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Design and Implementation of IoEV Platform for Grid Integration of Electric Vehicles

Submitted by

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In loving memory of Moka and León . . .

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ABSTRACT

Nowadays, the internet of electric vehicles (IoEV) has opened many new opportunities for various applications such as traffic safety, congestion avoidance, charging station selection, and user-comfort services. IoEV communication will support different applications such as vehicle to infrastructure (V2I), vehicle to vehicle (V2V), and vehicle to pedestrian (V2P). Different requirements for data rate, reliability, latency, security, and privacy are needed in order to support reliable IoEV communications. Extensive research has been conducted on the suitability of various short-range and long-range wired/wireless technologies for IoEV communications. These challenges include, for example, transmission range, latency, throughput, and power consumption. Different wired/wireless communication technologies are believed to play an essential role in supporting different IoEV applications. This work aims to investigate the performance of different communication architectures for supporting various IoEV applications such as Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), and V2V. The developed architectures are evaluated considering real scenarios for parking vehicles and vehicles on-the-move. Furthermore, the developed communication network is evaluated using off-the-shelf prototypes (sensors and MCU units) under practical scenarios on the UTFSM campus. The performance of the communication network has been evaluated with respect to latency and network reliability.

Keywords: Electric Vehicles, Charging Stations, Internet of Things, Communication Network, LoRa Technology.

RESUMEN

En la actualidad, la Internet de los vehículos eléctricos (IoEV) ha abierto muchas nuevas oportunidades para diversas aplicaciones, como la seguridad del tráfico, la prevención de congestiones, la selección de estaciones de carga y otros servicios para la comodidad del usuario. La comunicación IoEV admitirá diferentes aplicaciones, como vehículo a infraestructura (V2I), vehículo a vehículo (V2V) y vehículo a peatón (V2P). Se necesitan diferentes requisitos de velocidad de datos, confiabilidad, latencia, seguridad y privacidad para admitir comunicaciones IoEV confiables. Se han realizado amplias investigaciones sobre la idoneidad de varias tecnologías cableadas/inalámbricas de corto y largo alcance para las comunicaciones IoEV. Estos desafíos incluyen, por ejemplo, el alcance de transmisión, la latencia, el rendimiento y el consumo de energía. Se cree que diferentes tecnologías de comunicación cableada/inalámbrica desempeñan un papel esencial en el soporte de diferentes aplicaciones IoEV. Este trabajo tiene como objetivo investigar el rendimiento de diferentes arquitecturas de comunicación para admitir varias aplicaciones IoEV, como Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G) y Vehicle-to-Vehicle (V2V). Las arquitecturas desarrolladas se evalúan considerando escenarios reales como estacionamientos de vehículos y vehículos en movimiento. Además, la red de comunicaciones desarrollada se evalúa utilizando prototipos listos para usar (sensores y unidades MCU) en escenarios prácticos en el campus casa central de la UTFSM. El desempeño de la red de comunicaciones se ha evaluado con respecto a la latencia y la confiabilidad de la red.

Contents

List of Tables

List of Figures

1 | Introduction

1.1 Problem Statement, Context and Motivation

Nowadays, electric vehicles (EVs) have become a primary element in the smart city ecosystem, which contributes to reducing greenhouse gas emissions and pollution [3]. In this direction, many manufacturers are offering different models of EVs, and over the next few years, more EV models will be available. With the grid integration of a large number of EVs, managing and controlling the energy demand of EVs will become more challenging due to vehicle operation modes that adapt a bidirectional energy flow between the EVs and the power grid. The long-term solution to overcome the high energy demand of EVs is to upgrade the power system infrastructure (transformers, power lines, etc.), which will require a potential cost and investments. Other solutions such as scheduling techniques and intelligent control will play an essential role in solving such high EVs energy demand in the near term without infrastructure upgrading [4]. However, such techniques require appropriate communication architectures that enable communications among EVs, charging stations, energy management systems, and the power grid.

For the deployment of EVs, many countries have set ambitious plans supported by policies and regulations. In Chile, the national electromobility strategy aims to achieve 40% of private vehicles and 100% of public transport vehicles to be electric by 2050 [5]. As of July 2021, in Chile, there were a total of 2,164 electric vehicles, including vehicles, trucks, hybrid vehicles, and electric urban buses, according to the ministry of energy [6]. Furthermore, the number of electric buses fleet was about 841, which is the largest in the world after China.

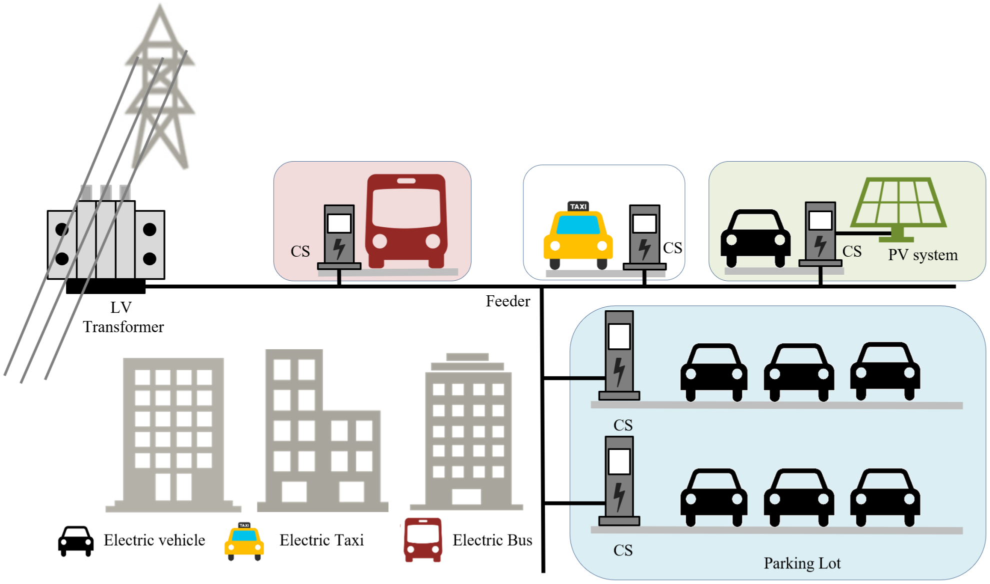


Figure 1.1: Grid integration of electric vehicles in distribution power system

Data transfer and communication networks among EVs, charging stations, and grid controllers are essential elements in the electric vehicle system. It is expected that the Internet of Things (IoT) technology will enable the grid integration of EVs through the incorporation of sensors, meters, and actuators devices while supporting various network functions and system automation. Figure 1.1 shows the main elements of the electric vehicle system including EVs, charging stations, and electric power network. Other elements include metering devices, sensors, roadside units (RSU), local/global controllers, and communication networks.

Internet of electric vehicle (IoEV) can be defined as a wide network of EVs, charging stations, sensors, and humans that collect and disseminate information related the electric vehicles and the environment with the aim to support different vehicle to grid (V2G) services, improving driving experience, enhancing road safety and avoid accidents [7]. Currently, the public transportation system supports different types of electric vehicles such as private EVs, electric taxis (ET), and electric buses. The charging patterns of buses, ETs, and private EVs are very different. A private car can be charged at home or the parking lot while the vehicle may spend the day, instead, an ET needs to serve many customers, therefore, ETs can not be stopped for a long time in charging stations because the mobility is related to their business. These challenges could be solved by remote monitoring and scheduling of electric vehicles and charging stations to meet the user requirements while preventing the grid overloading [8].

To mitigate the impact of the grid integration of EVs in a smart way, we need to monitor the state of charge (SOC) of the EVs batteries and the position of the EVs, in order to anticipate when and where it will need to be charged. To accomplish EVs monitoring, it is necessary to have sensors on the vehicle to measure SOC, and the vehicle location using a global position system (GPS) [9]. In most cases, these parameters are measured locally inside the EV because they are essential for the driver in order to decide when and where to charge. Therefore, the main challenge is the connectivity problem to exchange information among different entities while EVs are on-the-move. For parking vehicles, the communication between EVs and charging stations (CS) including information such as the arrive time, current SOC, departure time, and required SOC is important to decide the charging time and the charging rate. For on-the-move vehicles, the vehicle to infrastructure (V2I) communication enable the data exchange with RSUs [10]. The data exchanged with RSUs is small, so low power long-range (LoRa) technology is a promising candidate for this purpose [11]. With LoRa technology, a small number of gateways can support EVs communication over a wide coverage area.

In general, there are different types of charging stations, depending on the amount of energy they deliver. The chargers are ranked from level 1 (less energy) to level 3 (more energy). Level 1 charger used to be connected to low voltage single-phase AC supplies, level 2 is connected to 1 phase/3 phases low voltage systems, while level 3 is connected to 3 phases AC power systems. Based on battery capacity, the vehicle will need about 11-36 hours or 2-3 hours for level 1 and level 2, respectively, and about 12-30 minutes with level 3 [12]. This indicates that the waiting time for EV charging cannot be compared with conventional gasoline-based refueling. Figure 1.2 shows different levels of charging stations.

MODOS DE CARGA

La carga del vehículo puede ser de cuatro modos distintos según la norma IEC 61851-1, que se ha asimilado operacionalmente en la conectividad y comunicación entre el cargador y el vehículo.

MODO 1

Enchufe no dedicado

Sin comunicación

AC Corriente alterna
Limitado a 10 [A], 3,5 [kW]

- La conexión es a una toma de la corriente alterna estándar de una instalación eléctrica existente.
- Por seguridad, la instalación eléctrica debe poseer una toma de tierra, protección diferencial y protección termo magnética.
- La batería se recarga con el inversor AC/DC incorporado en el vehículo.
- No es recomendable por la incertidumbre de calidad y estado de la instalación eléctrica desde donde será tomada la energía.

MODO 2

Enchufe no dedicado con protección y control incorporada en el cable

Bajo control de carga con el dispositivo incorporado en el cable.

AC Corriente alterna
Potencia hasta 2,2 kW 1ø y hasta 11 kW 3ø.

En el modo de recarga 2, la conexión al auto se realiza a través de un cable donde se ha incorporado un sistema de seguridad, de comprobación de la toma de tierra, protecciones y con posibilidad de seleccionar la velocidad de carga.

- La conexión es en corriente alterna, se utiliza una instalación y enchufe estándar y entre el enchufe y el vehículo se incorpora el control.
- La batería se recarga con el inversor AC/DC incorporado en el vehículo.

MODO 3

Enchufe dedicado

Alto control de caxndable en lugares de acceso público acceso público y también en hogares.

AC Corriente alterna
Potencia hasta 3,5 kW 1ø y hasta 44 kW 3ø.

Este modo de recarga es una conexión del Vehículo Eléctrico a la red, utilizando un circuito y equipamiento de control incorporado en el cargador. Este modo incorpora la protección de sobrecarga, cortocircuito, diferencial, puesta a tierra y un piloto control de carga entre el equipamiento dedicado (cargador) y el Vehículo Eléctrico.

En este tipo de recarga, el Vehículo Eléctrico se conecta al cargador con un control (caja de pared o tipo poste) mediante un cable especial. El cargador es el que está dotado con un control "inteligente" que se encarga de gestionar la seguridad y proceso de carga.

MODO 4

Cargador externo

DC La carga se realiza con corriente continua desde un cargador que contiene un convertidor de corriente alterna a continua. Las potencias son sobre 40 kW y alto nivel de control de carga.

Este modo de recarga cuenta con un rectificador AC/DC externo al vehículo de mayor potencia (inversor interno del propio cargador), lo que traduce en menor tiempo de carga de la batería. Existe alto grado de comunicación entre el cargador y el vehículo para el control de carga.

- La instalación eléctrica hasta el cargador debe ser independiente y con las protecciones de sobrecarga, cortocircuitos, diferenciales y puestas a tierra respectivas.
- La infraestructura es mayor y más cara.
- La carga puede ser más rápida porque el cargador tienen mayor capacidad. La batería del vehículo y su capacidad de recibir energía determinará la velocidad de carga.

Figure 1.2: Different levels of charging stations [1]

Considering the challenges for private EVs such as short driving range, slow charging rate for home charging stations, and the lack for the availability of fast charging stations, many parking lots are now supporting parking and charging services for EVs. In order to support charging/discharging services, reliable communications are needed among EVs, parking lot local controller (PLLC), and the power grid [13]. In this direction, IEC 61850 standard will help to standardize the data exchanged between different entities in order to facilitate the grid integration of EVs.

1.2 Hypothesis

The current state of the art regarding the underlying communication infrastructure for supporting electric vehicles and charging stations is still underexplored. In this direction, IEC 61850 standard will help to standardize the data exchanged between different entities in order to facilitate the grid integration of electric vehicles. Most of the current charging stations are decentralized with complex structures which make real-time monitoring and management a difficult process. Real-time information of the status of charging stations such as availability and reservations will provide critical and valuable information for the end-user and the service provider. In this regard, information and communication technologies (ICT) are a key element to enhance the capabilities of electric vehicles and charging stations through data collection, storage, and analysis.

This work converges three different domains: distribution power system, electric vehicles, and communication networks. The work is guided by a main question to be solved: **how to develop a communication network architecture for electric vehicles coordination to prevent the overloading of distribution power system and assures the comfort of consumers.** Most of the related work for the grid integration of electric vehicles did not take into account the underlying communication infrastructure and/or assume perfect communications among different electric vehicle system entities (electric vehicles, charging stations, local control center). These assumptions are not accurate, as data losses and communication delays are unavoidable and may degrade the system performance. This work aims to evaluate the performance of different communication network architectures to enable reliable data exchange among different entities of EV system.

1.3 Objectives

General Objective:

- Design an IoEV architecture to support the grid integration of electric vehicles in the distribution power system.

Specific Objectives:

1. Develop IoEV architecture to support the integration of electric vehicles in the distribution power system. The proposed architecture consists of three layers: the physical layer, the network layer, and the virtual layer.
2. Develop an architecture model for monitoring the electric vehicle sub-system (EV and charging stations) based on IEC 61850 Standard.

3. Build a testbed to evaluate the capability of different communication technologies to support EV integrated grid in UTFSM campus.

1.4 Methodology

The methodology to meet the objectives stated above consists of the following steps:

1. Survey and analysis of recent literature and standardization for electric vehicles system in distribution power system.
2. Analysis of advanced communication network technology (wired/wireless) for measurement and control information for electric vehicles/charging stations in distribution power system.
3. Classifying different data types for EV, charging stations, power grid.
4. Determine the network design requirements and traffic parameters for the electric vehicle system.
5. Design of wired/wireless communication infrastructure for electric vehicles coordination.
6. Evaluate the capability of different communication technologies to support EV integrated grid in the UTFSM campus.

For Specific Objective 1:

1. Define the structure of IoEV architecture, providing a detailed description of each layer.
2. Define the relationship among EV, charging stations, and power grid.

For Specific Objective 2:

1. Define the architecture model for EV and charging station based on IEC 61850 Standard.
2. Determinate the type and amount of data that need to be exchanged.
3. Select communication technologies that meet the data requirements.

For Specific Objective 3:

1. Define the main components that will be needed for the implementation of the testbed.
2. Configure and programs the modules for communication.
3. Mount and test the components in UTFSM campus.

1.5 General Structure of the Document

The thesis is oriented to present the design and implementation of IoEV platform for the grid integration of electric vehicles. The document is divided into six chapters.

Chapter 1: Introduction. This section presents a brief introduction about the motivation and methodology on the subject.

Chapter 2: Related Work. This section start with introduction about the status of electromobility in Chile, then, explain detailed information about the state of art about the electric vehicle system.

Chapter 3: Internet of Electric Vehicles. This section presents the concept of Internet of Electric Vehicles and the developed architecture.

Chapter 4: Network Modeling and Simulation Results. This section presents network modeling and simulation results for wired/wireless architectures.

Chapter 5: LoRa-Based Architecture for IoEV. This section presents the LoRa implementation to support different services for electric vehicles on the move and charging stations.

Chapter 6: Conclusions and Future Work. This section presents the overall conclusions and the future work.

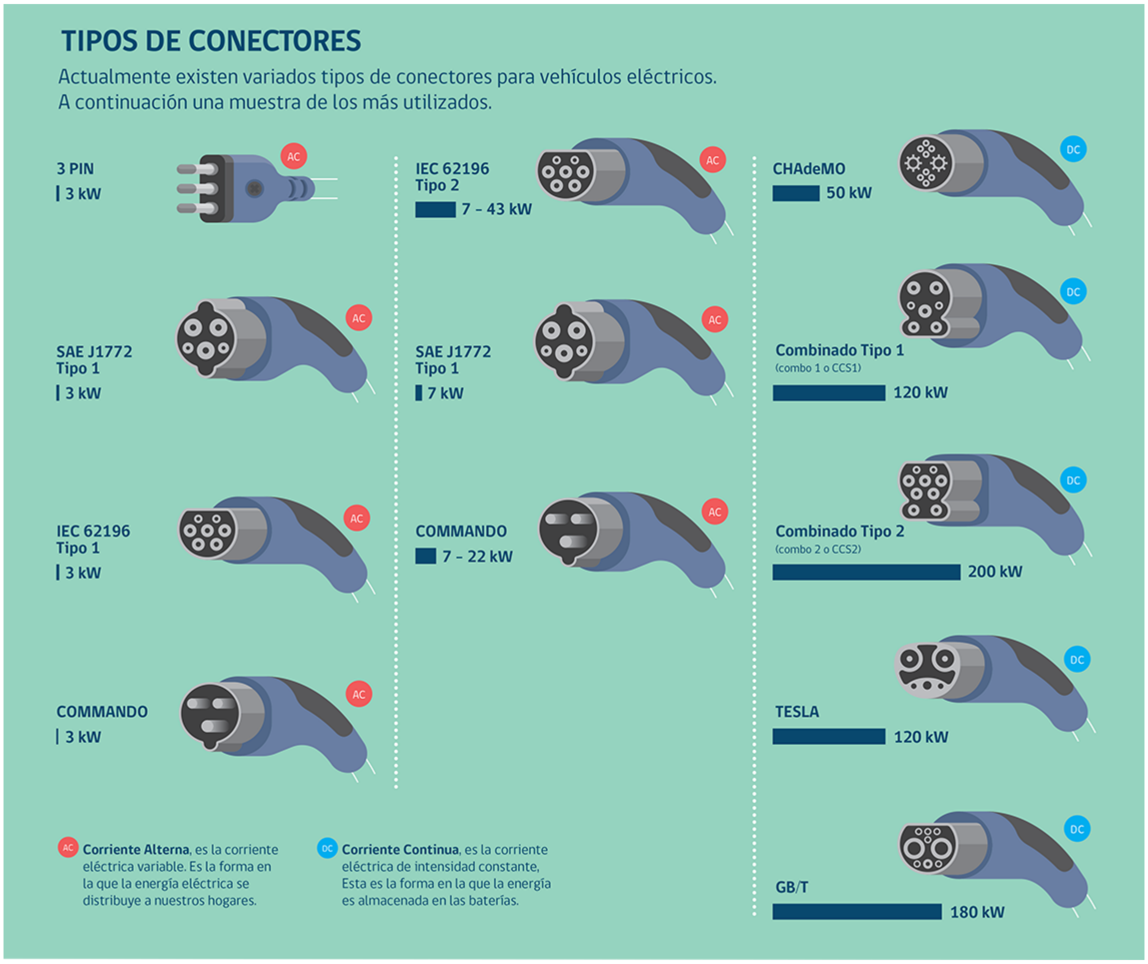
2 | Related Work

2.1 Status of Electromobility in Chile

The goals proposed by Chile in electromobility are ambitious and are in line with the global expectations on the subject. The electromobility plan is being done so that, by the year 2050, 100% of the public transportation and 40% of private vehicles will be electric (Figure 2.1). To this end, it is expected that the sale of new vehicles in 2035 will be completely electric [2]. The goals of the electromobility is also alined with the goal to be carbon neutral by the year 2050. To achieve this, an appropriate measure is to change the conventional fuel vehicles, since each year about 25% of greenhouse gases are produced by transport and cargo vehicles in Chile. Furthermore, Chile has acquired and ratified international agreements on GHG emissions and climate change, committing at the level of mitigation to reduce emissions intensity 30% by 2030 compared to the levels observed in 2007 (Committee of Ministers for Sustainability and Climate Change, 2015). [14].

