Design and Integration of a Control and Communication Unit (CCU) for a wireless charging platform in shared micro-mobility schemes

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Abstract of the master's thesis

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Abstract

Even though electrified transportation is increasingly being adopted, the lack of broad and reliable charging infrastructure is holding back its successful market penetration. Inductive Power Transfer (IPT) provided an option for the wireless transmission of electrical power through a safe, convenient, and flexible solution. Specifically, shared micro-mobility schemes would benefit from a smart wireless charging infrastructure, e.g., avoiding unsustainable battery-swapping and racking them in the city centers. Therefore, this thesis aims to integrate a Communication and Control Unit (CCU) in a wireless charging platform for electric kick scooters in shared schemes.

A technology comparison between Bluetooth Low Energy (BLE), Ultra-Wide Band (UWB), and Radio Frequency Identification (RFID) was accomplished to identify the best wireless short-range protocol for to the identified scenario's requirements. Afterward, BLE was chosen for the CCU implementation due to its robustness to interferences, low-power consumption, and market availability. Nevertheless, since this protocol does not provide reliable distance measurements in highly reflective environments, a distanceless algorithm was developed to detect where the vehicle is parked within the platform. A 5-states state machine was also delineated to develop key features, such as automated switching, alerts handling and State-of-Charge (SoC) monitoring. Finally, the system is tested throughout different possible users' behaviours and the relative correct unit reaction is assessed. Future improvements are suggested, such as the addition of a sleep mode on the receiving units and the transmission of key system parameters to cloud services through the MQTT protocol.

Keywords Wireless Power Transfer, Inductive Power Transfer, micromobility, Bluetooth Low Energy

Preface

Thanks to my family, myself and the universe.

London, 25.9.2022

Emanuele D. Engineer

Contents

Symbols and abbreviations

Symbols

$\mathbf{B}$	magnetic flux density
$\mathbf{BW}$	bandwidth
$\mathbf{c}$	speed of light
$\mathbf{C_{cap}}$	channel capacity
$\mathbf{E}$	electric field strength
$\mathbf{f}$	frequency
$\mathbf{H}$	magnetic field strength
$\mathbf{P}$	power
$\mathbf{t}$	time
$\mathbf{dl}$	infinitesimal element of a curve
$\mathbf{dS}$	infinitesimal element of a surface
$\mathbf{i_{enc}}$	current passing through a surface enclosed by a curve
ε	electromagnetic force
$\mu_{\mathbf{0}}$	magnetic vacuum permeability
$\phi_{\mathbf{B}}$	magnetic flux
λ	wavelength

Operators

$\oint_{\mathbf{C}}$	line integral of the closed curve C
$\iint_{\mathbf{S}}$	surface intergral of surface S
$\frac{\partial}{\partial \mathbf{t}}$	partial derivative with respect to variable t

Abbreviations

A4WP	alliance for wireless power
AC	alternating current
ACI	adjacent-channel interference
ADC	analog-to-digital converter
ADC	analog-to-digital converter
AES	advanced encryption standard
BLE	bluetooth low energy
CAN	controller area network
CCI	co-channel interference
CCU	control and communication unit
CPT	capacitive power transfer
CRC	cyclic redundancy check
CRU	communication receiving unit
CTU	communication transmitting unit
DC	direct current
EM	electromagnetic
EMF	electromotive force
EMI	electromagnetic interference
ETSI	european telecommunications standard institute
EV	electric vehicles
FHSS	frequency-hopping spread spectrum
FOD	foreign object detection
FPGA	field-programmable gate array
GAP	generic access profile
GATT	generic attribute profile
GPIO	general-purpose input output
GPS	global positioning system
GaN	gallium nitride
HF RFID	high frequency RFID
HF-AC	high frequency AC
HF-IPT	high frequency IPT
HW	hardware
I2C	inter-integrated circuit
I2C	inter-integrated circuit
I2S	integrated inter-IC sound
IC	integrated circuit
ICNIRP	international commission on non-ionizing radiation protection
IEEE	institute of electrical and electronics engineers
IPT	inductive power transfer
ISI	inter-symbol interference
ISM	industrial, scientific and medical

IoT	internet of things
LF RFID	low frequency RFID
LOS	line of sight
MIT	massachusetts institute of technology
MQTT	message queuing telemetry transport
PAN	personal area network
PCS	personal communications services
PLA	power loss accounting
PLD	power loss detection
PMA	power matters alliance
PRU	power receiving unit
PTU	power transmitting unit
PWM	pulse width modulation
Q	quality factor
RF	radio frequency
RFID	radio frequency identification
RMII	reduced media-independent interface
RSSI	received signal strength indication
RTOS	real-time operating system
R&D	research and development
SAR	specific absorption rate
SCL	serial clock
SDA	serial data
SIG	special interest group
SNR	signal-to-noise ratio
SPAC	special purpose acquisition companies
SPI	serial peripheral interface
SSR	solid state relay
SW	software
SiC	silicon carbide
SoC	state of charge
TTL	transistor-transistor logic
UART	universal asynchronous receiver/transmitter
UAV	unmanned aerial vehicle
UHF RFID	ultra high frequency RFID
USB	universal serial bus
UUID	universally unique identifier
UWB	ultra wide band
WPC	wireless power consortium
WPT	wireless power transfer

