionless protocols, which are Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) respectively. TCP provides reliability and data management services while UDP does not.

2.2.2.1 IoT Data link Protocols

This section discusses the data link layer protocols and standards. The discussion includes physical (PHY) and MAC layer protocols, which are combined by most standards.

2.2.2.1.1 Bluetooth Classic

The Bluetooth Classic radio, also known as Bluetooth Basic Rate/Enhanced Data Rate (BR/EDR), is a low-power radio that streams data over 79 channels in the 2.4GHz unlicensed industrial, scientific, and medical (ISM) frequency band[81][82]. It uses the specification of the IEEE 802.15.1 standard. Bluetooth BR/EDR supports point-to-point device communication and uses to enable data transfer applications and wireless audio streaming. It has become the standard radio protocol behind wireless speakers, headphones, and in-car entertainment systems.

2.2.2.1.2 Bluetooth Low Energy

Bluetooth Low Energy (BLE), also known as Bluetooth Smart, was defined for the first time in 2010 by the Bluetooth Special Interest Group (SIG) as part of the Bluetooth 4.0 specification, and it has emerged as a powerful low-power wireless technology transmitting data over 40 channels in the 2.4GHz unlicensed ISM frequency band [83][84][85]. BLE supports various communication topologies, ranging from point-to-point to broadcast and, most recently, mesh, allowing for establishing reliable, large-scale device networks[82]. Furthermore, the Internet Engineering Task Force (IETF) has developed the adaptation layer to support Internet Protocol version 6 (IPv6) over BLE, which facilitates the connectivity of BLE devices to the IoT [86]. BLE has achieved a dominant position in smartphones by leveraging standard Bluetooth circuitry to a considerable extent [84]. This allows smartphones to communicate with other devices such as sensors, actuators, and wearables via low-energy communication, as shown in Figure 2.3. BLE is widely employed as a positioning technology to meet the growing need for high accuracy indoor location services.

Figure 2.3: BLE Key features and applications (Source:[87]).

2.2.2.1.3 IEEE 802.11ah

IEEE 802.11ah or Wi-Fi HaLow is the least overhead version of IEEE 802.11 standards, which is lightweight to meet IoT needs. The original WiFi standards (IEEE 802.11) are unsuitable for IoT applications due to their frame overhead and high-power consumption. Hence, IEEE 802.11 working group initiated the 802.11ah task group to develop a standard that supports low overhead, power-friendly communication suitable for sensors and motes. The 802.11ah can be used for various purposes, including a very large sensor network, as depicted in Figure 2.4, increasing the range of hotspots and outdoors Wi-Fi that can be used for cellular traffic offloading.

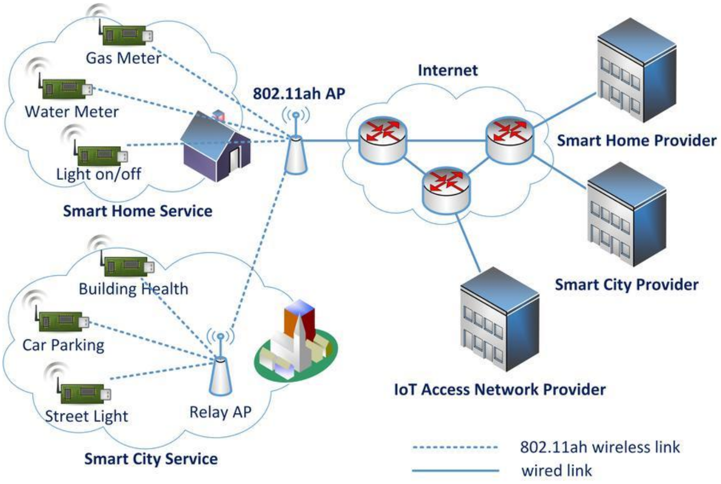


Figure 2.4: 802.11ah Network Model (Source: [88]).

2.2.2.1.4 IEEE 802.15.4

IEEE 802.15.4 is a data link standard that is commonly used in the MAC layer. The standard specifies the frame format, headers, destination, and source addresses and identifies how nodes can communicate with each other. The traditional frame formats used in networking are not suitable for power-constrained IoT devices. IEEE 802.15.4e was created in 2008 to extend IEEE 802.15.4 and support low-power communication. It uses time synchronization and channel hopping to enable high-reliability, low-cost communication in IoT data links.

Figure 2.5 shows the various layers of the ZigBee wireless technology architecture the relationship of the IEEE 802.15.4 standard to the ZigBee alliance MAC layer protocol model.

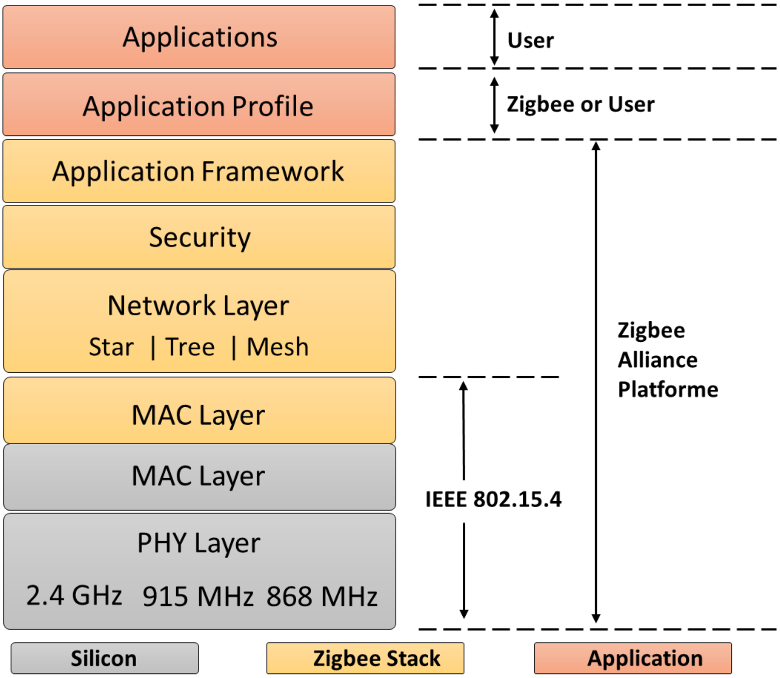


Figure 2.5: IEEE 802.15.4 and ZigBee architecture reference (Source: Author and [89]).

2.2.2.1.5 WirelessHART

WirelessHART is a MAC layer standard that works on top of IEEE 802.15.4 PHY and uses time division multiple access (TDMA) in its MAC. It meets some fundamental requirements, including easy use and deployment, self-organizing and self-healing, being flexible to support different applications, and being scalable, reliable, and secure. WirelessHART encrypts messages and verifies their integrity using advanced encryption algorithms. As a result, it is more secure and trustworthy than others. Its architecture consists of a network manager, security manager, and gateway to connect the wireless network to the wired networks, such as field devices, access points, routers, and adapters. The standard offers end-to-end, per-hop, or peer-to-peer security mechanisms. End-to-end security mechanisms enforce security from sources to destinations, while per-hop mechanisms only secure it to the next hop. Figure 2.6 illustrates an example of a WirelessHART network.

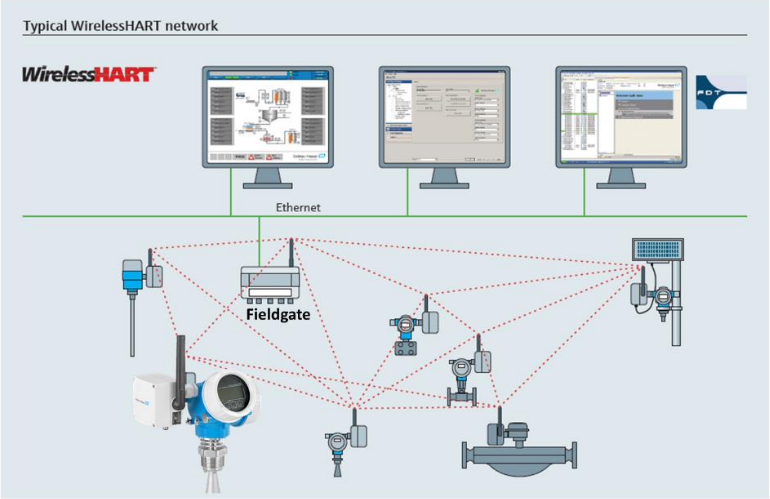


Figure 2.6: WirelessHART network for smart water meters (Source:[90]).

However, WirelessHART does not support dynamic and mobile large-scale networks due to a centralized network management scheme which limits flexibility, not being, therefore, a dominant standard. WirelessHART does not meet the strict and stringent QoS requirements of industrial systems. For example, it does not guarantee end-to-end wireless communication delay tolerance capacity [91][92].

2.2.2.1.6 Z-Wave

Z-Wave is a low-power MAC protocol that was originally developed for home automation but is now widely utilized in IoT applications such as smart homes and small commercial domains, as shown in Figure 2.7. It supports point-to-point communication over a distance of up to 30 meters and is ideal for sending short messages. In addition to tiny ACK (Acknowledgement) messages for reliable transmission, Z-Wave incorporates Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) for media access. It has a master/slave architecture, with the master controlling the slaves, sending them commands, and managing the network's schedule. Z-Wave has a number of limitations, mainly its data transmission speed, which is 100 Kbps unlike Wi-Fi and Bluetooth technologies, its limited number of nodes, unlike Zigbee, while limiting the number of allowed hubs to four, and its topology structure, which supports only a tree topology structure, makes it a legacy technology.

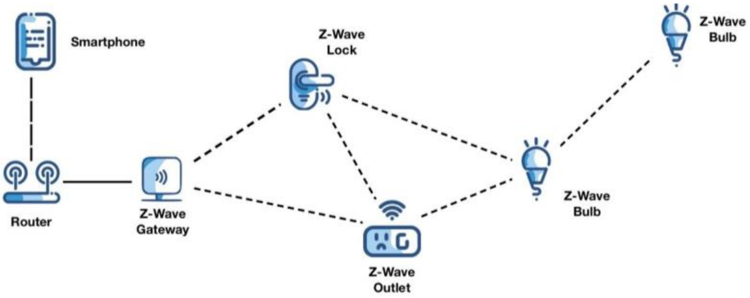


Figure 2.7: Z-Wave Mesh Routing (Source:[93]).

2.2.2.1.7 ZigBee Smart Energy

ZigBee is one of the most commonly used standards in IoT dedicated to medium-range communication in smart homes, remote controls, and healthcare systems, as shown in Figure 2.8. Its networking topologies include peer-to-peer, or cluster-tree, and star. A coordinator controls the network, located at the center of a star topology. It is the root of a tree or cluster topology and anywhere in the peer-to-peer topology. The ZigBee standard defines two stack profiles: ZigBee and ZigBee Pro. ZigBee Pro offers more features, including scalability using stochastic address assignment, security using symmetric-key exchange, and better performance using efficient many-to-one routing mechanisms.

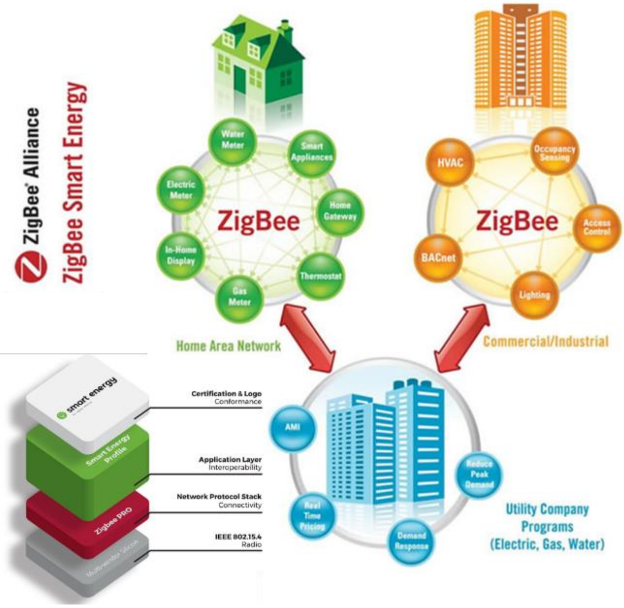


Figure 2.8: ZigBee Smart Energy wireless communication and automation (Source: Author, [94], and [95]).

2.2.2.1.8 DASH7

DASH7 is a new wireless communication protocol for active RFID devices that operates in industrial scientific medical (ISM) band, which is globally available In comparison to traditional ZigBee, DASH7 is primarily intended for scalable, long-range outdoor coverage with a higher data rate. It is a low-cost solution that supports encryption and

IPv6 addressing. It supports a master/slave architecture and is designed for lightweight, burst, asynchronous, and transitive traffic, making it suitable for IoT. Figure 2.9 illustrates a Smart Parking system using DASH7 technology.

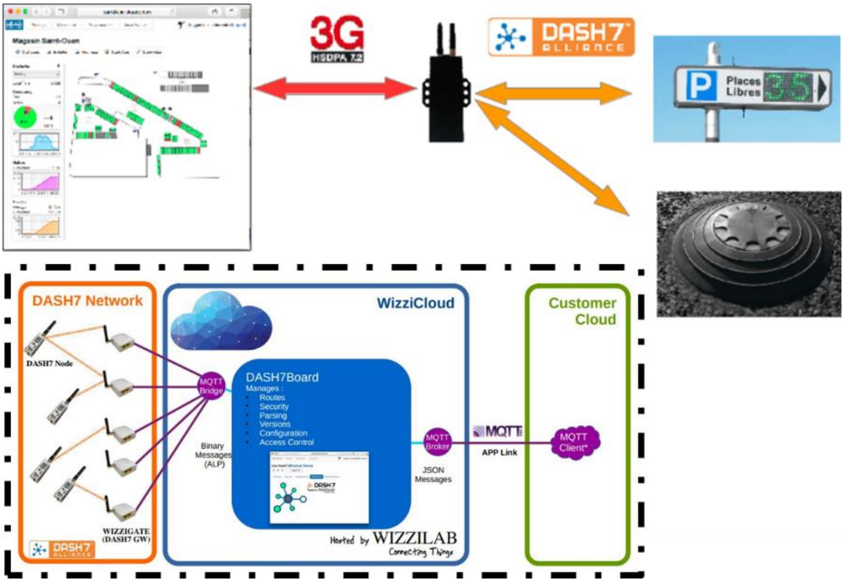


Figure 2.9: Smart Parking application and DASH7 network architecture (Source: [96]).

However, DASH7 has a smaller coverage range than LoRa, since, in LoRa, only one gateway can cover between 2-5 km in urban and up to 15 km in rural, whereas, in DASH7, one gateway can cover up to 1 km [97]. Furthermore, DASH7 requires more power consumption than LoRaWAN because the transmission method used by end-devices is based on CSMA/CA method. This method is inappropriate for large/active networks; latency will increase as the network expands rapidly[98]. Therefore, it is no longer a dominant standard.

2.2.2.1.9 LPWAN

Low-Power Wide-Area Network (LPWAN) is a wireless wide area network technology that is designed and used to interconnect low-bandwidth, battery-powered devices with low bit rates over long ranges[75]. In both licensed and unlicensed frequency bandwidth, many LPWAN technologies have emerged. Among them, Sigfox, LoRa, and MIoTy are today's leading emergent technologies that involve many technical differences.

- **LoRa**

Long-Range Wide-Area Network (LoRaWAN) is a MAC layer protocol standardized by LoRa-Alliance and built on top of modulation of LoRa wireless technology [99]. LoRaWAN is a non-cellular form of LPWAN technologies designed for IoT applications with power saving, low cost, mobility, security, and bidirectional communication requirements. The bidirectional communication is provided by the chirp spread spectrum (CSS) modulation that spreads a narrow-band signal over a wider channel bandwidth. The resulting signal has low noise levels, enabling high interference resilience, and is difficult to detect or jam [100][75]. LoRaWAN is adaptable for rural or indoor IoT applications, such as Smart farms, vaccine cold chain monitoring and Smart Bikes. Figure 2.10 shows the different modes offered by LoRa/LoRaWAN to build a network.

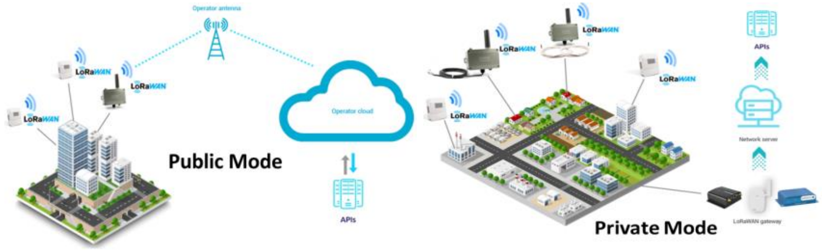


Figure 2.10: Public and Private LoRaWAN modes (Source:[101]).

- **Sigfox**

Sigfox is a private LPWAN network operator that offers an end-to-end IoT connectivity solution based on its patented technologies. It operates on multiple bands relying on the geographic location. Sigfox operates at 868 MHz ISM in Europe and in North America at 900 MHz ISM. It offers energy-efficient connectivity and low bit rates over long-range communication. There is a daily restriction of 140 messages sent over the uplink. Each uplink message can have a payload of up to 12 bytes in length. However, the number of messages over the downlink is limited to four messages per day, which means the acknowledgment of every uplink message is not supported. Each downlink message has a maximum payload length of eight bytes. Figure 2.11 illustrates the communication via Sigfox protocol.

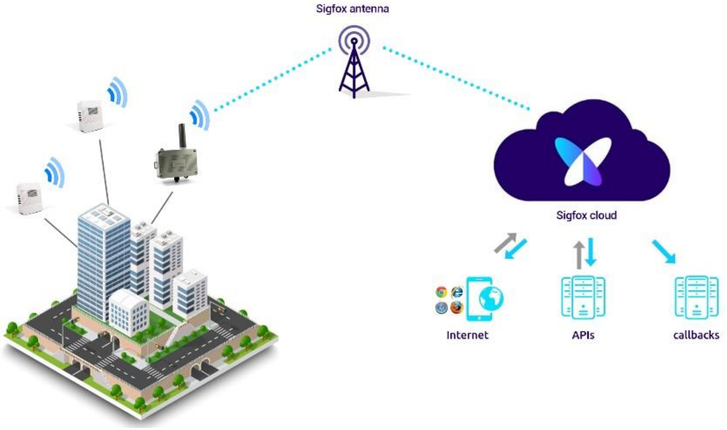


Figure 2.11: Wireless Communication via Sigfox protocol (Source:[102]).

- **MIOTY**

The Massive IoT Operating Technology (MIOTY) is an LPWAN protocol designed to provide the best-in-class reliability and scalability of all available LPWAN technologies today to support massive industrial and commercial IoT deployments. MIOTY is the first and only technology to comply with the technical specification of ETSI Telegram

Splitting Ultra-Narrow Band (TS-UNB) for low throughput networks (ETSI TS 103 357) [103]. Telegram Splitting divides the data packets to be transported in the data stream into small sub-packets at the sensor level. MIOTY supports the IIoT by facilitating the "last mile" communication with wireless data sources. Figure 2.12 shows the MIOTY module of Radiocrafts that can send a message of up to 245 bytes over a single transmission.

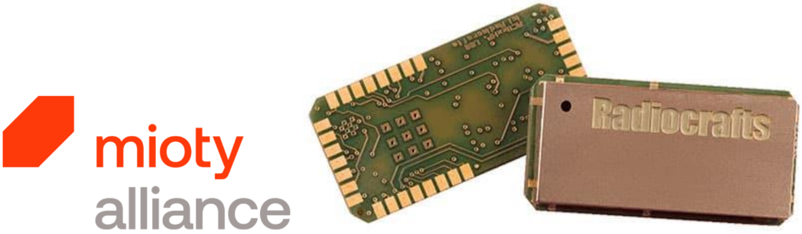


Figure 2.12: The Radiocrafts MIOTY module (Source [104])

2.2.2.1.10 Cellular IoT

Any IoT-based application that requires operation over a longer range can possibly access Global System for Mobile communications (GSM)/3G/4G cellular network capabilities. Although the cellular network is clearly capable of sending high quantities of data (especially 4G), power consumption and cost could be an unavoidable limitation for many of its applications [105][106]. Although, it can still be appropriate for sensor-based low-bandwidth-data applications that need very low amounts of data to be exchanged over the Internet. Thus, emerging technologies such as LTE Categories can prove useful for such tasks [107][108][109].

- **LTE-A**

Long-term evolution advanced (LTE-A) is a collection of cellular networking standards designed to meet M2M and IoT requirements in such networks. In comparison to other cellular protocols, it is one of the most scalable and cost-effective standards. LTE-A was first released in

2009, with multiple releases that are continuously coming to support new technologies. The architecture of LTE-A consists of a core network (CN), a radio access network (RAN), and mobile nodes. The new releases of LTE-A (LTE Rel-17 and Rel-18) will play a critical role in expanding both the availability and the applicability of 5G (5th generation), especially in the areas of Industrial Internet of Things (IIoT), Intelligent transportation systems (ITS) and vehicle-to-anything (V2X) communications.

- **LTE Cat-M1**

LTE Cat-M1 (M stands for Machine type communication) is a versatile Low Power Wide Area Networking (LPWAN) technology; specifically designed for IoT and M2M communications [110]. It is designed to reduce cost and complexity by 50% compared to LTE CAT1. Cat-M1 operates at 1.4 MHz bandwidth and supports full voice functionality via Voice over LTE (VoLTE), along with full mobility and in-vehicle hand-over [111], as shown in Figure 2.13. The major reason for its use in the automotive sector or other IoT-based applications is its extended range and deep penetration in buildings and basements. It also supports PSM – sends an acknowledgement before going to sleep, and then sends checks along with data (if any) to the network. The network would send data, if any.

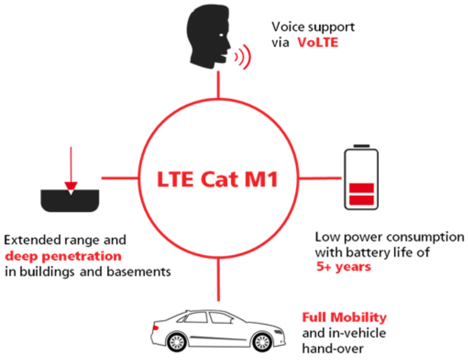


Figure 2.13: Features and the main areas of usage of LTE Cat M1 (Source:[112]).

- **NB-IoT**

Narrow Band IoT, also known as (Cat-NB1), is an LPWAN cellular technology specified in Release 13 of the 3rd generation partnership project (3GPP) in June 2016 [113]. NB-IoT can coexist with GSM and LTE under licensed frequency bands (e.g., 700 MHz, 800 MHz, and 900 MHz). NB-IoT uses Direct-Sequence Spread Spectrum (DSSS) modulation compared to LTE radios. NB-IoT occupies a frequency bandwidth of 180 kHz, which corresponds to one resource block in GSM and LTE transmission [114]. NB-IoT reduces the LTE protocol functionalities to the minimum, and it was optimized to small and infrequent data messages, and avoids the features not required for the IoT applications. Therefore, the end devices require only a small amount of battery, making the protocol cost-efficient. This standard focuses specifically on indoor coverage, low cost, long battery life, and enabling a large number of connected devices, but it has an added disadvantage in that it does not support VoLTE and mobility. With NB-IoT, sensor data is directly transmitted to the main server, and thus we will not require gateways. Figure 2.14 illustrates the features and the main areas of NB-IoT usage.

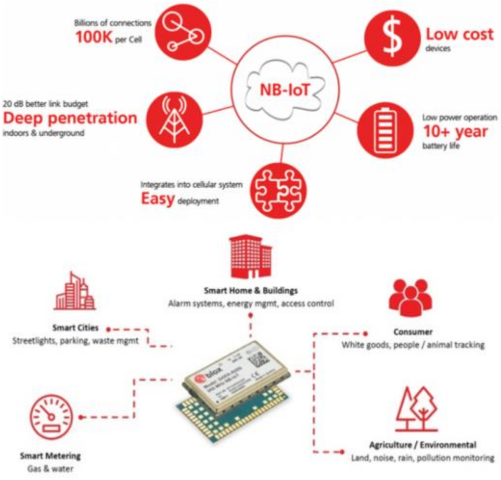


Figure 2.14: Features and the main areas of usage of NB-IoT (Source: [115][116]).

2.2.2.1.11 Comparative Analysis of Wireless Technologies

In this section, a comparative analysis of wireless technologies is presented. Table 2.1 shows a comparison between wireless technologies.

TABLE 2.1: WIRELESS TECHNOLOGY COMPARISON

Tech.	**Characteristics**			
	BW	***Bit Rate***	***latency***	***Power***
BLE	2.4 GHz band	125, 500 kbps, 1, 2 Mbps	6ms	<15mA
IEEE 802.11ah	863–868 MHz UE 755–787 MHz CN 902–928 MHz US	150 kbps to 78 Mbps	100ms	30mA
Zigbee	2 Mhz	20 - 250Kbps	254	52mA
LoRa	900 MHz <500 kHz	<10 kbps	>1s	24-44 mA
Sigfox	900 MHz 200 kHz	<100 bps	>1s	27 mA
WirelessHART	2.4 GHz band	20–250kbps	4ms	<50mA
Z-Wave	908.42 MHz	9.6, 40, 100 kbps	2-2.5s	23mA
LTE Cat-M1	1.4 MHz	1 Mbps	10-15ms	35-400mA
NB-IoT	200kHz	200 kbps	>1ms	<60 mA
DASH7	868 MHz UE 920 MHz US	Up to 256 bytes	305ms	<30mA

2.2.2.2 IoT Network Layer Protocols

This section highlights part of the IoT routing protocol and standards that handle the transfer of packets from source to destination.

2.2.2.2.1 6LowPan

The IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) is a standard developed by the Internet-Engineering Task Force (IETF) 6LoWPAN working group in 2007. It is the specification of mapping services required by the IPv6 over LoWPANs to maintain an IPv6 network. The 6LoWPAN specifications allow many features, including different length addresses, different networking topologies, low bandwidth, low power consumption, cost-efficient, scalable networks, mobility, reliability, and long sleep times, as shown in Figure 2.15. The 6LoWPAN standard provides header compression to reduce the transmission overhead, fragmentation to meet the IPv6 Maximum Transmission Unit (MTU) requirement, and forwarding to link-layer to support multi-hop delivery.

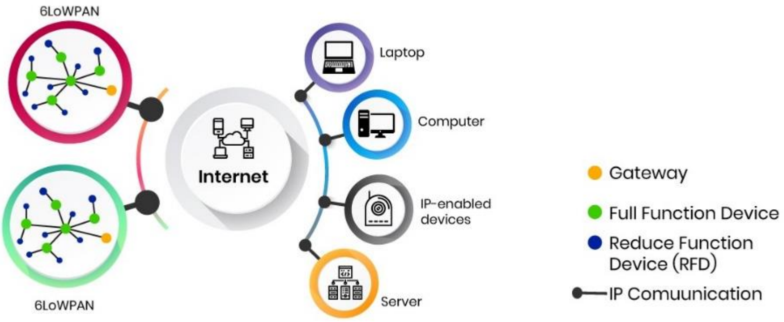
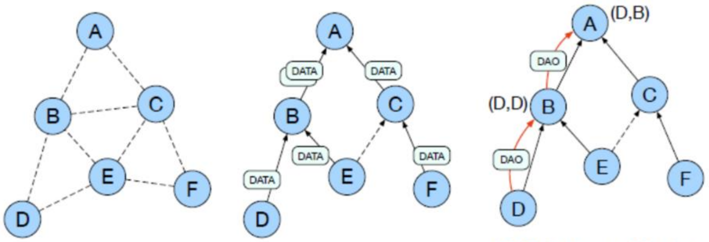


Figure 2.15: 6LowPan Architecture (Source:[117]).