Figure 2.1: Government goals of electromobility in Chile for the year 2050 [2]

- Status of Electric Vehicles: Currently, we are moving towards the planned strategy for electromobility by increasing the number of electric buses and private vehicles. In 2020, the number of electric vehicles in circulation was around 1,791 units and by June 2023 the number has increased to 6,812 units [14]. Today, in the metropolitan region, there is a fleet of electric buses of approximately 2,500 units, 40 in the city of Antofagasta, and another 10 in the city of Rancagua. In addition to this, there are other projects to bring electric buses to the regions of Atacama, Coquimbo, and Valparaíso [15]. This makes Chile the country with the largest fleet of electric vehicles in the world, only behind China. [16]. Despite the progress made, electromobility in Chile is still facing some important challenges. One of them is the high cost of electric vehicles compared to internal combustion vehicles [17]. To support EVs charging, different types of connectors for charging stations, as shown in Figure 2.2 [14].



TIPOS DE CONECTORES

Actualmente existen variados tipos de conectores para vehículos eléctricos.
A continuación una muestra de los más utilizados.

AC **Corriente Alterna**, es la corriente eléctrica variable. Es la forma en la que la energía eléctrica se distribuye a nuestros hogares.

DC **Corriente Continua**, es la corriente eléctrica de intensidad constante, Esta es la forma en la que la energía es almacenada en las baterías.

Figure 2.2: Different Type of Connectors for Chargers [1]

- Status of Charging Stations: To achieve mass adoption of electric vehicles, it is necessary to have a large network of charging stations. In Chile, up to 2023, the total number of chargers was about 908. The distribution of the charging stations by region can be seen in the Figure 2.3 [14]. Most of these charging stations are concentrated in the metropolitan region which also has the largest population (7+ million Censo 2017 [18]). There is also the largest fleet of buses for public transportation with about 25 charging terminals [19]. It is important that the energy used by electric vehicle charging stations comes from clean sources, otherwise greenhouse gases would be released elsewhere [14].

Figure 2.3: Distribution of charging stations in Chile [1]

The results of this long-term plan are already yielding positive results for people and the environment. The year 2023 had the best air quality since records began, confirming that we are moving in the right direction [20]. In addition to greenhouse gas pollution, noise pollution has been reduced on Santiago's main avenue Alameda. This reduction reached up to 44% due to the electric buses that travel in such area [21].

2.2 Electric Vehicle System

The grid integration of electric vehicles presents many challenges from power and communication perspectives. On the one hand, the challenges of electric power include, for example, grid stability, voltage fluctuation, frequency deviation, harmonics, and power outage [22]. On the other hand, wireless connectivity for vehicles and charging stations will play an important role in enabling communications with the internal/external environment. Existing technologies include, for example, ZigBee, Bluetooth, passive RFID, 60 GHz Millimeter-Wave (mmWave), and Ultra-Wideband [23].

2.2.1 Electric Vehicles

With respect to electric vehicles, an IoT perspective was developed in [3] for charging station recommendation and real-time electric vehicles load forecasting. With real-time information, many benefits can be achieved, such as avoiding the long waiting time at charging stations and reducing costs of energy and charging time. The communication challenges include reliability, delay, interruptions, and standardization. In [4], the authors provided a survey on standards, communication requirements, and technology candidates toward the IoEV. Furthermore, the work addressed the critical challenges associated with grid integration of electric vehicles and the role of information and communication technologies in the solution. An extensive review about topologies of battery charger and levels of charging power for electric vehicles was presented in [24], where the authors discussed the high energy demand and consumption of electric vehicles. In [8], a grid stability technique was proposed to schedule the charging time of electric taxis and private cars to reduce the load profile. In [9], an energy management strategy was simulated to save energy using multiple frequent routes, driver's behavior, and GPS for PHEVs.

2.2.2 Communication Networks

With the advances in vehicular networks, dedicated short-range communication (DSRC) and 4G will not be capable of supporting the high volume of data generated from different sensors such as LIDAR, cameras, and Radar. Therefore, mmWave communication was considered as a promising technology to support the high data rate required for different vehicular applications such as remote driving, vehicle platooning, and automated driving [25]. Other research work considered LoRa wireless technology as a promising candidate to support different V2X applications such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N) and vehicle-to-pedestrian (V2P) [26].

In Ref. [13], an OPNET simulation model of the communication network conditions to monitor charging stations in a parking lot based on the IEC 61850 standard was presented. In Ref. [7], the authors presented an overview for the security issues of the IoEV architecture as data exchange might be subject to many types of attacks such as DoS, false data injections, eavesdropping, modification, and spoofing. The work presented different V2X communication such as V2V, vehicle-to-road infrastructure, vehicle-to-internet, and vehicle-to-human services. A comprehensive survey on 5G-V2X use cases and enabling technologies shows the need for high-bandwidth communication for some applications [10]. In this case, the authors focused on high demanding data rate cases of uses over wireless communication between vehicles to everything (V2X). The authors in Ref. [11] studied LoRa in an urban environment using simulations and real measurements. The parameters of interest were packet delivery ratio, packet inter-reception time, and received signal strength indicator. Simulation results, provided by the NS3 simulator, were compared to the real measurements at a university campus.

2.2.3 Charging Stations

There are different modes and power levels for charging electric vehicles through electric vehicle supply equipment (EVSE) [4, 22, 27]. In general, the different levels are named level 1, level 2, level 3, and level 4. Level 1 is approximately 1.4–1.9 kW. This mode will enable EV to take an average of 8–12 h to reach the full state of charge for the battery. The main advantage of level 1 is the economic cost which does not require any additional infrastructure at homes. However, no communication nor control is supported when connected to the grid. In the residential charging system, the system does not support monitoring nor control due to the simple charging system at low voltage. Compared with level 1, level 2 charging usually takes 4–8 h, which is very suitable for residential buildings. Level 3 is considered as a fast-charging option that can be used in malls, highways, and public places which will support very quick charging. Level 4 is a DC charging (400–800 V DC) for heavy vehicles which is not suitable for residential places. In Ref. [27], the authors presented a review on charging infrastructure, charging technologies, and charging station recommendations. The work highlighted the need for a reliable communication network among electric vehicle system participants and IoT-enabled CSs. Ref. [28] presented a review on quality-of-service parameters for electric vehicles including scalability, resource allocation, energy demand, and capacity planning. Also, the work discussed EV communication infrastructure and technologies. Such vehicular communication (WAVE, DSRC, 4G/LTE, 5G, and VANET) is related to electric vehicle mobility and ITS to increase safety and reduce traffic congestion and collisions.

The authors of Ref. [29] presented a new strategy to minimize the charging cost of EVs based on the day-ahead electricity price and the battery degradation cost, considering the limitations of EVs SOC and the maximum power of the charger. The new methodology was applied to coordinate the charging of EVs in low-voltage networks. In Ref. [30], the authors developed a dynamic pricing model to manage PEV charging at charging stations, avoiding overlap with residential peak hours. Formulated as an optimization problem, the model employed a heuristic solution to adjust prices and direct demand. The results indicated improvements in reducing load during peak hours and waiting times, promoting network stability. In Ref. [31], the work explored the impact of ultra-fast charging stations on the distribution network and their integration into smart grids. Also, the communications necessary for the efficient operation of the ultra-fast charging stations, evaluating the reliability and use of data in the management of these stations. In Ref. [32], the work presented a methodology to use the collective storage capacity of slow-charging electric vehicles in parking lots as a resource for regulating services and as a buffer for fast-charging fluctuations.

In general, personal vehicles spend more time parking than moving (this also applies to electric vehicles). This under utilization opens the door to new possibilities that obtain better use of the vehicle. During the day, the main place where a vehicle spends its hours is a public parking lot. For this reason, it is necessary to convert regular electric vehicle parking lots into smart parking lots (SPL). The idea of SPL is that EVs can carry out energy transactions between the grid and vehicles (G2V), vehicle to vehicle (V2V), or vehicle to grid (V2G). For each of these three cases, we can add a factor that encourages and makes the exchange of energy by the EV user more interesting, which is the monetary gain by having variable and negotiable prices. On the part of the electrical network, placing incentives in the purchase of energy (G2V), from vehicles to the power network (V2G), in periods of peak consumption helps the stability of the power network. As well as selling cheap energy to electric vehicles outside of peak periods to flatten the consumption curve. When the exchange of energy is not carried out with the electrical grid, it can be done between EV users. To achieve an exchange between vehicles (V2V), an energy converter is needed. The most practical thing for this case is that the SPL chargers themselves allow the bidirectional flow of energy, ensuring that the clients can sell and buy energy. The local exchange of energy within the SPL favors the efficiency of the process by reducing energy transport losses between producing and consuming it.

In the near future, when electric vehicles become widespread in cities, it will be necessary to implement measures to reduce their impact on the electrical grid. This requires real-time information on the status of charging stations. Controlling the charging of vehicles at charging stations also necessitates real-time information. However, all these measures will not work effectively without a reliable communication network facilitating the flow of information between charging stations and the control center [33]. Users will demand increased utilization of the available chargers, so knowing whether a charger is in use (busy) or not in use (free) is crucial. This is because the charging times for electric vehicles are lengthy, and knowing where to drive for charging while being assured of availability is important [34].

Integrating electric mobility into urban environments requires the adoption of various promising technologies. Among these are Long Range (LoRa), Long Term Evolution for Machines (LTE-M), Narrowband Internet of Things (NB-IoT), and the rapidly evolving 5G networks, with future considerations for the advancements expected with 6G. These technologies facilitate efficient communication and data exchange between electric vehicles, charging infrastructure, and city management systems, enabling smoother operations and optimization of resources. In addition to these advanced technologies, there are scenarios where shorter-range options become relevant. Technologies like WiFi, ZigBee, and Bluetooth can play crucial roles in localized applications within smart city ecosystems. The versatility of these technologies allows cities to tailor their approach to electric mobility integration based on specific needs and infrastructure constraints [35].

While most of the research work highlighted the importance of communication networks for electric vehicles and charging stations [27, 28, 29, 30, 31, 32], the performance of communication network and the underlying communication infrastructures have been less defined and discussed.

- It is believed that communication networks will play an important role in electric vehicle coordination. There is a need to develop an IoEV architecture for real-time monitoring of electric vehicles and charging stations for numerous applications. Among these applications, charging scheduling (when electric vehicles should be charging/discharging at home/work/charging stations) while electric vehicles are parking, and charging station selection (where electric vehicles should be charged) while electric vehicles are on the move.
- Most studies assume that the communication network operates seamlessly and base their assumptions on this premise, overlooking the complexity involved when communication systems experience faults, delays, bandwidth limitations, etc. [36].

2.3 IoEV Services

Internet of Electric Vehicle (IoEV) services form the core for enabling electric vehicles to be part of smart cities. The interconnection and the exchange of information among them allow for the efficient management of urban resources, thereby enhancing the quality of life for residents. These services encompass a wide range of applications, including but not limited to traffic management and intelligent transportation systems (ITS), navigation for charging, smart parking lots, and energy trading.

2.3.1 Traffic Management

The ITS aims to use information about the real time traffic conditions on the streets to reduce trip time, congestion, pollution, etc. This can be done through the correct operation of traffic cameras and traffic lights. Also, ITS allows traffic diversions to be made when there are accidents to facilitate the arrival of rescue teams as well as reconfigure vehicle traffic to avoid congestion. Other services that can be enabled in the ITS are platooning to improve the safety and efficiency of passenger travel [28].

2.3.2 Navigation for Charging

One of the primary services required for electric vehicle users is accessing the real-time information regarding the locations of nearby EV charging stations. This is achieved through GPS technology which enables users to access details information about the physical facilities of interest, including charger types, connectors, and charging speeds. With this comprehensive information at hand, users can smartly-discriminate and prioritize based on their specific requirements [37].

2.3.3 Smart Parking Lots

From the perspective of EV users, real-time availability information of charging stations is crucial for deciding where to park and charge. The main objective is to match the user's requirements with the available services in the vicinity in order to find the optimal solution. This information should be seamlessly integrated into navigation platforms to prevent users from arriving at parking lots without available chargers. From the grid perspective, smart parking lots provide opportunities for managing charging to ensure grid stability. Additionally, they enable the utilization of EV batteries as distributed energy resources (DER), contributing to grid flexibility and resilience [38].

2.3.4 Energy Trading

EV users who park for a long period can buy/sell energy in smart parking lots from/to the grid or other users, depending on the prices. The EV users who do not need all the energy in their EV batteries can sell part of their energy at their convenience. An example of selling EVs are users who have renewable energies at home. Therefore, they can charge their EVs for a small cost and sell a part of this to the grid when the energy demand is high. This helps the grid stability, using the EV battery as a DER, and also gives an economical benefit for the EV user [39]. Below is an example for such scenarios.

- **Scenario 1:** An EV user with solar panels at home arrives, using the navigation platform, to a Smart Parking lot, as seen on Figure 2.4. The user estimates that he will stay at the parking lot for 4 hours. The EV user arrives with a battery of about 80% state of charge and needs only about 30% to go back home. So, this user has about 40% of the battery to sell during the stay. The user and the parking lot can agree on energy trading price, the amount of energy, and the time to complete the transaction. After 4 hours, the user will go back home with enough energy and a payment for the sold energy at the bank account. The EV state of charge in the process can be seen in Figure 2.5.

Figure 2.4: Selection process for a parking lot in Scenario 1

- **Scenario 2:** An EV user traveling a long distance needs to decide where to stop to charge his vehicle and continue with his journey. In this case, the availability and the time are crucial for this user. The EV user needs information about the available chargers that takes less time to charge the EV (EV user is not open to trade energy). In this case, the navigation platform will recommend a charging station on the route to charge. In this case, the parking lot will just sell the energy to the user.

An extensive review of related work is given in Table 2.1.

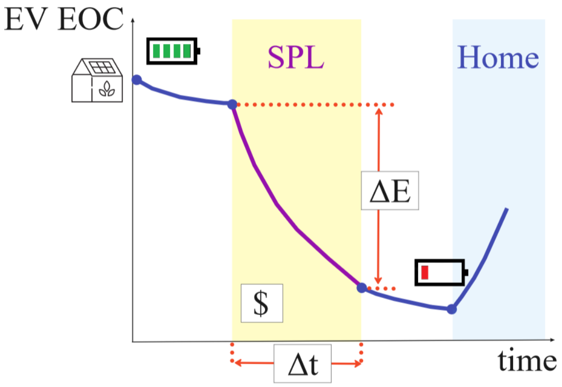


Figure 2.5: Battery Status of EV user for Scenario 1

Table 2.1: Comparison among related work. CS: charging station

Article	Year	Type	Networking Concept	Focus
[3]	2020	Technical	IoT	Develop a real time CS recommendation with reduced charging time and low economic costs
[4]	2014	Survey	IoEV	Survey on the role of information and communication technologies for grid integration of internet of electric vehicles
[7]	2018	Survey	IoEV	Overview of security issues for IoEV architecture and open research challenges
[8]	2021	Technical	Assume a communication network among CSs	Develop a two-stage integrated scheduling strategy for private EVs and ETs
[9]	2019	Technical	Assume vehicle location is known using GPS	Develop an energy management strategy for PHEVs with multiple frequent routes

Article	Year	Type	Networking Concept	Focus
[10]	2021	Survey	Vehicular communication for V2X	Survey on V2X use cases including the requirements and different 5G enabling technologies for vehicular communication
[11]	2020	Technical	Vehicular communication using LoRa technology	Evaluate the performance of LoRa technology for vehicular communication in urban mobility environment
[24]	2013	Survey	NA	Survey on battery chargers, topologies, charging power level, and infrastructure
[13]	2020	Technical	Ethernet and WiFi for a PL	Develop a simulation model for CSs in a campus PLs
[22]	2013	Survey	HAN, LAN, WAN	Survey on opportunities and challenges of grid integration of EVs including V2H, V2V and V2G technologies
[23]	2014	Survey	Wireless technologies for IoV and V2X	Survey on wireless solutions for IoVs including vehicle to sensor, vehicle to vehicle, vehicle to internet and V2I
[25]	2020	Survey	IoV for vehicular communication	Survey on the applications of mmWave communication for vehicles communications including MAC and physical layers
[26]	2020	Technical	Vehicular communication using LoRa technology	Present a LoRa based architecture for V2X communication including architecture design and prototype implementation

Article	Year	Type	Networking Concept	Focus
[40]	2019	Technical	e-mobility system architecture	Develop e-mobility system architecture model based on SGAM dimensions as well as mapping data and communication protocols
[41]	2023	Survey	Digital Twin, IoT, and IoV	Survey on digital twin technology for intelligent transportation system with focus on electric and autonomous vehicles
[42]	2022	Review	Digital Twin and CPS	Review digital twins applications in connected automated vehicles and ITS
[43]	2023	Technical	Digital Twin EV charging simulation using MATLAB	Develop a digital twin simulator for charging stations and electric vehicles to optimize the charging station
[44]	2020	Review	IoT and V2X	Present a review on emerging communication and computational technologies and standards for electric vehicles
[45]	2020	Technical	Message exchange between emulated EV and EVSE	Develop a communication model for electric vehicles charging and discharging based on IEC 61850 standard
[46]	2021	Technical	Message exchange between emulated EV and EVSE	Develop a co-simulation platform for EVs and CSs based on the information model of the IEC 61850 standard

Article	Year	Type	Networking Concept	Focus
[47]	2021	Review	IoEV and V2X	Present a survey on vehicle communication for electric vehicle charging coordination and management as well as the requirements
[48]	2019	Survey	IoT for Smart Grid	Survey on IoT-aided smart grid including architectures, prototypes, and future research direction
[49]	2015	Survey	IoT	Survey on IoT including technologies, protocols and applications
[50]	2018	Review	IoT for Energy System	Review on IoT in energy systems, challenges, and open research topics
[51]	2017	Survey	Security in IoT	Survey on IoT architecture, technologies, security and privacy
[27]	2023	Review	IoT	Review on charging infrastructure, charging technologies, and CS recommendation
[28]	2023	Review	IoT, IoEV	Review on QoS parameters for electric vehicles including scalability, resource allocation, latency demand, and capacity planning

EV: electric vehicle; ET: electric taxi; PL: parking lot; IoV: internet of vehicle; IoEV: internet of electric vehicle; V2X: vehicle to everything; DT: digital twin; CPS: cyber-physical system

2.4 Discussion and Limitations

In Chile, the current charging station network lacks information about the real-time status of charging points, availability of charging stations, and charging costs, which will impact the adoption of current electromobility plan. To the best of our knowledge, this is the first study for the performance evaluation of communication network to support the grid integration of electric vehicles in the distribution power system in Chile. The focus will be given for electric vehicle charging stations in Valparaiso region, Chile.