1 Introduction

Electrified transportation is increasingly being adopted as electrical motors have been revealed to be more efficient and more sustainable than traditional gasoline ones. However, the unavailability of broad and reliable charging infrastructure is limiting their fast diffusion. Recently, Inductive Power Transfer (IPT) provided an option for a safe charging process, as the lack of any mechanical contacts makes the system more robust against water and dust. Specifically, shared micro-mobility vehicles are considered the most feasible short-term application for this technology; for example, the electric kick scooter charging processes are currently comprising almost half of their operating costs. Yet, successful commercialization requires a smart Communication&Control Unit (CCU) to meet users' needs and make the charging as seamless as possible. This CCU together with the mentioned IPT could create an automated and convenient charging solution. Finally, this solution alongside the need of parking these vehicles in city centers could ultimately lead to a public integration of a smart wireless charging platform for shared micro-mobility vehicles.
Therefore, this thesis aims to design and integrate a CCU able to coexist with the wireless charging technology provided by Bumblebee [16]. The presented solution is focusing on electric kick-scooters, and it is considered a strong candidate for becoming the long-term strategy for enhancing the adoption of these vehicles. This unit would enable, among others, State-Of-Charge (SoC) monitoring possibly unlocking new market possibilities, which are not necessarily restricted to this specific application.
This chapter is structured as follows. Section 1.2 defines and explains the research questions, Section 1.1 highlights the scope of the study, Section 1.3 reports the adopted research methods, and Section 1.4 resumes the obtained results. Lastly, the structure of this thesis is delineated in Section 1.5.

1.1 Scope of the study

The scope of this thesis is the design of a Communication&Control Unit (CCU) that could be realistically integrated into a wireless charging platform for micro-mobility vehicles in shared schemes. The motivation for tackling this specific problem is due to this sector's need for a solution capable of dealing with both the charging and parking of these vehicles. Indeed, as it is explained in Section 3.2, battery charging is currently comprising almost half of the shared e-scooters operating costs, and the sector is lately facing severe regulations because their dockless nature interferes with public streets.
Therefore, the interest of this thesis is to delineate and implement the most suitable technology for communications, control solutions, and system monitoring for a kick-scooter wireless charging platform. Key system data needs to be defined to allow remote diagnostics and maintenance needs. These include, among others, authentication parameters, vehicle capabilities, state of the battery, and localization.
In a future widely deployed scenario, this unit would allow putting the charging profile as a top priority, extending batteries' lifetime, and finally reducing our dependence on fossil fuels.

1.2 Research questions

The research questions are based on the expected features of a smart wireless charging platform able to host multiple micro-mobility vehicles and charge them automatically. The research questions are:

- What is the best technology to meet communication and control purposes for a micro-mobility wireless charging platform in shared schemes?
- How to identify which position the vehicle is parked on within the platform?
- What are the key parameters to monitor for collecting system statistics?
- How this platform should efficiently react to different users' behaviors?

The first research question focuses on the short-range wireless protocol choice, which needs to be made accordingly to the expected electromagnetic scenario's characteristics. The second one highlights a crucial feature of the system, which is the position detection technique; this needs to be accomplished without involving any mechanical sensors to keep the platform as flexible as possible. The third question is purposed to find the key values that will be recorded for system diagnosis and statistics collection. Lastly, the fourth one aims to define a proper automated reaction to any realistic actions which might be taken by the users around the platform.

1.3 Research methods

The research in this thesis utilizes a systematic design methodology. First, the crucial features of the wireless charging circuitry are introduced to understand with which EM phenomena the developed unit has to coexist with. One key feature is represented by the adopted frequency because the medium will be shared with the designed wireless communications, therefore interferences must be considered. Afterward, the system requirements are derived and then used for a technology comparison between the 3 identified most suitable wireless protocols. After looking at the theoretical features of each one in the literature, the choice was also supported by market availability and resource support.
The designing of the single units finite-states protocols follow the expected scenario's fault conditions and aim for the system to react automatically to any user's behavior. AirFuel Alliance Resonant Wireless Power Transfer (WPT) System Baseline System Specification (BSS) was taken as a first reference to understand how to react efficiently in a similar wireless charging scenario.