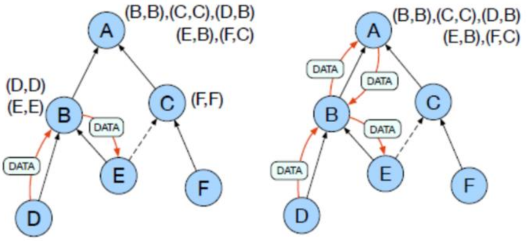
Nevertheless, one of 6LoWPAN's disadvantages is that it has a relatively long overhead which highly limits the size of payload within an IEEE 802.15.4 frame [118]. In addition, it has a small packet size, low bandwidth (250/4/20 kbps) aside from other mesh topology drawbacks [119].

2.2.2.2.2 RPL

Routing Protocol for Low-Power and Lossy Networks (RPL) is an IPv6 routing protocol that is standardized for the IoT by IETF [120][121]. It supports all MAC layer protocols and some other protocols that are not designed for IoT. RPL was designed to meet the most basic routing requirements through building a robust topology over lossy links. RPL forms a tree-like topology, which is based on a different optimizing process called Objective Function (OF). RPL is based on destination-oriented directed-acyclic graphs (DODAG) that have only one route from each leaf node to the root through which all the traffic from the leaf node will be routed to. This routing protocol supports simple and complex traffic models like multipoint-to-point, point-to-multipoint and point-to-point as shown in Figure 2.16.



(a) A sample wireless network.
(b) Multipoint-to-point communication.
(c) Point-to-multipoint route construction: storing mode.



(d) Point-to-point communication: storing mode.
(e) Point-to-point communication: non storing mode.

Figure 2.16: Routing in RPL. Existing routes are shown next to the network nodes (Source:[122]).

2.2.2.3 *IoT Session Layer Protocols*

This section review several IoT session layer protocols used for message passing and standardized by different standardization organizations. TCP and UDP are the dominant protocols at the transport layer for most applications, including IoT. However, several message distribution functions are required depending on IoT application requirements. These functions should be implemented in interoperable standard ways. These are the so-called "Session Layer" protocols that are described in this section.

2.2.2.3.1 MQTT

The Message Queue Telemetry Transport (MQTT) is a standard from the Organization for the Advancement of Structured Information Standards (OASIS). MQTT aims at connecting embedded devices and networks with applications and middleware. MQTT is built on top of the TCP protocol. It delivers messages through three levels of QoS. The connection operation uses a routing mechanism (one-to-one, one-to-many, many-to-many) and enables MQTT as an optimal connection protocol for the IoT and M2M. MQTT simply consists of three components: subscriber, publisher, and broker as shown in Figure 2.17. The publish/subscribe pattern provides transition flexibility and simplicity of implementation. An interested device would register as a subscriber for specific topics in order for it to be informed by the broker when publishers publish topics of interest. Also, Therefore, the MQTT protocol represents an ideal messaging protocol for the IoT and M2M communications and it is suitable for resource constrained devices that in unreliable or low bandwidth networks.

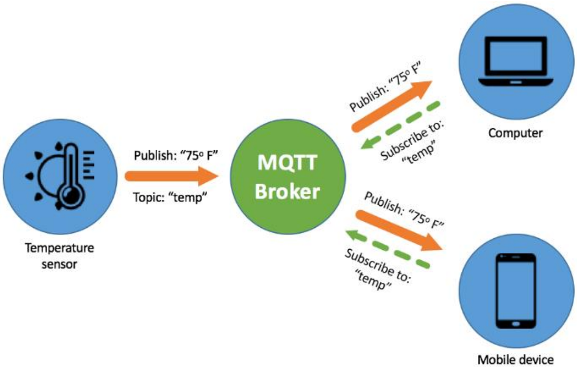


Figure 2.17: MQTT publish/subscribe to topics (Source:[123]).

2.2.2.3.2 CoAP

The constrained application protocol (CoAP) is session layer protocol designed in the IETF constrained RESTful environment (Core) working group to provide low overhead RESTful (HTTP) interface.

Representational state transfer (REST) is the standard interface that is extensively used in today's web applications. REST is a more straightforward mechanism for clients and servers to exchange data over HTTP. However, REST has a significant overhead and power consumption, which makes it unsuitable for IoT platforms. CoAP is designed to solve the REST problems and enable IoT tiny devices with low power, computation, and communication capabilities to use RESTful services while meeting their requirements. CoAP architecture is divided into two main sublayers: messaging and request/response, as shown in Figure 2.18. The messaging sublayer is responsible for the reliability and duplication of messages, whereas the request/ response sublayer is responsible for communication.

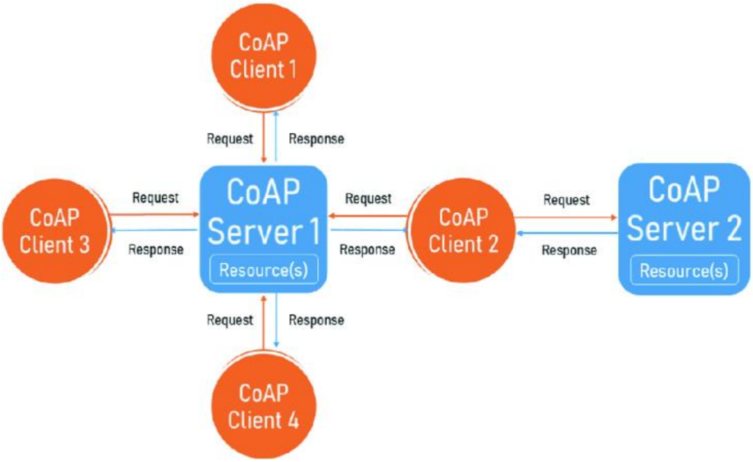


Figure 2.18: CoAP architecture (Source:[124]).

2.2.2.3.3 Comparative analysis of MQTT and CoAP protocols

This section presents a comparative analysis of the three widely accepted and emerging messaging protocols for IoT systems MQTT, CoAP, and HTTP, based on several criteria to introduce their characteristics comparatively. This complete comparative study is shown in Table 2.2. Figure 2.19 shows a comparison between MQTT and CoAP.

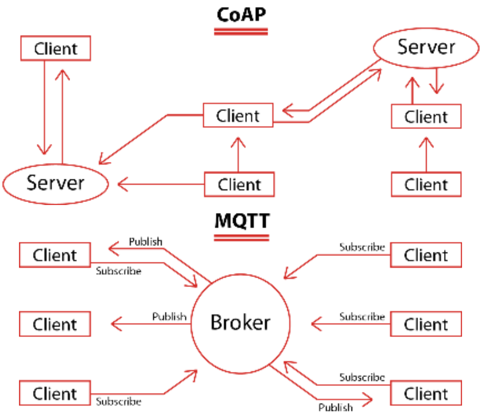


Figure 2.19: Comparison between MQTT and CoAP protocols (Source:[125]).

TABLE 2.2: COMPARATIVE ANALYSIS OF MESSAGING PROTOCOLS FOR IOT SYSTEMS: MQTT, COAP, AND HTTP

Features	MQTT	CoAP	HTTP
Standards	OASIS, Eclipse Foundations	IETF, Eclipse Foundation	IETF and W3C
Transport Protocol	TCP	UDP	TCP
Model used for communication	Publish-Subscribe	Request-Response Publish-Subscribe	Request/Response
Communication node	M:N	1:1	
Power consumption	Higher than CoAP	Lower than MQTT	Most high
RESTful	No	Yes	
Header Size	2 Byte	4 Byte	Undefined
Security	TLS/SSL	DTLS, IPSec	TLS/SSL

2.2.3 Middleware Layer

The middleware layer enables interactions between IoT heterogeneous devices by providing a connectivity layer used by connected objects and the application layers that provide services in the IoT applications. The middleware layer performs different technical processes, including publish/subscribe models, data ingestion and stream processing, data storage and processing, information extraction, service-oriented architectures, semantic models, and context awareness [126]. Middleware supports protocols, services, and APIs (Application Program Interfaces), providing a standardized environment that bridges the differences in devices, networks, and applications that need to interact in the IoT. The functionalities provided by middleware can span a wide range of the elements of the IoT, from simple device connectivity to advanced messaging and data analytics models. Several challenges are being addressed related to requirements like scalability, security, and interoperability. Using cloud computing makes the platform easily scalable to meet changing demand for IT resources, covering resources. It covers two main types of scalabilities: horizontal and vertical scaling, which provides highly customizable infrastructure according to necessity, leading cloud service providers or an on-premises infrastructure offer auto-scaling service, which monitors the performance of applications and automatically adjusts the capacity to maintain steady and predictable performance. Furthermore, Cloud-Health technologies can manage many elements of scalability across one cloud or multiple clouds.

2.2.3.1 Data ingestion and stream processing

Data ingestion is the process of getting data from its source to its home system as efficiently and correctly as possible [127]. This has always been a significant issue, and has been targeted by many previous research initiatives, such as data integration, deduplication, integrity constraint maintenance, and bulk data loading. Data ingestion is frequently discussed under the name of Extract, Transform, and Load (ETL).

2.2.3.1.1 Apache NiFi

Apache NiFi is an open-source software, which is developed as a tool for application developers to connect various systems together [128]. It has the Dataflow feature, which users can specify the connection path of the system by dragging them into a pipeline that can clearly show the connection path of the tools in the system. In addition, Apache NiFi is designed to work fast with an ability to support large systems, and to be used with a variety of systems. Figure 2.20 illustrates the Apache NiFi core concepts and NiFi dataflow.

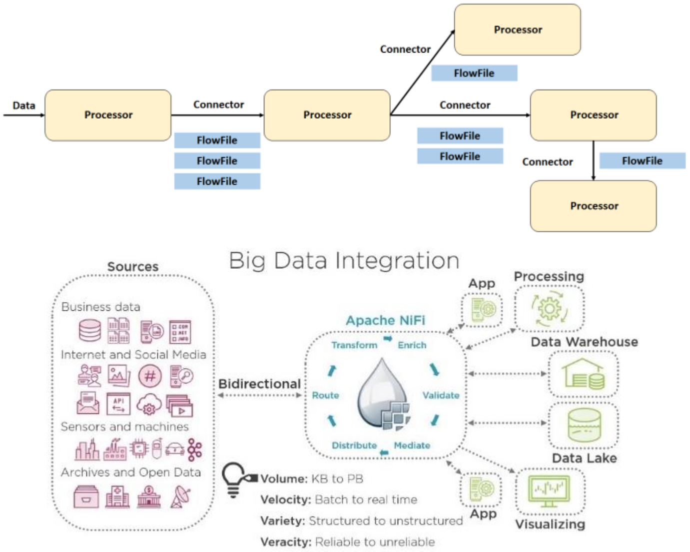


Figure 2.20: NiFi core concept (top) (Source: Author and [129]), NiFi Dataflow automation (bottom) (Source:[130]).

2.2.3.1.2 Apache Kafka

Apache Kafka [131] is an open-source developed by LinkedIn, which used as a message distribution center in the system designing for a fast, flexible, and easy to structure system with data security feature. Due to its cluster function, it makes the system resistant to damage, can support many forms of data, like data transmission in messages, such as messages, logs, events etc. Therefore, Apache Kafka is the first tool that developers tend to look for and apply for the system design with a large amount of data transmission and need for high data security. Figure 2.21 illustrates the architecture of Apache Kafka.

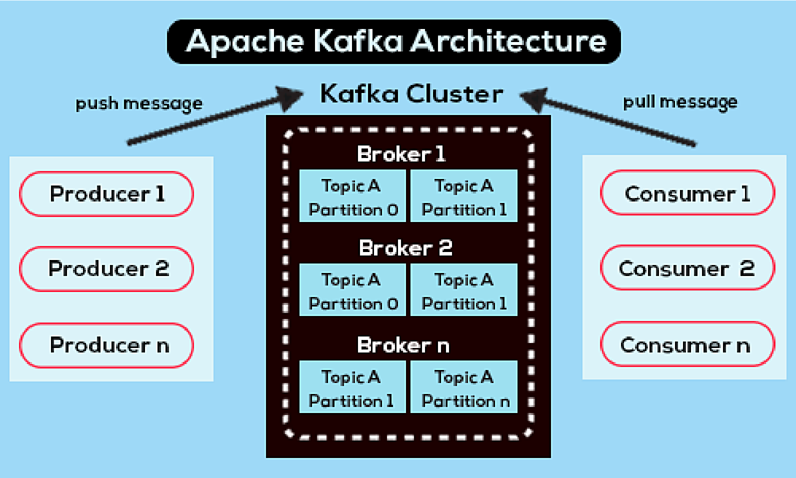


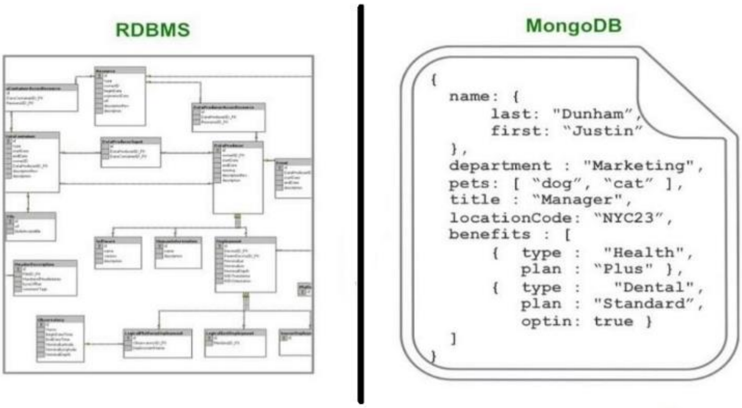
Figure 2.21: Apache Kafka Architecture (Source:[132]).

2.2.3.2 *Data storage, processing, and analytics*

The data generated by sensor nodes in the IoT has a massive volume quickly, and it is heterogeneous. The variations of such data can be classified as structured or unstructured data. Therefore, we need a data storage platform that can store and manage structured and unstructured data efficiently. SQL and NoSQL are a technology widely used as back-end media storage. One of the most significant differences between NoSQL and RDBMS (Relational Data Management System) are that NoSQL systems separate data storage and management. At the same time, the RDBMS tries to satisfy both. NoSQL systems are schema-free. The data stored in NoSQL systems do not need to have a pre-defined data model nor need to fit well into relational tables. This feature entrusts storing heterogeneous data with greater flexibility.

2.2.3.2.1 MongoDB

MongoDB is an open-source document-based, cross-platform NoSQL Database, having features like scalability, high availability, and high performance. It is developed using C++ and stores data in JSON format [133][134]. It can be used to store Big Data. MongoDB possesses the following characteristics, built-in failover and replication, native sharing and horizontal scalability, support map/reduce, and real-time aggregation on huge data. Figure 2.22 illustrates the data mode in RDBMS and MongoDB.



```
{
  name: {
      last: "Dunham”,
      first: “Justin”
  },
  department : "Marketing",
  pets: [ “dog”, “cat” ],
  title : “Manager",
  locationCode: “NYC23”,
  benefits : [
      {  type :   "Health",
         plan :  “Plus" },
      {  type :    "Dental",
         plan :  “Standard”,
         optin:  true }
  ]
}
```

Figure 2.22: The Data model in RDBMS and MongoDB (Source:[135]).

2.2.4 Application Layer

The application layer is responsible for inclusive applications management based on the processed information in the Middleware layer and delivering solutions to end-users. It enables device-to-device and human-to-device interactions reliably and robustly. The IoT applications can be smart health, Smart City, Smart Home, smart transportation, autonomous vehicles.

2.2.5 Business and Visualization Layer

The business and visualization layer manages the overall IoT system activities and services. The responsibilities of this layer are to build a business model, graphs, flowcharts, and many more, based on the received data from the Application layer. It is also supposed to design, analyze, implement, evaluate, monitor, and develop IoT system-related elements. The Business Layer allows decision-making processes to be supported by adequate data analysis processes. In addition, monitoring and management of the underlying four layers is achieved at this layer. Moreover, this layer compares the output of each layer with the expected output to enhance services and maintain users' privacy. Figure 2.23 illustrate a screenshot of the most popular data visualization and dashboards tools.

Figure 2.23: Grafana, Kibana, Splunk, and Zabdash tools screens (Source:[136]).

2.3 Real Scenario of IoT Reference Architecture

Cisco proposed a seven-layer Reference Model supported by 20 companies and the Industrial Internet Consortium that provides a guideline and architectural taxonomy for IoT implementations [137]. The reference Model composes of seven distinct layers of different activities that are conducted in a vertical slice of a typical IoT system as shown in Figure 2.24. The vertical slice refers to the fact that the system incorporates all 3 tiers of the systems (Constrained Devices or "Things", Edge, Cloud). While the typical architecture implies that layer1 is at the

"Things" tier, layers 2 and 3 at the Edge tier and layer 4 to 7 at the Cloud tier, the Edge computing paradigm pushes functionality from layer 4 to 7 down to layer 3.

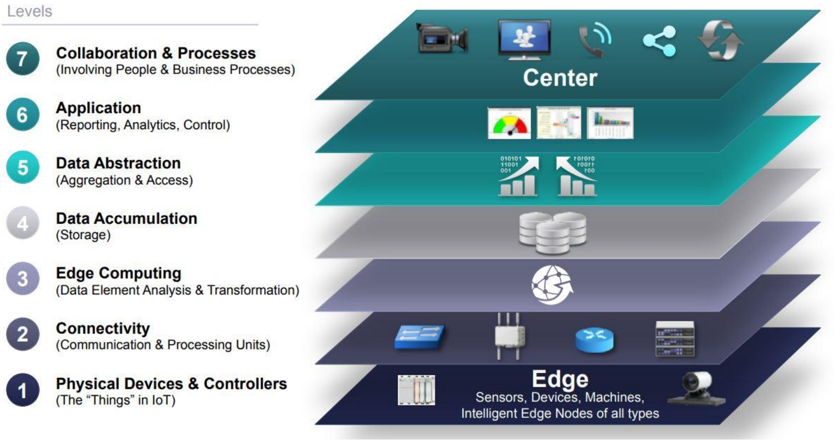


Figure 2.24: The IoT Reference Model by Cisco (Source:[137]).

2.4 Security in IoT

Security and privacy are responsible for authenticity, confidentiality, and non-repudiation. Security can be implemented in two ways: secure high-level peer communication, which enables the higher layer to communicate among peers securely and abstractly, and secure topology management, which deals with the authentication of new peers, permissions to access the network, and protection of routing information exchanged in the network. Security has been considered in all the functional blocks of the existing IoT middleware, from the user level application to the various parts of the functional blocks [138], to build a trustworthy design [139]. Other approaches to implement security and privacy in IoT-middleware are semantic ontology-based approaches to build a universal trust management system [140], device authentication [141], integrity service and access control [142].

Chapter 3

3 Performance Evaluation of Wireless Communication Networks for Smart Mobility with Smart City-Platforms

THIS chapter discusses the enabling communication and networking technologies used in smart cities. It also evaluates and categorizes smart cities' available and most applicable wireless technologies. The chapter highlights the characteristics and requirements of wireless communication protocols for smart city applications. In addition, it evaluates the performance of bike-to-bike wireless communication. It assesses different scenarios' range, throughput, and packet loss ratio. Ultimately, it experimentally characterized radio channels and wave propagation in the scenarios under investigation. The content of this chapter has been published in [143][144][145][146].

3.1 Introduction

Wireless communications are employed when high levels of user mobility, ubiquity and very large sensor node deployments are considered. In this case, different wireless communication systems can be employed, depending on coverage/capacity requirements, bandwidth needs, energy consumption and form factor restrictions, among others. Wireless communication systems can be classified as a function of their coverage range, spanning from wide area connectivity (mainly public land mobile networks), short range communications (wireless body area networks and personal area networks), high-capacity local area networks given by Wireless Local Area Networks (WLAN), and mid to long range low capacity and low energy wireless sensor networks. The election of the specific systems is given mainly by coverage/capacity relations (i.e., transceiver distance range as a function of receiver sensitivity, which is at the same time dependent on transmission bit rate and overall interference levels), as well by inherent form factor, cost, and reduced energy capabilities. The surrounding environment determines wireless channel performance, given by line of sight/non line of sight propagation conditions, the existence of strong multipath components and channel dynamic effects, such as Doppler shift, particularly in vehicular communications.

3.2 Evolution of Wireless Technologies for a Smart Cities

In this section, we compare the different wireless communication technologies and investigate the different networking and communication requirements of the various smart city applications and the protocols that can be used to connect the components used to support such applications [75][147][148].

Within the SC framework described, different systems can be considered as a function of coverage/capacity, energy consumption, form factor, cost and mobility requirements. In this sense, public land mobile network systems, such as 4G NB-IoT or LTE Cat M or 5G machine type communications can be employed, low power wide area networks such as ZigBee, LoRa/LoRaWAN or Sigfox; wireless local area networks, with focus on IoT specific protocols such as IEEE 802.11 ah. In order to evaluate wireless technology adoption in the SC of Pamplona, initial coverage/capacity estimations have been performed. To this extent, it is worth noting that the main urban region of Pamplona has an approximate surface of approximately 24 km², with a population (2020) of 204.000 inhabitants and an interaction region with surrounding municipalities (which share common transportation, water distribution and waste management systems) of 33 km² and a total of 350.000 inhabitants. Elevation heights can be divided in two main regions: within the city center of Pamplona (in the range of 435 m to 465m) and the interaction region, surrounding the city center, with lower heights (in the range of 405 m to 435 m). This leads to maximum link distances of 7 km, with variable partial obstruction conditions. A view of the region under analysis is depicted in Figure 3.1.

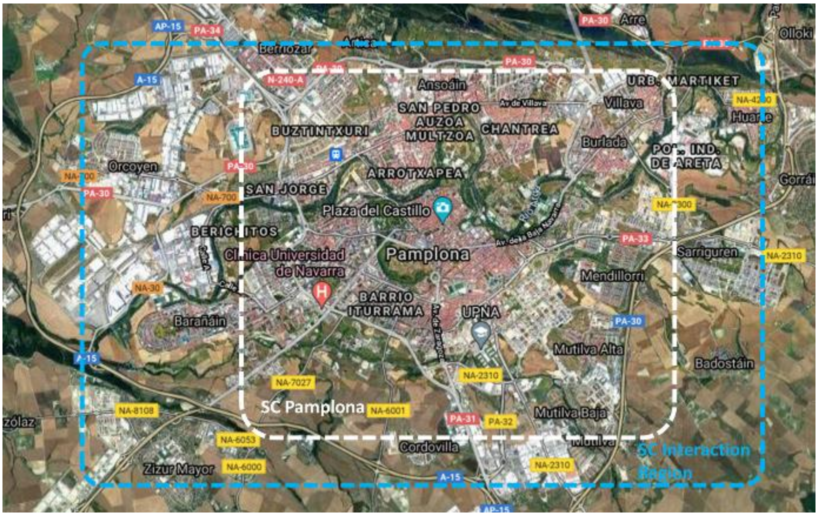


Figure 3.1: Delimitation of the Smart City of Pamplona and the SC interaction region. Maximum wireless link lengths are in the range of 7.

Coverage/capacity estimations have been obtained, by considering radio propagation losses employing COST 231 model, considering mid-range propagation to street angles (i.e., 35º to 55º). Different transceiver models have been considered for the case of LoRa/LoRaWAN (with sensitivity ranges in the order of -117 dBm to -148 dBm), depicted in Figure 3.2, and the cases in which ZigBee (2.4GHz), NB-IoT, IEEE

802.11ah and LTE Cat M transceivers are employed, depicted in Figure 3.3. From the results, it can be seen that coverage ranges extend from 300m to over 2.4 km links, depending on the system under consideration. The use of LoRa/LoRaWAN exhibits in general the longest ranges in terms of coverage, which can provide an optimal solution if low BW is required (a usual consideration in the case of telemetry applications, which is the case for example for environmental sensing within the Pamplona SC platform, water meter indication or EV battery status within electric bus lines, among others). In the case of higher BW requirements, joint communication capabilities are foreseen with 802.11 n/ac and future 802.11 ah/ax (which is the case for video transmissions in the case of controlled zone parking within the city center of Pamplona, for example).

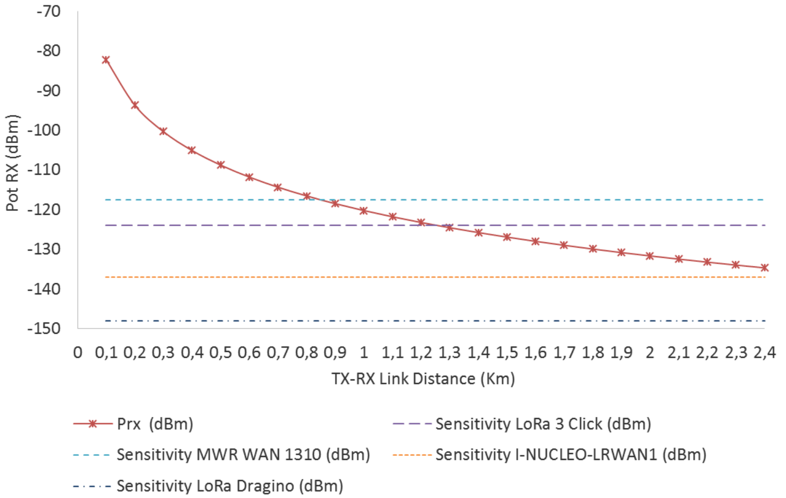


Figure 3.2: Coverage/capacity estimations, for different LoRa/LoRaWAN transceiver nodes.

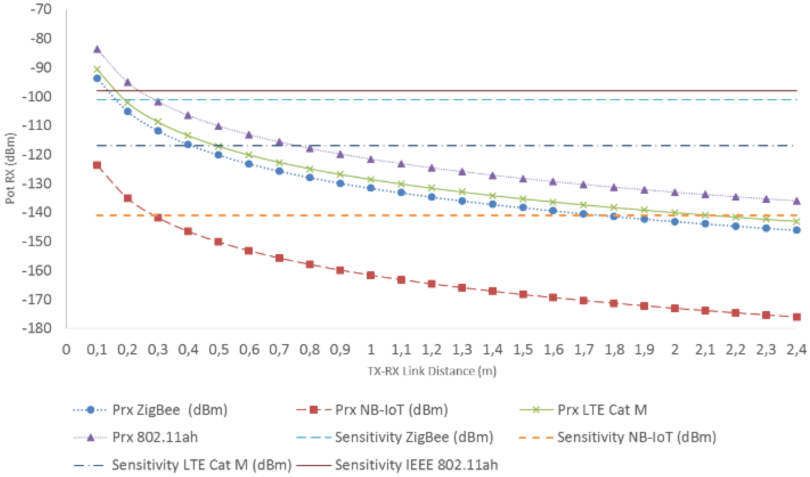


Figure 3.3: Coverage/capacity estimations, for different ZigBee, NB-IoT and LTE Cat M transceiver nodes.

The desire to have a low-cost, far-reaching access network has led to the development of a first pilot deployment of a LoRa network, which initially collects environmental data (temperature, humidity, sunshine, etc.), environmental, light, noise and radio pollution data, and information on the occupation and use of certain municipal resources such as bicycle parking facilities. This network can then be used for municipal solid waste collection by monitoring waste and recycling bins. This network can subsequently be used for the collection of solid urban waste by monitoring rubbish and recycling containers, for monitoring the occupation of roads and pavements using vehicle and pedestrian counters (PIR, radar, etc.).