- This work aims to develop an IoEV architecture to support the integration of electric vehicles in the distribution power system. The proposed architecture consists of three layers: the physical layer, the network layer, and the virtual layer. The developed communication network model for monitoring the electric vehicle charging stations is based on IEC 61850-90-8 Standard. We evaluate the capability of different communication technologies for monitoring charging stations considering real scenarios including a standalone charging station, charging stations in a parking lot of a university campus, and charging stations in Vina del Mar City, Chile.
- LoRa-based communication is a promising candidate and is believed to play an essential role in supporting different IoEV applications. We investigated the feasibility of LoRa-based communication architecture for supporting various IoEV applications. The developed architecture has been simulated considering different real scenarios. Also, the developed LoRa-based architectures have been evaluated using off-the-shelf prototypes under practical scenarios on a university campus, and the performance of the communication network has been evaluated with respect to latency and network reliability.

3 | Internet of Electric Vehicles (IoEV)

3.1 IoT-Based Architecture for the Electric Vehicle System

There are different architectures and models available for smart grid and IoT [48, 49, 50, 51]. The basic architecture model of IoT system is a three-layer: perception layer, network layer, and application layer. Other architectures add more abstractions and extend the three-layer model to five-layer architecture, as shown in Figure 3.1. Such architectures have not yet converged into common architecture [49].

The perception layer (also known as objects layer or terminal layer) consists of various types of IoT sensing devices and actuators for information acquisition, monitoring and control. The network layer aims to enable mapping and transmitting the data collected from the perception layer to the application layer through various technologies such as ZigBee, WiFi, 4G/5G, etc. The network layer is a very important layer in IoT architecture because various communication technologies and network devices are integrated in this layer. The received information at the application layer is processed in order to support different applications.

A four layered architecture consists of a terminal layer, a field network layer, a remote network layer, and a master station layer. Compared with the three-layered architecture, the terminal layer and field network layer represent the perception layer. The remote network layer represents the network layer, and the master station layer represents the application layer. A five layered architecture consists of perception layer, object abstraction layer, service management layer, application layer, and business layer. The service management layer represents the role of the middleware layer which enables the support of different vertical services and applications. In this work, we considered the three-layer architecture because of its simplicity, and it is easy to apply [50].

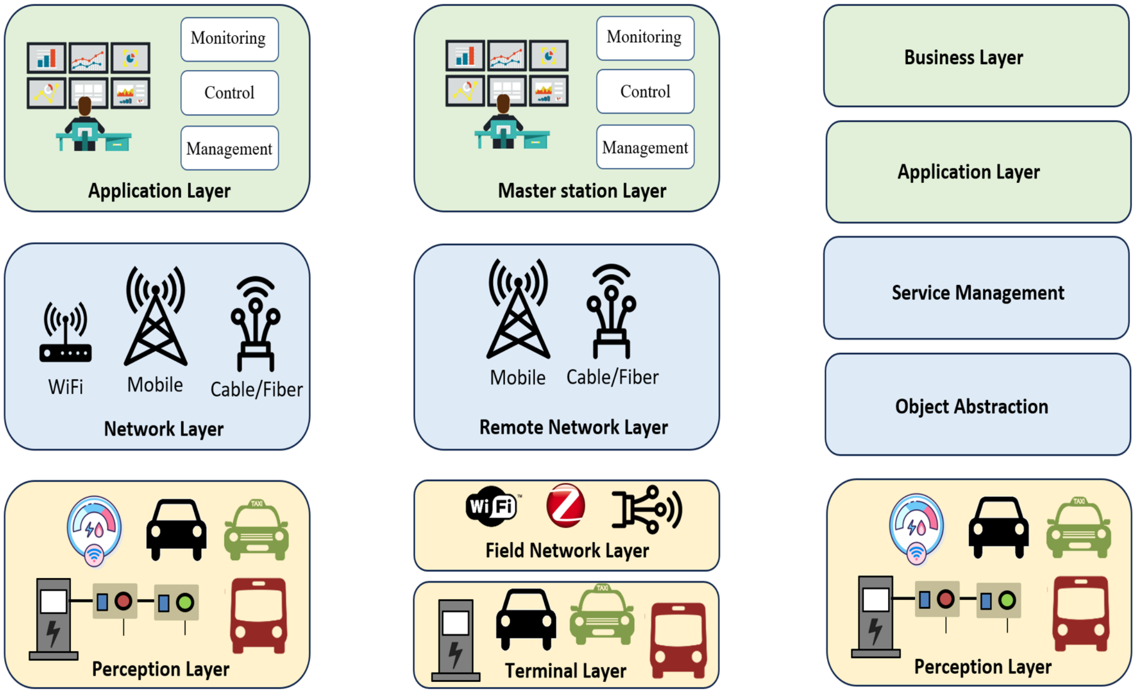


Figure 3.1: IoT-based architecture for the electric vehicle system

3.2 Developed IoEV Architecture

We defined the main entities of the electric vehicle system based on the smart grid architecture model (SGAM) [40]. The proposed architecture consists of different domains (power grid, energy transfer from/to electric vehicles, electric vehicles, and users) and zones (enterprise, operation, station, field, and process), as shown in Figure 3.2.

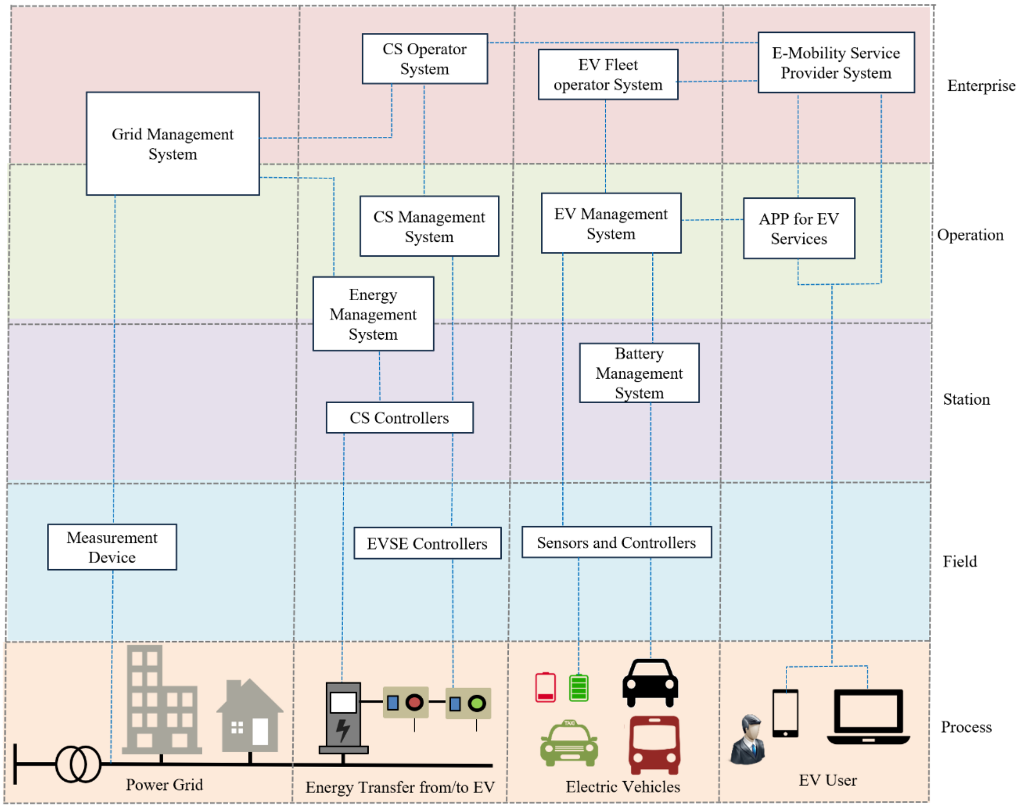


Figure 3.2: General architecture for electromobility based on smart grid architecture model

- **Power grid**: This contains the electricity system and the local power generation which support charging stations.
- **Energy Transfer from/to Electric Vehicles**: This includes charging station infrastructures and management systems for different services such as V2H, V2G, and V2V.
- **Electric Vehicle**: This includes different entities such as electric vehicles, electric buses, electric scooters, and electric bikes as well as the monitoring and management systems.
- **Electric Vehicle User**: This includes the end users' interfaces such as personal computers and mobile devices, as well as other services such as searching, reserving, booking, navigation, and route planning for charging stations or electric vehicles.
- **Process**: This includes the physical equipment. Such entities include, for example, the electric power grid, charging stations, electric vehicles, and end-user devices.

- **Field**: This includes the main equipment used for real-time monitoring, protection, and control of the power grid, charging stations, and electric vehicles.
- **Station**: This includes data aggregation for an area or zone such as a charging spot with many charging stations or internal communication of an electric vehicle.
- **Operation**: This includes the management system for the processing of data aggregated from electric vehicles or charging stations.
- **Enterprise**: This includes services for organizations and enterprises such as service providers, utilities, etc.

With the direction toward digital twin for electromobility, the presence of communication network is a key element for the difference among digital model (mimics physical object/system with no communication or data exchange), digital shadow (one-way communication from physical model to digital model), and digital twin (two-way communication from physical model to digital model) [41, 42, 43, 44]. In electromobility domain, the advances made in IoT, AI, and big data will enable digital twin concept to provide real-time data and services for end user and service provider.

We developed an architecture model for the electric vehicle system which consists of three layers: the physical layer, network layer, and the virtual layer, as shown in Figure 3.3. The main entities are the physical entities of the physical layer (PE), the digital models in the virtual layer (VM), the communication connection (CN) between the physical and virtual layers, the big data created (DD).

The physical layer consists of electric vehicles, charging stations, and other facilities. Sensor nodes and measuring devices are used to connect different entities in the physical layer to the network layer which transmit data such as traffic condition, vehicle speed and position, status of charging stations, etc. The network layer enables the communication and interaction between the physical layer and the virtual layer using different short-range and long-range communication technologies. At the virtual layer, different servers for data storage and decision-making tasks are used to support different services to the end-user and the service provider. Both real-time data and historical data are used to develop energy efficiency solutions, smart charging algorithms, etc.

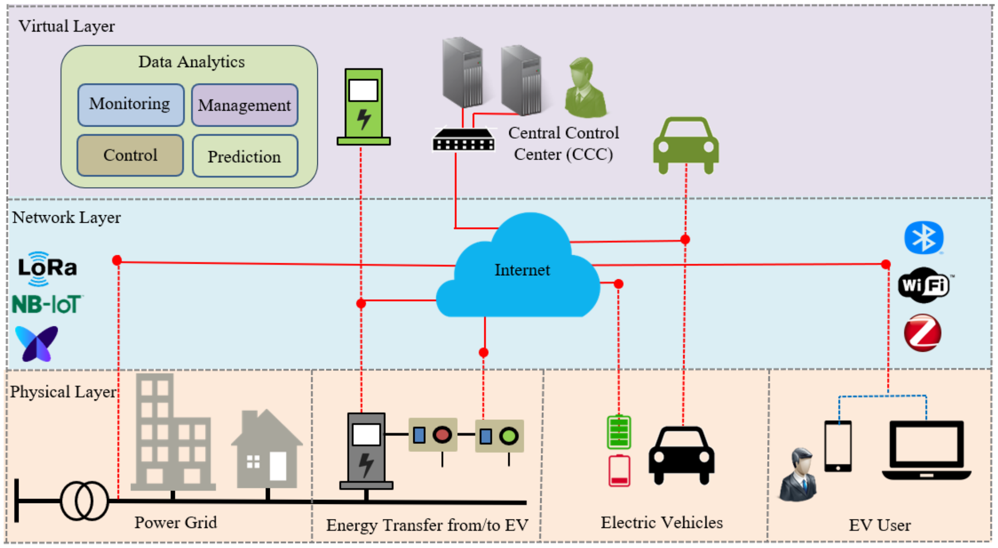


Figure 3.3: Proposed IoEV architecture model for the electric vehicle system

3.3 Data Model for Monitoring CS Based on IEC 61850 Standard

IEC 61850 standard has been used for modeling different smart grid components. In this work, based on IEC 61850-90-8 (object model for E-mobility), we defined the logical nodes for electric vehicle system [45, 52, 46]. The logical nodes contain the information related to monitoring and controlling the electric vehicle (EV) and electric vehicle supply equipment (EVSE), as shown in Table 3.1 and Table 3.2. In order to coordinate the communication between electric vehicle and charging station, the electric vehicle is equipped with electric vehicle communication controller (EVCC) while charging station is equipped with supply equipment communication controller (SECC) at the station side, as shown in Figure 3.4. The E-mobility operator is the legal entity which maintains and operates the charging stations.

Table 3.1: Logical node of EV based on IEC 61850-90-8 standard

Data Name	**Explanation**
Descriptions	
EVNam	EV nameplate
Status Information	
ConnTypSel	Selected connection type according to 61851-1
Measured and metered values	
SoC	State of Charge
Setting	
EVID	EVCCID Identifier
DpTm	Departure time
EnAmnt	Amount of energy required by EV
VMax	Maximum voltage supported by EV
AMax	Maximum current per phase supported by EV
AMin	Minimum current per phase supported by EV
SchdRef	Reference to schedule

Table 3.2: Logical node of EVSE based on IEC 61850-90-8 standard

Data Name	**Explanation**
Descriptions	
EVSENam	EVSE nameplate
Measured and metered values	
ChaV	Charging voltage
ChaA	Charging current
Setting	
EVSEID	EVSE ID Identifier
ChaPwrRtg	Rated max charging power of EVSE
ChaPwrLim	Charger power limit
ConnTypeDC	True = DC charging is supported
ConnTypPhs	True = AC n (n =1, 2, 3) phase charging is supported

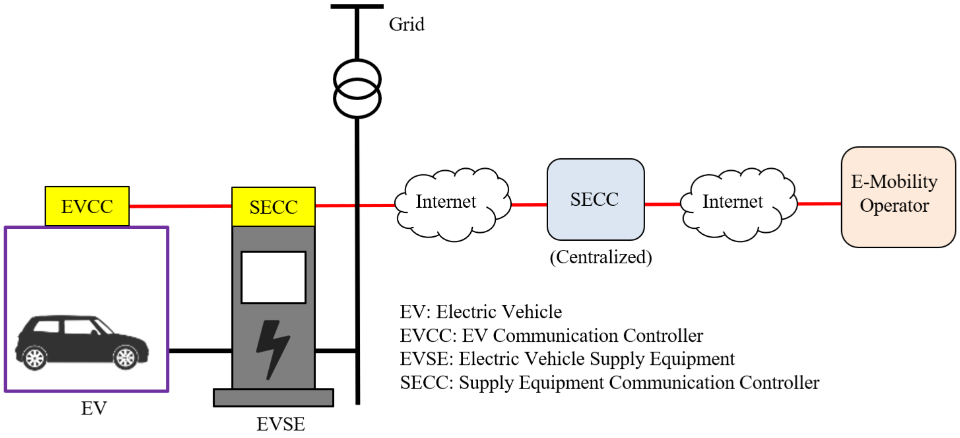


Figure 3.4: Schematic diagram for communication architecture for EVCS based on IEC 61850-90-8 standard

In general, there are different types of data transmission from EVCSs: random data and cyclic data. Examples of random data are alarm information and control commands while cyclic data are continuous and generated according to certain time intervals. Figure 3.5 shows the communication architecture for EVCS based on IEC 61850-90-8 standard. It consists of two parts: a real-time monitoring for information such as voltage and current, while the second part is related to protection and control information from various intelligent electronic devices (IEDs) including merging unit (MU), circuit breaker (CB) and protection and control (P&C).

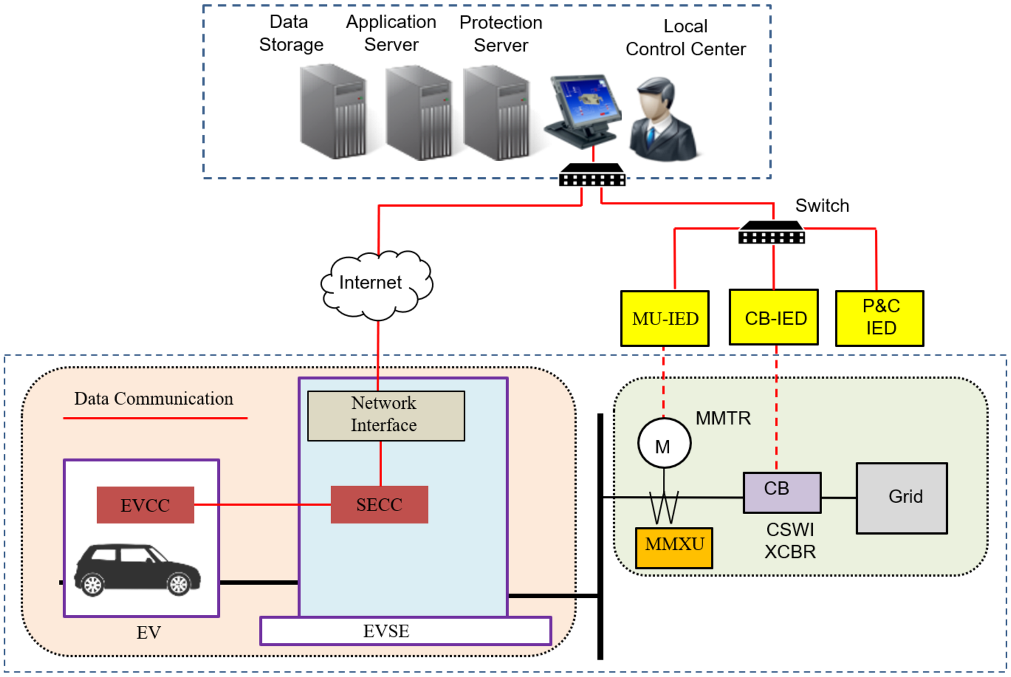


Figure 3.5: Communication network and information model for EVCS

3.4 Communication Requirements for IoEV

IoEV is based on a communication network in order to support real-time monitoring and control of electric vehicles and EVCSs. The communication standard and technologies could be divided into two categories: the first is related to home/building charging while the second is related to mobile electric vehicle charging. In general, the charging stations are connected to an energy management unit (EMU) in a home/building/city through a communication network. Such a communication is needed before charging (identification and authorization), during charging (charging parameters and battery information), and after charging (measurement and billing information). Based on the target application, there are different communication requirements such latency, bandwidth, reliability, and security for end-user (e.g., electric vehicle, aggregator, the utility). Among the most popular technologies for home/building are ZigBee, WiFi, and Ethernet. Note that the communication requirement between electric vehicle and charging station is in milliseconds, while communication between charging station and energy management unit is in the order of seconds [4, 47]. Table 3.3 shows different standards and communication technologies for IoEV.