1.4 Results

This thesis developed a Communications&Control Unit (CCU) for a wireless charging platform in shared micro-mobility schemes. The presented system is able to work reliably alongside the company's wireless charging circuitry, and to promptly react to different realistic users' behaviors.
The key result of this thesis is the design of a location detection algorithm that does not involve distance measurements. This is a crucial feature of the system as it allows for using the identified most suitable technology, BLE, whose distance measurements are not reliable in this highly-reflective scenario. A 5-states protocol is also provided for handling different conditions of the platform, and the key parameters to be monitored are delineated. The system follows a client-server architecture, where one central unit (the client) communicates with different peripherals (the servers). The central unit is hereby defined as Communication Transmitting Unit (CTU), while the others as Communication Receiving Units (CRUs). The results suggest the developed CCU could be integrated with existing micro-mobility vehicles to obtain an automated and monitored wireless charging process. Even though the tests were made with e-scooters, this unit could be suitable for any other micro-mobility vehicle. It should be noted that not all the requirements defined in Chapter 4 were implemented for time allowance reasons; however, the remaining one could be taken as a reference for future improvements. For example, sleep mode and MQTT connectivity are suggested for allowing better power consumption and remote monitoring.

1.5 Structure of the study

The rest of this thesis is organized as follows. Chapter 2 explains the underlying wireless charging technology adopted by the company Bumblebee [16], with which this thesis was carried out. Chapter 3 focuses on the micro-mobility application, defining how a wireless charging platform would bring great advantages to the problems this sector is currently facing. The communication and control requirements are then defined in Chapter 4, which constitute the basic criteria upon which the technology comparison was made in Chapter 5. Chapter 6 reports the system implementation, from the conceived key parameters to the design of a distanceless localization algorithm and the finite-state protocols of the individual units. Chapter 7 makes a thorough evaluation of the units' energy demand and their correct reaction to different scenarios. These were divided into 5 simple and 5 complex ones, and they can be taken as reference for any behaviors of both vehicles and users around the wireless charging platform. Lastly, Chapter 8 concludes the thesis with a discussion of future steps necessary for system improvements.

2 Wireless Power Transmission

Although the main focus of this thesis is the development of a Communication and Control Unit (CCU), a brief explanation of the underlying wireless charging technology is considered necessary as the mentioned unit must cooperate without interfering with it.
Therefore, this first chapter gives an overview about the evolution of Wireless Power Transfer (WPT). Its initial origins are presented in Section 2.1, including a short review of wirelessly charged products that have been successfully commercialized during the 20th century. Then, Section 2.2 resumes the most recent developments of the Wireless Power Consortium (WPC) and the AirFuel Alliance. Section 2.3 gives a broad picture of WPT's different techniques, and Section 2.4 highlights the principles of a High-Frequency Inductive Power Transfer (HF-IPT) system, which represents the one used by Bumblebee Power. [16]

2.1 History

The origins of WPT can be traced back to the late 19th century through the scientific efforts of Nikola Tesla. The naturalized Serbian-American physicist accomplished some of the most well-known experiments to test the transmission of electrical energy without any wires. In 1904, the California Historical Radio Society resumed his results obtained first in Colorado and then in Long Island, USA, explaining his vision of using the air as a natural medium for a resonating electromagnetic field. [57] Specifically, Tesla intensively worked on the Wardenclyffe Tower Facility, shown in Figure 1, for various goals but mainly towards the Wireless Power Transmission (WPT). Even though his theory wasn't disproved, his technology was not efficient enough to find the required funds, and the tower has been eventually dismantled during World War I. [60]

Figure 1: Tesla's Wardenclyffe tower facility

After his experiments, the use of electromagnetic waves was mainly directed towards the transmission of information, thanks also to extraordinary inventions for mass communication such as the radio and television. However, albeit in a more limited form, various techniques for transmitting energy wirelessly were pursued in the following decades. For example, [14] presents an Unmanned Aerial Vehicle (UAV) powered through a Radio Frequency (RF) beam back in the decade of the 1970s; nonetheless, the research and development of the 20th century have later focused on transmitting solar energy collected by orbiting satellites to the ground. [13] Unfortunately, both such long-range implementations revealed three main drawbacks. Firstly, the transmitter and receiver must be in remarkably accurate optical visibility, meaning complicated pointing and tracking mechanisms are needed to maintain the required Line Of Sight (LOS). Secondly, high-frequency and high-intensity electromagnetic fields are essential to overcome the great distances, but the necessary high-power levels involved would eventually cause harm to the objects in between the beam, including human beings. Thirdly, energy transmission by cable is much more efficient than one by the atmosphere, especially over long distances as the excellent electrical conductivity of copper introduces low energy losses along the path.
It's important to mention that remarkable experiments have been made in the late 1990s by a research group from the University of Auckland to wirelessly power industrial machines [11], whose exclusive patents were bought in 2017 by Apple and utilised in its recent wireless *Qi* standard. [6]
Nevertheless, for all these reasons, wireless energy transfer has reached commercial products only for applications requiring very short distances and very low power. One successful example is the passive RFID (Radio Frequency Identification), Figure 2a, a technology for the automatic identification of objects, animals, or people. This system is based on the reading, at a distance of a few centimeters, of information contained in an electronic tag powered by the electromagnetic field generated by a compatible reader. Moreover, the wireless charging of cordless appliances used in potentially wet environments, such as electric shavers and toothbrushes, Figure 2b, has reduced the risk of electric shock. Another usage has been found in the transcutaneous recharging of biomedical prosthetic devices implanted in the human body to avoid the inconvenient replacement of batteries via surgery, for instance insulin pumps and cardiac pacemakers. [30] The last one is illustrated in Figure 2c.