The location of the network infrastructure is conditioned by the location and height of the municipal buildings and the terrain and can be used to monitor the security of the buildings themselves.

3.2.1 Criteria for Comparison Wireless Communication Protocols

This section underlines a group of criteria that are considerable on the process of selecting an appropriate wireless communication protocol [149][150][75][148][151].

- **Bandwidth**: The increase in bandwidth affects power consumption and reach, making bandwidth an essential consideration when selecting a wireless communication protocol for data transmission.

- **Energy Efficiency:** One of the crucial aspects of selecting a wireless communication protocol for an IoT node is energy consumption. Minimizing the amount of time that IoT node is active, reducing the transmission time, constant and activity of IoT node has led to significant savings in energy efficiency.

- **Reliability:** It guarantees a successful transfer of data to the destination as quickly as possible. Increased reliability is directly proportional to increased bandwidth, so reliability is an important criterion to consider when selecting a wireless communication protocol.

- **Mobility**: Another important feature of smart city applications is mobility. Smart grids, gas pipeline monitoring and smart water networks are examples of low or medium-mobility systems. Other systems, such as smart transportation, have a high level of mobility. As a result, networking protocols used to connect smart city systems with medium to high mobility must be robust and adapt well to node mobility without consuming too much bandwidth on control messages and related processing to readjust to changes in the network topology.

- **Security:** Depending on the criticality of the service and the information stored, systems require a certain level of security. Monitoring of lighting, environmental conditions, noise and light pollution or automatic irrigation systems are low security level systems. In contrast, smart grid applications, the monitoring of energy poverty in housing or water consumption require high security due to the sensitivity of the data and the criticality of the functions performed.

In the case of IoT applications, wireless communication systems in principle need to provide service to a large number of devices, with low/moderate transmission rates, low cost and low energy consumption.

Within the array of different wireless communication systems, several of them are candidates in order to support IoT, such as NB-IoT/LTE Cat-M in the case of Public Land Mobile Network (PLMN), BLE in the case of Wireless Body Area Network (WBAN) and LPWAN standards in the case of WSN, such as ZigBee or LoRa/LoRaWAN, among others. The specification and characteristics for these system are described in Table 3.1, Table 3.2, and Table 3.3 [75][152][147][153][148][154][155][156][157].

TABLE 3.1: WIRELESS COMMUNICATION STANDARDS IOT/C-IOT.

System	Description	T. Ran	Data Rate	Security	Advantages	Limitation
BT / BLE	Bluetooth is a short-range wireless radio technology.	0-100 m, dep. upon power of devices and radio class.	1, 2, 3 Mbps	Bluetooth authentication using shared secret key	Easily upgradeable. Less HW, devices communicate directly. The technology has been adopted in many products such as headset, in car system, printer, etc.	Security issue, it is open to interception and attack. Distance Limitations and Interference.
Zigbee	Zigbee is a wireless mesh network , low-power digital radios based on an IEEE 802 standard.	Up to several km, depending on TRX type and operation mode.	20, 40, 250 Kbps	Uses CBC-MAC for authentication and uses AES block cipher for encrypting the data.	A low-cost, low power and wireless mesh network standard.	The quality and compatibility difference between devices. It might interfere with Wi-Fi network or microwave.
Wi-Fi	(Wireless fidelity) is one is one of the most used wireless technology. It follows a series of standards in IEEE 802.11.	50m (indoors).	Can be > 1Gbps (802.11ac and above).	Uses WPA2 (Wi-Fi Protected Access II) for authentication, and 32-bit CRC for data protection.	Wi-Fi's bandwidth is high—up to 2MHz. Wi-Fi allows to connect to the Internet. Flexibility at work makes the productivity high.	High power usage. Wi-Fi is not designed to create mesh networks. It has limited range.

TABLE 3.2: (CONT.) WIRELESS COMMUNICATION STANDARDS IOT/C-IOT.

System	**Description**	**T. Ran**	**Data Rate**	**Security**	**Advantages**	**Limitation**
GSM 2G	It is the second-generation mobile telephone system. It is an old system; it is widely adopted, and hardware is available at low cost.	35km (hard technical limit)	Up to 64 kbps	Mature standard suffers from exploits.	Inherent wide area communications, employed for tracking applications, fleet control or metering systems, among others.	High energy consumption, so not suitable for battery operated devices.
LoRaWAN	LoRaWAN is a low speed, long range and low power communication protocol.	5-10km typical (in LOS conditions)	27-50 kbps	Based on sessions, where every session is started with static keys, but after a key exchange a unique set of AES keys are used. It uses the AES cryptographic	Appropriate for an isolated or private network. It is ideal when sensors scarcely send a value, like a soil moisture sensor. Longer battery life than NB-IoT. It supports the bidirectionality and it works well when they are in motion.	Due to high latency on delivered messages, it is not suitable for IoT solutions that require an immediate feedback. It requires a gateway to work. It has lower data rates and a longer latency time than NB-IoT.
Sigfox	Sigfox is a proprietary network and protocol. It is a Low Power Wide Area Network (LPWAN), but at the same time a long range.	25 Km	0.1 - 0.5 kbps	Data is transferred over the air interface without any encryption. An end-to-end encryption can be performed in the application layer.	Mostly uses where downlink messages to the device aren´t required, whereas the Sigfox is uplink only. Low power consumption.	Sigfox limits the number of messages to a message every 10 mins in 24 hours. Sigfox system works well in fixed location, mobility is difficult with Sigfox devices.

TABLE 3.3: (CONT.) WIRELESS COMMUNICATION STANDARDS IOT/C-IOT.

System	Description	T. Ran	Data Rate	Security	Advantages	Limitation
LTE	LTE (Long-Term Evolution) is the 4th generation mobile network system. It has a range less than GSM, but the attainable data rate is orders of magnitude more. LTE can compare to long range Wi-Fi.	2km	Up to 100 Mbps	It has different security features such as multiple unique identifiers, static keys, and encryption methods used for the different protocol levels.	Broadband wireless internet connection.	Low power consumption, low latency, long range end devices that should last for years on batteries.
NB-IoT	NB-IoT is a Narrow Band IoT technology specified in Release 13 of the 3GPP, based on the LTE protocol.	Up to 20km (enhanced RX Sens)	250 kbps	NB-IoT inherits LTE's authentication and encryption.	Good coverage. Faster response times than LoRa. Low power consumption compared to LTE. Exhibits low latency compared to Sigfox.	Difficult to implement firmware-over-the-air (FOTA) or file transfers
LTE-M	LTE-M (Long Term Evolution, category M1) is a low power wide area (LPWA) technology standard published by 3GPP in the Releases 13-15 specific.	Up to 20km (enhanced RX Sens)	1024 kbps	Benefits from PLMN security and privacy features.	Supports IoT through lower device complexity and transmits small amounts of data over long periods of time, with low power consumption.	LTE-M has higher throughput with lower latency and battery use is optimized accordingly.
5G	5th generation mobile network system. deployed on the concept of WISDOM (Wireless Innovative System for Dynamic Operating Mega communications concept).	Depending on coverage/capacity relations	50 Mbps-2 Gbps	IMSI encryption	It supports significantly faster mobile broadband speeds and heavier data usage than previous generations as well as to enable the full potential of the Internet of Things.	Initially, less widespread coverage comparing to 3G and 4G. Initial higher cost

3.2.2 Long-Range Wireless Communication Technologies Evaluation Experimental Results Using LoRaWAN and Sigfox Network

In order to assess different long-range wireless communication technologies for their implementation in urban environments, a measurement campaign has been carried out within an urban test scenario in the city of Pamplona. For that purpose, SigFox and LoRaWAN technologies have been chosen, both operating at 868 MHz frequency band. Figure 3.4, shows the employed hardware.

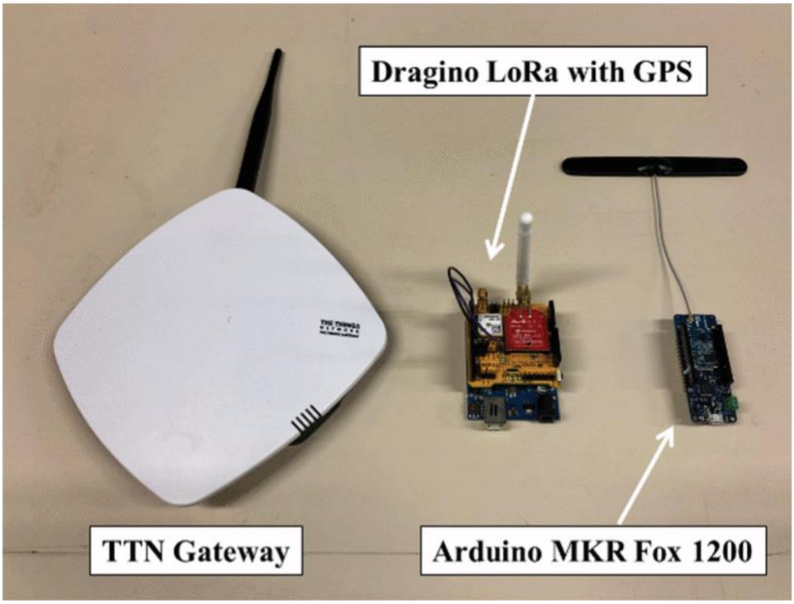


Figure 3.4: Employed LoRaWAN and SigFox hardware for measurements.

On the one hand, the The Thing Newtwork (TTN) LoRaWAN Gateway from The Things Networks and the Dragino LoRa shield with GPS mounted on an Arduino UNO board have been employed to assess LoRaWAN technology. The TTN Gateway has been deployed within the Electric, Electronic and Communications Engineering Department building of the Public University of Navarre (UPNA), and it is represented by a blue circle named "G" in Figure 3.5. The gateway has been located on the second floor, near a window, in order to increase link visibility. On the other hand, the Arduino MKR FOX 1200 device has been used for SigFox technology assessment. In this case, no gateway deployment is needed since SigFox alliance provides the network infrastructure and coverage, so unlike LoRaWAN, there is no need to establish and maintain the wireless communication network infrastructure.

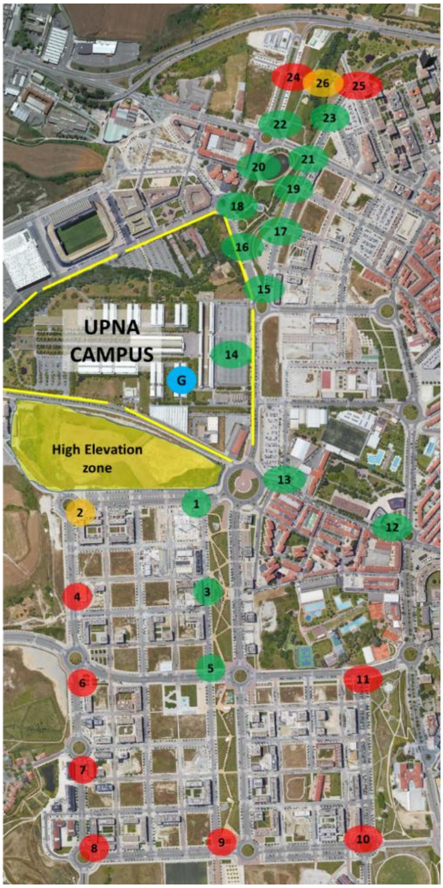


Figure 3.5: LoRaWAN measurements results. Green: No packet losses. Yellow: some packet losses. Red: All packets lost.

Figure 3.6 shows a map where the UPNA campus is delimited by yellow lines. The LoRaWAN gateway location is represented by the blue circle, and the 26 measurement points where the mote based on Dragino LoRa shield has been deployed are shown with different colors. Green color represents that no packet has been lost in the communication; yellow color means that some packets have been lost; and red color that all packets have been lost. For each measurement point, 4 packets have been transmitted from the mote to the TTN gateway. The packets have been sent every 30s, which is the shortest interval between packets allowed by LoRaWAN. The equivalent measurement set for the case of SigFox setup is depicted in Figure 3.6.

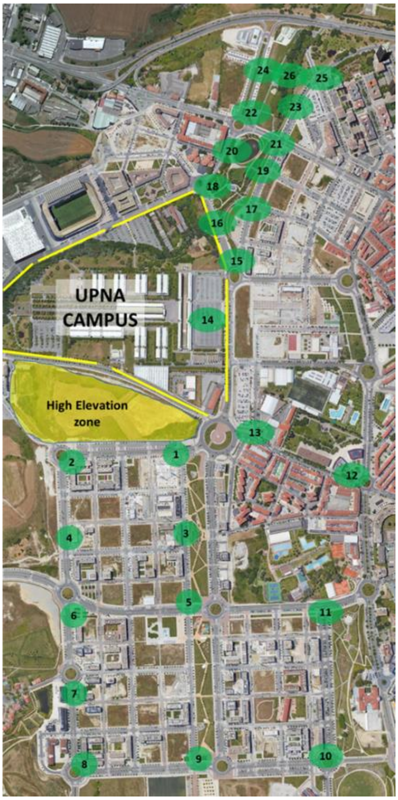


Figure 3.6: SigFox measurements results. Green: No packet losses. Yellow: some packet losses. Red: All packets lost.

Figure 3.7 presents the Received Signal Strength Indicator (RSSI) of the packets received by the gateway and stored in the cloud. Note that in some 'Green' cases (e.g. 14), less than 4 points are seen in the graph, but four packets were received: different packets with the same RSSI value are represented by the same point in the graph. As it can be seen, the Gateway covers a wide area of the surrounding of the UPNA campus, but the high elevation zone (marked in yellow in Figure 3.5, which is higher than the tallest building of the University) causes great losses in the communication with the nodes deployed across the hill, even for short distances from the Gateway (e.g., measurement points 2 and 4). It is worth noting that the coverage would be expected to be better if the Gateway could be deployed in higher levels. All these results and facts show that even the LoRaWAN technology is an interesting one in order to cover wide urban zones, the deployment of the Gateway and the overall radio planning tasks have a great impact in the performance of the network.

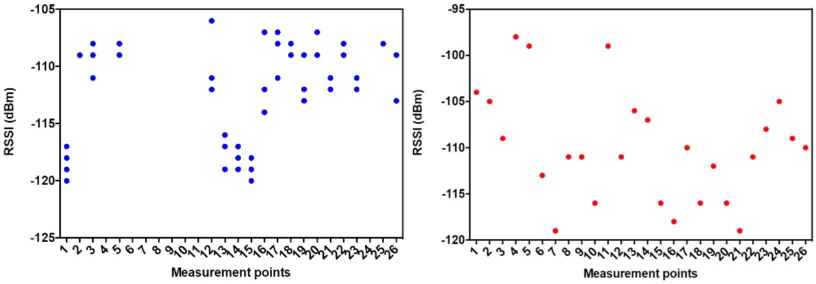


Figure 3.7: RSSI values for LoRaWAN measurements (left) and SigFox measurements (right).

The same measurements have been taken for the case of SigFox technology. As mentioned, in this case, no network infrastructure is needed to be deployed. Therefore, only the Arduino MKR FOX 1200 mote has been deployed in the same 26 measurement points. Again, 4 packets have sent in every point, with 30s interval time. In this case, all the packets have been successfully received and stored in the cloud.

SigFox shows better performance within this urban environment in terms of coverage, with no infrastructure deployment requirements. However, control on wireless communication network by the user isn´t enabled and per node costs arise in the use and operation of the system. In relation with system scalability as related to wireless network capabilities, in the case of LoRaWan, the limitation in the number of connected devices is given mainly by the handling capability of each one of the gateways provided within the service area under analysis, as well as by interference thresholds (in the case of simultaneous transmissions). In this way, several thousands of transceivers can be handled by each gateway in the case of non-simultaneous transmissions, providing feasible wireless connectivity in different urban/city related applications.

3.3 Use cases

3.3.1 Bike-to-Bike Wireless Communication

Cycling has emerged as one of the most sustainable means of urban travel due to its flexibility, low costs, reduced carbon emissions, improved traffic, and mobility in cities. Bikes can play an important role in achieving sustainability for cities, through a set of data that can be got during their movement within the city if they have a set of requirements, such as internet connection, besides a set of sensors. Vehicle-to-Vehicle (V2V) communication is becoming a reality standard. Non-motorized vehicles, such as bikes, are expected to participate in V2V and Vehicle-To-Everything (V2X) networking alongside cars and trucks, although they have gotten significantly less attention.

However, current communication techniques between bikes, bike-to-station, and the transmission of data from bikes over the Internet depend on communication technologies including LTE, LoRa, LoRaWAN, and NB-IoT. The use of cellular communication networks (3G or 4G) is limited by the overhead generated by subscriber management, which they must do for each client connecting to their network. Each bike would be run and managed like a mobile phone or smartphone client, making the operation of such an infrastructure inefficient. The transceiver module on the bike would have to be equipped with a Subscriber Identity Module (SIM) card, which again drives hardware and operating costs. In addition, these technologies have a high-power consumption.

Other existing infrastructures, such as WLANs, are available in cities in public areas, but lack continuous coverage. Ouyang et al. in [158] have discussed a network infrastructure that assumes network nodes in public places with a high frequency of bikes crossing. This concept of an ad hoc network requires network nodes or stations throughout the coverage area, and bikes will be out of reception between station's cells.

Wireless Personal Area Networks (WPANs), whose solutions are widely developed by the IEEE 802.15 Working Group, and emerging trends in LPWAN play an important role in connecting bikes [159] [160]. This opens an opportunity to design a data communication network that perfectly suits/adapted to the dynamic movement of bikes. Bikes will be equipped with a wireless communication module and a set of sensors for sensing environmental parameters, such as measuring temperature, humidity, etc., and transmitting the information in the form of messages to other bikes in the network. The packets with the information will travel from one bike to the other until it reaches a coordinator node, then the packets of sensory data are converted into Internet Protocol (IP) packets for sending to the cloud server through internet connectivity. The advantage of such an ad-hoc network is the absence of any dedicated and static network nodes, making it cost effective, and robust. The more bikes are in a certain area, the amount of data to be communicated is rising; but at the same time, the capacity of the network increases with each bike added.

In this section, we analyze and experimentally evaluate Bike-to-Bike (Bi2Bi) wireless communication in different urban scenarios, considering full topo-morphological characteristics of urban environments by means of deterministic 3D Ray Launching hybrid simulations. Communication and data exchange between bikes relies on the IEEE 802.15.4 standard, and specifically, on ZigBee. We have evaluated range, throughput, and packet loss ratio for different scenarios. In order to simulate results, we have employed an in-house 3D-RL simulation tool. The architecture and implementation of the system are described in Chapter 4. A schematic description of the contribution within this work is depicted in Figure 3.8.

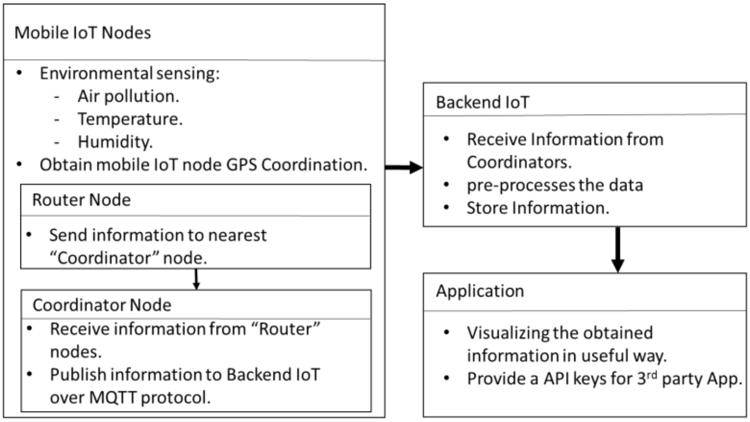


Figure 3.8: Schematic description of the contribution.

3.3.1.1 *Related work*

During recent years, several researchers have come up with ideas for a network of bikes that exchange information among themselves. They have also evaluated which wireless network technology is appropriate to achieve that connection. Eisenman et al. [161] have introduced a project called "BikeNet" based on mobile operators' infrastructure with GSM subscriber modules for the bikes. The BikeNet was unpromising due to the high charges for operating the network. Isemann et al. [162], have proposed a chaotic ad-hoc network for data messaging for bikes, independent from 3rd party network infrastructures. The proposed communication network requires a minimum number of active bikes to make an RF link to the following bike; otherwise, the bikes are isolated. Santos et al. [163] have evaluated in less power-intensive wireless technologies for Bi2Bi connectivity operating in the 2.4GHz ISM band. The relative positioning of bikes and antenna orientation affect the link performance.

Municio et al. [164] have presented a solution that relied on ANT+ wireless technology to communicate with the different bike sensors, and 6TiSCH, which builds the long-range 6LoWPAN network of bikes.

The specific characteristics of bike to infrastructure as well as of Bi2Bi connectivity require to consider the impact in terms of wireless channel behavior and hence, overall system performance. Experimental characterization of Bi2Bi communication links has been presented in [163], considering different WLAN, 802.15.4 CrossBow nodes and Bluetooth transceivers, all of them operating in 2.4GHz frequency bands. The experimental setup considered constant separation between bikes of 1m and as scenarios, an empty parking lot as well as an urban pedestrian area. A cooperative bike communication system is described in [165], in which bike groups, in the form of platoons, are interconnected by means ZigBee nodes, where a brief analysis of wireless communications is presented. The impact of the bike structure as well as the location of the transceiver antennas has been described in [166], considering 6 different antenna locations within the bike frame. Specific antennas have also been considered for the integration of wireless sensor network capabilities within bikes, by embedding a helical antenna within the bike frame, considering frequencies of operation in the 170MHz or the 430MHz bands [162]. Wireless connectivity in order to enable vulnerable road user detection involving the detection of bikes is described in [167], where the radiation diagrams for vehicles and bikes as well experimental values of RSSI distributions have been obtained, considering operating frequencies in the 2.4 GHz bands. Wireless characterization has also been performed for other bike related applications, such as the integration of RFID chips for anti-theft systems [168], with experimental validation of reader ranges, the implementation of indoor/outdoor bike tracking systems supported by particle swarm optimization–artificial neural network processing of path loss calculations [169], or multi-modal communication capabilities in order to implement an optimized e-biking sharing infrastructure among others [170]. The different approaches in relation with communication solutions within bike scenarios have been summarized in Table 3.4.

TABLE 3.4: RELATED WORK TO BI2BI COMMUNICATION.

Ref.	Contribution	Comment
[161]	• It introduced the concept of a "bike area" network with the capability of bike-to-bike and bike-to-environment communication. • It presented a mobile sensing-based system embedded into a bicycle to gather quantitative data about cyclist's rides and environmental variables. • It displays information and query submission on a web server: BikeView.	• One of the earliest research in the field of bicycle networking to improve cyclist fitness. • High charges for operating the network because it based on mobil operators' infrastructure.
[162]	• It presented a chaotic ad-hoc network for data messaging for bicycles. • It proposed a decentralized communication network between bicycles independent from 3rd party network infrastructures. • It used AX.25, a data link layer protocol, to transport the data.	• The implementation provides a significant cost advantage by using a decentralized network involving existing phone operators. • The system requires a minimum number of active bicycles to make an RF link to the next bicycle.
[163]	• It evaluated the performance of wireless communication links in Bicycle-to-Bicycle links that operate in an ISM band of 2.4GHz. • It assessed the range, throughput, and packet loss ratio of these wireless technologies.	• Position, orientation, and type of the antenna influence the radiation pattern and affect the link performance. • The positioning of bicycles can significantly affect the link performance.

Ref.	Contribution	Comment
[164]	• It presented a solution for monitoring cycling environments by combining a network of body sensors and a dynamic mesh network of bicycles. The combination forms a multihop wireless sensor network providing the connectivity between each bicycle and the sink. • It relied on ANT+ wireless technology to gather the sensed data from the cyclist in an ad-hoc manner, and on 6TiSCH technology to send these data to the sink.	• The combination of the ANT+ and 6TiSCH provides a real time, dynamic sensor communication channel that cover cycling events without need to cellular network coverage. • One of the limitation that could faces the prototype is necessity for a fixed central node.
[165]	• It presented a cooperative bike communication system, in which bike groups in the form of platoons are interconnected by means of ZigBee nodes.	• A brief analysis of wireless communications is presented.
[166]	• It examined the impact of the bike structure and the location of the transceiver, taking into account 6 different antenna locations within the bike frame.	• It examined the impact of the bike structure and the location of the transceiver, taking into account 6 different antenna locations within the bike frame.
[167]	• It presented wireless connectivity to detect vulnerable road users, including the detection of bikes, taking into account operating frequencies in the 2.4 GHz bands. • It provided a radiation diagrams for vehicles and bikes as well experimental values of RSSI distributions.	• The communication between bike and car is based on using in-car wireless devices in the 2.4 GHz band, which requires a prior connection setup between bike and car to the built-in Wi-Fi hot-spot placed inside the car. This loses the flexibility of the system.
[168]	• It presented anti-thief and certification bike management system using RFID technology. • It provided wireless characterization for the presented system.	• It is suitable for specific purpose, since the RFID tag mounted to the body of the bike during the production stage.

Ref.	Contribution	Comment
[169]	• It presented two methods aimed at determining the distance between the bicycle's location on the track and the anchor node. The first method was based on traditional Log-Normal Shadowing Model (LNSM), whereas the second approach was based on a proposed hybrid Particle Swarm Optimization-Artificial Neural Network (PSO-ANN).	• The presented methods help to control the transmitted power of the sensor nodes, thus the power consumption of the WSN can be reduced and the battery life of the sensor node extended. • It is based on a fixed anchor node and not a moving node.
[170]	• It presented a bike-sharing system implementation architecture compatible with the IEEE 1451 standard family. Each e-bike has been equipped with sensors to measure available battery energy, ozone and detect fall.	• The system architecture did not include the Bi2Bi communication; it only discussed the communication between bike-station and bike-user.
[171]	• It proposed a prototype of Multimodal Alerting Interface with Networked Short-Range Transmissions (MAIN-ST) to connect bicycles and advances bicycle safety by providing cyclists with enhanced hazard awareness.	• It presented an approach to move a bicycle onto a connected vehicle network and provide novel safety features using this connectivity.
[172]	• It presented an IoT-based smart bike system for cycling training. • The design of the system covered both hardware and software components. • The system offers web and mobile App for monitoring the important parameters for training and collaborating between cyclists and trainers.	• The design did not provide the ability of bike-2-bike communication. • High-cost system design for public purpose.
[173]	• It introduced an IoT Crowd Sensing platform that provides a series of services including the monitoring of the air pollution and anti-theft service.	• GSM-based platform with high power consumption. • The communication between bikes themselves is unavailable.

3.3.1.2 Bi2Bi ZigBee Communications Assessment

Once presented the proposed system, this section presents the assessment of the ZigBee-based wireless communication between bikes in different sub-urban scenarios where bikes are commonly present. First, the algorithm employed for deterministic radio propagation analysis is presented. Then, simulation results for the scenarios under analysis are shown. And finally, wireless communication quality experiments for several use cases are presented.