Table 3.3: Communication Standard for different levels of IoEV

Level	**Standard/Technology**	**Application**
EV ⇔ EVCS	SAE, IEC	Energy Transfer
EVCS ⇔ EMU	ZigBee, WiFi, LoRa, 4G/5G, LTE, Cable	HAN, BAN, WAN
EMU ⇔ Grid	LoRa, 4G/5G, LTE, Cable	Charging Services
EV (on-the-move) ⇔ CC	LoRa, 4G/5G, LTE	Charging Services

4 | Network Modeling and Simulation Results

4.1 Network Modeling for Charging Stations

In this work, a network simulation tool (OPNET Modeler) is used to evaluate the performance of the communication network for charging stations under different architectures and configurations. The communication network is configured for charging stations connected to a local control center (LCC) and for a group of charging stations connected to a centralized control center (CCC), as given in Table 4.1. Such configurations could be through a public or a private network. Based on the coverage area and the scale size, different scenarios are considered including a standalone charging station (Figure 4.1), charging stations in a university campus parking lot (Figure 4.2), and charging stations in Vina del Mar City, Chile (Figure 4.3).

Table 4.1: Parameters configurations for simulation models

Scenario	Network	Configuration
Standalone charging station	1 Charging Station	1 workstation
	1 IED	1 workstation
	1 Server	1 Server
	LCC	1 workstation
	Switch	Ethernet Switch
	Media	ZigBee, WiFi, Ethernet
Charging stations in a parking lot, university campus	10 Charging Stations	10 workstations
	10 IEDs	10 workstations
	Server	1 Server
	LCC	1 workstation
	Switch	3 Ethernet Switch
	Media	Ethernet
Groups of charging stations in a city	7 Charging stations	7 Sub-networks
	1 Control Center	1 Server
	Cloud	IP32_Cloud
	Links	PPP_DS3, PPP_DS1

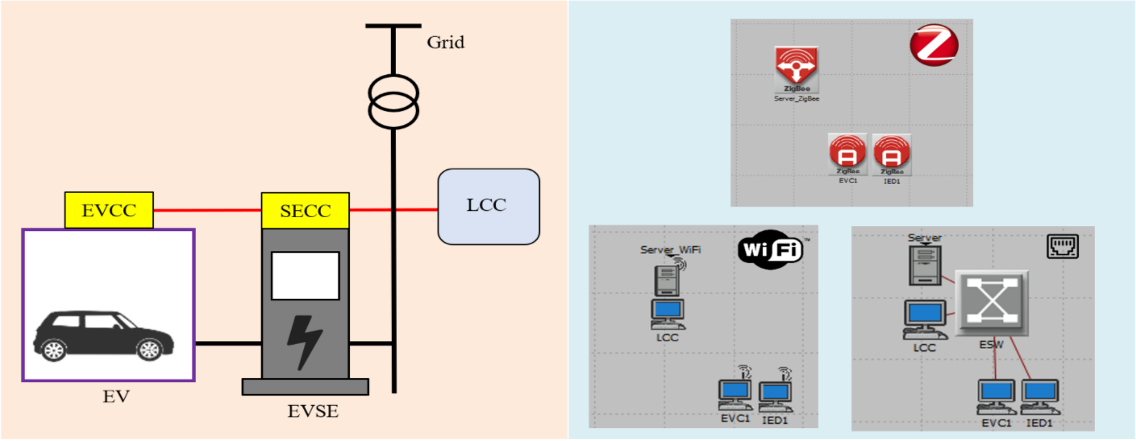


Figure 4.1: Communication network model for a standalone charging station using ZigBee, WiFi, and Ethernet

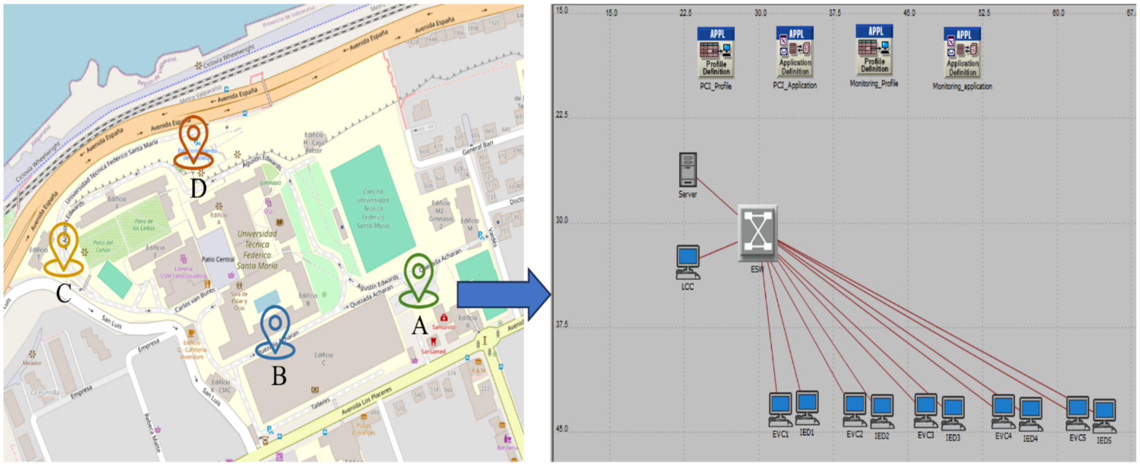


Figure 4.2: Locations of charging stations in parking lots at UTFSM campus, Valparaiso, Chile, and the simulation model of communication network

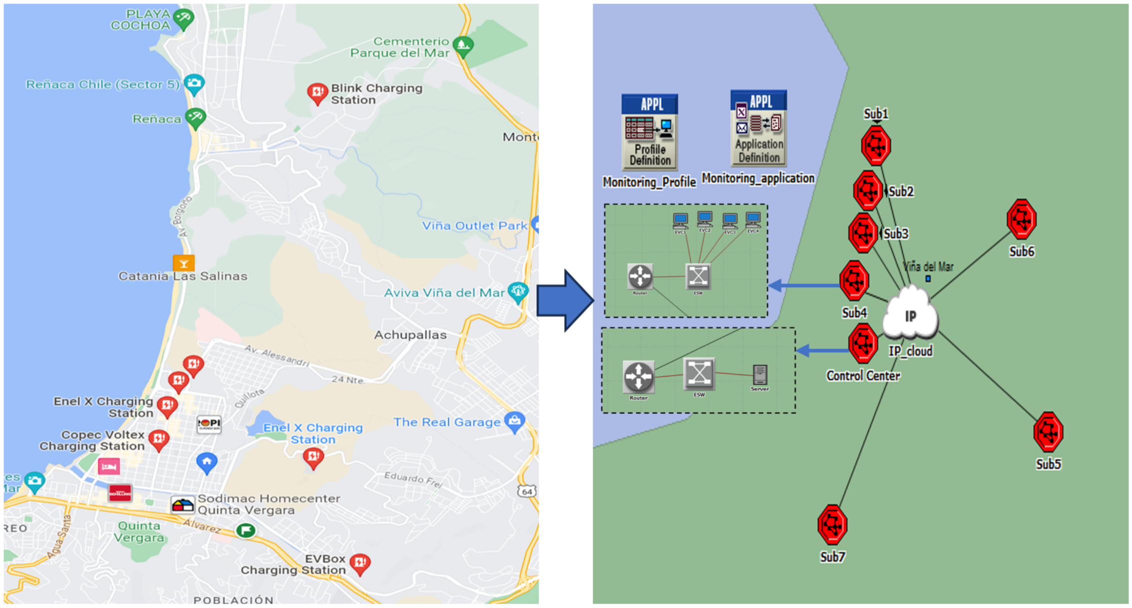


Figure 4.3: Google map with location of charging stations in Viña del Mar City, Chile, and the simulation model of communication network

For a standalone charging station, the scenario considers a single charging station connected to a local controller through a local area network. For the scenario of charging stations in a parking lot, we assume a future scenario where charging stations are installed in a parking lot in a university campus to support electric vehicles charging. The campus includes different parking lots in different zones. Each zone has a different layout, dimension, and the number of spots. Table 4.2 shows the data type and message exchange between the electric vehicle charging station (EVCS) and the local controller.

Table 4.2: Message exchange for EVCS

Source	Destination	Data Type	Data Rate
EVSE	LCC Server	Voltage	720 bytes/s
		Current	720 bytes/s
		Power	10 bytes/s
		Frequency	20 bytes/s
		Status Information	2 bytes/s
IED	LCC Server	CB-IED	16 bytes/s
		MU-IED	76,800 bytes/s
		P&C IED	76,816 bytes/s

To evaluate the network capacity and scalability, we selected the parking lot (A) in UTFSM, located near Building (C), because it is near the gate entrance which could support offering the charging service to university vehicles as well as other vehicles in the neighborhood. The parking lot dimensions are about 50 m x 15 m with a maximum capacity of about 40 parking spots. We considered a local control center (LCC) responsible for real-time monitoring of electric vehicles and charging stations. The LCC could also support real-time monitoring of other parking lots inside the campus. The traffic information for monitoring data and IEDs data have been configured in the simulation using profile definition and application definition. The traffic is generated every second from the charging stations and the IEDs and the destination is configured for the server of the local controller.

4.2 Standalone Charging Station

For the standalone scenario, three commonly used communication technologies are simulated using: Ethernet, ZigBee, and WiFi. The ZigBee-based architecture, based on IEEE 802.15.4 standard, supports a data rate of 250 kbps which is suited for applications with a short-range low-data transmission. For a standalone charging station, the results show that the total data received successfully by the ZigBee coordinator is 78,288 bps and the average end-to-end delay is 0.158 seconds. For Ethernet-based and WiFi-based architectures, Table 4.3 and Table 4.4 show the results for a standalone charging station. We consider different Ethernet channel capacities (10Mbps, 100Mbps, 1Gbps) and different WiFi data rates (11Mbps, 24Mbps, 54Mbps).

For the Ethernet-based architecture, the wired network configuration is simple and

Table 4.3: Ethernet end-to-end delay for a standalone charging station

EVCS	**Ethernet**		
	10 Mbps	100 Mbps	1000 Mbps
1	2.331 ms	0.233 ms	0.024 ms

Table 4.4: WiFi Average end-to-end delay for a standalone charging station

EVCS	**WiFi**		
	11 Mbps	24 Mbps	54 Mbps
1	1.921 ms	0.924 ms	0.601 ms

inexpensive. However, one of the drawbacks of Ethernet is the difficulty for changing the network topology after the network is placed. Therefore, we considered WiFi-based architecture, which is flexible and supports a high data rate compared with ZigBee-based architecture. Also, WiFi network is available in the university campus. The results for Ethernet-based architecture are given in Table 4.3. The end-to-end delay of all packets received by all the stations is about 2.331ms, 0.233ms, and 0.024ms for channel capacity of 10Mbps, 100Mbps, and 1Gbps, respectively. The results for WiFi-based architecture are given in Table 4.4. The average end-to-end delay is about 1.921ms, 0.924ms, 0.601ms, for data rate of 11Mbps, 24Mbps, and 54Mbp, respectively.

4.3 CS Network in a University Campus Parking Lot

For the parking lot scenario, we considered Ethernet-based architecture for a network of 5 and 10 charging stations. Data from EVSEs and IEDs are transmitted to the LCC. Table 4.5 shows the end-to-end delay for the parking lot. The end-to-end delay of Fast Ethernet and Gigabit Ethernet is about 2.309ms and 0.227ms, respectively.

Table 4.5: Ethernet end-to-end delay for a parking lot

EVCS	**Ethernet**		
	10 Mbps	100 Mbps	1000 Mbps
5	13.343 ms	1.110 ms	0.113 ms
10	30.732 ms	2.309 ms	0.227 ms

4.4 Charging Station Network in a City

We also considered the scenario of Vina del Mar City, Chile. There are different charging stations which are geographically distributed in the city. The developed communication model considers that each charging station is connected to a local control center (LCC) through a local area network (LAN) and the LCC is connected to a centralized local control center (CCC) via a router device. We developed the communication network model based on the available information on Google Maps for the number and the locations of electric charging stations. Figure 4.3 shows the map of Vina del Mar City, Chile, while Table 4.6 shows the name, location, and specifications of each charging station. Only 7 stations were considered because they have information while other stations have been discarded.

Table 4.6: List of charging stations in Vina del Mar city

Name	**Address**	**Type**	**Charging Slots**
Station 1	Mall Espacio Urbano	Fast Charging	(2) CCS, 60 kW (1) CHAdeMO, 60 kW (1) CHAdeMO, 50 kW
Station 2	Av. Libertad 1390	Slow Charging	(4) J1772, 7.4 kW (2) Type 2, 7.4 kW
Station 3	Av. Libertad 11 Nt.	Slow Charging	(1) Type 2, 3.9 kW
Station 4	6 Nte.(Copec)	Fast Charging	(5) CHAdeMO, 50 kW (3) CCS, 50 kW (1) Type 2, 43 kW (6) Type 2, 22 kW
Station 5	Shopping mall Jumbo	Fast Charging	(2) Type 2, 22 kW (2) Type 2, 11 kW
Station 6	Adolfo Ibanez University	Fast Charging	(2) Type 2, 22 kW
Station 7	Variante Agua Sta 4211	Fast Charging	(1) Type 2, 15 kW

We developed a communication network model consisting of 8 subnetworks (7 representing charging stations and one representing the control center). Each charging station subnetwork comprises a group of workstations, an Ethernet switch, and a router. Each charging station is configured to transmit the status of the charging spot and the charging status of electric vehicles to the local/remote control center. Such information could be used to schedule the charging and/or energy management. The communication links inside the LAN subnetwork have been configured with Fast Ethernet (100 Mbps). The connection to the internet has been configured through IP Cloud. The communication links were configured with PPP-DS1 (1.544 Mbps) and PPP-DS3 (44.736 Mbps). Table 4.7 shows the IP end-to-end delays between charging stations and the central control center. The delay results for PPP-DS3 are about 0.6 ms. Station 1 and station 7 show a higher delay of about 10 ms using PPP-DS1.

Table 4.7: IP End-to-End delay between charging stations and control center

Subnetwork		PPP-DS1	PPP-DS3
1	EVC1	8.380 ms	0.584 ms
	EVC2	8.380 ms	0.584 ms
	EVC3	10.750 ms	0.584 ms
2	EVC1	8.494 ms	0.582 ms
	EVC2	8.379 ms	0.582 ms
3	EVC1	8.378 ms	0.581 ms
4	EVC1	8.377 ms	0.580 ms
	EVC2	8.600.ms	0.580 ms
	EVC3	8.377 ms	0.580 ms
	EVC4	8.377 ms	0.580 ms
5	EVC1	8.381 ms	0.585 ms
	EVC2	8.381 ms	0.585 ms
6	EVC1	8.380 ms	0.583 ms
7	EVC1	8.8890 ms	0.586 ms

4.5 Prototype Implementation

To validate the developed architecture, we designed and implemented a low-cost IoEV platform (hardware and software) using SONOFF devices which support WiFi connectivity, as shown in Figure 4.4. WiFi technology has been selected as the university campus has a 100% coverage with WiFi networks. The firmware of SONOFF devices has been updated to support data transmission between SONOFF nodes and the server using MQTT protocol. The following services are supported in the current prototype:

- Real-time monitoring: the information received from SONOFF devices provides access to real-time information such as voltage, current, power, etc.

- Status information: the platform provides the status information of charging stations including on/off status.

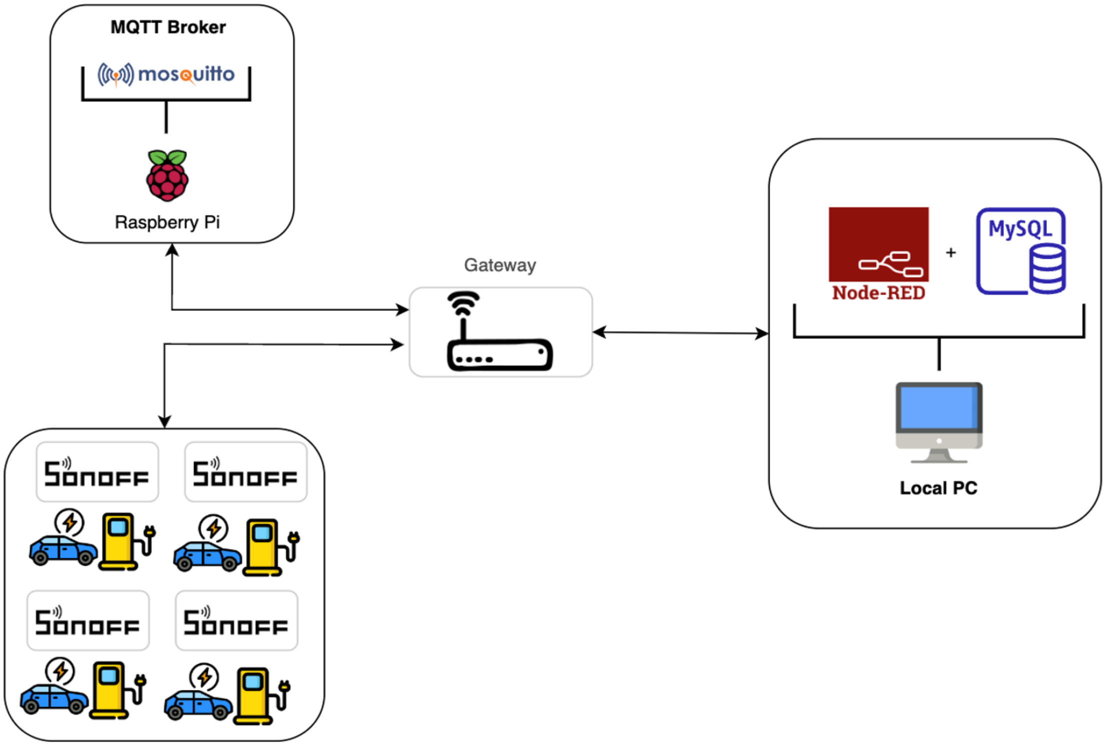


Figure 4.4: Testbed implementation of IoEV platform to validate the developed architecture

The developed testbed, shown in Figure 4.4, consists of an edge-based middleware system, utilizing a Raspberry Pi Model B as the MQTT broker, paired with a local PC for data processing. The Raspberry Pi runs Eclipse Mosquitto (https://mosquitto.org/), enabling the communication between the SONOFF devices and the PC. On the PC, we created a Node-RED dashboard for real-time monitoring of the charging stations, complemented by a MySQL local database for storing the historical data. Figure 4.5 shows the platform's main dashboard showing the location of the charging stations and four bottoms to access their consumption information. By clicking on each of the charging stations, we monitor in real-time the power, current, energy, and voltage, as shown in Figure 4.6. Data from charging stations was emulated by using appliances with similar on/off behavior.