(a) (b) (c)

Figure 2: RFID (a), e-toothbrush (b), and pacemaker (c).

2.2 Recent development

In the scenario presented in Section 2.1, however, a spatial and energy domain remained unexplored, namely that of wireless energy transmission within a radius of a few meters, with powers of the order of a dozen watts. Suddenly, interest in this domain has revived due to the need to power billions of low-consumption electronic devices without batteries or to recharge new portable devices without having to be connected to the mains. This represented a complete change in implementation philosophy from a technological point of view, as the research has moved from transmitting energy employing microwaves (frequencies above 300MHz) to transmitting it with low-frequency fields through non-radiative fields.
In 2006, the Massachusetts Institute of Technology (MIT) brought the WPT to the forefront through a series of demonstrations, later founding the 'WiTricity Corporation'. They published promising results in [29], validating the theoretical models of how electrical power is transferred wirelessly depending on the geometry, distance, and electrical properties of the used devices. This paper has attracted much attention worldwide, leading many academic institutes and corporations to conduct extensive research on WPT technology since then. Now the company is focusing on Electric Vehicles (EV) wireless charging solutions, and it is considered a key entity in this market as it holds more than 900 patents (and more than 550 pending). [46]
Afterwards, three competing wireless charging standards groups have emerged: the Alliance for Wireless Power (A4WP), the Power Matters Alliance (PMA), and the Wireless Power Consortium (WPC). The latter published the Qi standard in 2009, which allows for wirelessly powering of portable devices of up to 5 watts at kilohertz frequencies; this represents the most successful wireless charging standard so far as more than 8000 compatible products are present in the market. [65] However, the other two organizations decided to band together in 2015 to form the "AirFuel Alliance", which is believed to become a strong alternative in the next few years. [4]
Since it operates at megahertz frequencies, it could experience an abrupt acceleration led by the recent improvements in high-frequency power converters, increasing its role in the low and mid-power wireless charging applications market.

2.3 Techniques for WPT

WPT is used as a broad definition that comprises many wireless power transfer techniques; however, the majority of its modern methods are based on ElectroMagnetic (EM) waves. Then, they directly exploit the scientific discoveries of Ampère [19] and Faraday [1] dated back in the 19th century, which have later been described by the mathematical models of Maxwell. [2] They can be classified into far field (radiation field) and near field (induction field), as Figure 3 shows, depending on their operating wavelength. [42] Even though there is not a precise boundary between them, scientific consensus agrees that the far field occurs when the distance from the source is larger than one wavelength, and vice versa.
In the far field, the relationship between the electric field component E and the magnetic one H is that characteristic of any freely propagating wave: their magnitudes

are the same anywhere and their polarization can be defined by a single type. [64] This is exploited by the EM radiation WPT technology to achieve a greater transfer distance, using RF/Microwave and Photons/Laser. However, these techniques imply orienting devices, low efficiency, and possibly hazards to humans.
In the near field, instead, the relationship between E and H becomes very complex as all four polarization types can be involved: horizontal, vertical, circular, and elliptical. [64] The generated fields are called "evanescent" because they decrease very rapidly with distance. Unlike in the far field region, their energies remain trapped near the antenna, not drawing power from the transmitter unless they excite a receiver located close to the EM source. Therefore, the transmitter supplies extra power only when a second antenna is placed in the closest near field zone, inherently adapting to the scenario.
Moreover, EM induction WPT technologies can be divided by the type of field they work with. The first one is often referred to as Capacitive Power Transfer (CPT) and it takes advantage of the electric field generated by the metal plates on both the transmitter and the receiver sides. Nonetheless, this type of field is more likely to cause hazards and thus has stricter regulations to respect; its systemic high-intensity field is a challenge that has not found a solution yet in commercial applications. [40] EM induction WPT is where the interest of this thesis firmly relays, which exploits magnetic fields instead. Magnetic fields interact very weakly with biological organisms, humans, and animals, thus they are scientifically considered harmless; we are constantly surrounded by the magnetic earth field. Then, the following Section 2.4 is presenting this technology also known as Inductive Power Transfer (IPT).