A. 3D RAY Launching Technique

The design of accurate propagation models for realistic wireless vehicular communications, and Bi2Bi communications in particular, must take into account unique characteristics such as the antenna placement and the characteristics of different surrounding environments [174]. Urban environments encompass a wide variety of scenarios which are characterized by the combinations of different objects and elements such as buildings, pedestrians, urban furniture, vegetation and different kind of vehicles (buses, cars, trucks, bikes, scooters, motorcycles, etc.). In the same way, their size and density have a great impact on the propagation of wireless signals [175]. Propagation phenomena such as reflection, refraction, diffraction and scattering, as well as the Non-Line-of-Sight (NLoS) and Quasi-Line-of-Sight (QLoS) situations make this kind of scenarios very complex in terms of radio propagation. Besides, the mobility of the elements within these scenarios changes the radio propagation conditions continuously, being the main challenge for channel modeling in vehicular communications, and extensively, in Bi2Bi communications.

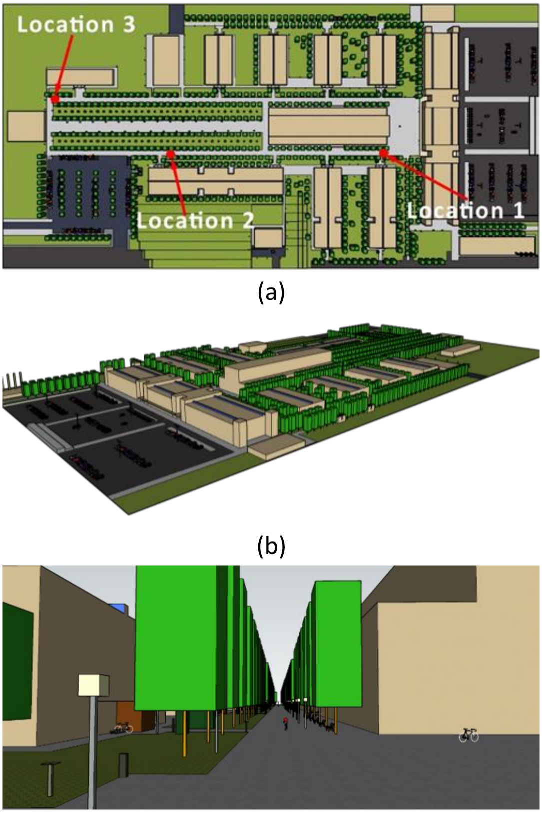
In general, channel modeling approaches are classified as Empirical, Stochastic, Geometry-based stochastic or deterministic [176]. Unlike empirical and stochastic models, deterministic models provide an accurate modeling of all the elements within the specific scenario under analysis [177], making them the most accurate option for radio planning tasks of urban and sub-urban environments [178][179]. In the literature, many V2V propagation models and channel simulators can be found [180][181], but further investigations are needed regarding the Bi2Bi wireless communications.

With the aim of analyzing the Bi2Bi channel in urban scenarios, an in-house developed deterministic 3D-RL simulation tool has been employed in this work. The detailed operating mode of this deterministic algorithm can be accessed in [182], and it is based on the creation of complete 3D scenarios, where the complete volume is meshed into a fixed number of cuboids. The transmitter antennas and their characteristics are the input parameters of the algorithm. Then, rays are launched form the transmitter following a combination of electromagnetic theory and equations based on Geometrical Optics (GO) and Geometrical Theory of Diffraction (GTD). The propagation parameters are calculated along the path of each ray, which interacts with all the elements within the scenario, creating radio propagation phenomena such as reflection, refraction, and diffraction. These characteristics, added to the implementation of the material properties of all the elements within the scenario (conductivity and permittivity) lead to an efficient and robust technique already employed and validated in many different environments, including large urban environments[183][184].

The next two subsections present the radio propagation analysis performed for ZigBee wireless communication between bikes in two different environments where bikes are usually present. First, a University campus has been assessed, and then, a common urban scenario. The campus environment presents some building, empty spaces and many vegetation elements. Furthermore, the urban scenario contains narrower spaces between buildings and higher density of obstacles, such as cars. Finally, empirical evaluation for both scenarios is presented, using ZigBee-based transceivers.

B. Bi2Bi Communication in University Campus Environment

Nowadays, many students and academic staff use bikes to go to the university. Thus, a Bi2Bi radio link estimation at a university campus is important. In this context, a 3D Ray Launching scenario replicating the campus of the Public University of Navarre in Spain has been created to study the feasibility of the proposed Bi2Bi communication system in university campus environment. The created scenario of the campus is illustrated in Figure 3.9.



(a)

(b)

(c)

Figure 3.9 : (a) Top view, (b) 3D view, and (c) transmitter at location 1 within the created university campus scenario.

The dimensions of the scenario are 590 m of length, 290 m of width and 30 m of height, resulting in a volume of 5.1 million m^3. The existing elements and materials at the campus such as trees, foliage, grass, streetlights, baskets, benches, cars and buildings were all taken into account while simulating the presented scenario. Moreover, since the dielectric properties of any material depend on the radio frequency, temperature and humidity levels, the dielectric properties of the materials used in the presented scenario were taken from [185] for a considered humidity level of 20% and a Temperature of 20 ºC. Table 3.5 depicts the dielectric properties of these materials.

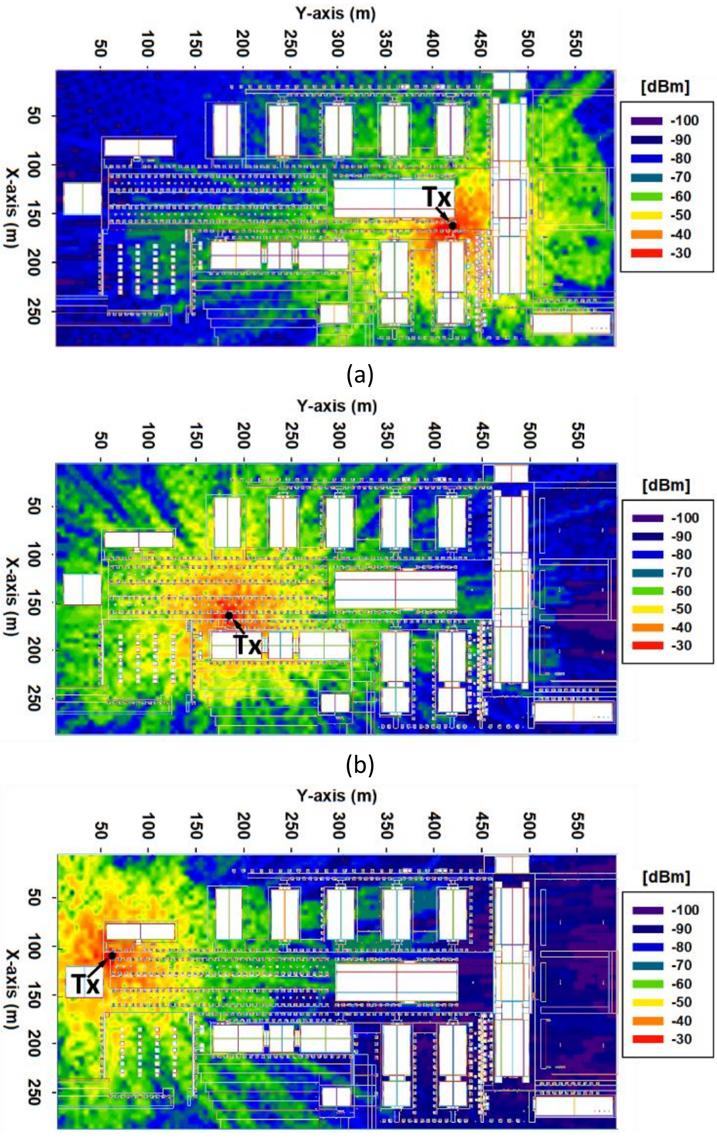
TABLE 3.5: MATERIAL PROPERTIES FOR THE 3D RAY LAUNCHING SIMULATION.

Parameter	Relative Permittivity	Conductivity (σ) [S/m]
Metal	4.5	37.8×10^{6}
Plastic	8.5	0.02
PVC	4	0.12
Asphalt	5	0.7
Glass	6.06	0.11
Trunk tree	1.4	0.021
Tree foliage	4.48	0.02
Air	1	0
Brick wall	4.44	0.11
Grass	30	0.01

In the performed simulations, the transmitter was placed on the front part of the bike at three different locations, as illustrated in Figure 3.9 (a). The purpose of choosing these locations is to estimate the radio coverage under LoS and NLoS Bi2Bi links. One of the main advantages of the 3D-RL code is the ability to perform analysis at any location in the three-axis within the 3D scenario. Figure 3.10 shows the estimated RF power distribution planes at 2.41 GHz for the transmitter placed at the three locations at 1.15 m from the ground level.

Figure 3.10 shows that one bike can cover the half of the campus. Moreover, it is shown that higher radio coverage is offered by bikes placed at locations 2 and 3 due to the low buildings density. However, the bike at location 1 is surrounded by buildings, resulting in signal attenuations.

It can be observed in Figure 3.10 (a) that a reliable Bi2iB communication can reach 150 m radius from the transmitter bike at location 1. For a transmitter placed at location 2, high link quality is offered at 180 m radius, as illustrated in Figure 3.10 (b). Finally, From Figure 3.10 (c), it is demonstrated that a Bi2Bi communication can reach 200 m for a transmitter placed at location 3.



(a)

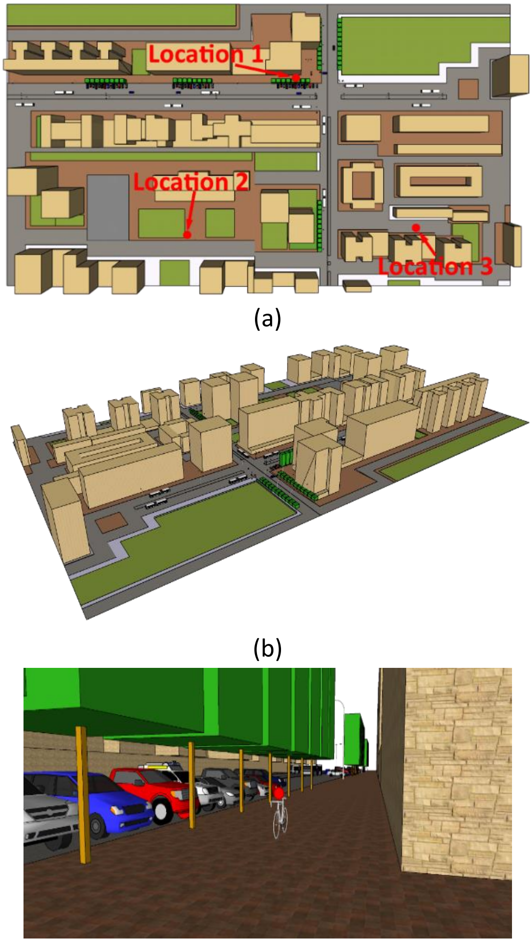
(b)

(c)

Figure 3.10: The estimated RF power distribution planes for transmitters placed at (a) location 1; (b) location 2; (c) location 3.

C. Bi2Bi Communication in Urban Scenario

Another important condition to be taken into account for a reliable Bi2Bi communication is the urban scenario, which is a complex environment with high buildings, vegetation and vehicles density levels. In this context, the 3D Ray Launching algorithm has been used to perform radio coverage estimation for Bi2Bi communication in urban scenario.



(a)

(b)

(c)

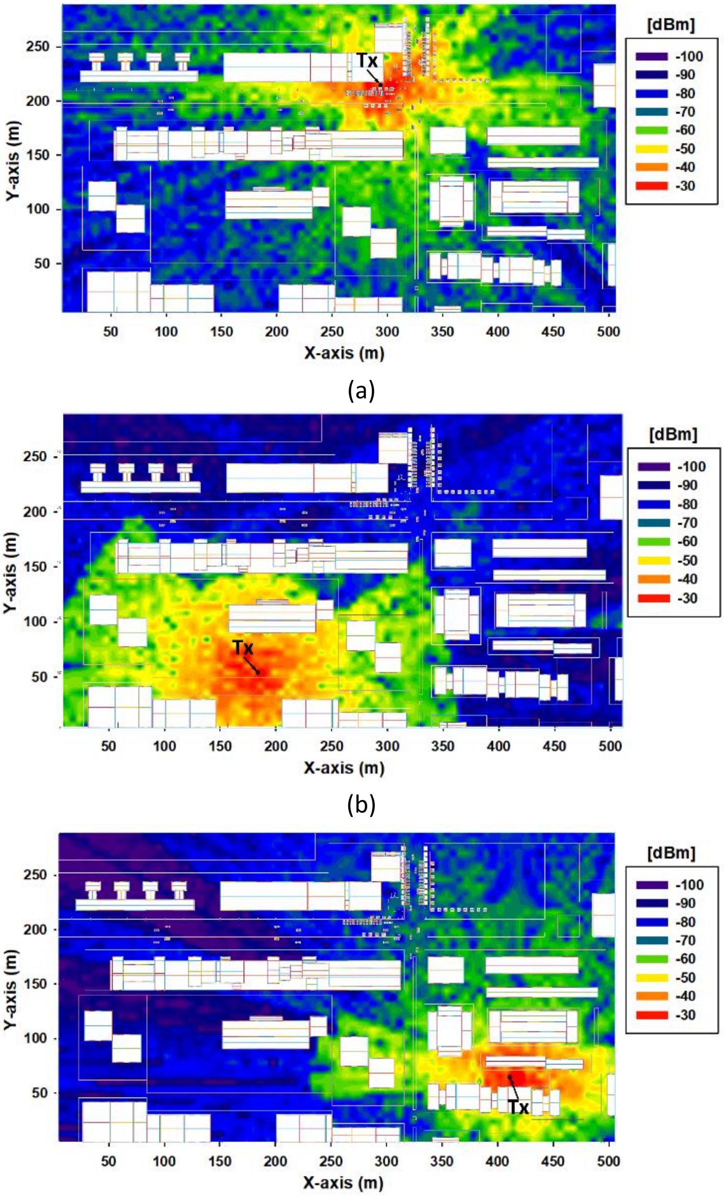
Figure 3.11: (a) Top view, (b) 3D view, and (c) transmitter at location 1 within the created urban scenario.

The presented scenario in Figure 3.11 is a replica of a real part of the city of Pamplona in Spain. The created scenario has dimensions of 510 m in length, 285 m in width and 50 m in height, resulting in a total volume of 7,267,500 m3. The scenario is created considering all the existing components in the real scenario such as bikes, buildings, trees, streetlights, vehicles, human body, baskets, benches and all the metallic elements, as it is illustrated in Figure 3.11 (c). The dielectric properties of these components are those of Table 3.5.

The created urban scenarios have been simulated using cuboids size of X = 6 m, Y = 6 m and Z = 2m. The angular resolution of both vertical and horizontal ray launching is $\Delta\theta = \Delta\varphi = 1°$. Diffractions have been taken into account in this scenario and the number of the defined reflections until extinction is 6. The transmitter bikes have been placed at three different locations, as it is shown in Figure 3.11 (a). The purpose of choosing these locations is to estimate the radio coverage under different density levels.

The estimated RF power distribution planes at 2.41 GHz for the transmitter placed at the three locations at 1.15 m from the ground level are illustrated in presented in Figure 3.12.

It can be observed in Figure 3.12, that the received power levels are higher than the receiver's sensitivity threshold at large areas surrounding the transmitters located at the three locations. Moreover, it is shown that higher radio coverage is offered by bikes placed at locations 1 and 2 due to the low buildings' density. However, the bike at location 3 is surrounded by buildings, resulting in signal attenuations. From Figure 3.12 (a), it can be seen that a reliable Bi2Bi communication can reach 200 m radius from the transmitter bike at location 1. For a transmitter placed at location 2, high link quality is offered at 190 m radius, as illustrated in Figure 3.12 (b). Finally, From Figure 3.12 (c), it is demonstrated that a Bi2Bi communication can reach 150 m for a transmitter placed at location 3.



(a)

(b)

(c)

Figure 3.12: The estimated RF power distribution planes for transmitters placed at (a) location 1; (b) location 2; (c) location 3.

D. Experimental Evaluation

This subsection presents several experiments with ZigBee modules set on the bikes. The aim of these experiments is to study the performance of the wireless communication between two moving bikes, in terms of packet losses. For that purpose, two different scenarios have been tested. On one hand, a path along a wide sub-urban environment has been measured, which contains different zones with different types of buildings and urban furniture. In addition, the path has significant altitude changes (see Figure 3.13 -a-). On the other hand, the second suburban scenario is specific one: a University campus (see Figure 3.13 b, -c-). This scenario corresponds to the scenario simulated with the 3D RL (see Figure 3.11).

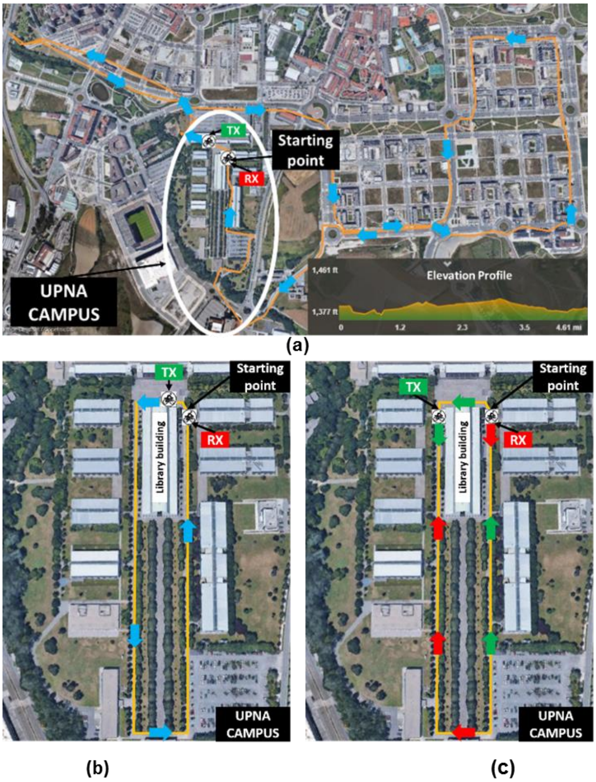
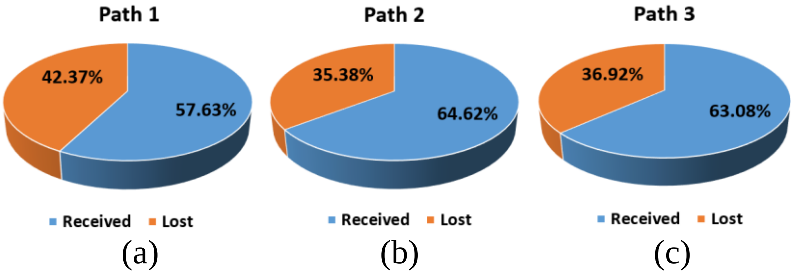


Figure 3.13: (a) Path 1; (b) Path 2; (c) Path3.

Figure 3.13 shows the Bi2Bi measurements carried out using the IEEE 802.15.4 modules for path 1 (Figure 3.13 a) in a sub-urban area and paths 2 (Figure 3.13 b) and 3 (Figure 3.13 c) on the UPNA university campus. In Figure 3.13 (a), and Figure 3.13 (b), the first bike (transmitter) is 10m ahead of the second bike (receiver). In the case of Figure 3.13 (c), the bikes (transmitter and receiver) go in opposite directions around the UPNA Library building. For all the cases, a packet has been sent every 5 seconds. It is worth noting that this value of 5 seconds has been chosen in order to test the ZigBee-based dynamic wireless link between bicycles under difficult conditions (ZigBee technology was designed to deploy monitoring WSNs with low data rates).

Figure 3.14 summarizes the Packet Error Rate per path where the highest rate of packets lost is obtained on path 1 due to the obstacles and elevation profile of the suburban scenario. In the case of paths 2 and 3, the Packet Error Rate is similar.



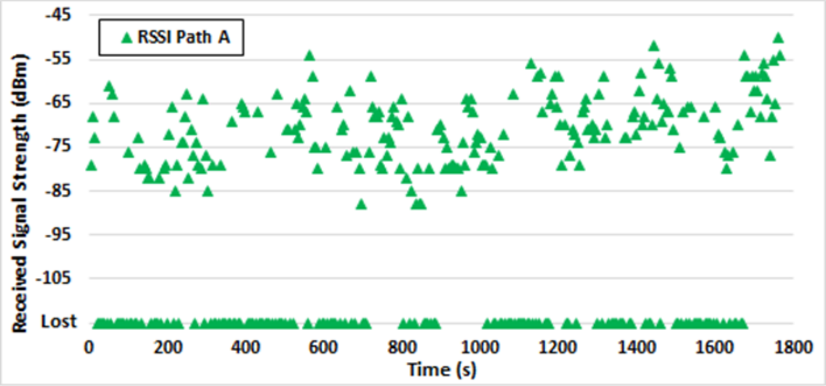
(a) (b) (c)

Figure 3.14: Packet Error rate per path.

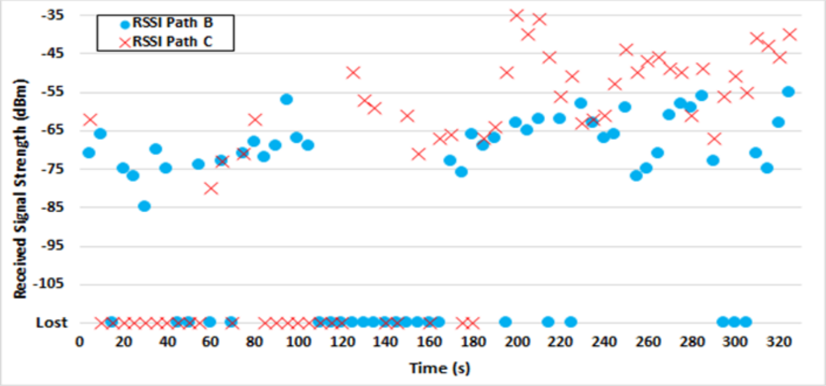
Figure 3.15 shows the RSSI for each received packet for three paths (Figure 3.15 -a-, and Figure 3.15 -b-) where the lost packets have been reflected with a level below the sensitivity of the devices that is -100 dBm. As can be seen in the results shown in Figure 3.14, 30 to 40% of packet losses is a significant value, but it is very important to note that the measurements correspond to a dynamic wireless link, where both bikes are moving along paths that go by a changing environment. Thus, the main reason for such losses is the changing environment itself. For example, the Library Building present in the campus scenario (Figure

3.13 -b-, -c-) is the responsible of most of the lost packets due to the shadowing effect that creates when the two bikes are in NLoS situation.

This effect can be clearly seen in the results shown in Figure 3.15 b, where the packets lost due to the building effect are indicated. In the same way, the graph also shows how very few packets are lost when there is no building between the bikes (NLoS situation). The same effect can be seen in the results from Figure 3.15 a, with zones with high losses and zones with no losses.



(a)



(b)

Figure 3.15: Received Signal Strength for (a) Path 1; (b) Path2 and 3.

In the presented work, the estimated received power levels using the 3D-RL algorithms are not compared to the ZigBee commercial nodes RSSI for multiple reasons. First of all, the RSSI is based on the radio signal power amount measurement. It is only an indication of the RF energy detected at the antenna port. The RSSI reported may include energy from background noise and interferences, resulting in high signal strength values. In some complex scenarios, it is possible to measure high RSSI values and still have communication errors. Thus, The RSSI is an approximation for signal strength received on an antenna and not for link reliability estimation. It only gives an indication of the received power. For this purpose, the received power levels are estimated in the proposed scenarios for a more accurate RF analysis. Moreover, the measured RSSI levels are often less accurate than the received power levels, with an estimated error between 1 dB and 10 dB, and more depending on the hardware used [186].

The use of LPWAN systems operating within ISM bands provides flexibility in terms of rapid deployment and adoption, but are also subject to inherent limitations such as interference. The 2.4 GHz spectrum can exhibit high levels of background interference, owing to multiple sources such as intra-system, inter-system or external interference sources. In this sense, considering the employed transmission bit rates and the expected density of bike users as compared with the total amount of potential users (e.g., static users connected to 2.4GHz WLAN or BT/BLE connections, or pre-existent wireless sensor networks for telemetry/telecontrol purposes within the urban infrastructure), in the pilot case described in this work, interference levels are within the usual interference background levels within the urban area of Pamplona (i.e., spectral density values in the 0-6GHz range in the order of -100 dBm/Hz to -95 dBm/Hz). This leads in general to normal operation in terms of packet error rate. However, a larger increase in device density, leading from dense to ultra-dense transceiver environments can lead to an increase in the background noise level and hence to degradation in system operation. In this sense, intensive coverage/capacity analysis is compulsory in order to adequately characterize traffic distribution as well as to map interference, in order to consider alternative options, such as LPWAN operating within other frequency bands, or the use of other systems such as IEEE 802.11 ah (sub 1 GHz WLAN focused on massive IoT deployments and currently under development) of 5g NR FR1 transceivers. This is a topic that is currently under analysis will be discussed in future works.

3.3.2 Intelligent SDN-Based multi-protocol selector for IoT-enabled NMT networks

This section introduces an intelligent SDN-Based multi-protocol selector for IoT-enabled Non-Motorized Transportation (NMT) networks. The principal purpose of this work is to give the mobile nodes within the IoT-enabled NMT networks the flexibility to choose the appropriate wireless communication protocol from among several protocols they have for transmitting information, according to a set of criteria; such as battery lifetime, data size, and priority of the packet in order for most important data to pass first.

NMT is a form of commuter that relies not on an engine or a motor for movement. NMT comprises bicycle and small-wheeled transport such as kick scooters and skateboards [187]. Integrating NMT into the IoT system provides a high benefit to cities, especially those seeking sustainable development and transforming into smart cities. IoT-enabled NMT could become one of the primary resources for dynamic information such as atmospheric (weather, humidity, or temperature) and air quality information during its movement in/within different parts of the city; besides, it has zero carbon emissions.

However, several challenges facing wireless communications are to be addressed to deliver this information to the destination effectively, including data rate, communication range, energy efficiency, diverse quality-of-service, and selecting the suitable wireless communication protocol. An essential key pillar of an application's success or failure is choosing the appropriate wireless communication protocol in a given situation. This would mostly be effective as unsuitable wireless technology can hamstring critical aspects of the performance of the application, and thus, it becomes unusable. Software-Defined Networking (SDN) emerged as an intelligent networking solution that uses dynamic software programs to make communication management easier and to improve network performance, especially in access networks [188]. The SDN separates the control logic from the sensor nodes, making it a suitable solution for the inflexible management of WSNs.

Several literature works have discussed how to deal with multiprotocol wireless communication in heterogeneous networks. An approach based on fuzzy logic is proposed in [189], where it takes QoS measurements of the trajectories between origin and destination as input parameters and determines the weights of all trajectories. Gao and Chang have introduced in [190] a scalable and flexible communication protocol that serves as a bridge between the Internet and numerous heterogeneous wireless networks. Kang et al. have proposed in [191] a self-configurable gateway that detects and configures smart things in real time over wireless networks. Bonaiuto et al. have presented in [192] a system for elite sports applications based on a wireless sensor network consisting of peripheral nodes (up to eight) that communicate with the user and collect data through a Wi-Fi connection, and a master node. Kim et al. have proposed in [193] an access gateway for the network environment of the Internet of Vehicles (IoV), where it manages the traffic of incoming data to the In-vehicle Network (IVN) and the traffic of outgoing data to the IoV. The gateways suffer difficulties since they are pre-configured, rely on vendor-specific APIs, and are restricted to just authorized devices and policies

3.3.2.1 System Architecture

The intelligent SDN-Based multi-protocol wireless communication selector aims to give the mobile nodes within the IoT-enabled NMT networks the flexibility to choose the appropriate wireless communication protocol from among several wireless protocol modules that they have for transmitting information, according to a set of criteria such as bandwidth, energy consumption, and reliability as mentioned before in Section 4.1.1, which are considerable on the process of selecting an appropriate wireless communication protocol. The mobile node (in our case is IoT-enabled NMT) is equipped with several wireless communication modules, in addition to various types of sensors as shown in Figure 3.16.