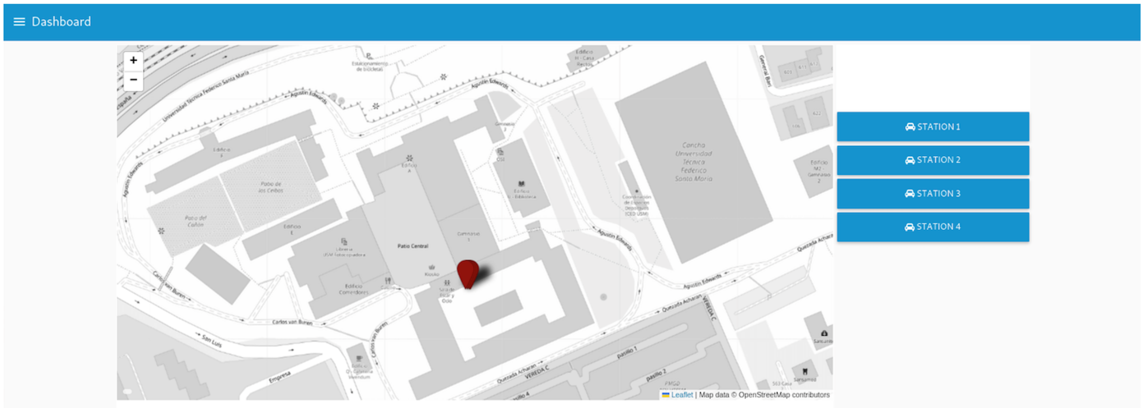


Figure 4.5: Platform main dashboard

Figure 4.6: Station 3 view shows information of status, power, energy, current, and voltage

Using a Raspberry Pi as an MQTT broker and a PC for data processing provide significant advantages for monitoring charging stations. This setup allows real-time data processing, enabling immediate insights and alerts for charging status and performance. Furthermore, it offers scalability, allowing easy expansion to accommodate multiple stations. The local processing reduces latency and ensures reliable operation independent of external networks. Custom dashboards via Node-RED and historical data storage in MySQL enable future tailored data analysis, predictive maintenance, and optimized usage. The system's low-cost and modular infrastructure supports effective control and automation, making it a cost-effective and adaptable solution for charging station management.

Our system achieves communication performance through minimal latency, measured at approximately 49.3 milliseconds average, and demonstrates a data throughput of approximately 0.0347 Kbps based on the provided MQTT message sizes. However, this very low throughput is likely due to the small size of individual MQTT messages and the relatively long-time intervals between them in the logs obtained. For a fair comparison with previous approaches, we need to analyze a larger set of data transmissions over a more extended period, considering factors like network stability and potential variations in message sizes. The developed architecture provides a local processing capability, coupled with reduced operational costs and easy scalability. Our platform not only provides a complete validated system with a user-friendly interface for real-time monitoring but also delivers enhanced performance and economic viability for managing EV charging stations.

4.6 Discussion

The design of a reliable communication infrastructure has a direct impact on the integration of electric vehicles and charging stations into the electric power grid. Such integration requires appropriate and efficient communication which is essential for supporting different applications and services. In this work, we developed an IoEV architecture for electric vehicle systems which consists of three layers: the physical layer, the network layer, and the virtual layer. We developed a communication network model for electric vehicle charging stations based on IEC 61850-90-8 standard. The developed communication network has been modeled and simulated using mostly used communication technologies including ZigBee, WiFi, and Ethernet. Various future scenarios were considered including a standalone charging station, a group of charging station in parking lot, a group of charging station in a city. Results show that wireless technologies such as ZigBee and WiFi can be used successfully for communication networks of a standalone charging station in home/building area network or a parking area network. Such wireless configurations could provide a low installation cost compared with Ethernet-based solutions. For a parking lot, Fast Ethernet and Gigabit Ethernet could be used to support a group charging station (10 charging stations) in a parking lot with an end-to-end delay of about 2.309 ms and 0.227 ms, respectively. This work contributes by providing an insight view into the performance of different communication technologies and their adequacy for the implementations of various future scenarios.

5 | LoRa-Based Architecture for IoEV

5.1 LoRa Technology for Electromobility

Nowadays, there are different platforms that facilitate electric vehicle users to search for available charging stations. However, in Chile, such solutions are still in the development phase, as there is nothing similar that allows sharing the real-time information of the status of charging stations. The absence of such platforms causes additional stress for users. In general, such platforms consist of three main layers: communication network, middleware, and interface. Each of these layers required an appropriate selection among different technologies to validate the decisions and technologies used.

Many research work considered LoRa technology as a promising candicade to support different applications for electromobility. The authors in [53] developed an efficient electric vehicle charging architecture based on LoRa communication to avoid the waiting time of electric vehicles at the charging station. The work considered LoRa, as a wireless communication technology, among electric vehicles and charging stations which is powered by a solar panel. The charging station informs the EV if it has the available resource to charge in order to reserve a spot; otherwise, it notifies the EV to come back later. This communication logic between different entities can be used to inform the EV user about the waiting queue for each electric station through different messages. The authors in [54] studied the LoRa-based communication system for data transfer in microgrids. The work considered LoRa communication between LoRa modules and a gateway. Node-RED has been considered to decrypt the message sent through LoRa to visualize the voltages measured by each node.

The authors in Ref. [26] considered the LoRa-based architecture for V2X communication. The LoRa-based device-to-device communication approach aims to reduce latency by offering direct communication among vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I), instead of routing the data through the LoRaWAN server. Tests and analyzes verify that the system can reliably communicate with infrastructure and other vehicles at speeds between 15 to 50 km/h. The authors in Ref. [55] presented a review article on the integration of vehicle to grid and renewable energy sources. The work included a comprehensive review and evaluation of the advancement of electric vehicles (EV) and their interaction with the smart grid. This includes both the strategy to integrate electric vehicles into the electrical grid, intelligent technologies of charging electric vehicles with the perspective of V2G (Vehicle-to-Grid) and the influence of renewable energy sources.

Authors in Ref. [56] discussed the communication requirements for EV demand management in urban environments, focusing on mobile communication between EVs and smart grids. The work considered the use of low power wide area network (LPWAN) as a possible alternative solution. The results showed that the technology LPWAN is capable of handling an adequate amount of information for the scenario proposed with the architecture. The authors in Ref. [57] developed a proof of concept for an IoT-based public vehicle tracking system using LoRa (Long Range) and Intelligent Transportation System (ITS) services for tracking public transportation service. Using test nodes, the work considered different experiments with communication between nodes and sending GPS information to the server. The work recommended the parameters for the optimal network configuration options based on your experiments. Table 5.1 summarize related work of LoRa based communication for supporting different applications for electromobility.

5.2 LoRa-Based Architecture for IoEV

In this work, the developed LoRa-based architecture for IoEV consists of three layers: perception layer, communication network layer, and application layer, as shown in Figure 5.1.

- **Perception Layer**: This is the lower layer of the architecture which represents all the peripheral hardware that interacts with the system. These entities correspond to, for

Table 5.1: Summary of related work for LoRa-Based communication.

Ref.	Type	Sensor Nodes	Communication Network Layer	Application Layer	Contribution
[53]	Technical	NO	YES	NO	Presented a design for the management of energy within the communication between Solar powered CSs and EVs.
[54]	Technical	YES	YES	YES	Presented a wireless communication based on LoRa for data transfer data in micro-grids.
[26]	Technical	NO	YES	NO	Presented communication technologies such as LoRa that play an important role in developing a secure and reliable communication.
[55]	Survey	NO	YES	NO	Analyzed and evaluated the interaction of EVs with smart grid and the future of electric energy model.
[56]	Survey	NO	YES	NO	Analyzed the communications needs for demand management of EVs in the urban environment focusing on mobile communication between EVs and Smart-Grid.
[57]	Technical	YES	YES	YES	Developed a monitoring system for public vehicles based on IoT, using LoRa technology and ITS services ITS for the improvement of public transport.

example, the electric vehicle and charging stations which are very important for data generation.

- **Communication Network Layer**: This layer considers the communication network devices (hardware and software) that are responsible for transmitting and interpreting the information sent. Different technologies can be used, both wired and wireless, to send and receive information from electric vehicles and charging stations.
- **Application Layer**: This is the last layer of the architecture which enable the end-user to access to the data and support different services and decision making.

5.3 Network Modeling and Simulation Results

This section shows the network modeling and the results obtained by both simulation and experiments using LoRa technology. The scenarios were classified into 3 groups: Theoretical (T) scenarios, Simulation (S) scenarios, and Experimental (E) scenarios.

Due to the characteristics of the LoRa technology such as its long range and low transmission data rate, it was thought to establish the following scenarios of interest for

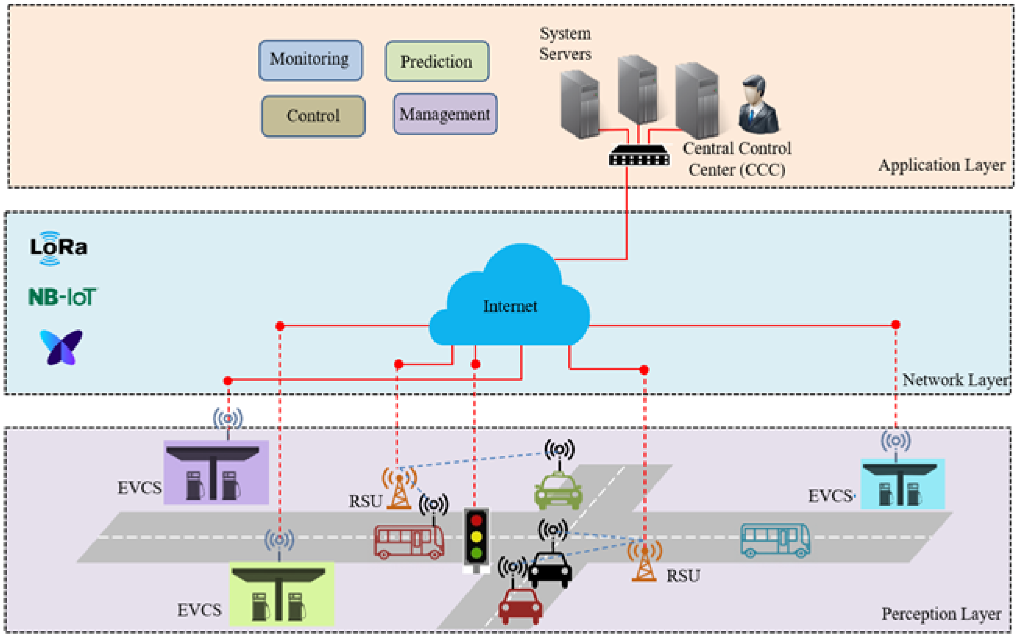


Figure 5.1: Developed LoRa-based architecture model for the electric vehicle system

Table 5.2: Description of Theoretical Scenarios

Scenario	Description
1T	One LoRa base station for a single parking lot
2T	Each parking lot with a LoRa base station
3T	One LoRa base station for many parking lots
4T	Roadside units (RSU) to gather vehicle information on movement

IoEV, as shown in Table 5.2.

In Scenario 1T, there is a standalone parking lot where a LoRa base station collects information and communicates with each charger within the parking lot, as shown in Figure 5.2.

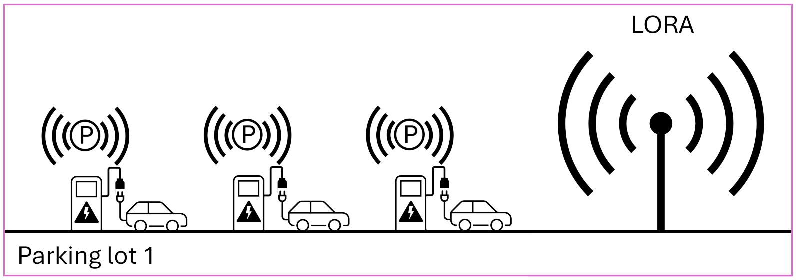


Figure 5.2: Scenario 1T. One LoRa base station for a single parking lot

The Scenario 1T can be replicated many times in different parking lot locations, representing Scenario 2T for a group of parking lots, as shown in Figure 5.3.

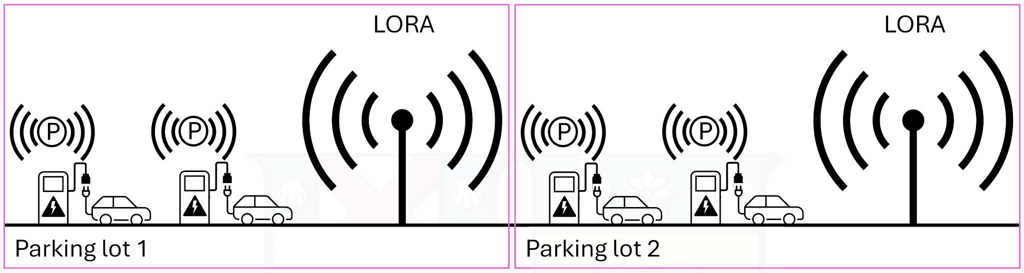


Figure 5.3: Scenario 2T. Group of parking lots and each parking lot with a LoRa base station

To reduce the number of base stations required for LoRa communication and take advantage of the LoRa range, it is possible to monitor more than one parking lot (within the coverage) with a single base station, as shown in Figure 5.4 and Figure 5.5. The Scenario 3T proposes that a single base station could serve multiple non-adjacent parking lots, leveraging the technology's range to enable communication for each charger.

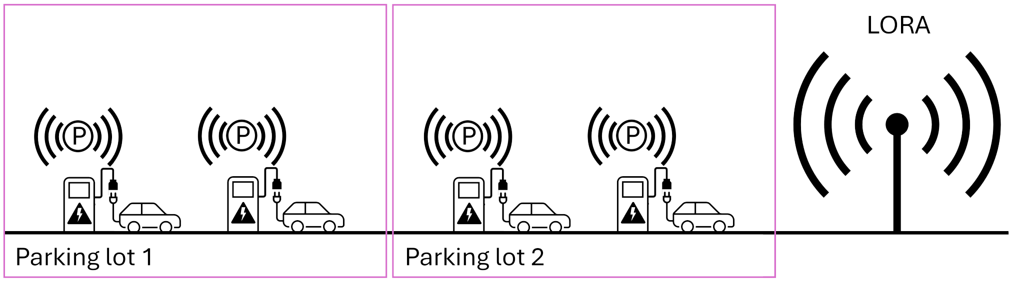


Figure 5.4: Scenario 3T. One LoRa base station for many parking lots

Figure 5.5: Scenario 3T. One LoRa base station for many parking lots (map view)

In a city where LoRa base stations are widely deployed, we can think about integrating LoRa base stations into IoEVs networks. Each of these LoRa base stations can operate as a Road Side Unit (RSU) to exchange useful information with EVs that are in range. The exchanged information can be, for example, the State of Charge (SoC), position of the vehicle, and availability of chargers nearby. This scenario is represented in Figure 5.6.

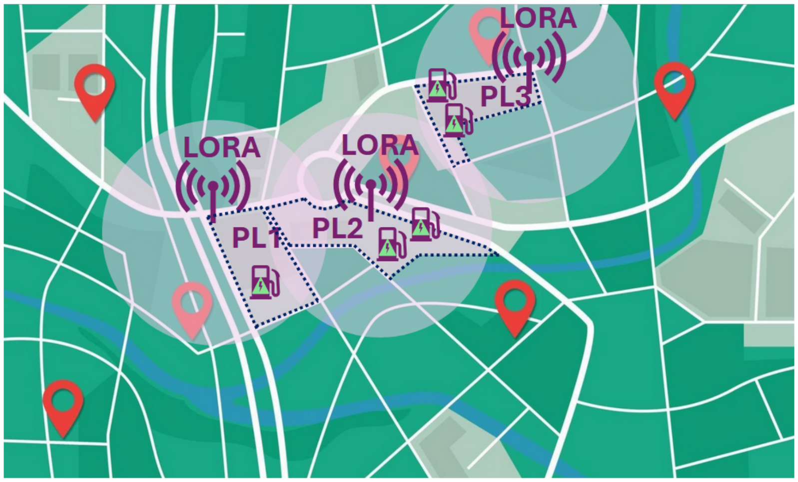


Figure 5.6: Scenario 4T. Road side units to exchange vehicle information on movement

To explore the potential applications of LoRa in facilitating communication between charging stations and electric vehicles, extensive simulations are being carried out for various scenarios using CupCarbon [58]. The CupCarbon simulation tool, renowned for its versatility in wireless technology simulations, encompasses a range of protocols including WiFi, ZigBee, and LoRa. Leveraging CupCarbon's capabilities, researchers can not only adjust communication radio parameters but also simulate scenarios involving both static and mobile nodes. This approach enables a thorough exploration of how LoRa technology performs in different urban environments, considering factors such as signal propagation, interference, and network scalability. By analyzing these simulations, valuable insights can be gained into the feasibility and efficacy of integrating LoRa into the infrastructure supporting electric mobility, paving the way for more informed decision-making and optimized deployment strategies.

Several simulations for a real environment were carried out at CupCarbon for a flat terrain and the vicinity of the UTFSM University, as described in Table 5.3.

Table 5.3: Description of Simulated Scenarios in CupCarbon

Scenario	Description
1S	Range test
2S	Stationary Node sending messages to stationary gateways
3S	Moving Node sending messages to stationary gateways on Route 1
4S	Moving Node sending messages to stationary gateways on Route 2
5S	Moving Node sending messages to stationary gateways on Route 3
6S	Moving Node sending messages to stationary gateways on Route 4

5.3.1 Scenario 1S

The first requirement we identified was to estimate the coverage range of a single LoRa node. To achieve this, we designed Scenario 1S, where a single LoRa node transmit messages to a LoRa reception node at various distances in a free obstacle and plain terrain without the interference of buildings or climate, as shown in Figure 5.7. The transmitter will send messages every 5 seconds and the receiver will change location every 100 messages received, covering distances of 3, 5, 10, 20, 50, 100, 200, 500, 1000, 2000, 5000 meters from the transmitter. For each scenario, certain parameters associated with LoRa, such as bandwidth and spreading factor, were varied. This systematic approach allows us to understand how different configurations impact the reach and reliability of LoRa communication, providing valuable insights into its performance under various conditions. The LoRa communication parameters were varied in terms of bandwidth (BW) [125, 250, 500 kHz] and spreading factor (SF) [7, 8, 9, 10, 11, and 12], totaling 18 different combinations. The coding rate (CR) was set to a fixed value of 4/5, which is appropriate for the scenarios we are studying [33].

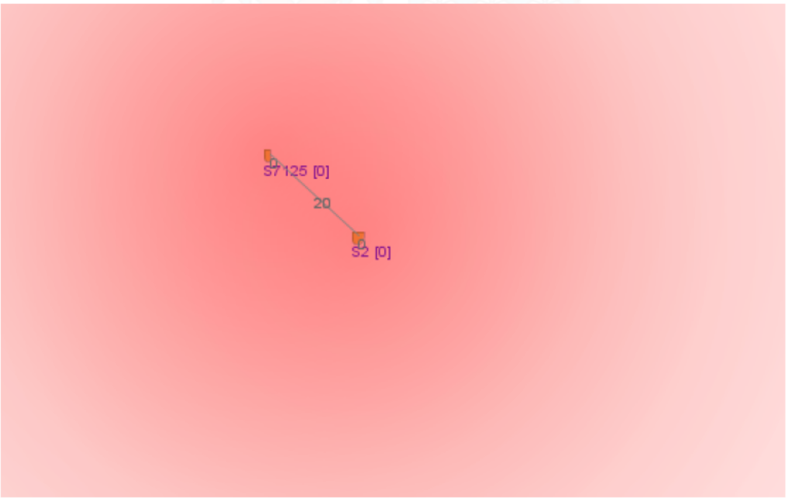


Figure 5.7: Scenario 1S: Transmitter and receiver nodes in flat sector

The results of Scenario 1S are displayed in Table 5.4 , where configurations with a successful link between the transmitter and receiver are indicated with a check-mark. From these results, we can infer that all configurations are reliable at distances less than 1 Km. It is also noteworthy that there are some configurations that exhibit reliable performance at distances of 2 Km and 5 Km. These configurations could be considered as promising candidates for deployment in Scenario 3T.