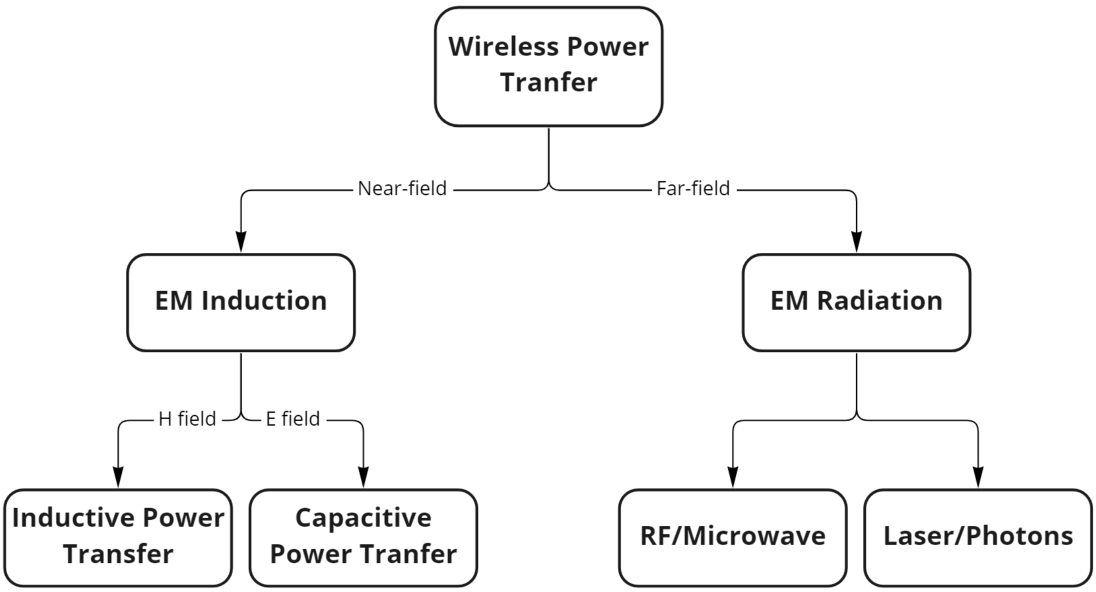


Figure 3: WPT techniques.

2.4 Inductive Power Transfer (IPT)

Inductive Power Transfer (IPT) is the underlying technology that this thesis is dealing with. This chapter is presenting its basic principles to then delineate a typical IPT system that Bumblebee employs. [16] This company was born inside the Wireless Power Lab of the Imperial College, and it has recently detached from it to found a private company. [37]
The theoretical principle of IPT, also called magnetic induction, is illustrated as follows. An Alternating Current (AC) i_{enc} flows in a closed loop of wire, called a coil, generating an alternating magnetic flux B around it according to Ampere's law:

$$\oint_C B\ dl = \mu_0\ i_{enc} \tag{1}$$

Henceforth B creates a magnetic flux ϕ_B:

$$\phi_B = \iint_S B\ dS \tag{2}$$

Therefore, an induced ElectroMotive Force (EMF) ε is generated from the variable magnetic flux according to the Maxwell-Faraday equation:

$$\varepsilon = \frac{\partial \phi_B}{\partial t} \tag{3}$$

The EMF then create a current on the receiving circuit, transferring electrical power without any wires. The coupling between the coils can be intensified making them oscillate at the same resonance frequency, thus increasing the phenomenon efficiency and transmission distance. A practical example is the mechanical resonance of a child on a swing: only pumping the legs at a precise time allows to impart substantial energy to the system. Tesla was the first to think about resonant systems to improve magnetic induction. [57]
Today, IPT can efficiently transmit power through different distance ranges, from tens of centimeters to a few meters [34]; also, it is suitable for both low and high-power systems, from a few milliwatts to several kilowatts. Bumblebee's systems work with HF-IPT, as the operating frequency of 6.78 MHz is found within the first Industrial, Scientific, and Medical (ISM) band. One of the main reasons for utilizing such a high frequency is allowing for the link to be constructed with low inductance but high Quality factors (Q) coil. This is a crucial component in this system, as it eliminates or minimizes the need of magnetically permeable materials.
Nevertheless, the most challenging aspect of HF-IPT is driving the transmit coil and rectifying the high frequency induced voltage without significantly increasing the switching losses of the power converters. Fortunately, these technologies have experienced many recent developments, such as the introduction of wide bandgap devices, namely silicon carbide (SiC) and gallium nitride (GaN). [41] Therefore, the maturity of HF-IPT systems has now improved to the point where they could soon start being integrated into commercial products. [42]
Figure 4 shows the block diagram of a typical end-to-end IPT system. The input is the standard distributed low frequency (50 or 60 Hz) Alternating Current (AC),