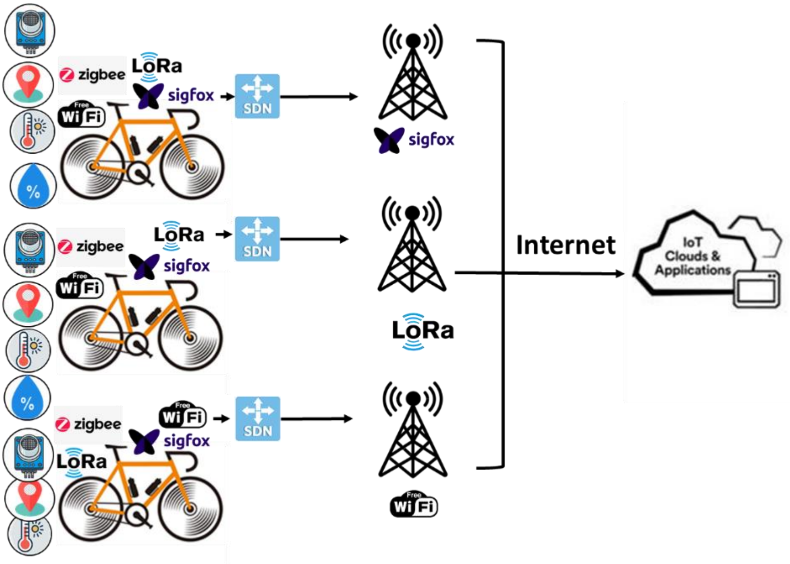


Figure 3.16: IoT-enabled NMT system description.

Each of them is responsible for collecting data and detecting the changes in the environment, and then responding to some output in the other system. The SDN-Based multi-protocol wireless communication selector organizes the process of sending this data based on a set of rules stored in a knowledge base, which will be used by a fuzzy logic control system. These rules, for example, include prioritizing some data over other data and selecting the appropriate wireless communication protocol that corresponds to the characteristics of that data. The main characteristics of each technology of wireless communication technologies used in IoT systems are described in Section 3.2.1. Figure 3.17 illustrates the presented system architecture.

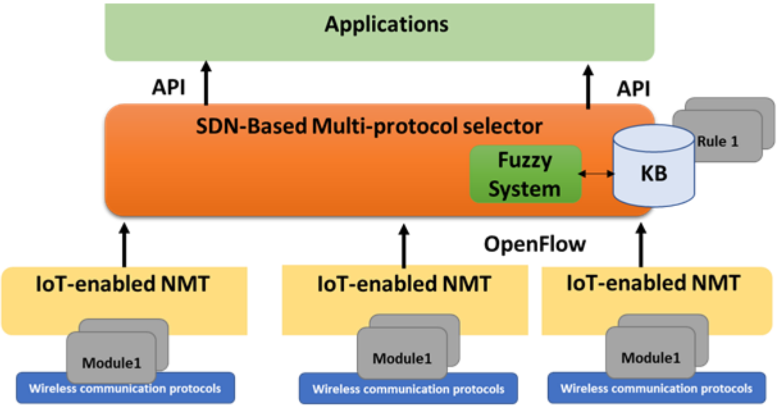


Figure 3.17: IoT-enabled NMT System architecture.

3.3.2.2 *System Implementation*

This section briefly introduces the fuzzy logic control system, semantic reasoner and demonstrates how we integrate a system like that into a mobile IoT node for better wireless communication protocol selection. This would lead to better network traffic management to meet QoS requirements for various services.

A. Fuzzy Logic Control System

The fuzzy logic is defined as sort of multivalued logic that is quite similar to human thinking than the traditional logical system. A fuzzy logic control system transforms linguistic control strategies into an expert knowledge-based automatic control technique [194]. Fuzzy logic control system consist of three stages: 1) fuzzification, 2) fuzzy inference, and 3) defuzzification. [189]. There are three functions in the fuzzification phase: a) measurement of the input variable values, b) The transformation of input data into linguistic values that can be used as fuzzy set labels, c) scale mapping of input values in the appropriate universe of discourse. A fuzzy logic controlling system's brain is the fuzzy inference logic phase. This stage models human decision-making based on fuzzy concepts. Fuzzy control is inferred using fuzzy implication and fuzzy logic's inference procedures. In the defuzzification step, a variety of output parameters are translated into a corresponding discourse, and a non-fuzzy control action is generated from a fuzzy control action inferred.

B. Semantic Reasoner

Semantic reasoners are software applications that can response questions or calculate deductions, reasonable consequences using ontologies-based logical knowledge bases [195]. An ontology is a formal description of the application domain's notions, relationships, and individuals [196]. Ontologies are widely used to represent knowledge, emphasis on the integration of information, the reuse of components, and the discovery of latent knowledge, among other things. They are expressed with the standard language; Web Ontology Language (OWL 2) [197]. OWL Lite, OWL DL, and OWL Full are three increasingly expressive sublanguages of the OWL [198]. OWL DL is a type of description logic that is extremely expressive with a RDF syntax. Description Logics (DLs) are a type of knowledge representation formalism that is based on classes (concepts)[199]. One of the reasoners that deal with extensions of classical DLs is fuzzyDL, an extension to classical DLs with the goal of dealing with fuzzy / vague / imprecise concepts [200]. The combination of fuzzy logic with DLs or ontologies makes it possible to represent imprecise knowledge and to perform approximate reasoning.

C. System functionality

The SDN-based multi-protocol selector is responsible for selecting the most appropriate wireless communication protocol for data transmission according to several rules. This considers the type of data, its size, its importance, and the characteristics of each protocol to ensure the fulfillment of specific QoS requirements. The characteristics of each communication protocol listed in Table 3.1, Table 3.2, and Table 3.3 are preloaded to the SDN-based multi-protocol selector, along with sensory data type, size, sensor reading time interval, and degree of importance. The SDN-based multi-protocol selector receives data for the input parameters and fuzzifies them based on the associated function of the corresponding input variables using the defined fuzzy logic control system.

For instance, information such as videos, audio, and thermal imaging has a massive size and needs a high bandwidth communication protocol for transmitting. Also, with non-motorized transportation, there is no need for real-time processing, as in autonomous vehicles and drones. Therefore, these data will be marked as not important data, and it will be queued until the mobile nod is near a public Wi-Fi hot-spot to transmit them. On the other hand, dynamic information such as atmospheric (weather, humidity, or temperature) and air quality information does not require a high bandwidth communication protocol for transmitting, but this information needs to be transmitted over fixed periods of time, which means a higher rate of energy consumption, due to the need to active (wake) the node. Therefore, the SDN-based multi-protocol selector should choose a communication protocol that has a low energy consumption and at the same time has a low bandwidth. In other cases, such as a fall detected, it requires the SDN-based multi-protocol selector to use all available resources and select the highly reliable communication protocol to transmit the alert message as shown in Figure 3.18.

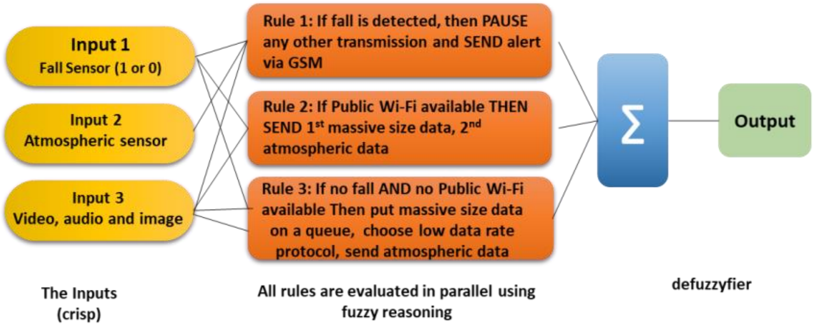


Figure 3.18: Fuzzy Inference Process.

Semantic technologies are used in this work to describe the context of the IoT-enabled NMT network as well as the mobile node with its characteristics and capacity. The reasoner uses the information available from the characterization of each radio interface and the occupancy levels of each of the QoS queues we have defined (urgent, streaming, irrelevant...). These (crisp) ontologies are stored in a fuzzy knowledge base (KB). fuzzyDL enables for the importation of OWL Lite queries to make it easy to represent fuzzy KBs. It also uses a fuzzy element to estimate the occupancy of the queues.

Chapter 4

4 Enabling Customizable Services for Multimodal Smart Mobility with City-Platforms

THIS Chapter discusses the development and evaluation of a prototype / testbed for SCP as a supportive infrastructure for the development of an SC. Several functionalities are addressed, including the acquisition of information from the environment through sensors, open data sources or other alternative sources that meet security and privacy requirements. Three different use cases are described, which have been implemented in the city of Pamplona, Spain, as vertical services linked to the platform: intelligent urban mobility-bike handling, bike-2-bike communication, and restricted vehicle access zone control system. The content of this chapter has been published in [143][144][145][146].

4.1 Introduction

Today, there is a requirement for a long-term method of developing sustainable cities by managing the life cycles of cities through improving economic performance over the entire life cycle. It provides opportunities by introducing healthy competition in terms of online services like waste management, education, healthcare, transportation systems, safety and many more [201][202]. The SC concept is based on the collection of data and information from large areas such as urban infrastructures (water, energy, telecommunication, transport), urban services (administrative, education, municipal waste, culture, health, sport, property), buildings use and consumption, and other data such as those related to the air quality, congestion, urban incidents, weather, security and economic activity. The challenge of managing the massive amounts of data generated by IoT-based sensors and systems, however, is a primary one that end users and vendors alike must address.

SCPs are unified frameworks for city operation and services that allow sensing, data fusion and integration, communication, customizable service providing, and intelligent decision-making, among others. The SCPs provide a set of different real-time data visualization and control panels that help manage the city effectively and make it easier for residents to access and understand the information available. This allows citizens to feel an integral part of the city and actively participate in its sustainability and energy efficiency, since citizens can see for themselves the impact of their behavior on the city as a whole.

Different issues must be addressed by SCPs in relation with:

- Scalable and standardized data model, working with heterogeneous data sources.
- Information management with different levels of security and protection.
- Capability of providing useful and innovative services and mechanisms for interaction with third parties.
- Analyze information, extract knowledge and optimize process flows.
- Promotion of energy sustainability (mobility and self-consumption),
- Technological independence of organizations,
- Use and support of smart contracts, ensuring transparency with citizens.

Currently, few municipalities have platforms or systems for real time monitoring and subsequent inference of urban process parameters. The commonly employed strategy is data collection, offline analysis, and action, followed by system adjustments and repetition of the whole process. Based on that, this chapter discuss the development and evaluation of our prototype for a SCP as a supportive infrastructure for the development of a SC, address the challenges that facing the development of SCP, and to demonstrate the benefits of open data and open platforms for SC adoption. In addition, we present an integrated solution for sensor systems and environmental sensing as a vertical service linked to the platform, which enables smart services using open data, in our case smart mobility.

4.2 City Platforms as Service Enablers

The challenge is given by the fact that the IoT systems collect increasingly significant amounts of data. Without a context, the data is meaningless and rarely effectively leveraged because of the difficulties in interpreting data models and efficient linking of data across distributed systems. Therefore, the platform deals with most of the available information that comes from the different sector applications and IoT systems in the city – in our example, the city of Pamplona, Spain [203].

SCP can be described as system that: 1) ingest heterogeneous data harvested from different sources (open data, IoT devices, citizen's information…), 2) a tool to provide city data (energy, transport, crowdsourced data…) sharing and integration, 3) an efficient tool to map, store and provide useful management dashboards, as illustrated in Figure 4.1.

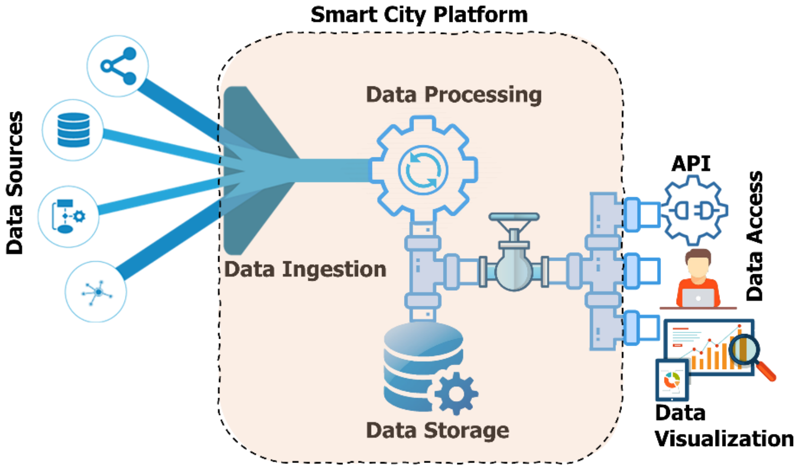


Figure 4.1: Schematic description of the smart city platform.

SCP requires several essentials to ensure its efficient operation. SCP needs to enable data coordination, provide customizable integral services, favor the creation of business activity, develop innovative applications and services, and enable urban planning and the evaluation of new policies (such as smart urban mobility, healthy habits, citizen awareness, among others). SCP must focus on citizens and be the catalyst that allows the flow of information and service to and for the citizen. Ultimately, SCP should emerge as an infrastructure that will conform the citizen-administration relationship, allowing not only the efficient conclusion of administrative procedures or the provision of services adapted to the needs of users. It will also offer an efficient and effective mechanism for auditing and granting transparency of administrations. The platforms should allow citizens to see how their behavior affects the welfare of the city, as a vehicle to raise awareness among them that municipal management begins with the citizens themselves.

4.2.1 Related work

Although many proposals have been made in the field of SCPs, we will now analyze some of the most relevant contributions in this field.

Zanella et al. introduced in [17] the need for these platforms to include a large number of diverse end systems, providing open access to different digital services. The provision of services and backing to third parties require to give proactive and relevant support to citizens with services capable of creating and managing digital identities [204]. The reuse of the functionalities of legacy systems and applications by adapting them to new architectures has been described in [205]. The analysis in the provision of multiple data sources related to smart city services consumers and the impact of data simplification is described in [206], whereas providing distributed frameworks for service discovery does in [207].

Common and interoperable data model definition, as well as interoperability are addressed in [208], where a modular approach to achieve interoperability is presented. Cross-platform interoperability for sensors is addressed in [209], whereas in the case of [25], the interaction is performed by means of adaptive semantic adapters. The standardization issue is addressed in [210], where the ISO 37120 standard for city services and quality of life is suggested as unified framework for smart city dashboards; and [211], where a summary of smart city standardization is presented.

The relevance of fog computing for sustainable smart cities is addressed in [212], which discusses the challenges an issues of fog-based IoT environments, highlights main applications of fog computing and discusses various caching techniques in the IoT era, even considering Unmanned Aerial Vehicles (UAVs) and AI/ML techniques and technologies.

Smart contracts are currently an interesting object of study, as they make possible interesting interrelations among smart cities, and between these and their citizens. Ekiden [213] leverages a novel architecture that separates consensus from execution, enabling efficient Trusted Execution Environments (backed confidentiality) preserving smart contracts and high scalability, while [214] analyzes the need of a distributed network formed among cities, allowing the integration of distributed electric energy into the power grid.

Security and personal data management, preserving policies and regulations related with personal data protection, are addressed in [215][216][217][218]. Privacy as well as security aspects have to be considered [215] granting an end-to-end secure solutions and environments where personal data, in transit or/and storage, remains under the full control of the users. The efforts to standardize security solutions for the IoT ecosystem initially introduced in [218] focused on communication security solutions for IoT, and their standardization, but it also applications, data custody and services. Protecting information is crucial and specific security mechanisms must be designed and implemented [217]. Blockchain techniques have also been considered to build secure and reliable data sharing platform among multiple data providers, where IoT data is encrypted and then recorded on a distributed ledger [218].

Regarding the comparison with other smart cities in terms of the technologies used in the different layers by the different cities, and the major components in other SCPs; the challenge in this regard is the majority of these projects are not open/open-source, so the information available about the components and technologies used is limited and in most cases is not accessible. Furthermore, factors such as climate, terrain, infrastructure, in addition to cities worldwide have vastly differing backgrounds, priorities, capabilities, culture, strengths, and objectives, make the comparison process difficult because each model was built based on these factors, which differ from one city to another. In this case, the

Table 4.1 below describes the characteristics and features of most smart cities projects based on the available information.

TABLE 4.1: COMPARISON BETWEEN DIFFERENT SMART CITIES PLATFORMS.

City	Characteristics	Features
Santander [219]	• A testbed project. • Thinking City Platform [220], implemented by Telefonica Company (private sector). • Limited access to information.	• Parks and gardens irrigation. • Outdoor parking management and driver guidance.
Dubai [221]	• Developed and implemented by Du Telecom Company (private sector). • No information available in relation to the technologies used.	• Use Blockchain technology to forego paper transactions altogether and execute the entirety of its transactions. • Mobility as a Service: Seniar App • Reduce congestion.
Valencia [46]	• Focused on measuring a city's intelligence and sustainability based on U4SSC KPIs that are developed based on Recommendation ITU-T Y.4903/L.1603 [222]. • Limited access to information in relation to the technologies used.	• Public Wi-Fi networks-WiFi4EU. • Urban noise management. • Service management dashboard.
Trento [223]	• One of the Lighthouse cities in the Stardust project. • Same KPIs of Pamplona - the KPIs of the STARDUST project.	• Emission reduction of CO2 and NOx. • Quality of open data.
El Hierro [224]	• Smart Island. • Sensitization, data transport and intelligent information management. • Limited access to information in relation to the technologies used.	• The main smart control elements installed on the island of El Hierro are: Weather Stations, Open Data portal, and Geovisor web client.
Cambridge (UK) [225]	• Better quantity, quality and use of data. • Embedding digital solutions and emerging technology • Limited access to information in relation to the technologies used.	• Intelligent City Platform (iCP). • Reduce congestion and use more sustainable transport – MotionMap Mobile App.
Cambridge (US) [226]	• Sense human activity on roadways. • Limited access to information in relation to the technologies used.	• Improve traffic safety and make streets safer.

4.2.2 City Platform Architecture Design

The definition of the architecture of a SCP must be as generic as possible, achieving the maximum possible interoperability, scalability, efficiency, and simplicity. Figure 4.2 depicts the different layers and components that a SCP must include. The lower level is referred to data acquisition. The next higher level refers to the flow of the data acquired at the lower level (data adaptation, information standardization, information source and destination flows…). The third level refers to the storage, analysis and processing of this data; and finally, the upper level refers to the provision of services to third parties, system monitoring, the presentation of control panels, etc.

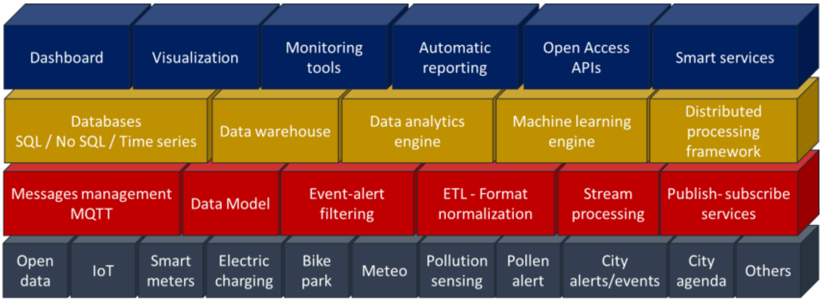


Figure 4.2: Schematic description of the city platform layer architecture.

The proposed prototype of the city platform is structured in five main layers, namely, perception layer, communication layer, data acquisition layer, data management layer and application services and visualization layer, as shown in Figure 4.3.

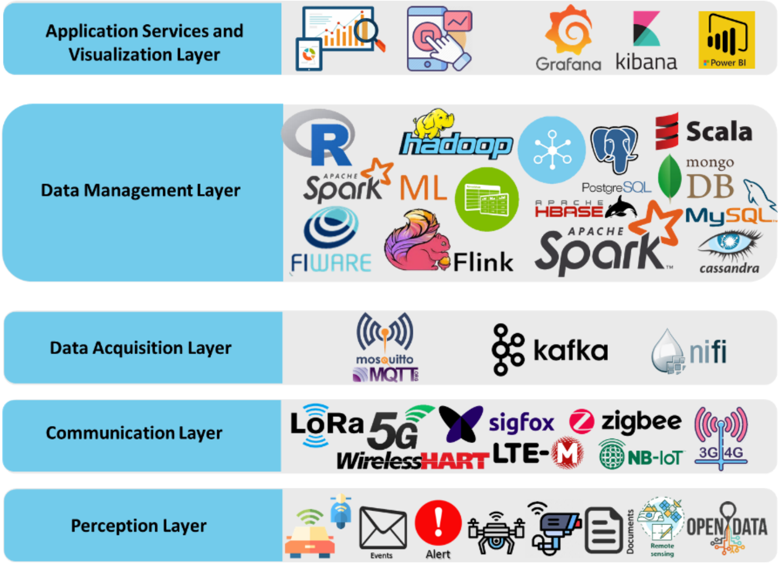


Figure 4.3: The Platform architecture.

The perception layer consists of physical objects, which are monitored by sensor and actuator devices, having as main objective the collection of sensor data and command actuation. The Data Acquisition layer is composed of several communication technologies such as LoRaWAN [227], Sigfox [75], broadband cellular network technology, etc. To transmit sensory data and commands between the upper layers and the perception layer. Chapter 3 presents a comparative analysis for different wireless technologies.

The Data Acquisition layer includes protocols and software components for data acquisition (e.g., MQTT [228], Kafka [131], and NiFi [229]) are the key characteristic of this layer, in addition to security and device management functions. The FIWARE IoT Agent GE also belongs to this layer as it translates the internal FIWARE data representation in JSON from/to devices. The Data Management layer includes software components responsible for data streaming, data storage, processing and distribution based on one of FIWARE GEs (Orion). The Application Services and Visualization Layer is responsible for information presentation, exchange, and use.

This architecture offers adequate scalability, since it allows the municipal managers to define the platform's service catalog (either incorporation or cancelation of services) as required. In this sense, scalability is achieved in three dimensions. The first is the possibility of defining and offering new services and functionalities, or the possibility of cancelling them, as the situation requires. The second dimension is the use of mechanisms for publishing services and access to the platform through a REST API and JSON files, which allow adequate accessibility to the platform while maintaining adequate distributed performance. Finally, the implementation of the platform in a virtualized system, which allows to adapt the operative instances of each component to the needs of each moment.

4.2.3 City Platform Implementation

In this section, we highlight the techniques, tools, and services used to design and implement the city platform in order to evaluate the performance of data flow components; sources, transformations, and destinations between the different layers of the SCP. In this sense, we present several use cases for intelligent mobility as vertical services linked to the SCP.

The development of a real city platform poses many challenges when integrating some legacy information systems and their associated services, into the service catalog. Many of the services provided use information delivered in non-standardized formats, require specific communication protocols, or even use third-party proprietary formats. This implies the need to have a layered architecture that allows the introduction of adapters and parsers that guarantee the necessary standardization and easy maintenance of the platform as shown in Fig. Figure 4.4. The viability of the platform is therefore directly conditioned by its scalability, ease of maintenance, standardization, the semantic efficiency of its data model and its accessibility.

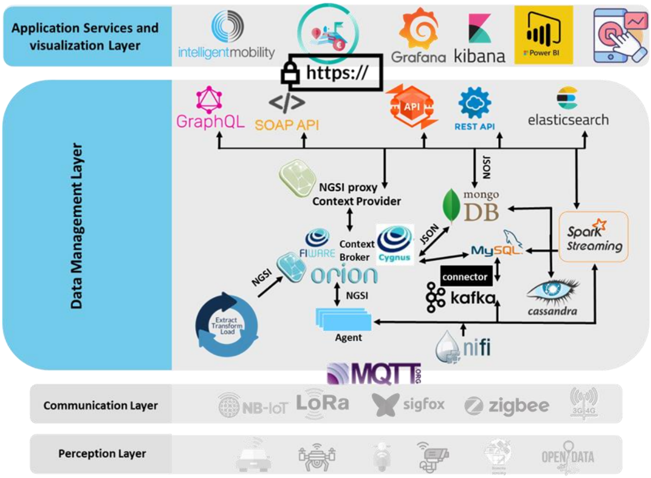


Figure 4.4: The Platform implementation.

To ensure the proper operation of this architecture, it is compulsory to have a suitable data model that guarantees the semantic integrity of the system and allows the transformation of data into information, and later into knowledge. It is far from frequent that SCPs share the same data model. Therefore, obtaining the data model is a complex task in administrations, which have multiple systems and information sources that have been implemented at different times and for different purposes, but which coexist in an unstable balance. In fact, the lack of standardization at this level is one of the main causes of the difficulties observed when exchanging information between siloed IoT applications, cities, institutions or even companies or organizations providing services. The data standardization and context information management provide the ability to integrate existing services, different technologies, and protocols, introduce new third-party services or applications, and extend applications' interoperability.

The European Union (EU) is making a major effort to make FIWARE [230] the tool to support global interoperability. FIWARE is a vast ecosystem providing standardized APIs used in open-source implementations of Generic Enablers (GEs) based on open specifications.

FIWARE has now turned into a foundation focused on the high-level data interoperation of IoT and other systems using a Context Information model extended from the Open Mobile Alliance Next-Generation Service Interface (NGSI) 9/10 standard [231][232][233]. Probably one of FIWARE's most useful contributions is its data modeling given by the Context Information Management API NGSI-LD (LD stands for linked data), which supports linked data, property graphs, and semantics (JSON-LD). Data Models play a crucial role because they define the harmonized representation formats and semantics that will be used by applications both to consume and to publish data. Figure 4.5 shows the three main concepts of NGSI data model.

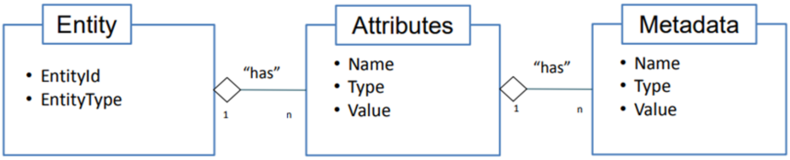


Figure 4.5: NGSI data model.

The NGSI-LD is designed to allow cross-domain sharing while preserving the need to enable restrictions based on General Data Protection Regulation (GDPR), privacy, security, or licensing concerns. The NGSI-LD defines a simple way to send or request data using a serialization format (JSON-LD), which is already well known to many software developers, enabling its rapid adoption.

FIWARE provides a set of data models and makes them available to software developers to be used wherever they want, but with compliance to FIWARE NGSI version 2 and NGSI-LD to enable data portability for different applications including, Smart Cities, Smart Agrifood, Smart Environment, Smart Sensoring, Smart Energy, Smart Water and other domains. Each one of these domains consists of several "Topics" including Alert, Streetlighting, Transportation, Urban Mobility, and many more as shown in Figure 4.6.