It is important to note that these results were obtained from simulations under perfect conditions. We anticipate that there may be differences in a real environment due to factors such as multi-path interference, movement, obstacles, and other environmental variables. Therefore, further testing and validation are necessary under real-world conditions to confirm the reliability of these configurations.

5.3.2 Scenario 2S

Scenario 2S consists of several nodes as LoRa base stations (gateways) and a fixed LoRa node sending messages. The idea is to demonstrate the reception of data between this fixed node and the base stations without movement. The LoRa configuration in CupCarbon is set with SF = 7 and DR = 2500. We will focus on looking for packet loss and seeing the energy consumed by transmitter node (vehicle). Figure 5.8 shows the locations of parking lots at UTFSM and Figure 5.9 shows the simulation scenarios with the existence of the

Table 5.4: Coverage for different configurations in Scenario 1S

Parameters		**Distance [m]**									
SF	BW	3	10	20	50	100	200	500	1000	2000	5000
7	125	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
7	250	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
7	500	✓	✓	✓	✓	✓	✓	✓	✓	X	X
8	125	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
8	250	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
8	500	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
9	125	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
9	250	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
9	500	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
10	125	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
10	250	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
10	500	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
11	125	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
11	250	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
11	500	✓	✓	✓	✓	✓	✓	✓	✓	✓	X
12	125	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12	250	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
12	500	✓	✓	✓	✓	✓	✓	✓	✓	✓	X

buildings that exist in the place. As we can see in Figure 5.8, there are five parking spaces, therefore, it was decided that each parking space will have their respective information collecting unit or LoRa gateway. These gateways are named GW_1, GW_2, GW_3, GW_4, and GW_5, which will be used in other simulation scenarios, while the LoRa node will be on the move for different routes inside the campus.

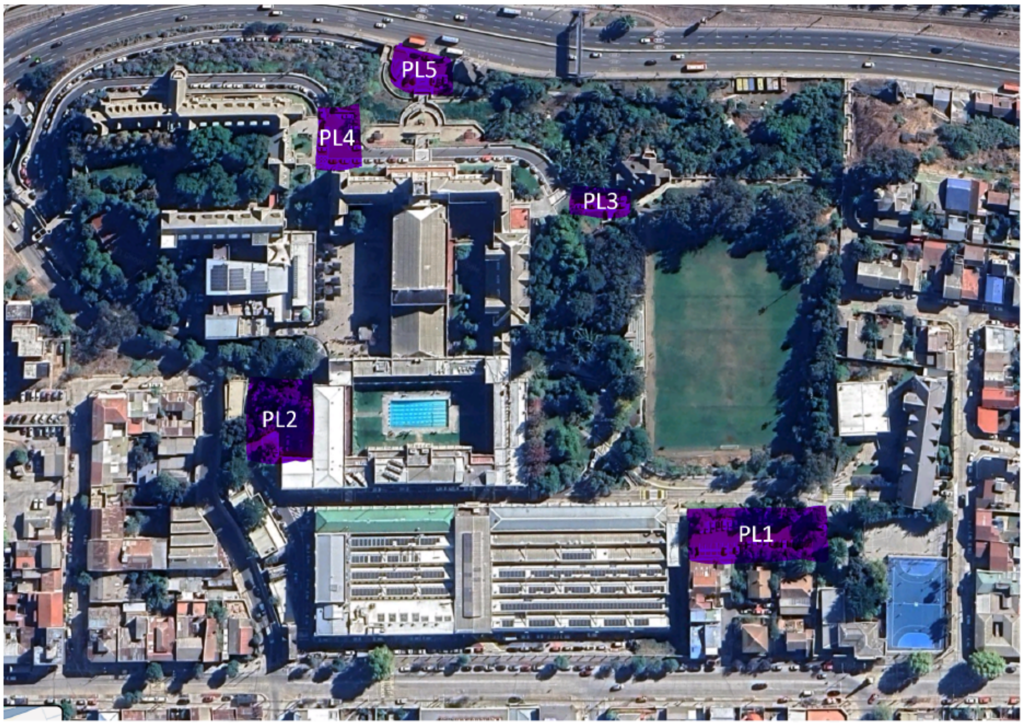


Figure 5.8: Location of the parking lots and LoRa gateways at UTFSM.

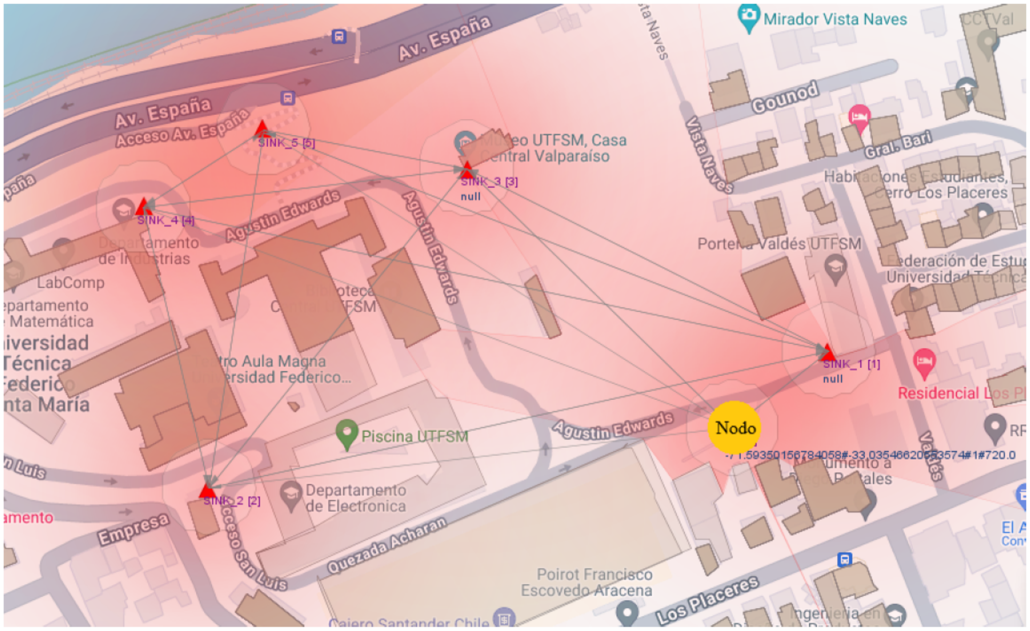


Figure 5.9: Scenario 2S. Stationary Node sending messages to stationary gateways.

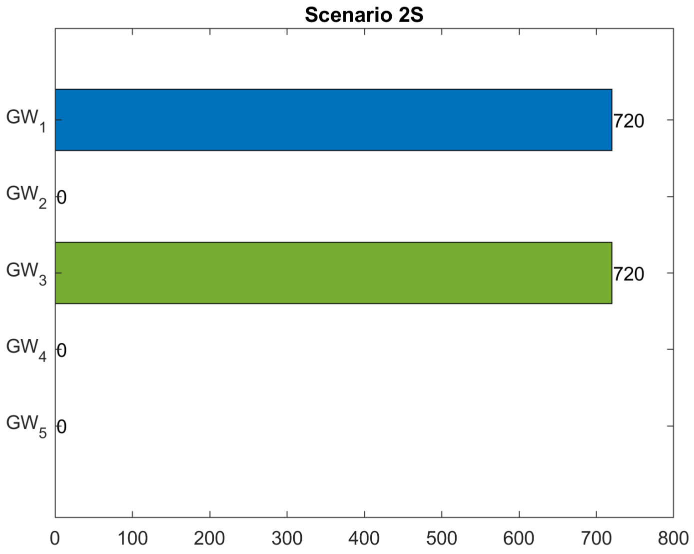


Figure 5.10: Received messages at each gateway for Scenario 2S.

For Scenario 2S, we consider a fixed node, as shown in Figure 5.9, near the parking lot 1 (PL1), where messages were sent every 5 seconds for a period of one hour, giving a total of 720 messages. The results in Figure 5.10 show the number of messages which are received by LoRa gateways that are within line of sight of the node. GW_1 and GW_3 were able to receive the sent messages. We can also realize that the messages received by one gateway may be duplicated in another gateway. This is because the messages sent by the node are in broadcast mode, which enables any gateway to receive them. The messages have the following format: «< lat > # < long > # < node_id > # < message_counter >», giving a maximum size of 43 bytes in each message.

5.3.3 Scenarios 3S, 4S, 5S and 6S

The Scenarios 3S to 6S are corresponding to the same fixed LoRa base stations (gateways) , given in Scenario 2S, but now the LoRa node is on-the-move traveling in 4 different routes. In those scenarios, a single LoRa node is occupied, which will follow a specific route, with an average speed of 20 km/h. The routes can be seen in the Figures 5.11, 5.12, 5.13 and 5.14. Each route starting point corresponds to each entrance to the UTFSM campus. As in the previous Scenario 2S, the messages are sent every 5 seconds, following the same format.

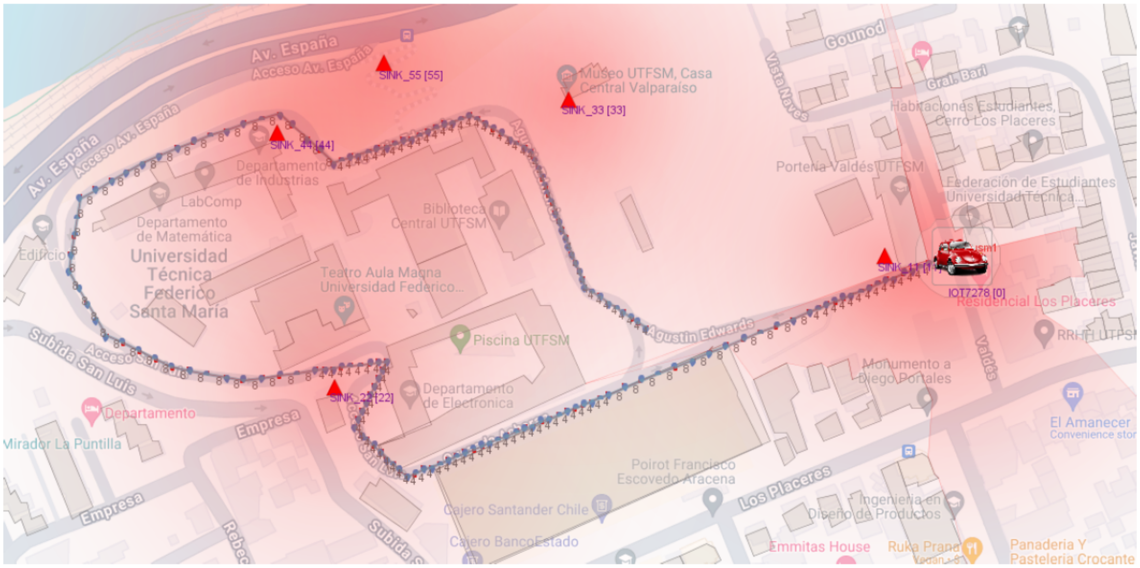


Figure 5.11: Scenario 3S. Moving Node sending messages to stationary gateways on Route 1.

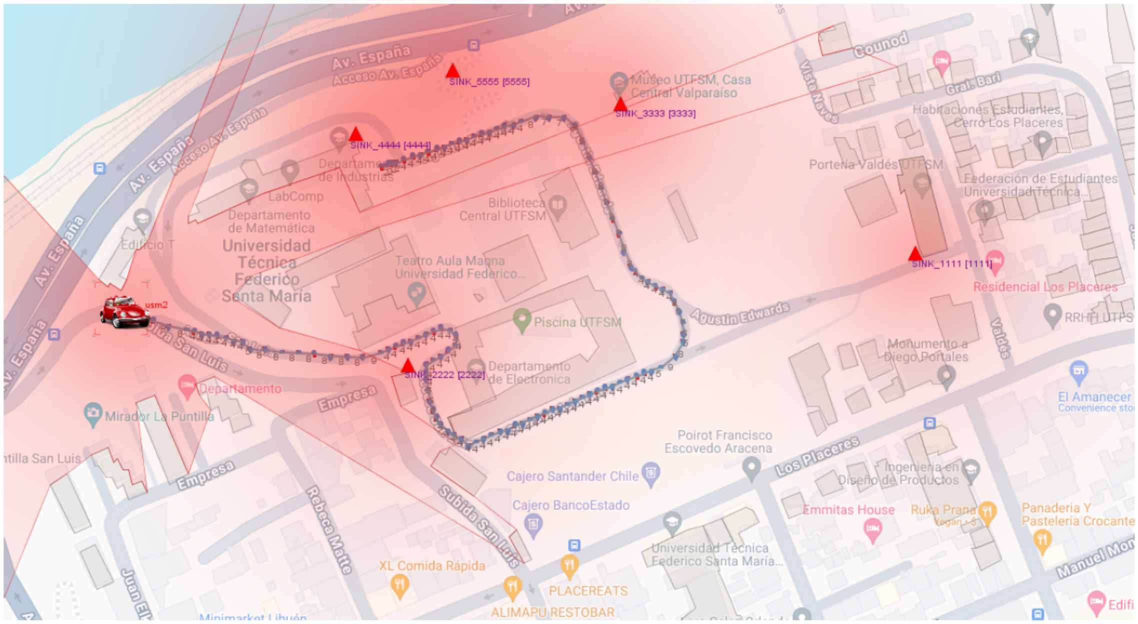


Figure 5.12: Scenario 4S. Moving Node sending messages to stationary gateways on Route 2.

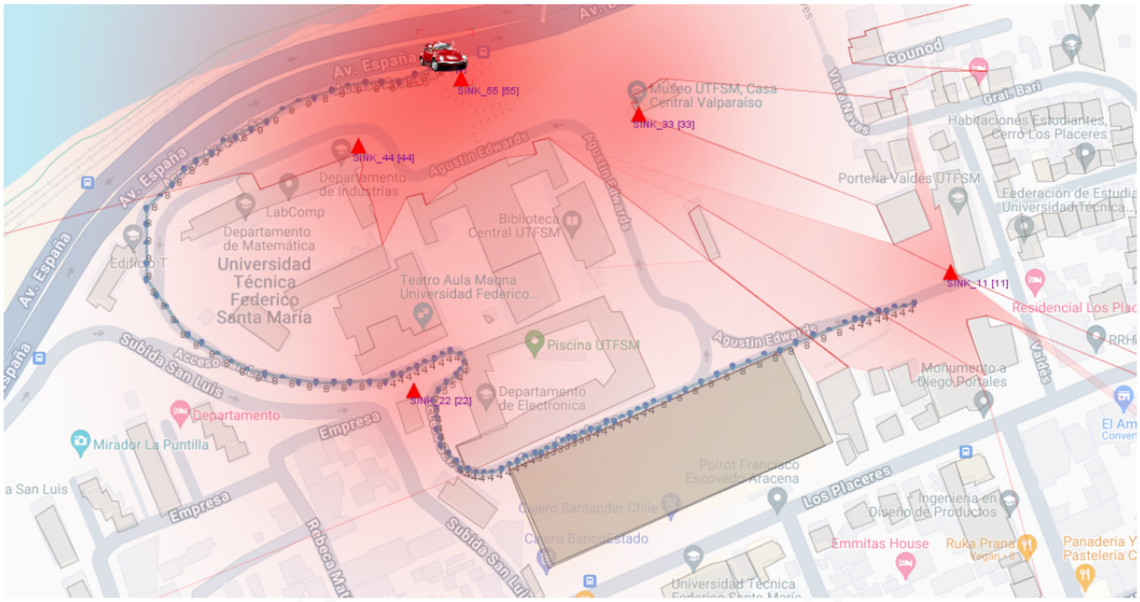


Figure 5.13: Scenario 5S. Moving Node sending messages to stationary gateways on Route 3.

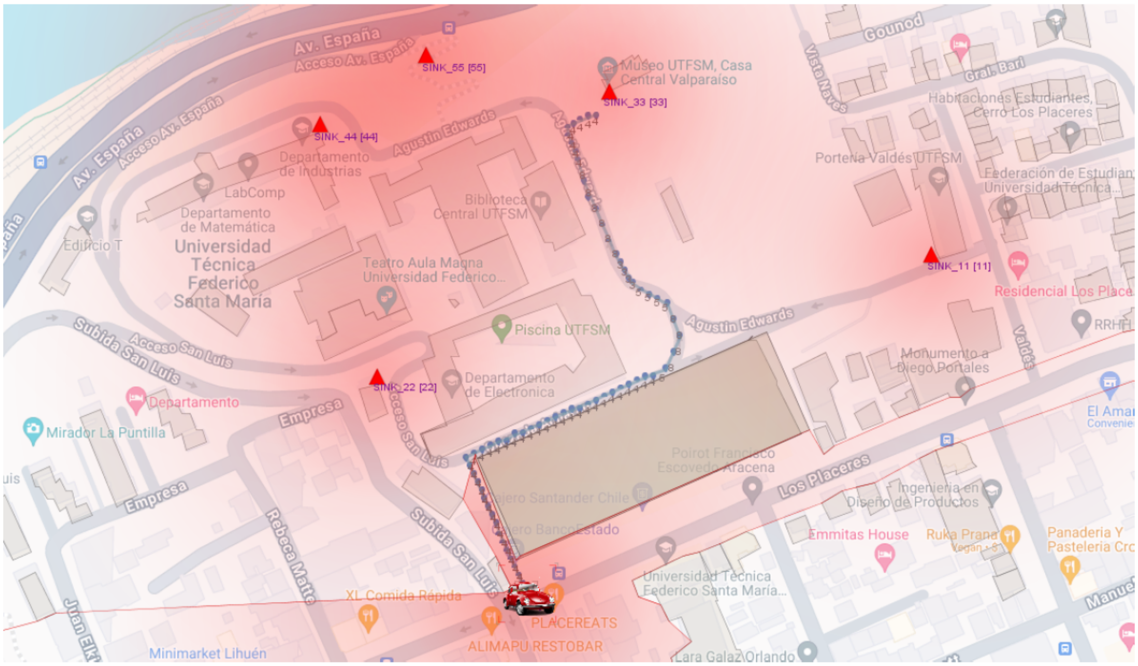


Figure 5.14: Scenario 6S. Moving Node sending messages to stationary gateways on Route 4.

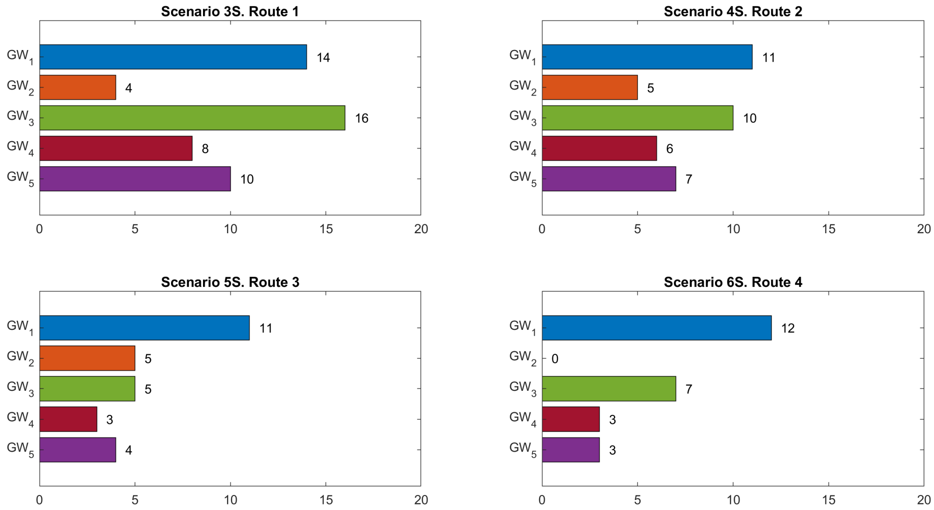


Figure 5.15: Received messages at each LoRa gateway for Scenarios 3S, 4S, 5S and 6S.