which is converted to a Direct Current (DC) through the mains-rectifier; this goes into the inverter to generate an HF-AC. Here is where the IPT-link happens, meaning the AC drives the transmitting coil creating an alternating magnetic field that passes through the receiver coil inducing an EMF within it. Then, attached to the receiver coil, a rectifier is placed to convert the energy back to a DC. A load emulation circuit acts as a dynamic DC-to-DC converter, presenting the optimal load in order to maintain maximum link efficiency even when loading conditions or the coils' coupling factor change. Finally, the DC load is found, which can be either an electronic device or an energy storage such as a battery.

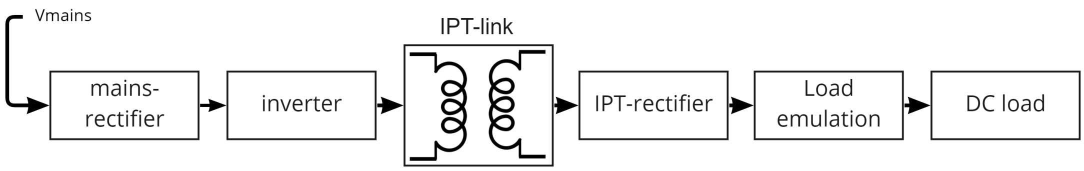


Figure 4: Diagram of a typical IPT system.

3 Micro-mobility

Electrified transportation is increasingly adopted as electrical motors have been revealed to be more efficient and more sustainable than traditional gasoline ones. Unfortunately, the unavailability of a broad and reliable charging infrastructure is limiting fast diffusion of EVs. Three different methods can potentially allow the wireless charging of an EV: static charging, quasi-dynamic charging, and dynamic charging. The first one involves a vehicle at rest, whereas the last one comprises an in-motion one. These solutions can be even complementary to each other or, as in the second one, develop a hybrid mode for specific situations, such as bus stops. [3] Nevertheless, this thesis focuses on static charging, evaluated as the most short-term feasible since it can be installed in practical locations, such as both private and public parking slots.
The following Section 3.1 first introduces the target application of this thesis, the micro-mobility EVs, and it analyzes its recent exponential trend. Its currently adopted charging solutions and relative problems are presented in Section 3.2, to then explain the possible advantages that a wireless charging solution could bring to this sector in Section 3.3.

3.1 Micro-mobility application

Micro-mobility is a broad term for a growing category of vehicles, mainly represented by e-scooters and e-bicycles, Figures 5a and 5b, that provide an alternative to traditional transportation in cities and communities. [8] Nonetheless, it has also been established as a hybrid solution to cover short distances which are not publicly served, getting individuals from their origin to the nearest transportation hub and vice versa. Users can both move by their own means of transport or take advantage of a shared scheme, which provides temporary access to these vehicles. The latter is where the application focus of this thesis relies.

(a) (b)

Figure 5: Electric kick-scooter (a), VOI model [61], and an electric bike, Pashley model [47].

One core micro-mobility strength is sustainability. Indeed, EVs produce no emissions while they are moving, and they can help make traditional public transportation services more popular by reducing first and last-mile distances. [36] The wide availability of micro-mobility services then may provide the fastest and cheapest path to lower carbon emissions, expand access to public transportation, and redesign cities for people instead of automobiles.
Moreover, another strength is represented by their social effects, which have been led by their wide availability and accessibility. Communities that have historically been underserved suddenly got access to affordable and flexible options to move, which made the concept of equity resonate.
Although micro-mobility tends to be a transport solution with huge potential, especially in overcrowded cities with increasing individual car congestion, the necessary legislative regulations are still being worked through. These should ensure these vehicles not to be just a fast and cheap way to move in a city, but to be in the first place a safe transport for the drivers as well as for people in their surroundings. [12] This and other relative problems, like the need for parking among the public shared schemes, are explained deeper in the following Section 3.2.