It compiles the subjects of:

- dataModel.Building
- dataModel.Parking
- dataModel.ParksAndGardens
- dataModel.PointOfInterest
- dataModel.Ports
- dataModel.Streetlighting
- dataModel.Transportation
- dataModel.UrbanMobility
- dataModel.WasteManagemer
- dataModel.Weather

List of data models

The following entity types are available:

- ArrivalEstimation. Arrival Estimation
- GtfsAccessPoint. GTFS Access Point
- GtfsAgency. GTFS Agency
- GtfsCalendarDateRule. GTFS Calendar
- GtfsCalendarRule. Smart Data Models.
- GtfsFrequency. GTFS Frequency

```
{
    "id": "urn:ngsi-ld:ArrivalEstimation
    "type": "ArrivalEstimation",
    "hasStop": {
        "type": "Relationship",
        "object": "urn:ngsi-ld:GtfsStop:
    },
    "hasTrip": {
        "type": "Relationship",
        "object": "urn:ngsi-ld:GtfsTrip:
    },
    "headSign": {
        "type": "Property",
        "value": "Plaza Italia"
    },
```

Figure 4.6: Part of FIWARE data models for several domains (Source: Author and [234]).

As can be seen from Figure 4.6, "Smart Cities" data models include several data models related to SC domains, including data models for buildings, parking, parks and gardens, point of interest, transportation, urban mobility, weather and waste management. These models have been devised to be as generic as possible, thus allowing to deal with different scenarios. For instance, transportation harmonized data models describe the main entities involved with smart applications that deal with transportation issues. This set of entities is primarily associated with the vehicles and SC vertical segments and related IoT applications. "EVChargingStation" one of these entities that represents a public charging station supplying energy to electrical vehicles.

Figure 4.7 shows a snapshot of NGSI-LD representation of this entity.

```
{
    "id": "urn:ngsi-ld:EVChargingStation:ValladolI+D_Covaresa",
    "type": "EVChargingStation",
    "socketType": {
        "type": "Property",
        "value": ["Wall_Euro"]
    },
    "capacity": {
        "type": "Property",
        "value": 2
    },
    "name": {
        "type": "Property",
        "value": "Agencia de Innovaci\u00f3n"
    },
    "allowedVehicleType": {
        "type": "Property",
        "value": ["car"]
    },
    "source": {
        "type": "Property",
        "value": "https://openchargemap.org/"
    },
    "location": {
        "type": "GeoProperty",
        "value": {
            "type": "Point",
            "coordinates": [-4.747901, 41.618265]
        }
    },
```

Figure 4.7: NGSI-LD representation of “EVChargingStation” entity (Source:[235]).

As Figure 4.4 shows, services like NiFi are used to automate the data flow among different information systems and components. While stream-processing tools such as Apache Kafka and Spark stream allow to handle and transform real-time data feeds, minimizing latency and maximizing data throughput. In addition, the platform has an adequate mechanism for data ingestion, transformation, and storage. Data ingestion can occur synchronously or asynchronously, from very heterogeneous sources and in large volumes. For this reason, it is mandatory to standardize the data model as much as possible and to transform data before its storage. The NiFi process provides the means to take a given stream of data in JSON format and transform it to the FIWARE model. The normalized and standardized data are then transmitted to the FIWARE Orion context broker to perform the data storage with the support of the Cygnus component (see Figure 4.8).

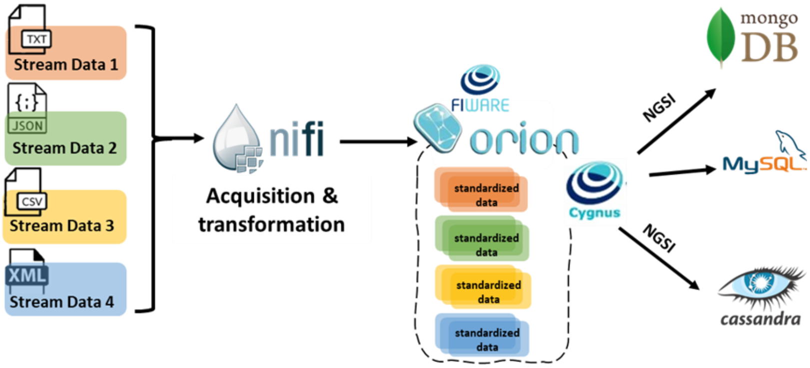


Figure 4.8: Streaming data transformation.

Data storage follows the NGSI data model and can be performed either into relational or non-relational databases. If requires, distributed file systems as HDPS can also be used.

Furthermore, context information management provides the exchange of cross-cutting context information, to be used in SC use cases, particularly scalability and extensibility. The NGSI version 2 is an open, RESTful API that allows providers to export data, using JSON representations, of different nature and origin uniformly. Therefore, the platform provides a set of APIs to software developers and third-party applications to interact with data, thus, to accelerate the development of smart solutions.

Finally, cloud-based solutions such as those provided by Google, Azure or Amazon, make the platform easily scalable to meet changing demand for IT resources. They cover two main types of scalability: horizontal and vertical scaling, which provides highly customizable infrastructure according to necessity. Thus, leading cloud service providers or an on-premises infrastructure offer auto-scaling service, which monitors the performance of applications and automatically adjusts the capacity to maintain steady and predictable performance. Furthermore, CloudHealth technologies provide the ability to manage many elements of scalability across one cloud or multiple clouds.

4.3 Uses Cases

This section presents a set of vertical services linked to the platform. Each one of the smart cities projects define its own key performance indicators (KPIs) in the context of smart sustainable cities (SSCs). The International Telecommunication Union (ITU)[236], provides the KPIs (Recommendation ITU- Y.4900/L.1600, T Y.4901/L.1601, and Y.4902/L.1602) related to ICT adoption and use in the context of SSCs. In our case, the KPIs of the STARDUST project focus on Carbon dioxide (CO_2) emission reduction in the domain of building and district, energy and E-mobility, Nitrogen oxides (NOx) emission reduction in the domain of E-mobility, improve the interoperability between systems, and quality of open data in the domain of ICT.

In this phase of the Stardust project, we can validate and evaluate the success by comparing the results of previous data with current data. Since the comparison of the results with other cities within the same project (Stardust) takes place in 2023, two years after the end of the evaluation phase, which was in 2021.

4.3.1 Customizable Multi-modal Urban Mobility

We conceive multimodal smart mobility as a customized and on-demand service provided to users to solve their mobility needs effectively and efficiently. For example, it will be more helpful to the residents with respiratory diseases if they know which parts of the city have the highest air pollution to avoid these areas during their mobility. In addition to meeting the individual criteria of each user, the mobility service will seek to promote sustainable mobility and minimize the impact of the carbon footprint. For example, information related to

Electric Vehicles (EV) charging stations such as location, charging speed, connector type, and availability contribute to saving time, avoiding traffic congestion and reducing pollution.

In this section, we present one of the applications linked to our urban data platform for the SC. We introduce a customizable multimodal urban mobility, which is one of the many benefits of open data and urban data platform for smart city development. It is an integrated solution for several sensing systems, open data generated by city domains (government, health, environment, transportation, etc.), which enables experimentation with applications and services in order to enhance their operation, being one of them smart urban mobility, as illustrated in Figure 4.9.

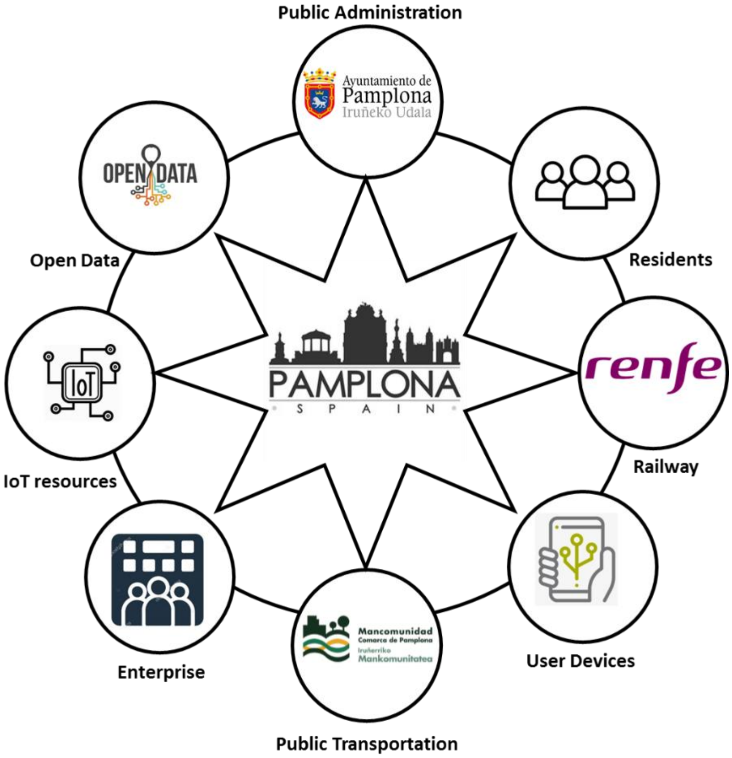


Figure 4.9: Interoperability between several service domains in a smart city of Pamplona.

The idea is to use the data produced from IoT systems as well as from other sectors to create urban mobility solutions that are more comfortable, efficient, and take into account environmental and societal constraints.

This information contains, for example, the schedule for bus and trains, the availability of public parking among the town, the warnings that come from the municipal government, and the traffic jam information that comes from provincial traffic offices, among others.

Data garbage and import from logical sources is performed automatically by a set of specific bots that update the information automatically with the programmed frequency to the platform. As the municipal services schedule any cultural, institutional, sport, social, educational, environmental or safety (pollution, traffic…) activity or event, the information is automatically uploaded to the platform so that it can be available for the mobility services to offer an adequate service.

After subsequent data processing and handling, interoperable context information is generated according to relevant contexts for smart applications in proper formal definitions. Finally, the extracted knowledge is used to build the decision-making process and, at the same time, to provide information to the end-user, as shown in Figure 4.10. Figure 4.11, shows the data flow of the information.

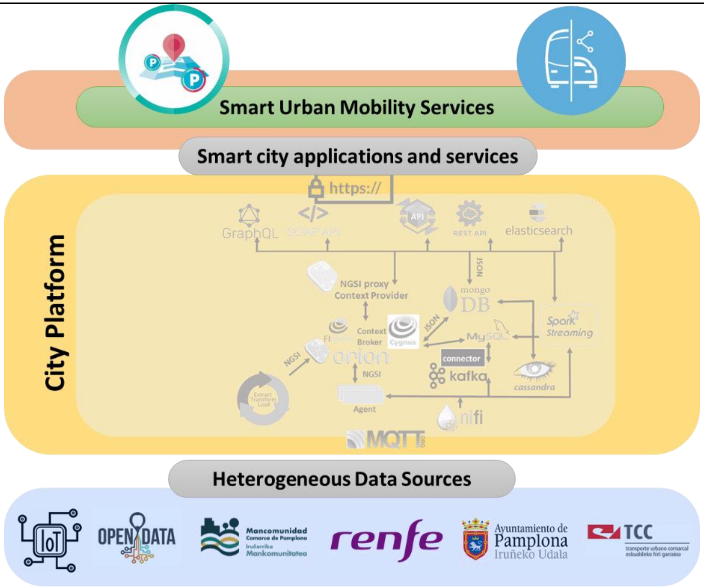


Figure 4.10: Multimodal smart mobility system architecture.

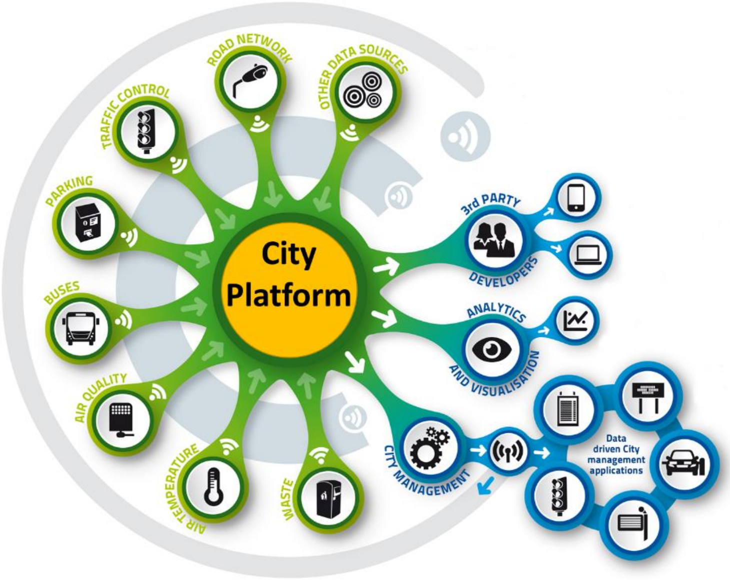


Figure 4.11: Dataflow pipeline of information (Source: Author and [237]).

4.3.1.1 *Related work*

Efficient and effective urban mobility and public transportation can significantly contribute to achieving economic, ecological, and sustainable objectives. Current efforts focus on considering mobility as a service [238][239][240], since smart mobility allows energy saving policies, relevant reductions of polluting emissions and a better quality of life for citizens. Table 4.2 summarizes some relevant contributions on the field of customizable travel support and multi-modal routing planner.

TABLE 4.2: RELATED WORK CONCERNING URBAN MOBILITY, PUBLIC TRANSPORTATION, AND CUSTOMIZABLE MULTI-MODAL ROUTING PLANNER.

Ref.	Contribution	Comments
[241]	• Enhancement of travel planners and micro navigators with the aid traveler context. • Provides a high-level analysis of how and in which situations context information can be useful. • Addresses different types of context information and possible risks.	• Appropriate only for the Swedish context. • The system may not be applicable in other countries if the Swedish PTS (public transport systems) and travel support are not like them. • The study focuses only on context-aware travel support during unplanned public transport disturbances, whilst other kind of situations have not been considered.
[242]	• An IoT enabled navigation system for urban bus riders. • Interconnects the commuters with the real-world of public bus infrastructure. • It has the capability to recognize and predict crowds inside the bus.	• Focuses on micro-navigation and crowd-aware route recommendation. • User Preferences are not taken nor external factors.
[243]	• Identified significant types of contexts such as, location, identity, time, and activity.	• Provide useful knowledge regarding context-awareness.
[244] [213]	• A mobile recommender system for personalized multi-modal routes	Did not take into account contextual information such as

Ref.	Contribution	Comments
[214]	based on collaborative filtering and knowledge-based recommendations. • Developed for route recommendation, primarily targeted for private cabs and taxis.	weather. This is an important part of a RS route, as a user may want to avoid walking or cycling in bad weather and prefer a less popular route instead if it provides protection from rain, wind or snow.
[245]	• A based personalized end-to-end mobile App for bus route recommender system, based on commuters' individual comfort preferences.	• Did not take into account, contextual information and environmental factors.
[246]	• Provides multimodal trip information obtained from variant journey planners. • Realizing a comprehensive information service.	• Suitable for International trip. • User context-awareness are not taken, even external factors.
[247]	• An Algorithm for itinerary prediction based on personal preference and real-time network congestion conditions. Prediction based on personal preference.	• Did not take contextual information such as the weather and location into account.
[248]	• An information gathering system for sharing the information related to the bus location relies on a collaborative mechanism with a Bluetooth board and smartphones.	• The system requires installing an App on the user's phone, which may not be suitable for some users. • No Context-awareness factors are taken or external factors.
[249]	• A framework for the navigation system to recognize the context of commuters in public transportation.	• User Preferences are not taken as well as external factors. • It requires the stability of the Internet connection.
[250]	• An Android App to evaluate the commuter's satisfaction and identify the necessity for personalized route recommendations in public transit based on commuters' feedback.	• The recommendation is only based on convenience without taking into account user context-awareness and environmental factors.
[251]	• A big data analysis of different datasets related to public transit	• User preferences, user context-awareness, and external factors

Ref.	**Contribution**	**Comments**
	network to identify user's perception-related problems.	are not considered.
[252]	• Mathematical model for preference aware transport matching.	• User context-awareness are not taken nor external factors.
This work	• Comprehensive multimodal trip information, taking user preferences, user context-awareness, and other external factors into consideration.	• It deals with various sources of real-time data, making the recommended route more comprehensive, dynamic and able to change depending on the surrounding conditions.

4.3.1.2 Data Model

This subsection presents the data model of the intelligent urban mobility service. Figure 4.12 illustrates the implemented semantic model (ontology). The idea is to make use of the huge amount of data, obtained from the different sectors within the smart city system, to provide a new urban mobility service to the user. The challenge lies on the fact that this amount of data comes with different data types and formats, so there is a need to build a knowledge base as a semantic representation to convert and formalize it from unintelligible format to a textual and meaningful format. This can be achieved by building semantic reasoning and representation that facilitates the perception of multiple data sources as meaningful. Therefore, building an ontology is to enhance the system performance by describing the different formats and data types more knowledgeably and better representing the data context.

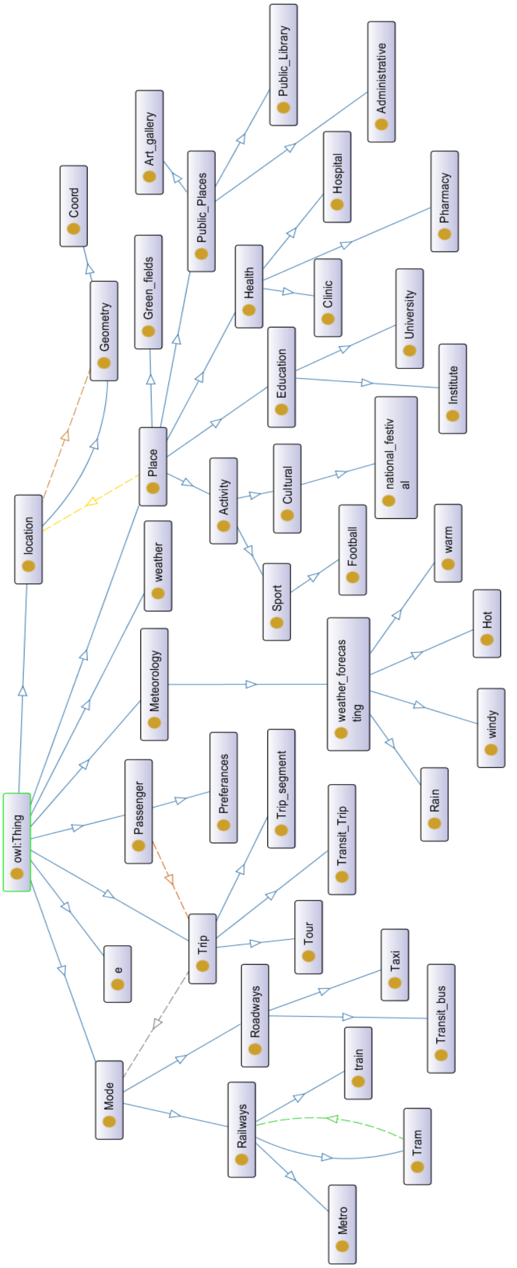


Figure 4.12: Semantic model of the multimodal smart mobility.

To provide customizable multimodal service to citizens, the platform offers a REST API to allow third-party applications, which will be described later. Figure 4.13 describes the behavior and data flow of the smart mobility service. The query engine manages the interaction between data and knowledge and provides, with the aid of the REST API, the information required to the third-party apps.

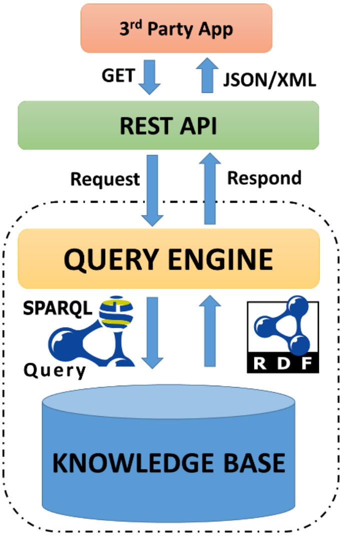


Figure 4.13: Multimodal smart mobility service schema.

The REST API allows third-party Apps to interact with the smart mobility service. The engine receives the requests (JSON format), builds the appropriate SPARQL queries and executes them against the knowledge base obtaining a set of RDF triplets, which describe the conceptual model. The engine takes into account both the customized parameters included into the request and the triplets recovered, and provides a JSON file with the results, which is submitted to the App. Finally, the third-party App receives the response in JSON format (also available in XML format if required) and then displays the information.

4.3.1.3 Data Source

To offer such a customize mobility, the system has to deal with a heterogeneous data source as shown in Figure 4.14.

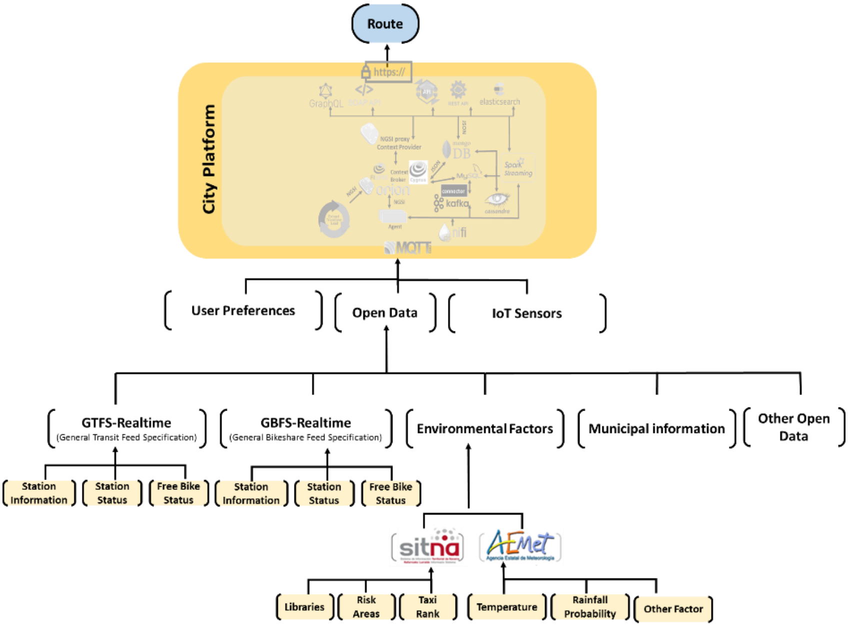
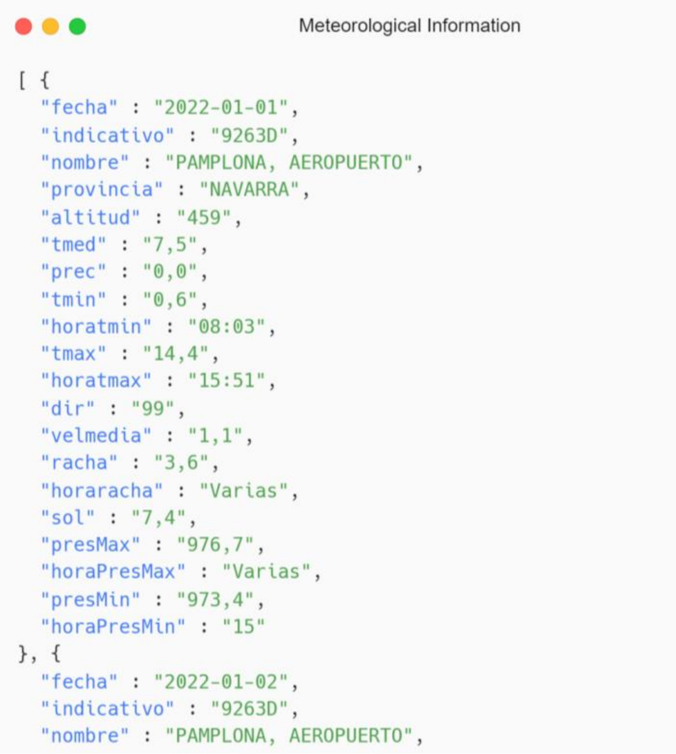


Figure 4.14: Data sources of multimodal smart mobility system.

We acquired the environmental factors from three major sources. The first one is AEMET (Agencia Estatal de Meteorología, Spain's meteorological agency) [253]. It provides open data about meteorological and climatological information. This information includes weather forecasting, warnings, announcements, and public attention. Figure 4.15 illustrates a snapshot of the JSON file that we imported from the AEMET's web service to acquire meteorological information.



```
[ {
  "fecha" : "2022-01-01",
  "indicativo" : "9263D",
  "nombre" : "PAMPLONA, AEROPUERTO",
  "provincia" : "NAVARRA",
  "altitud" : "459",
  "tmed" : "7,5",
  "prec" : "0,0",
  "tmin" : "0,6",
  "horatmin" : "08:03",
  "tmax" : "14,4",
  "horatmax" : "15:51",
  "dir" : "99",
  "velmedia" : "1,1",
  "racha" : "3,6",
  "horaracha" : "Varias",
  "sol" : "7,4",
  "presMax" : "976,7",
  "horaPresMax" : "Varias",
  "presMin" : "973,4",
  "horaPresMin" : "15"
}, {
  "fecha" : "2022-01-02",
  "indicativo" : "9263D",
  "nombre" : "PAMPLONA, AEROPUERTO",
```

Figure 4.15: A snapshot of meteorological information in JSON format.

The second source of the environmental factors is SITNA (Sistema de Información Territorial de Navarra) [254]. SITNA provides information including various topics: orthophotos, cartography, facilities, hydrography, culture, environment, infrastructures, and so on. Figure 4.16 shows a snapshot of two GeoJSON files from SITNA that have information regarding taxi stands and municipal parks which including (ID, type, coordination, etc.). We used this information to provide a set of mobility options depending on the user preferences.

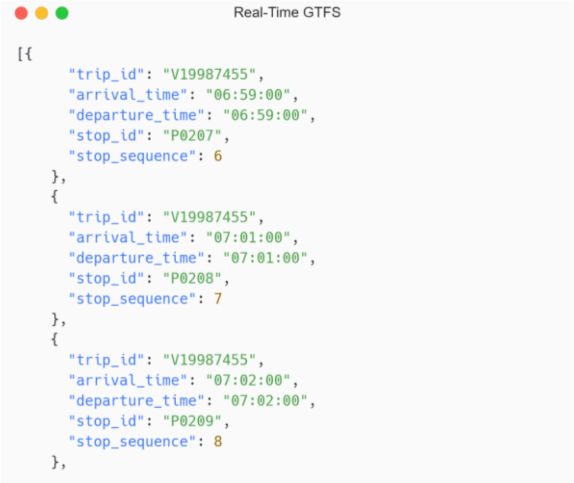
```
▾ object {4}
    type : FeatureCollection
    totalFeatures : 40
  ▾ features [40]
    ▾ 0 {5}
        type : Feature
        id   : TRAURB_Sym_TUCTaxis.1
      ▾ geometry {2}
          type : Point
        ▾ coordinates [2]
            0 : 613463.076398
            1 : 4740560.97749678
        geometry_name : the_geom
      ▾ properties {5}
          FEATURE : 10200059
          CPARADA : 940
          PARADA : Mendillorri - c/ Palacio (c/ Concejo de Olaz)
          LONGITUD : 18
          BEGINLIFE : 05/09/2017
    ▸ 1 {5}
    ▸ 2 {5}
    ▸ 3 {5}
    ▸ 4 {5}
    ▸ 5 {5}
```

```
▾ object {4}
    type : FeatureCollection
    totalFeatures : 117
  ▾ features [117]
    ▾ 0 {5}
        type : Feature
        id   : PAMPLO_Pol_JuegosInf.1
      ▾ geometry {2}
          type : MultiPolygon
        ▾ coordinates [1]
          ▾ 0 [1]
            ▾ 0 [5]
              ▾ 0 [2]
                  0 : 608822.177
                  1 : 4742323.242
              ▸ 1 [2]
              ▸ 2 [2]
              ▸ 3 [2]
              ▸ 4 [2]
        geometry_name : the_geom
      ▾ properties {11}
          FEATURE : 60100006
          CJUEGOINF : 60
          JUEGOINF : Paseo de Santa lucía
          BARRIO : Buztintxuri
          FECHAJUEGO : 2005
```

Figure 4.16: A snapshot of territorial information in GeoJSON format.