In Figure 5.15, we can see the number of messages received by each LoRa gateway along the route. Some of these messages are received by more than one LoRa gateway. To consider this condition, every message has a unique ID. After the simulations, we can filter: the number of messages not received, the number of messages received from only one gateway, and the number of messages received from more than one gateway. The result of this filtered information can be seen in Figure 5.16.

Figure 5.16: Total transmitted and received messages for each node in Scenario 3S, 4S, 5S and 6S.

Considering that the routes are different and the amount of messages sent is not equal in each scenario. We considered to calculate the package loss in each scenario, as shown in Table 5.5.

Table 5.5: Packet loss for Scenarios 3S, 4S, 5S and 6S for vehicle on the move.

Scenario	**Packet loss**
Scenario 3S	16.13 %
Scenario 4S	12.5 %
Scenario 5S	13.64 %
Scenario 6S	0 %

Table 5.6: Description of Experimental Scenarios

Scenario	Description
1E	Node to Node communication
2E	Node to Node communication with data storage
3E	Node to Gateway with data storage
4E	Node to Gateway with data storage and GPS coordinates

5.4 LoRa Prototype and Implementation Results

LoRa technology will play an important role in supporting different IoT-based solutions related to electric vehicle systems including EVs and charging stations due to low power consumption, high range, and low operation cost. To validate the developed LoRa-based architecture, we designed and implemented a low-cost IoT platform (hardware and software) to evaluate different scenarios. Different configurations for LoRa parameters have been evaluated such as received signal strength indicator (RSSI), Signal to noise ratio (SNR) and packets losses. The experiments were conducted with a LoRa node and a LoRa gateway. The experimental setup and data collection were done with the support of undergraduate students Mario Araya and Rudolf Hartmann.

The experimental (E) scenarios were created starting from the simplest one (Scenario 1E) as a proof of concept, up to a scenario with real GPS information (Scenario 4E). In all four scenarios, the test involved measuring the parameters RSSI, SNR, and packet loss at 10 different distances ranging from 6 to 60 meters, in a 6-meter increments (a distance of 6 meters typically corresponds to the length of a standard parking spot or the width of two parking spots side by side). The following scenarios were considered, as shown in Table 5.6.

In this work, for the configuration of the LoRa gateway and the LoRa sensor node, there is a need for a certain devices to be connected with their respective modules for a correct operation. We tried to use a Raspberry Pi 4B connected to a Dragino LoRa/GPS Hat. This device was selected for its availability in the laboratory and the versatility that this device has with IoT technologies, and with the number of libraries available to be used. Unfortunately, the use of this device was difficult to support the different configurations needed in the test cases. It was difficult to create a LoRaWAN server and also we were not able to use a specific BW. With this condition, it was not possible to continue with the Raspberry Pi option for creating the LoRa network. With this in mind, we tried another solution using LoRaWAN gateway with Dragino LG308-EC25, due to availability, versatility, and ease of use. With this solution, it was possible to change the previously mentioned parameters, as well as the possibility of connection with a MQTT server. All the 18 test cases carry out with their respective settings have been done with the gateway Dragino LG308.

The below section describes the implementation of the software configuration in the LoRa node, the LoRa gateway, and the network server.

- LoRa Gateway: A Raspberry Pi 4B was the first option. It was used as a LoRa gateway with a Dragino Lora/GPS HAT. To configure this device, Dragino's official documents were used [59]. After connecting the HAT to the Raspberry, it has to be configured, starting with activation of the SPI kernel module. In this way, we can communicate with the HAT module. Then different libraries were installed. Once the Dragino library was installed, the LoRa frequency, SF and the pins were configured using the file global_conf.json. Then, we run the program dual_chan_pkt_fwd in order to obtain the Gateway ID, which is equivalent to GateEUI in TTN. Having configured our LoRa service, we had to register it in TTN. If we want to register a gateway, TTN asks for the GateEUI,. With this, the Raspberry Pi was registered as a gateway on the TTN servers. Afterwards, the frequency spectrum and the Spreading Factor were requested, here it was indicated that they will be frequencies between 915-928MHz. There are a variety of frequencies used for uplink and downlink. This also involves the use of different SF and BW in a pre-configured way. Now, since these variables cannot be configured statically, that is, a frequency cannot be configured in particular to receive and/or send messages, nor the Spreading Factor or the Bandwidth. Being unable able to execute the test cases with the 18 different configurations with TTN, it was not possible to continue with the Raspberry Pi option for our implementation.
- Dragino LG308-EC25.: This was a second option. We used the Dragino LG308-EC25 gateway. To configure it, we enter the console through the browser by accessing the IP 10.130.1.1 with its respective username and password. We were able to configure different parameters, such as frequency, spreading factor, and bandwidth. In this

device, we have the option to configure different parameters, for example, choosing the frequency 917.1 MHz as the only frequency that we will use. This configuration is not the one used in TTN. Also, the gateway device allows us to decode messages that arrive via the ABP protocol and send them via MQTT to some private server.

- Network Server: We used Node-RED as a network server. Node-RED is a visual programming tool designed for IoT applications, emphasizing ease of use in connecting hardware devices, APIs, and online services. The Node-RED flows are subscribed to topics, where the first diagram (Figure 5.17) is a flow that is subscribed to an MQTT topic in which the messages from the node-RED connections arrive, specifically for the Scenario 2E.

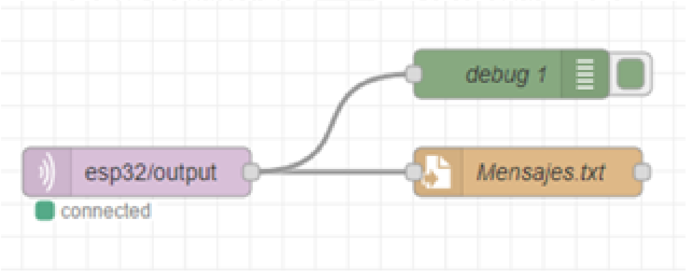


Figure 5.17: Node-RED configuration for Scenario 1E and Scenario 2E

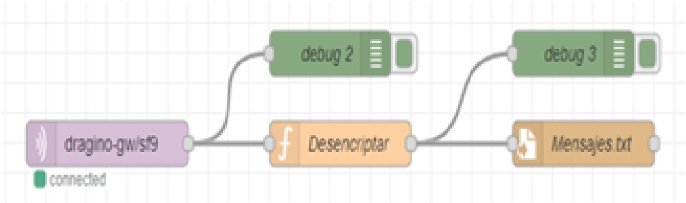


Figure 5.18: Node-RED configuration for Scenario 3E and Scenario 4E

The second diagram (Figure 5.18) is a flow which is subscribed to the topic where the node-gateway connection, through which each message that arrives is decrypted and saved in a plain text database. The messages of the Scenarios 1E, 2E and 3E have the following format: “Message <Message_Number>” format. For the Scenario 4E, the message format is «< Latitude >, < Longitude >, <message_number>».

- LoRa Node: There are different configurations for the LoRa nodes in our test cases, as given below:

(1) LoRa node data transmitter: this is equivalent to a LoRa node transmitting test

messages without security protocol, sending an unencrypted message at a given frequency, with modifiable spreading factor and bandwidth (used in Scenario 1E and Scenario 2E, Figures 5.19 and 5.20).

(2) LoRa receiver node: this is a LoRa receiver node without security protocol, receiving test messages at a given frequency, with modifiable spreading factor and bandwidth (used in Scenario 1E and Scenario 2E).

(3) LoRa transmitter node to TTN gateway with OTAA protocol: this is a LoRa node with keys of the OTAA protocol security granted by TTN, sending messages in a range of frequencies, with a spreading factor and bandwidth predetermined by TTN and not modifiable (not used in any scenario).

(4) LoRa node without GPS transmitter to gateway with ABP protocol: this is a LoRa transmitter node of test messages with ABP protocol keys extracted from TTN, but often, determined and modifiable spreading factor, and bandwidth (used in Scenario 3E, Figure 5.21).

(5) LoRa node with transmitter GPS to gateway with ABP protocol: this is a LoRa transmitter node of test messages with real-time GPS location and with extracted ABP protocol keys of TTN, with modifiable spreading factor, and bandwidth (used in Scenario 4E, Figure 5.22).

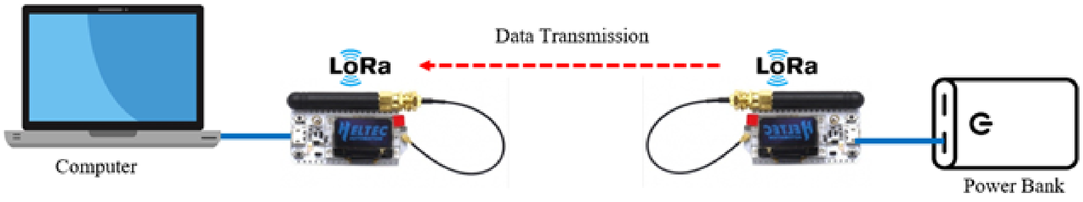


Figure 5.19: Scenario 1E Implementation

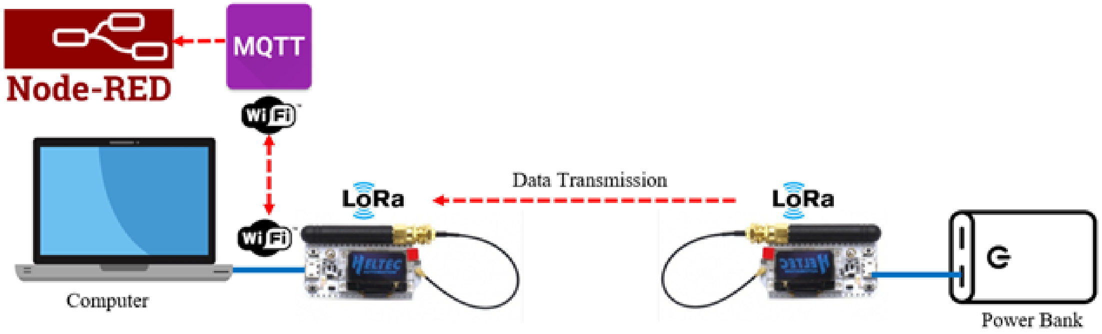


Figure 5.20: Scenario 2E Implementation

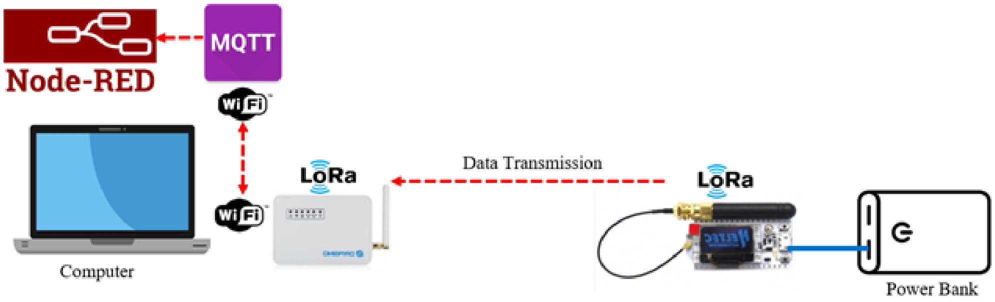


Figure 5.21: Scenario 3E Implementation

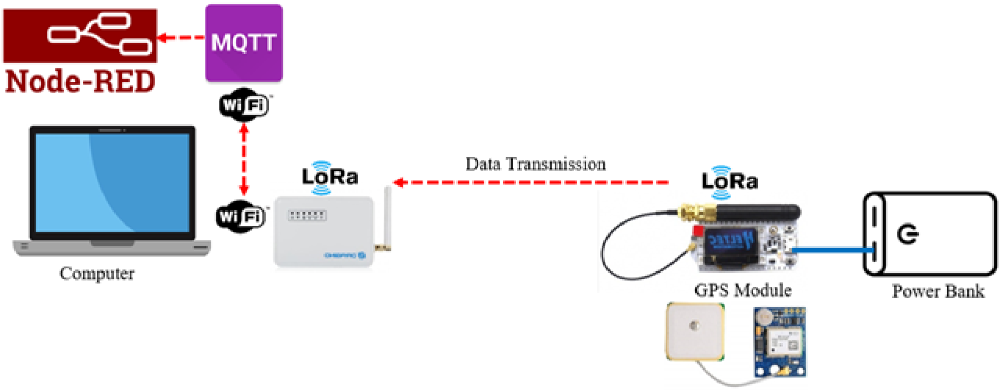


Figure 5.22: Scenario 4E Implementation

All scenarios were conducted with line-of-sight between the transmitter and the receiver. The Scenario 1E and Scenario 2E were conducted at the UTFSM university in an indoor space surrounded by walls. However, the Scenario 3E and Scenario 4E were conducted outdoor to incorporate GPS information into the measurements, as shown in Figure 5.24. For Scenario 1E, the same 18 parameters used in Scenario 1S were tested. Ten tests were conducted for each combination at every point along the 60 meters.

Figure 5.23: Scenarios 1E and 2E (indoor)

Figure 5.24: Scenarios 3E and 4E (outdoor)

5.4.1 Scenario 1E

The scenario 1E was done on 17 January 2024, between 02:00-06:00 PM, to validate 18 different configurations. The LoRa node was configured to send 10 messages every 6 meters along the walking path in front of B-110 in building B, UTFSM. The LoRa transmitter node was configured to transmit every 3 second to the LoRa receiver node which was connected to a notebook computer via USB.

Figure 5.25 shows the average RSSI at each position for the indoor scenario given in Figure 5.23. All the results for different combination of SF and BW for Scenario 1E are displayed in the same figure. Figure 5.26 shows the results for SNR at each position for the indoor scenario given in Figure 5.23. All the results for different combination of SF and BW for Scenario 1E are illustrated in the same figure.

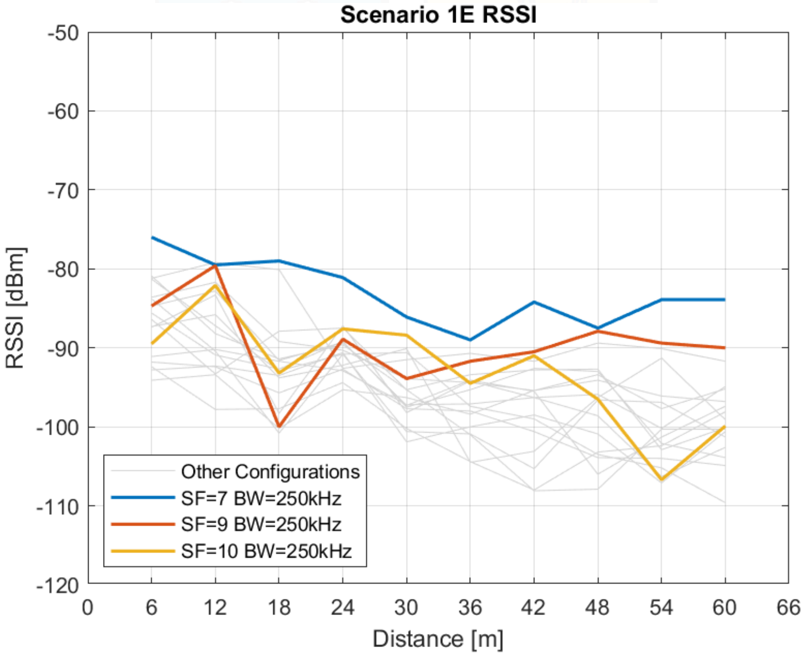


Figure 5.25: RSSI vs Distance values for the configurations used in Scenario 1E

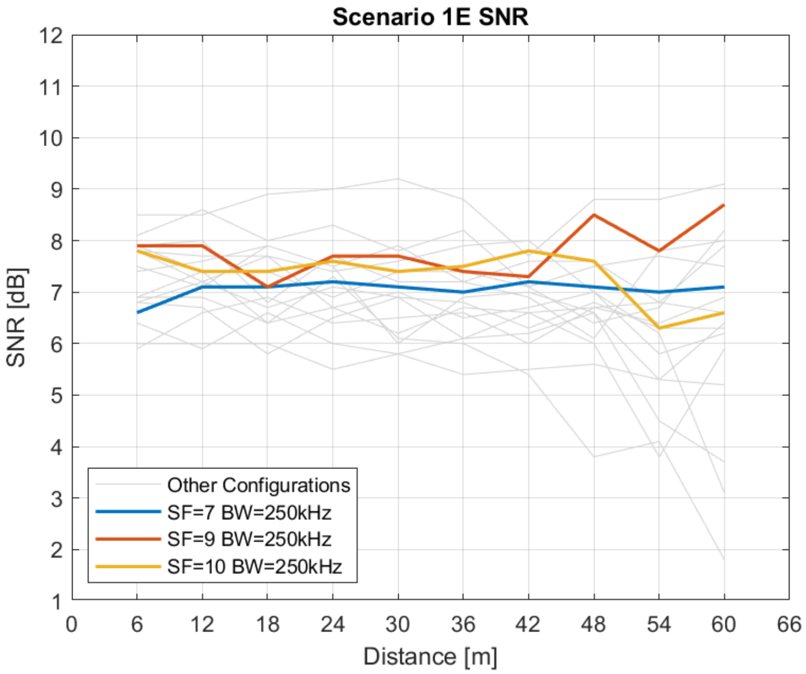


Figure 5.26: SNR vs Distance values for the configurations used in Scenario 1E

Since the first configuration, with SF=7 with BW=250 kHz, has a lower SNR than the other configurations, as shown in Table 5.7. The same colors remain in the graphs to make easier to follow the following experiments. Based on the measurements taken in the Scenario 1E, we have selected the best configurations to proceed with testing in Scenarios 2E, 3E, and 4E. The information obtained in Scenarios 2E and 3E serves as intermediate steps to reach Scenario 4E, where measurements are conducted with relevant information for the process.

Table 5.7: Results of average of RSSI and SNR for packet received in scenario 1E.

Configuration	Average RSSI	Average SNR	Packet Received
SF=7, BW=250 kHz	-82,14	7,1	100%
SF=9, BW=250 kHz	-88,16	7,8	100%
SF=10, BW=250 kHz	-90,74	7,4	100%

5.4.2 Scenario 2E

The scenario 2E was done on 18 January 2024, between 03:00-04:00 PM, in the same place of scenario 1E. The LoRa receiver node was configured for WiFi data transmission to a MQTT server connected on the notebook computer, with the same WiFi network using the Node-RED flow given in Figure 5.17. Please note that the WiFi connection was setup using a mobile phone hotspot. Figure 5.27 and Figure 5.28 show the results of RSSI and SNR, respectively. Table 5.8 shows the average RSSI, SNR, and percentage of successful packets received .