3.2 Current problems

Despite the micro-mobility advantages, these vehicles are facing some problems which still need to be solved, which can be resumed in two words: charging and parking. The first one is currently mitigated with costly and manual solutions such as the swapping of batteries, whereas the second one with different approaches to docking and parking in each city country. However, more robust approaches are expected in the following years when the number of e-scooters and e-bikes is going to raise. Indeed, the micro-mobility sector is expected to make a strong post-pandemic recovery. [17]
According to a recent Bird's Special Purpose Acquisition Companies (SPAC) document, battery charging comprises 45% of their operating costs. [10] This happens because companies employ teams to pick up and charge them, moving them back and forth to their charging depots which inevitably leads to extra maintenance costs. Alternatively, users are also encouraged to sign up and charge them at home to get paid in cash or riding credit; but this is not a common practice as houses in city centers are often unsuited for this purpose. Some other companies adopt a battery-swapping approach, replacing the discharged battery with a charged one, so the vehicles do not necessarily move to the warehouses anymore. However, the batteries inevitably still do, making the expenses rise.
Moreover, this approach requires battery redundancy which could even deteriorate their environmental effects compared to the previously adopted charging approach. In fact, the batteries have an extremely complex recycling and disposal process since they are composed of dangerously polluting heavy metals; for instance, just one gram of mercury left in the environment is enough to pollute 1000 liters of water. [20] Then, this last approach may eventually be proved as a very pollutant solution that would thwart the sustainability mission of e-scooters and e-bikes. Therefore, it is

clear how the micro-mobility charging is now a critical Research and Development (R&D) field in which operator and solution providers have not found a long-term strategy yet.
Furthermore, many micro-mobility services are dockless, meaning they do not need a fixed infrastructure to operate. Instead, they leverage GPS and cellular connectivity to track whichever vehicle is being rented and to immobilize it wherever it is left at the end of the journey. Even though this extreme flexibility was their strength during the "launch-first, permit-later" deployment process, it is now evolving into their weakness. [8] Their dockless nature is causing excessive confusion in the city centers, as riders often leave them in impractical and unsafe locations that inconvenience pedestrians; a common episode is presented in Figure 6. They are found in the middle of pavements, on ramps, and at crossroads blocking them from the passage of others, and they can also be life-threatening for visually challenged or physically disabled people. Therefore, the industry is lately facing severe roadblocks which prevent e-scooters and e-bikes to operate in several cities. While these services do not rely on fixed infrastructure to pick up and drop off, these for-profit companies rely on publicly-funded city commons infrastructures like bike lanes and sidewalks, eventually creating a negative social impact by blocking them.

Figure 6: E-scooters blocking a pedestrian walkway.

To summarise, the micro-mobility sector must find a long-term reliable answer to the presented issues in order to overcome reservations from local authorities, the general public, and the government. Specifically, a wireless charging platform for the mentioned shared vehicles would both tackle the charging and parking problems. The wireless advantages, which are explained in the following Section 3.3, combined with the need for racking the vehicles in the city centers, could ultimately lead to its public integration of a charging platform. The flexibility of their "dockless" nature would be reduced, possibly but not necessarily adding locks, in favor of more regulated infrastructures. Eventually, the mentioned platform could be also integrated into dedicated spaces inside buses or trains to enable seamless, point-to-point journeys. This strategy would help increase the customer base for both public-transit and micro-mobility operators.

3.3 Wireless advantages

Hereby the advantages of a wireless charging solution are illustrated, considering the consequent benefits it could bring to the micro-mobility current problems presented in Section 3.2. Specifically, this is centered on the AirFuel standard, as it is the one adopted by the company Bumblebee Power. [16] Therefore, some features are related to this particular standard and do not necessarily apply to any wireless charging technology. Finally, the need for a joint Communication&Control Unit (CCU) is delineated in order to introduce the individual practical scope of this thesis.
The advantages of wireless over wired solutions are:

- **Reliability**:
  Batteries and connectors are the most dangerous components of any electrical system and the first ones to be prone to short-term failure, as their free exposure to dust and water makes them very vulnerable.
  Firstly, batteries slowly decrease their charge storage capacity in each recharging cycle. This systematic characteristic varies according to many factors, such as the usage frequency, the environment temperature and humidity, and the completion of charging. Specifically, the charging profile highly impacts the battery lifetime; for instance, researchers agree that keeping the State Of Charge (SoC) level between 20% and 80% would help to maintain high efficiency and cycle life. [28] However, the current adopted micro-mobility charging solutions involve a frequent cycle from a complete discharged to a fully charged battery status, because of reducing the expensive vehicles/batteries journeys from/to the charging depots. Instead, a widely distributed wireless charging platform infrastructure would allow putting the charging profile as a top priority as it should logically be.
  Secondly, the connectors undergo a long-term oxidation process every time they are touched or left in a dusty environment. Their performance quality diminishes, and they eventually become dangerous. Therefore, it is clear how the lack of electrical contacts makes the system more reliable.

- **Efficiency**:
  Even though over long distances the wired transmission of energy proved to be more efficient, this supremacy does not strictly apply over medium and short distances. Different research papers reached a system efficiency comparable to the traditional wired solutions, sometimes even overcoming the related device charger when cost-driven choices are prioritized. Indeed, manufacturers of wired chargers do not always place efficiency as a top priority but prefer other market logic. Also, the required energy conversion blocks of a wireless charger can be even fewer than the wired ones, which stands out as an advantage since each conversion stage inevitably comply some losses. Bumblebee [16] technology has a speed equivalent to the wire, thus providing a scooter charging time similar to the currently utilized solutions.