The third source of the environmental factors is the information provided by the Government of Navarre concerning air quality control [255] and meteorology [256].

We also obtained the General Transit Feed Specification (GTFS) information from the Regional Urban Transport - Transporte Urbano Comarcal (TCC) [257]. Figure 4.17 shows a snapshot of the real time GTFS in JSON format.



```
[{
      "trip_id": "V19987455",
      "arrival_time": "06:59:00",
      "departure_time": "06:59:00",
      "stop_id": "P0207",
      "stop_sequence": 6
    },
    {
      "trip_id": "V19987455",
      "arrival_time": "07:01:00",
      "departure_time": "07:01:00",
      "stop_id": "P0208",
      "stop_sequence": 7
    },
    {
      "trip_id": "V19987455",
      "arrival_time": "07:02:00",
      "departure_time": "07:02:00",
      "stop_id": "P0209",
      "stop_sequence": 8
    },
```

Figure 4.17: A snapshot of real-time GTFS

With respect to crowd counting, we used a Wi-Fi RSSI (Received Signal Strength Indicator) - based crowd counting system implemented in-house to estimate the number of people in a crowd at a certain area. So, depending on estimates, the system avoids the routes of these overcrowded locations, which contributes to reducing traffic congestion and shortening the trip time. The working principle of Wi-Fi RSSI- based crowd counting system is based on reading the strength of the Wi-Fi signal from the user's mobile. In this way, the system does not need any kind of registration or pairing to work, ensuring that the privacy of the user is not violated. Figure 4.18 illustrates the heat map of the number of Wi-Fi access points and Figure 4.19 illustrates the heat map of the RSSI values received during a journey in the city of Pamplona.

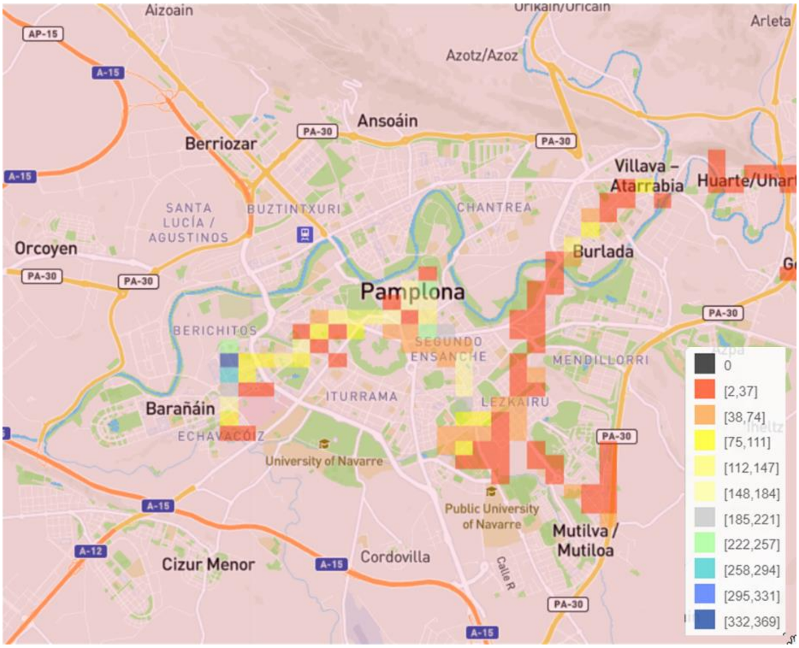


Figure 4.18: Heat map of number of Wi-Fi access points found within 300m^2.

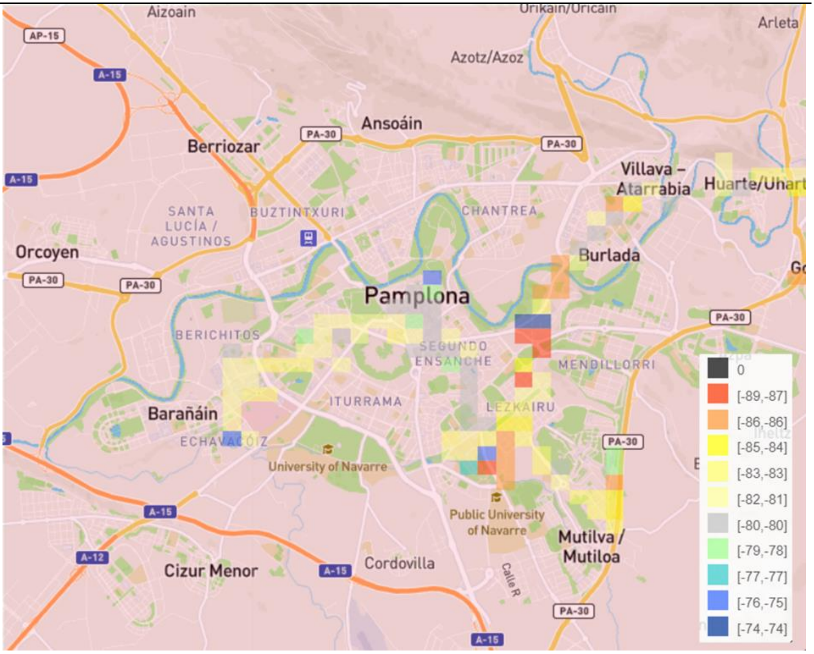


Figure 4.19: Heat map of RSSI values crowdsensing estimations within 300m^2.

4.3.1.4 Data Visualization

Figure 4.20 shows several recommended routes based user requests, in our case from the Public University of Navarre (UPNA) to the University of Navarra (UNAV). The route in red color represents the bicycle route, whereas the one in blue color is for the urban bus route. The mobility proposal can include intermodality if desired. In this case, the system considers the possibility of booking a guarded parking slot or that the folded bicycle can be transported in the bus.

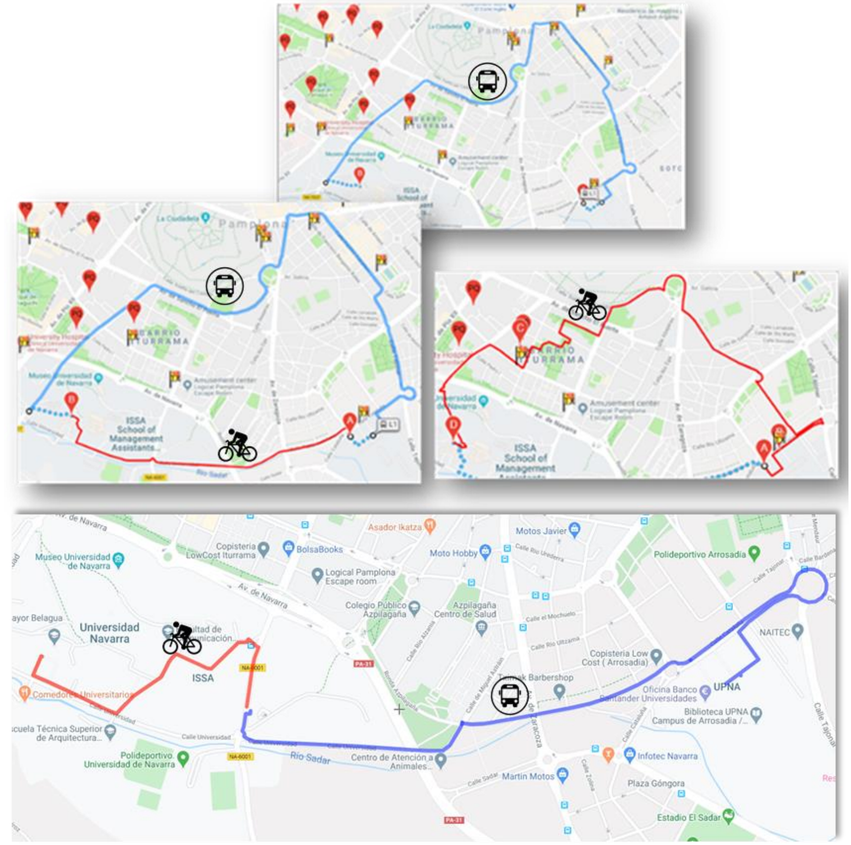


Figure 4.20: Data visualization of several recommended routes from UPNA to UNAV.

4.3.2 Bi2Bi Communication

Cycling is the most sustainable means of urban travel, practical for most short and medium-distance trips - commute to and from work and school, shopping, visiting friends – and for leisure and exercise. Cycling has emerged as one of the most important alternative modes of transport because of its flexibility, low costs, reduced personal carbon and collective footprint, improved traffic flow, and mobility in cities, as well as potential contributions to the development of more sustainable cities.

The IoT-Enabled bike, equipped with sensors and processing devices, would enable dynamic transmission and reception of crucial information to support new mobility optimization services, improve existing service quality, and provide additional services such as environmental monitoring, safety emergency services, and point of interest.

In this section, we analyze Bi2Bi communication and cooperation towards sustainable smart mobility, providing a tool based on the city platform to monitor and understand the impact of mobility at both city and citizen level and to provide accurate information on carbon footprint reduction.

In Chapter 3, we analyzed and experimentally evaluate the performance of Bi2Bi wireless communication in various urban scenarios.

4.3.2.1 System Architecture

A. Hardware Architecture

The hardware architecture is divided in two layers: perception layer and communication layer as shown in Figure 4.21.

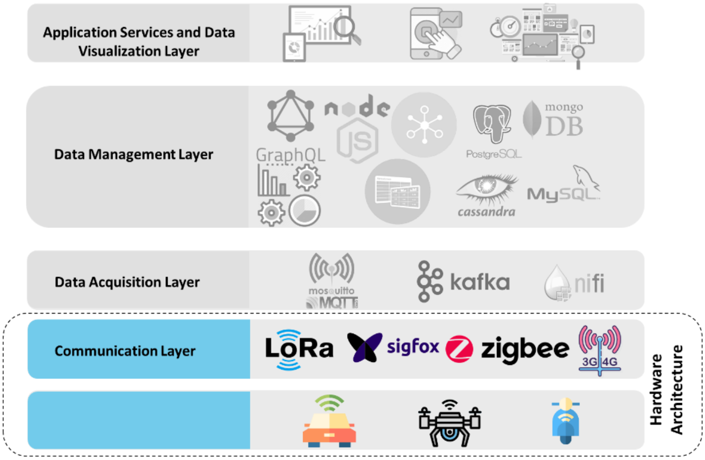


Figure 4.21: Hardware Architecture.

- **Perception Layer**

The perception layer is the physical layer that is generally in a smart environment scenario, to cope with the sensing and gathering of information about the environment. The gathered information can be location, temperature, humidity, air quality, etc. This gathered information transmits through the communication layer toward the upper layer.

- **Communication Layer**

The Communication layer handles the connectivity, message routing among remote devices, and routing between devices and the upper layers, further details have been presented in chapter 3.

B. Software Architecture

The software architecture is divided into three layers: sensor data acquisition layer, management, and visualization, as shown in Figure 4.22.

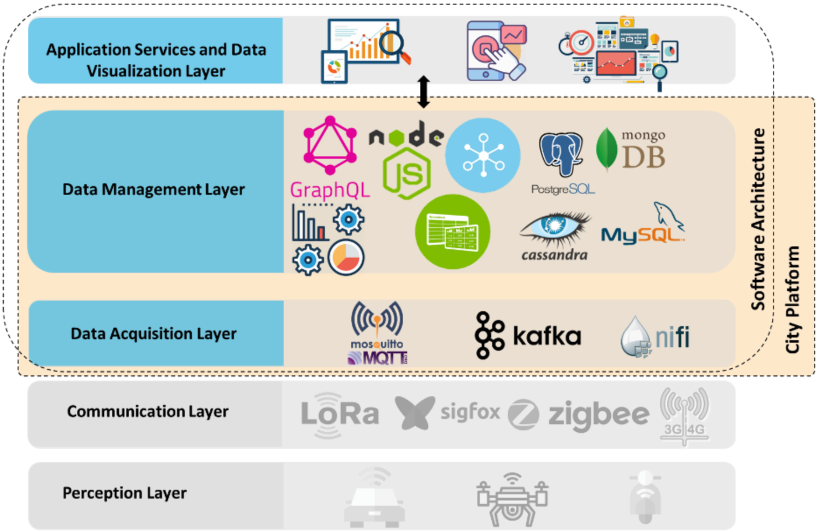


Figure 4.22: Software architecture.

- **Data Acquisition Layer**

The Data Acquisition layer is composed of several communication protocols and software components for data acquisition such as the MQTT - it is a publish-subscribe, lightweight network protocol to transfer messages between devices- to transmit sensory data and commands between the upper layers and the perception layer.

- **Data Management Layer**

The Data Management layer acts as an intermediate layer between the IoT devices that gather data and the applications accessing the data for analysis purposes and services. The sensory data comes from the acquisition layer with varying formats and structures. Therefore, the data management layer pre-processes the data to handle missing data, remove redundancies, and integrate data from different sources into a unified schema before being committed to storage. The storage of data is performing in relational or non-relational databases or both of them.

- **Application Services and Data Visualization Layer**

The application layer uses the data that stored, aggregated, filtered, and processed in the previous layer to provide services including analytics, reporting, and device control to end users.

4.3.2.2 SYSTEM IMPLEMENTATION

This section describes the hardware, software, components, and tools used to implement the system. The hardware part represents the mobile IoT node (in our case, the bike) that supports sensing, data gathering, exchanging data between bikes, and then sending it to the back-end server. The second part is the software part, where the collected data is stored and processed to be later displayed on the client web portal.

A. Hardware Implementation

The hardware and wireless technology used in the implementation phase for the mobile IoT nodes is outlined in this section. Figure 4.23, illustrate the implementation components.

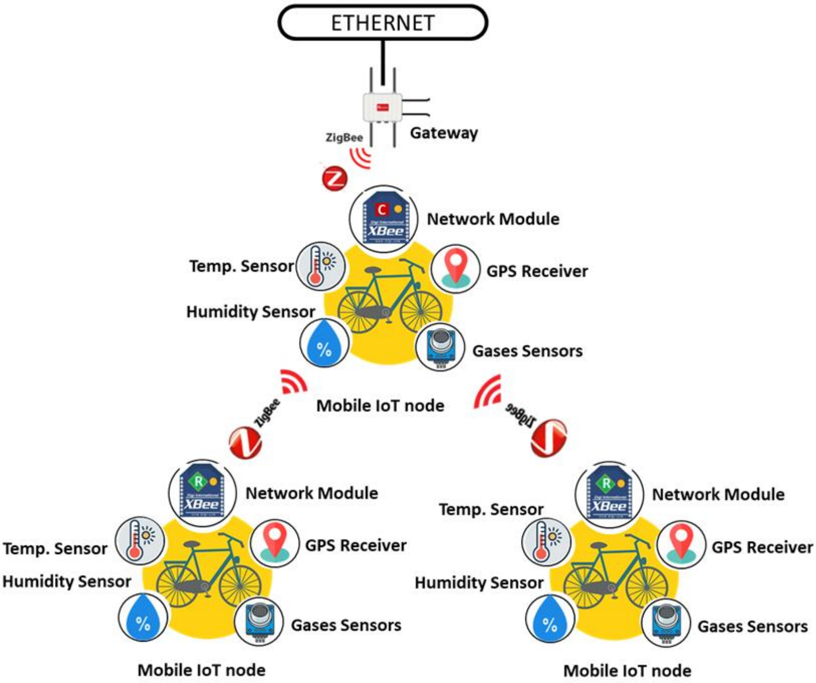


Figure 4.23: Bi2Bi hardware implementation.

- **Mobile IoT Node**

The mobile IoT node is composed of a microcontroller board, a wireless network module, GPS module, power source, and a set of sensors to monitor environmental parameters such as temperature, humidity, and different types of gases to monitor the air quality. All of them placed on a box attached to the bike as shown in Figure 4.24.

Figure 4.24: Mobile IoT Node.

We used a Waspmote microcontroller board, it has an ATmega 1281 microcontroller with a clock speed of 8MHz. It has also a slot for a SD card up to 2GB and sub system such as timer, UART, SPI, I2C. To obtain the humidity level from the environment, we used 808H5V5 humidity sensor. The MCP9700A sensor used to monitor the temperature. The TGS2442 sensor used to measure the changes in concentration of Carbon Monoxide (CO). The MiCS-2610 sensor used to measure the variation of the Ozone (O3) concentration. The MiCS-2710 sensor used to measure the presence of concentrations of Nitrogen Dioxide (NO2). The MQ-136 sensor used to detect the Sulfur Dioxide (SO2) in the air. The Waspmote GPS module is used to track and map bike movements within the city. The tracking and mapping feature can also be used to recover stolen bikes. It can also examine and analyze the behavior of bikers in terms of the most frequently used tracks by them, which has an impact on infrastructure improvements. Transferring data from an IoT node to the next layer is done through an IEEE 802.15.4 wireless network module to send all sensor measurements to the server over a MQTT protocol.

B. Software Implementation

This section outlines the development tools and technologies used in the implementation phase for the Bi2Bi system. Figure 4.25 illustrates the implementation components.

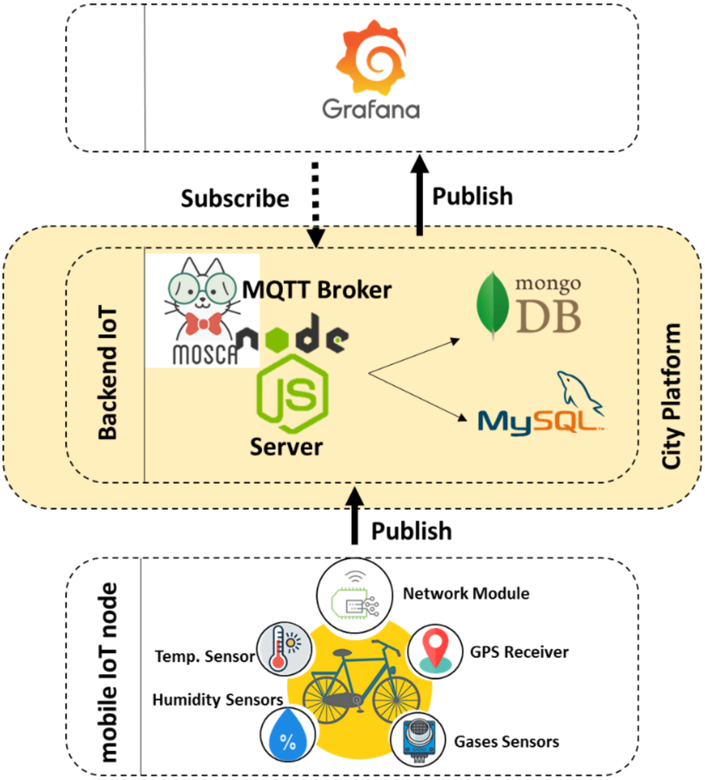
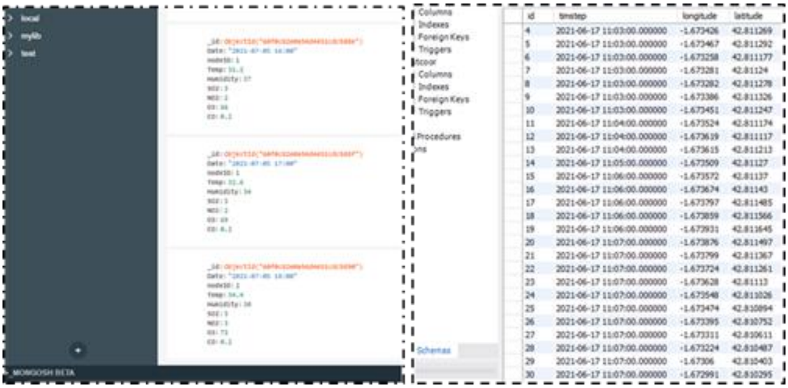


Figure 4.25: Bi2Bi system Implementation Components.

- **Backend IoT**

In this layer, we have used Node.js to build a server application to create a private Mosca MQTT broker to handle all the messages from the clients (Mobile IoT Nodes) and re-routing them to their appropriate destinations. Also, the server application processes the coming data and act as a data access layer for saving and retrieving data in/from the databases. We have used two types of databases. The first is a relational database; MySQL, an open-source relational database management system. The second is a non-relational database; MongoDB, an open-source document-oriented database as shown in Figure 4.26.



id	timstep	longitude	latitude
4	2021-06-17 11:03:00.000000	-1.673426	42.811269
5	2021-06-17 11:03:00.000000	-1.673467	42.811292
6	2021-06-17 11:03:00.000000	-1.673258	42.811177
7	2021-06-17 11:03:00.000000	-1.673281	42.81124
8	2021-06-17 11:03:00.000000	-1.673282	42.811278
9	2021-06-17 11:03:00.000000	-1.673386	42.811326
10	2021-06-17 11:03:00.000000	-1.673451	42.811247
11	2021-06-17 11:04:00.000000	-1.673524	42.811174
12	2021-06-17 11:04:00.000000	-1.673619	42.811117
13	2021-06-17 11:04:00.000000	-1.673615	42.811213
14	2021-06-17 11:05:00.000000	-1.673509	42.81127
15	2021-06-17 11:06:00.000000	-1.673572	42.81137
16	2021-06-17 11:06:00.000000	-1.673674	42.81143
17	2021-06-17 11:06:00.000000	-1.673797	42.811485
18	2021-06-17 11:06:00.000000	-1.673859	42.811566
19	2021-06-17 11:06:00.000000	-1.673931	42.811645
20	2021-06-17 11:07:00.000000	-1.673876	42.811497
21	2021-06-17 11:07:00.000000	-1.673799	42.811367
22	2021-06-17 11:07:00.000000	-1.673724	42.811261
23	2021-06-17 11:07:00.000000	-1.673628	42.81113
24	2021-06-17 11:07:00.000000	-1.673548	42.811026
25	2021-06-17 11:07:00.000000	-1.673474	42.810894
26	2021-06-17 11:07:00.000000	-1.673395	42.810752
27	2021-06-17 11:07:00.000000	-1.673311	42.810611
28	2021-06-17 11:07:00.000000	-1.673224	42.810487
29	2021-06-17 11:07:00.000000	-1.67306	42.810403
30	2021-06-17 11:07:00.000000	-1.672991	42.810295

Figure 4.26: Snapshot of sensory data stored in different databases: a) MongoDB, b) MySQL.

The mobile IoT node connects to the broker, and it can subscribe to any message "topic" in the broker. The coordinator of the mobile IoT node publishes its sensor readings as messages, besides other readings it has received from the router nodes to the broker under the topic "IoTNodeData". Once the data arrived at the broker, the server application processes this data, extracts the information, and saves sensor data into the database. The connection between the node and broker can be a plain TCP/IP connection or an encrypted TLS connection for sensitive messages.

- **Application and Data Visualization**

The application layer uses Grafana, a multi-platform open-source analytics, and an interactive visualization web application. Grafana consumes the data stored in MongoDB and MySQL to visualize it in a graphical representation as shown in Figure 4.27. As it can be seen, the dashboard offers several panels; each of these panels displays a graphical representation of the data set. Figure 4.28 shows the historical air-quality data, while Figure 4.29 shows the historical temperature measurements.

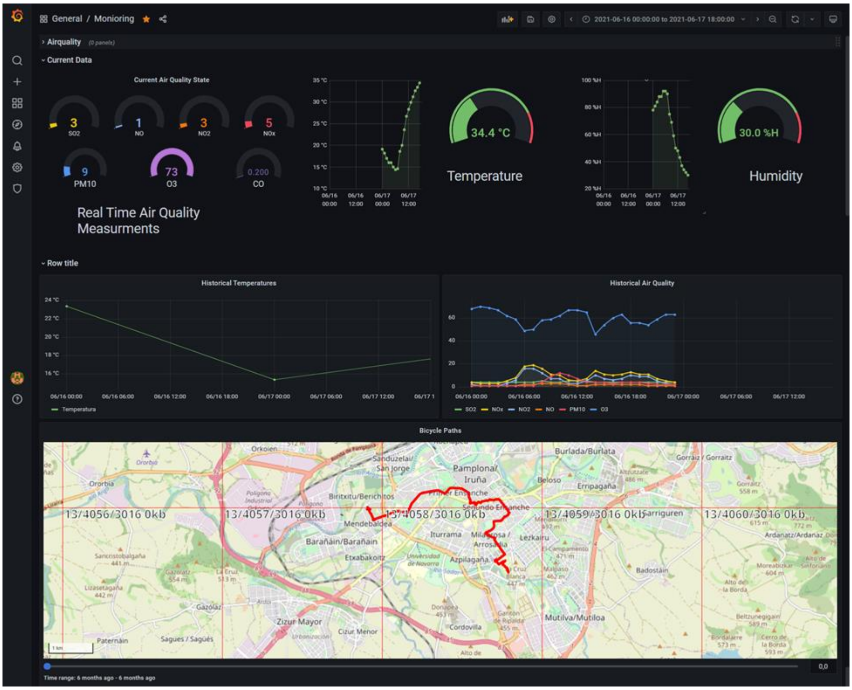


Figure 4.27: Grafana main dashboard.

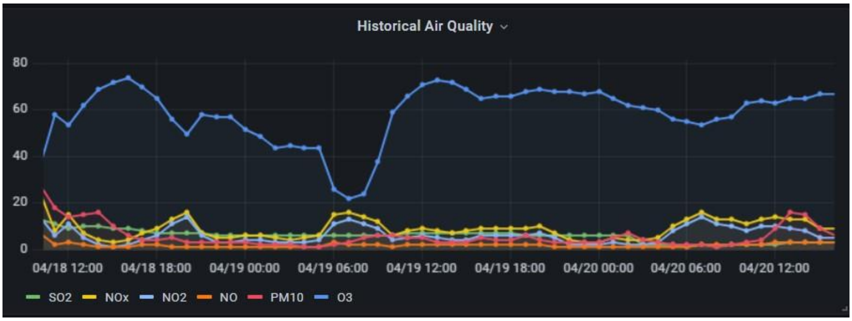


Figure 4.28: Historical air-quality data.

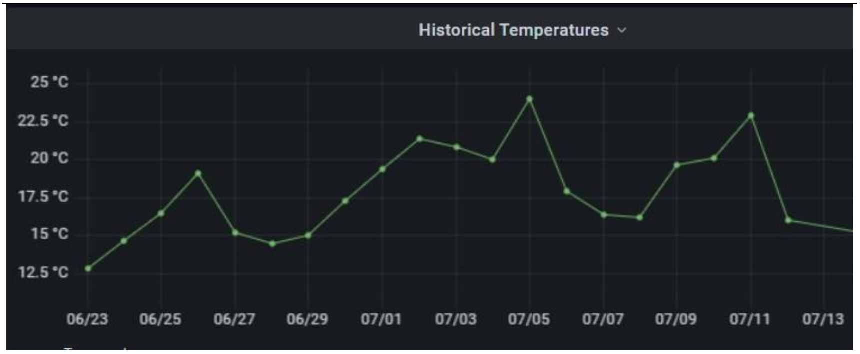


Figure 4.29: Historical temperature measurements.