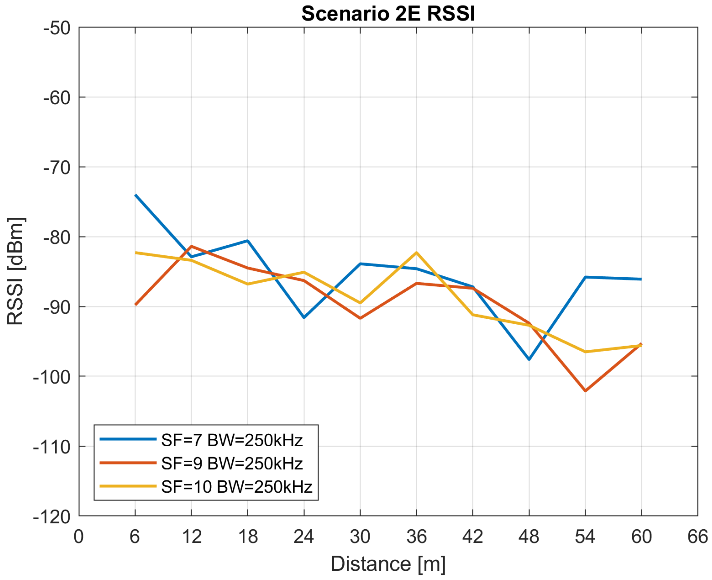


Figure 5.27: RSSI vs Distance values for the configurations used in Scenario 2E

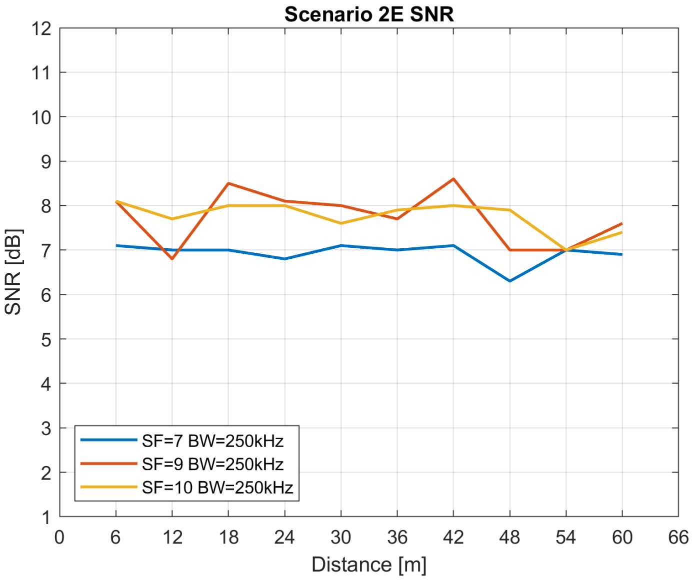


Figure 5.28: SNR vs Distance values for the configurations used in Scenario 2E

Table 5.8: Results of average of RSSI and SNR for packet received in scenario 2E.

Configuration	Average RSSI	Average SNR	Packet Received
SF=7, BW=250 kHz	-83,46	6,9	97%
SF=9, BW=250 kHz	-88,19	7,8	100%
SF=10, BW=250 kHz	-87,17	7,8	99%

5.4.3 Scenario 3E

The scenario 3E was done on 7 February 2024, between 04:00-06:00 PM, in Pirque, Santiago. In this configuration, we used a LoRa gateway to replace the LoRa receiver node. The gateway is connected to the same WiFi for the MQTT server and the node-RED is running on the notebook computer. The messages were configured to be sent every 10 seconds for the configuration of SF=9, and every 18 seconds for the configuration of SF=10. The received messages by the gateway were published to a MQTT topic for the node-RED configuration shown in Figure 5.18 . Figure 5.29 and Figure 5.30 show the results of RSSI and SNR, respectively. Table 5.9 shows the average RSSI, SNR, and percentage of successful packets received .

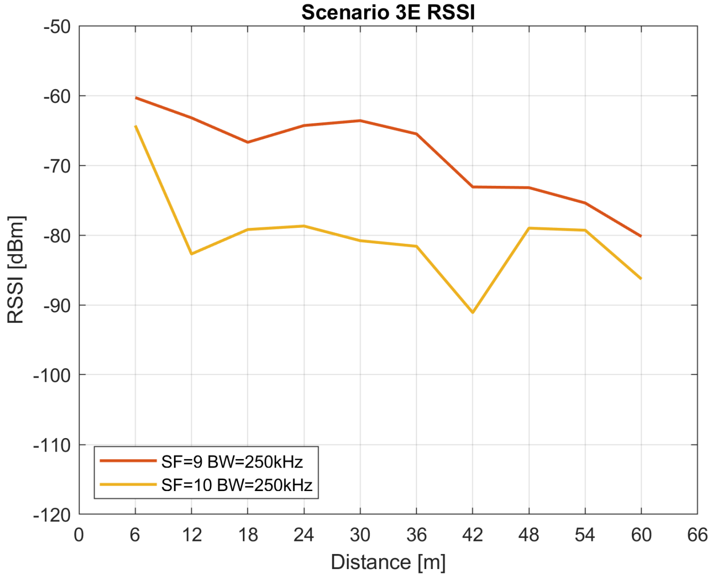


Figure 5.29: RSSI vs Distance values for the configurations used in Scenario 3E

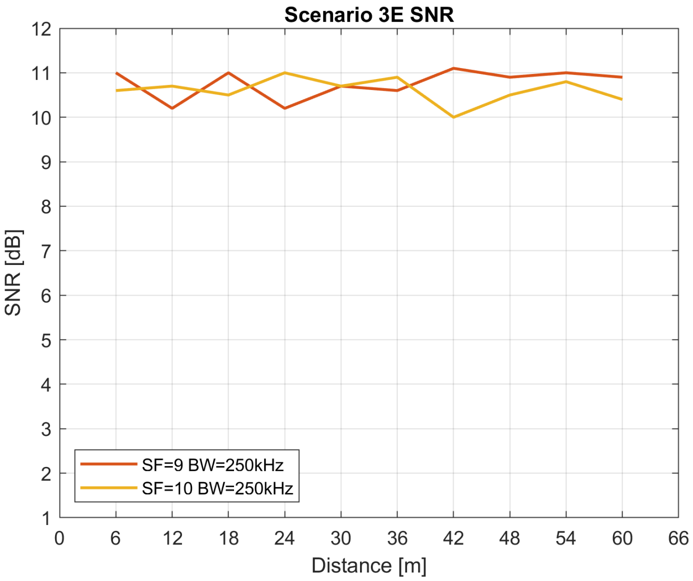


Figure 5.30: SNR vs Distance values for the configurations used in Scenario 3E

Table 5.9: Results of average of RSSI and SNR for packet received in scenario 3E.

Configuration	Average RSSI	Average SNR
SF=9, BW=250 kHz	-66,69	10,8
SF=10, BW=250 kHz	-77,20	10,6

5.4.4 Scenario 4E

The scenario 4E was done on 13 February 2024, between 05:00-07:00 PM, in the same place for scenario 3E (Pirque, Santiago). The data of the transmitted messages includes real-time information of latitude and longitude of the node. Figure 5.31 shows the RSSI level of Scenario 4E, while Figure 5.32 shows the SNR parameter of the same scenario. Both RSSI parameters decrease with the distances as expected and both have enough power for a reliable reception at 60 meters.

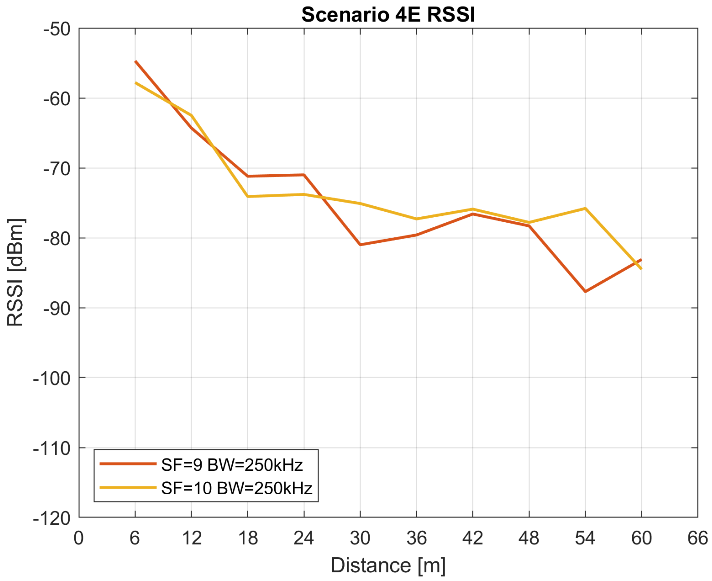


Figure 5.31: RSSI vs Distance values for the configurations used in Scenario 4E

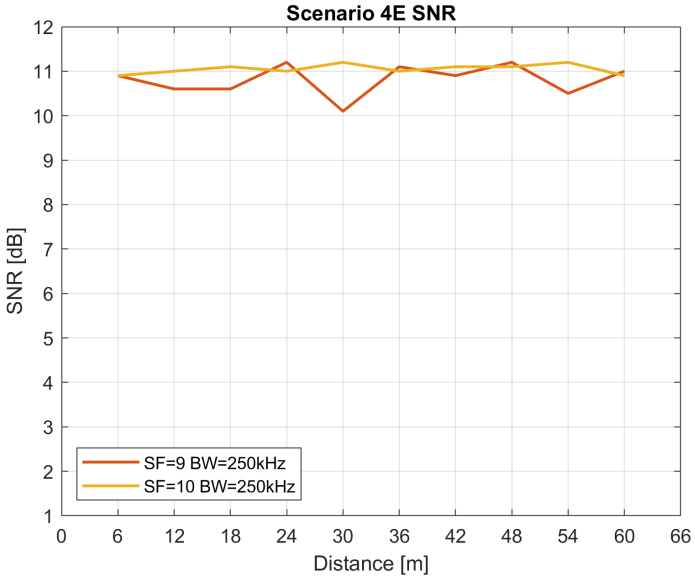


Figure 5.32: SNR vs Distance values for the configurations used in Scenario 4E

Table 5.10: Results of average of RSSI and SNR for packet received in scenario 4E.

Configuration	Average RSSI	Average SNR
SF=9, BW=250 kHz	-68,92	10,8
SF=10, BW=250 kHz	-69,73	11,1

The results of LoRa-based communication confirm the possibility of using LoRa communication to support communication among electric vehicles and charging stations in both open and closed environments. In this work, both the indoor cases (Scenario 1E and 2E) and the outdoor cases (Scenario 3E and 4E) are possible to cover a parking lot of 10 vehicles in length, or the equivalent of 20 vehicles in width, as the defined in our study case.

6 | Conclusions and Future Work

The design of a reliable communication infrastructure has a direct impact on the integration of electric vehicles and charging stations into the electric power grid. Such integration requires appropriate and efficient communication which is essential for supporting different applications and services. In this work, we developed an IoEV architecture for electric vehicle systems which consists of three layers: the physical layer, the communication network layer, and the virtual layer. We developed a communication network model for electric vehicle charging stations based on the IEC 61850-90-8 standard. The developed communication network has been modeled and simulated using mostly used communication technologies including ZigBee, WiFi, and Ethernet. Various future scenarios were considered including a standalone charging station, a group of charging stations in a parking lot, and a group of charging stations in a city.

Results show that wireless technologies such as ZigBee and WiFi can be used successfully for communication networks of a standalone charging station in a home/building area network or a parking area network. Such wireless configurations could provide a low installation cost compared with Ethernet-based solutions. For a parking lot, Fast Ethernet and Gigabit Ethernet could be used to support a group charging station (10 charging stations) in a parking lot with an end-to-end delay of about 2.309 ms and 0.227 ms, respectively. This work contributes by providing an insight view into the performance of different communication technologies and their adequacy for the implementations of various future scenarios.

LoRa-based architecture will play an important role in supporting several IoEV applications. The common point that most of these applications have is the low amount of data that needs to be transmitted. Furthermore, the advantage of LoRa over other technologies, available in the city, is its low power consumption and the long coverage range. This allows LoRa communication to support the information exchange in future smart parking lots and also LoRa gateways to be used as Road Side Units throughout the city. The combination of different simulation tools, such as OPNET and CupCarbon, together with the implementation of the prototypes in a real environment allowed us to have an extended understanding of what is needed and how to better integrate EVs into the Smart City.

As IoEV is a multilayer architecture with massive data generated from electric vehicle subsystems, fog and edge computing will play an important role in enabling IoEV architecture to provide better quality of services and a faster response. Instead of sending the data to the centralized cloud infrastructure, IoT devices could process the data at the network edge which will result in improving the bandwidth and latency. Our ongoing work aims to build a real testbed, in a laboratory environment, to validate the simulation results. Also, we aim to develop a complete digital twin platform where charging stations and electric vehicles could interact between the physical domain and the virtual domain through the communication network. Such a platform will enable real-time monitoring and management of EV systems where the collected data from charging stations and electric vehicles could be utilized to generate value-added services.

6.1 Contributions

- Mohamed A. Ahmed, Leonardo Guerrero Flores, and Patricia Franco “Network Modeling and Analysis of Internet of Electric Vehicles Architecture for Monitoring Charging Station Networks — A Case Study in Chile”, Sustainability, Vol. 16, No. 14, pp. 5915, July 2024, DOI: https://doi.org/10.3390/su16145915.
- Mohamed A. Ahmed, Leonardo Guerrero Flores, and Rudolf Hartmann “LoRa IoT-Based Communication Architecture for Internet of Electric Vehicles” In progress.

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A | Appendix

For Scenario 1E, the top 3 configurations were selected from the TableA.1. The criteria was to be over the average on RSSI and SNR from the Table A.2, then the highest 3 RSSI were selected. The three selected configurations are showed in Figure 5.25 and Figure 5.26 in color. The RAW data for Scenario 1E is avaliable on Table A.3 and Table A.4.

Table A.1: Scenario 1E Averages for RSSI and SNR for each configuration

SF	BW	RSSI [dBm]	SNR [dB]
7	125	-92,50	6,56
7	250	-82,14	7,05
7	500	-86,16	5,63
8	125	-92,01	7,14
8	250	-95,69	7,48
8	500	-89,91	6,73
9	125	-93,75	7,45
9	250	-88,16	7,81
9	500	-96,92	5,62
10	125	-94,24	7,42
10	250	-90,74	7,35
10	500	-90,73	6,88
11	125	-98,73	8,74
11	250	-96,45	6,85
11	500	-92,47	6,31
12	125	-94,23	6,50
12	250	-91,42	7,77
12	500	-92,79	5,82

Table A.2: Scenario 1E Averages for RSSI and SNR for all configurations

RSSI Average [dBm]	SNR Average [db]
-92,17	6,95

Table A.3: Scenario 1E RAW data for RSSI for all configurations and distances

Configuration		**Distance [m]**									
SF	**BW [kHz]**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**48**	**54**	**60**
7	125	-87,30	-85,80	-93,80	-92,20	-90,10	-104,50	-103,10	-96,30	-91,30	-99,10
7	250	-76,00	-79,50	-79,00	-81,10	-86,10	-89,00	-84,20	-87,50	-83,90	-83,90
7	500	-81,20	-79,20	-80,10	-92,60	-91,50	-90,70	-91,70	-89,40	-90,10	-91,70
8	125	-81,30	-87,20	-92,90	-90,80	-90,60	-97,40	-99,00	-103,50	-105,20	-109,60
8	250	-94,10	-93,40	-100,20	-95,30	-96,30	-98,40	-95,40	-93,40	-97,70	-95,20
8	500	-83,60	-81,70	-89,20	-90,30	-93,90	-94,40	-95,40	-94,10	-96,10	-96,80
9	125	-86,40	-93,30	-87,90	-87,50	-95,30	-101,00	-108,10	-107,90	-100,30	-100,30
9	250	-84,70	-79,60	-100,00	-88,90	-93,90	-91,70	-90,50	-87,90	-89,40	-90,00
9	500	-91,80	-92,40	-95,70	-92,70	-97,70	-98,00	-100,60	-103,90	-104,00	-104,90
10	125	-83,80	-90,40	-100,80	-90,80	-100,60	-100,90	-105,30	-96,60	-96,90	-101,30
10	250	-89,50	-82,10	-93,20	-87,60	-88,40	-94,50	-91,00	-96,50	-106,70	-99,90
10	500	-80,90	-88,20	-91,40	-89,60	-95,30	-93,40	-92,80	-92,70	-102,90	-100,10
11	125	-92,40	-97,80	-97,70	-94,40	-100,20	-104,40	-108,00	-103,20	-102,40	-98,10
11	250	-92,80	-92,30	-93,50	-90,60	-101,90	-100,00	-98,50	-100,90	-107,10	-100,60
11	500	-87,40	-83,30	-98,30	-87,20	-98,20	-94,20	-96,30	-98,60	-106,30	-102,60
12	125	-91,10	-90,20	-91,70	-92,90	-97,20	-97,10	-96,30	-95,90	-100,20	-94,90
12	250	-84,70	-82,80	-91,60	-89,30	-97,30	-94,10	-95,50	-106,00	-101,30	-97,40
12	500	-85,60	-90,90	-92,70	-89,20	-97,50	-95,30	-92,60	-93,00	-102,10	-103,90

Table A.4: Scenario 1E RAW data for SNR for all configurations and distances

Configuration		**Distance [m]**									
SF	**BW [kHz]**	**6**	**12**	**18**	**24**	**30**	**36**	**42**	**48**	**54**	**60**
7	125	6,8	6,7	5,8	6,5	6,9	6,1	6,6	6,7	6,8	6,6
7	250	6,6	7,1	7,1	7,2	7,1	7,0	7,2	7,1	7,0	7,1
7	500	6,0	6,0	6,0	5,5	5,8	5,4	5,5	5,6	5,3	5,2
8	125	7,8	7,7	7,7	7,4	7,6	7,9	8,0	7,0	6,2	3,1
8	250	7,9	8,0	6,8	7,7	7,2	7,2	7,6	7,6	6,8	7,9
8	500	6,8	7,2	6,7	7,1	6,9	6,8	6,3	6,8	6,3	6,3
9	125	7,4	7,6	7,9	7,5	7,9	7,2	6,9	6,1	7,8	8,0
9	250	7,9	7,9	7,1	7,7	7,7	7,4	7,3	8,5	7,8	8,7
9	500	6,9	6,9	6,4	7,3	6,1	6,0	5,4	3,8	4,1	1,8
10	125	7,9	7,4	7,4	6,9	7,4	7,4	7,1	7,5	7,7	7,5
10	250	7,8	7,4	7,4	7,6	7,4	7,5	7,8	7,6	6,3	6,6
10	500	7,8	7,2	7,7	6,7	7,0	6,5	6,7	7,0	5,8	6,2
11	125	8,5	8,5	8,9	9,0	9,2	8,8	7,7	8,8	8,8	9,1
11	250	7,5	7,1	7,9	7,5	6,0	6,9	7,0	6,6	5,3	6,4
11	500	6,9	7,4	6,4	6,7	6,2	6,7	6,6	6,0	3,8	5,9
12	125	5,9	6,6	6,9	6,4	6,5	6,6	6,0	6,7	6,4	6,9
12	250	8,1	8,6	8,0	8,3	7,8	8,2	7,1	6,4	6,7	8,2
12	500	6,4	5,9	6,6	6,0	5,8	6,1	6,2	6,6	4,5	3,7