Figure 4.30 shows the air quality measurements. Figure 4.31 shows the real-time temperature and humidity level. Figure 4.32 illustrate the map of bike movements within the city of Pamplona.

Figure 4.30: Real-time air-quality measurements.

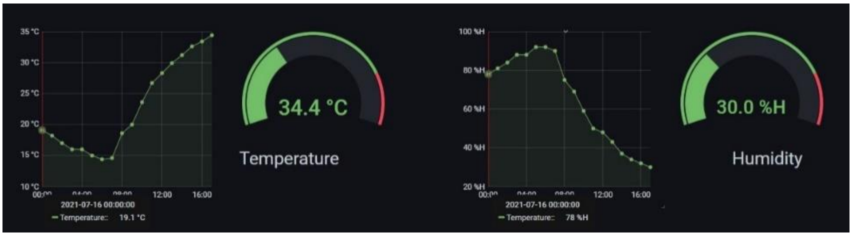


Figure 4.31: Real-time measurements of the temperature and humidity.

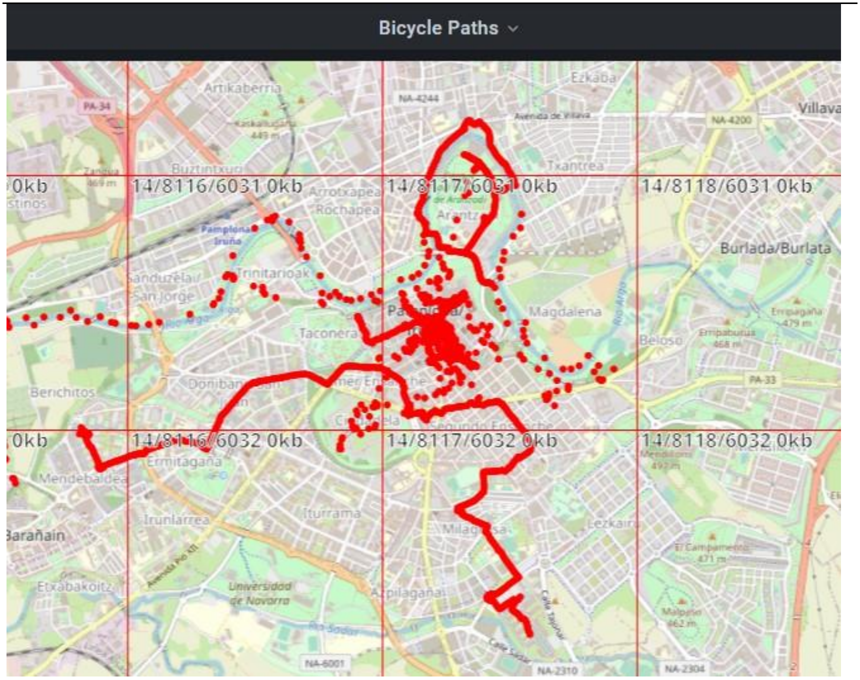


Figure 4.32: Most frequent bike paths within the city center of Pamplona.

4.3.3 Interaction with Third-Party Systems

Interaction with third-party systems is provided by means of Swagger [258], an Interface Description Language (IDL) for describing RESTful APIs expressed using JSON. The REST API follows the OpenAPI 3.0 specification [259] and uses the JWT (JSON Web Token), based on the RFC 7519 standard, to define a compact and self-contained way of securely transmitting information between parties as a JSON object. This information can be verified and trusted because it is digitally signed. One of the main features of JWT is that it does not need to store the tokens into a database on the server or support an authentication service. An example of query may be:

GET

https://XXX.XXX.XXX/events?id_types=8,12,14&idZone=SouthEast&includeTraffic=true&dateFrom=2020-11-12&dateTo=2020-12-31

```
GET https://XXX.XXX.XXX/events?id_types=8,12,14&idZone=SouthEast&includeTraffic=true&dateFrom=2020-
11-12&dateTo=2020-12-31
```

Obtaining as result a JSON file including all the information available that satisfies the conditions of the query. Swagger provides the needed transparency in order to interact with the remote service with a minimal amount of implementation logic. This makes it relatively easy to develop and deploy new services and applications based on the mobility service above described and the support of the city platform.

4.3.3.1 Pamplona CityApp

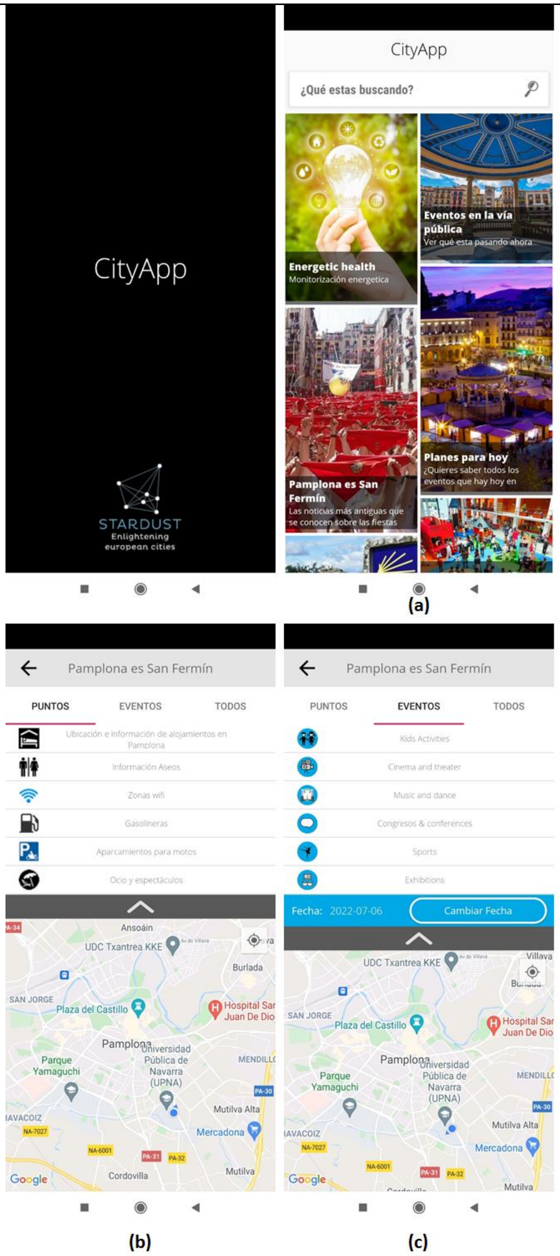
We present the “Pamplona City App,” a mobile application that allows, among other things, citizens to organize their routes according to their interests, monitor their carbon footprint and know the impact of their mobility on the city. It aims to encourage citizens to use sustainable transportation modes by showing the percentage of CO2 reduction compared to the use of vehicles using fossil fuels. In addition, noise pollution is also reduced.

In our case, the Pamplona CityApp, providing a tool based on the city platform to monitor and understand the impact of mobility at both city and citizen level and to provide accurate information on carbon footprint reduction. The CityApp developed within the framework of the STARDUST [14] project, allows people to organize their routes according to their interests, answering questions such as: which route do I have to take to visit the Museum of Navarra between 10 and 12 in the morning, eat in a vegetarian restaurant and go to a jazz concert starting at 8 in the afternoon. When generating the route, the app even takes into account some of the user's own requirements, such as, for example, taking into account that user has a pollen allergy to avoid passing close to heavily wooded areas. In case of cycling the route, the app shows the locations and availability of the bike parking (known as igloos), analyzes the CO_2 reduction compared to the use of vehicles using fossil fuels and shows the citizen's contribution to the sustainability of the city.

The app has an initial screen (Figure 4.33 -a-) which shows, in addition to relevant tourist information, information on sustainable mobility and energy efficiency in the city (results of the H2020 European STARDUST project). The services include a set of preselected filters that limits the scope of the search, and a complete and customizable search tool for events, locations and mobility proposals. A highly demanded service is the planning of routes in the city related to the San Fermines: “Pamplona en San Fermines”. Also noteworthy is the monitoring service to monitor the carbon footprint and to improve the sustainability of the city.

When one of the services is selected (Figure 4.33b corresponds to the case of *Pamplona in San Fermines*), the app shows the different geolocated elements that the user can access. In case of being interested in the events, the user can select this option and, for a given date, view the events on the map.

The user can organize his route in the city taking into account the geolocated events and his interests. In this case, by selecting the “TODOS” option (Figure 4.34a), the user can view information on each event (Figure 4.34b) and select those events that interest him (Figure 4.34c). When selecting several events, the app proposes you to make a route, which is created by clicking on the “Create Route” button. The result is a route that passes through the different events and that can be selected to be carried out in different means of transport. The route can be viewed by the user on Google Maps by clicking on the "Start Route" button (Figure 4.34d). By pressing this button, the app locally saves information about the user's interests, which are considered when providing him information about events.

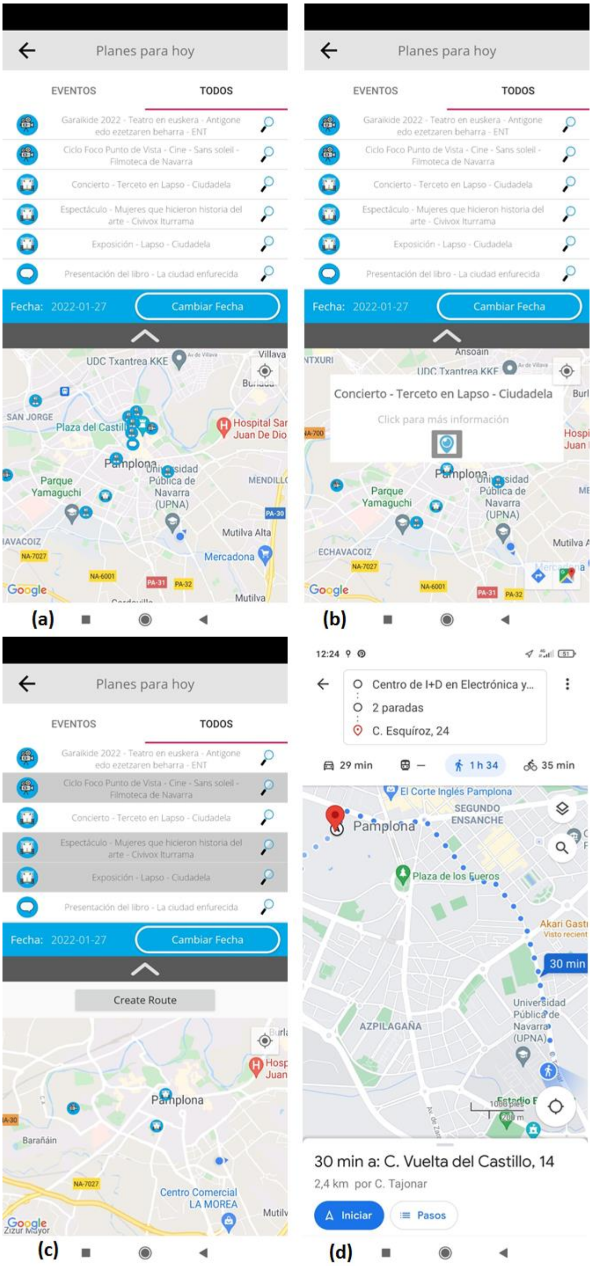


(a)

(b)

(c)

Figure 4.33: Geolocated city services and events with Pamplona's CityApp.



Planes para hoy

EVENTOS | TODOS

- Garaikide 2022 - Teatro en euskera - Antigone edo ezetzaren beharra - ENT
- Ciclo Foco Punto de Vista - Cine - Sans soleil - Filmoteca de Navarra
- Concierto - Terceto en Lapso - Ciudadela
- Espectáculo - Mujeres que hicieron historia del arte - Civivox Iturrama
- Exposición - Lapso - Ciudadela
- Presentación del libro - La ciudad enfurecida

Fecha: 2022-01-27 Cambiar Fecha

Concierto - Terceto en Lapso - Ciudadela

Click para más información

Create Route

12:24

Centro de I+D en Electrónica y...

2 paradas

C. Esquíroz, 24

29 min — 1 h 34 35 min

30 min a: C. Vuelta del Castillo, 14

2,4 km por C. Tajonar

Iniciar Pasos

Figure 4.34: Select geolocated events and create a route using CityApp.

In addition, the app indicates the level of emissions that are reduced if the route is carried out on foot or by bike (Figure 4.35).

Exposición - Lapso - Ciudadela

Sala del Polvorín de la Ciudadela - Sala de Exposiciones Municipal

Precio

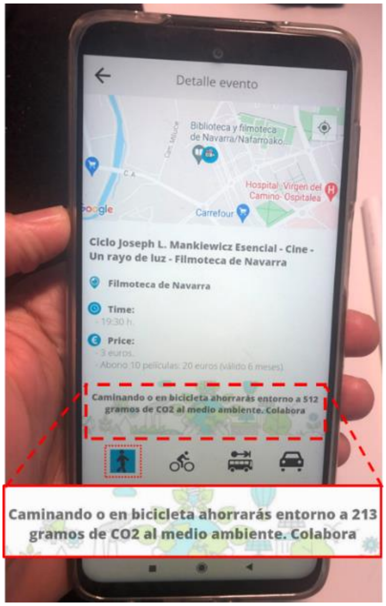
- Entrada gratuita, hasta completar el aforo.

Caminando o en bicicleta ahorrarás entorno a 239 gramos de CO2 al medio ambiente. Colabora

Figure 4.35: The level of CO2 emissions that are reduced by walking.

The collaborative system here described allows collecting data from citizens in order to know the state of the city (noise, electromagnetic and air pollution), and at the same time to know the mobility patterns and habits of the citizens. This information makes it possible to know the carbon footprint of citizens' travel and to actively promote policies to reduce this footprint. With the help of this application, citizens have an interesting help to manage their mobility and synchronize it with the events and situation of the city, but they can also know their personal and collective contribution to the goal of sustainable development. In the same way, decision-makers can know the degree of involvement of citizens and can promote the right policies to minimize the carbon footprint of their city. Four important stakeholders are clearly identified: the user of the city app, the other citizens, the city council and the company that manages the shared bicycles. Each of these stakeholders obtains relevant information for the planning of resources and activities, and also obtains information on the sustainability of their activities individually, and in relation to other citizens. Figure 4.36 shows the carbon footprint information provided to the user, but the App also provides information on the user's relative contribution to the common target over time.

The information about the user's interests is kept as local information and is not shared with third parties, ensuring the privacy of the information. Furthermore, the app shows the user the reduced amount of personal and collective carbon footprint depending on the mode of transport.



Ciclo Joseph L. Mankiewicz Esencial - Cine - Un rayo de luz - Filmoteca de Navarra

Filmoteca de Navarra

Time:
- 19:30 h.

Price:
- 3 euros.
- Abono 10 películas: 20 euros (válido 6 meses)

Caminando o en bicicleta ahorrarás entorno a 512 gramos de CO2 al medio ambiente. Colabora

Caminando o en bicicleta ahorrarás entorno a 213 gramos de CO2 al medio ambiente. Colabora

Figure 4.36: Reduced personal carbon footprint.

4.3.4 ZAC SYSTEM

In order to provide insight in relation with the system developed, a specific case study is presented in this section. The ZAC (Restricted Access Zone - Zona de ACceso restringido) is a traffic-restricted area located in the middle of the city of Pamplona, in the so-called Old Town. The streets which are part of the restricted traffic zone are mainly pedestrian, with the goal of preserving freedom of transit and safety of pedestrians and cyclists. The aim of ZAC is to reduce the volume of motor vehicles on the streets of the Old Town, guaranteeing greater urban quality in the area by improving the aesthetics and reducing the noise and smoke generated by motor vehicles. This area is monitored and controlled by cameras distributed across the entrances to the ZAC, in order to enforce access to authorized users. The authorized users are those who can only enter by their private cars, whereas the bicycles are exempt from requesting authorization. Therefore, we used the data that come from the ZAC system in our intelligent mobility application to avoid passing into this area in the absence of a permit for that or to recommend the use of bicycles in case the location of the destination is inside this area.

Figure 4.37 depicts the ontology implemented in linked-data and NGSI-LD standard in the ZAC system to control the entrance of vehicles to the restricted zones in the Old Town.

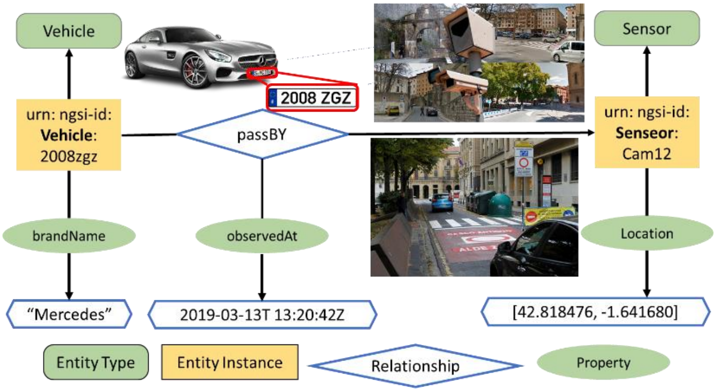
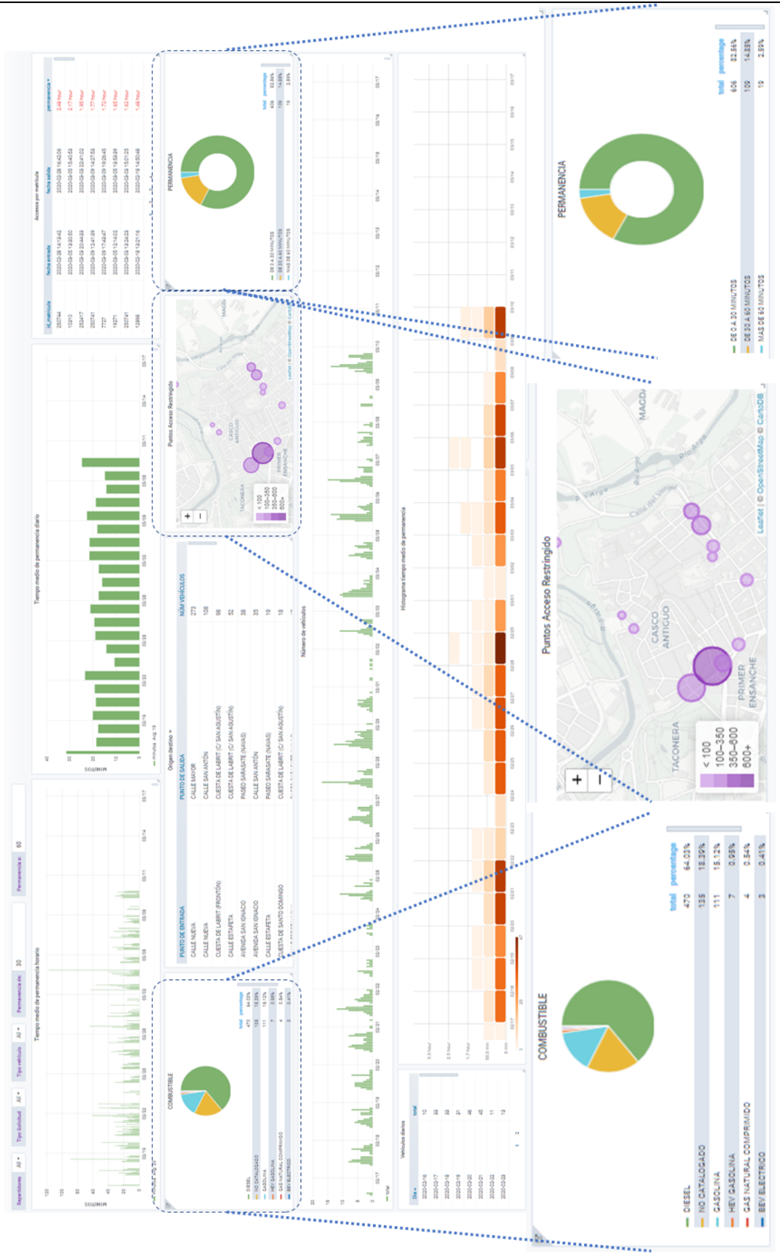


Figure 4.37: Combined data Exchange – ZAC system.

Figure 4.38 illustrates the dashboard of the ZAC system used by the city council of Pamplona. Built from the data provided by the city platform using the interactive visualization tool Grafana, the dashboard presents information about the restricted zone such as the number of vehicles that entered, the average of daily stay time, vehicle registration plates, presence/absence of transit permit, the level of air pollution, vehicle entry/departure time, the stay time for each vehicle, and many other details.

The ZAC use case presents coverage/capacity requirements given by communication links that can span up to 1 km, with very low communication transmission rates. In this sense, LWPAN communication protocols provide adequate service in terms of scalability, power consumption, coverage and bit rate requirements.



	total	percentage
DE 0 A 30 MINUTOS	606	82.56%
DE 30 A 60 MINUTOS	109	14.85%
MAS DE 60 MINUTOS	19	2.59%

	total	percentage
DIESEL	470	64.03%
NO CATALOGADO	135	18.39%
GASOLINA	111	15.12%
HEV GASOLINA	7	0.95%
GAS NATURAL COMPRIMIDO	4	0.54%
BEV ELECTRICO	3	0.41%

Figure 4.38: View of the implemented ZAC control dashboard. [Source: Ayuntamiento de Pamplona]

Chapter 5

5 Conclusions and Future Work

TIS chapter presents the main conclusions obtained throughout the investigation, which, in turn, are based on the scientific publications achieved as products of this research. In addition, it highlights the future work that can be developed from this research.

5.1 Conclusion

In conclusion, this work summarizes key points of the digital transformation taking place in cities and their endeavor to benefit from it towards transforming into SCs to make the lives of citizens more comfortable and safer and provide a better governance system. We provided a brief explanation of smart cities' concepts and technologies that are involved under this concept, the components of a SC, and the services provided by them, and their impact on the city's sustainable development, providing insight in relation with the project/vision of the Pamplona Smart City within the STARDUST framework; an EU H2020 SCs project. We have also provided the required background in technologies, concepts, solutions, and requirements relevant to the smart cities' paradigm requiring IoT. We have also presented an evaluation and classification of available and most applicable wireless technologies for SCs. Further, we highlight the wireless communication protocols characteristics and requirements for data collection and exchange in SC applications. We have discussed the development of an urban data platform as a supportive infrastructure in the development of a SC. A range of functionalities are addressed including obtaining information from the environment through sensors or open data sources or other alternative sources fulfilling security and privacy requirements. In order to fulfill interoperability requirements, the obtained data are normalized to the NGSI format, translating from the formats, and different protocols of the data source to the platform data models. The normalized data is then distributed to the various vertical services linked to the platform, in our case the urban mobility. The platform architecture is implemented following a five-layer model that considers elements from perception, sensing to data management, processing, and visualization. In order to evaluate the performance of the platform, three different use cases are described, which have been implemented in the city of Pamplona, Spain, as vertical services linked to the platform: intelligent urban mobility-bike handling, vehicle access zone control system and Bi2Bi communication. The Bi2Bi communication system integrated within the multi-modal SCP of the city of Pamplona, with the aim of enhancing transportation and transit within the urban surroundings of the city, following a holistic approach from the physical layer to the impact on end user application and interaction. In this sense, wireless channel characterization for the bike links has been performed with full 3D Ray Launching simulation technique implemented in-house and optimized in order to handle large scenarios with full topo-morphological considerations, which enables the viability analysis in the use of LPWAN technologies, such as ZigBee and LoRa/LoRaWAN in order to provide interactive capabilities. Evaluation results have been obtained in relation with range, throughput, and packet loss ratio for different urban scenarios within the municipality of the city of Pamplona. Wireless communication quality experiments for several use cases are presented, considering different link types and conditions. As a use case, the “Pamplona CityApp” has been developed, which is a mobile application for sustainable mobility in which people can organize their routes according to their interests, can know and monitor the personal and collective carbon footprint, enforcing sustainable mobility and energy efficiency in the city. The proposed platform enables services aimed towards different stakeholders, such as bike users, bike platform service providers, local/regional authorities and the general public.

5.2 Future work

The COVID-19 crisis emphasized the need to invest in connectivity infrastructure and solutions that improve the efficiency of e-governments and alleviate public health and safety concerns. The demand for online interactions with government agencies/departments has also increased because of the movement to electronic transactions and electronic signatures. In addition, the necessity for safe and secure transport grew to make systems safer by providing real-time warnings about crowding, access problems, or delays to help people make better informed public travel decisions. Therefore, the SCP must be capable of dealing with this amount of data effectively and securely to meet users' needs. Here we present a list of various future research directions that can be pursued in order to continue the work started in this thesis, comprising:

- **Big Data Processing:** By implementing a generic, scalable and evolvable Big Data architecture that enables both streaming and historical data processing. In addition, providing a reusable service that can support the requirements of several customer applications. As one of the main objectives of SCP development is to share computational resources and reusable services across multiple applications. More specifically, big data services will be crucial for future SCs, as they could potentially integrate a large amount of data from different sources that need to be processed promptly to provide valuable results for cities.

- **Federated Learning:** The most common methods for optimizing traffic control in SCs are Sensing as a Service (S2aaS) and Mobile Crowdsensing. Mobile Crowdsensing is an emerging, effective, non-dedicated paradigm in SCs sensing. It is cost-effective, highly scalable, and has enormous mobility [260]. Mobile Crowdsensing allows individuals to participate in a sensing event by providing data through their sensor-enabled mobile devices [261]. Data is often processed using machine learning, deep learning, and statistical methods to generate a trend, decision-making or conclusion. Mobile Crowdsensing faces challenges by using the devices of users for sensing. Users are exposed to potential privacy and personal information leaks. The goal is to provide a machine learning framework that complies with data privacy, security, and regulatory requirements, allowing AI systems to make better use of the data [262]. Federated Learning is essentially a distributed machine learning technology or machine learning framework. Federated Learning is a novel concept that aims to solve the privacy and security issues encountered in the process of data collection, while still complying with laws and regulations, such as GDPR [263].

5.3 List of Publications

- A. Al Rahamneh, J. J. Astrain, P. Lopez Iturri, J.Villadangos, H.Klaina, I. P. Guembe, and F. Falcone, *"Enabling "Customizable Services for Multimodal Smart Mobility with City Platforms*", IEEE Access , vol. 9, pp. 41628 41646, 2021.

- A. Al Rahamneh , J. J. Astrain, P. Lopez Iturri, J.Villadangos, H. Klaina, I. P. Guembe, and F. Falcone, "*Bi2Bi Communication: Toward Encouragement of Sustainable Smart Mobility*", IEE E Access , vol. 10, pp. 9380 9394, 2022.
- A. Al-Rahamneh, J. J. Astrain, P. Lopez-Iturri, I. P. Guembe, and F. Falcone, “Intelligent SDN-Based Multi-protocol Selector for IoT-enabled NMT Networks,” *4th IEEE Int. Conf. Knowl. Innov. Invent. 2021, ICKII 2021*, pp. 30–33, Taichung (Taiwan), July. 2021.
- A. Al-Rahamneh, J.J. Astrain, J. Villadangos, H. Klaina, I. Picallo, P. Lopez-Iturri, F. Falcone, “An IoT Framework for SDN Based City Mobility,” International Symposium on Ubiquitous Networking (UNet 21), pp. 116–124, Marrakesh (Morocco), May 2021.

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