- **Spatial freedom**:
  A wireless solution would increase the spatial freedom, as cables often take

up space and lead to excessive inconvenience being shorter or longer than necessary. Connectors reduce this freedom too; for example, different devices may have different physical adapters even though their battery requirements are similar to each other. Moreover, the avoidance of fixed-length cables makes the system more convenient because as soon as the vehicle is parked, the charging begins automatically or at the click of a button. Bumblebee [16] technology provides efficient power transfer over large air gaps and misalignments, which is greater than what is achieved by existing standards. [15] An IEEE workshop on emerging technologies [33] reports the integration of a wireless inductive charging solution for an e-scooter, which ensures a full charge to the battery even when the vehicle is moved laterally or angularly by 10 cm. This is possible through the adopted power electronic circuits which maintain high efficiency even over large changes in reflected load. Therefore, this type of wireless charging is considered less bespoke and more suitable for a real-application scenario.

- **Sustainability**:
  Another core advantage of wireless charging in shared micro-mobility schemes is it would boost their sustainability effects, increasing the number of low-emissions journeys and therefore decreasing the traditional ones supplied by pollutant fossil fuels. Therefore, these EVs would avoid the generation of greenhouse gases, while also reducing the billions of yearly disposed batteries incremented by the battery-swapping approach. Lastly, different required cables and connectors often lead to excessive waste; obviating this would be helping the environment too.

- **Design**:
  Nowadays design has become a critical factor in every technological device commercialization; in parallel with its functionalities, beauty is what sells devices. Here, the nature of wireless charging comes across, allowing different coil geometries to be designed accordingly to the vehicle's dimensions. In fact, the power level scales with the size of the coils, so smaller coils can be studied for smaller vehicles, which tend to require less power, and larger coils can be designed for larger vehicles, which have got space for them, which tend to require more power.
  Bumblebee high-frequency fields employ thin and light coils which could easily be integrated into modern micro-mobility vehicles. They would later be designed without any external connectors, resulting as smoother and eventually even lighter, as batteries could be also smaller in a widely deployed wireless infrastructure future scenario.

- **Safety**
  Transmission of non-contact electrical power is generally considered safer than traditional wires, as the absence of mechanical connectors protects the system against water and dust thus avoiding electric shocks and burns. Furthermore, the magnetic non-radiative near-field minimally interacts with biological organisms.

For example, the article [32] simulated in CTS Microwave Studio a human body in proximity (5 cm from the transmitter coil) of a 600 W electric scooter wireless charging system to evaluate its compliance with human EM field exposure limits. At the chosen frequency, the basic restrictions from ICNIRP 1998 (thermal effects - specific absorption rate) and ICNIRP 2010 (non-thermal effects – internal E-field) are relevant. Then, the maximum localized Specific Absorption Rate (SAR) resulted in 0.28 W/kg, which is less than the general exposure limit of 4 W/Kg; whereas the 99th percentile of the internal E-field was 38 V/m, which is below the general public exposure limit of 915 V/m. It should be noted that both obtained values are more than 10 times below the relative EM exposure limits.

Finally, control and communication capabilities can be added to the wireless charging technology to render the process smarter and thus easier to be adopted. The constant information exchange between the power transmitter and the receiving circuitry is essential before, during, and after the completion of the charge, and it could enable several system features, creating new opportunities for adding value. On the other hand, the current wired charging solutions lack these capabilities. Therefore, a joint Communication&Control Unit (CCU) is delineated in the following chapters, starting with the requirements such a system would necessarily need.

4 Communication and control requirements

It is understood the need for a platform capable of both charging and parking micro-mobility services. Ideally, this solution should also meet users' needs, who should not be seriously concerned about the charging process. This can be achieved by a joint Communication&Control Unit (CCU) which cooperates with the wireless charging circuits, allowing the exchange of information between the transmitter and the receiver. The mentioned unit must know how many vehicles are parked in the platform, and their relative positions and capabilities, monitoring parameters such as authentication and state of the charge.
This chapter then delineates the CCU requirements of a wireless charging platform for shared micro-mobility schemes. Firstly, Section 4.1 explains the importance of making the system scalable; Section 4.2 clarifies the differences between out-of-band and in-band communication; Section 4.3 shows the consideration to be made operating in a possible very noisy environment, as numerous reflections and therefore interferences are expected. Then, Section 4.4 explains a critical feature the CCU must have: localize the correct position of the receiver. Moreover, the unit must be able to detect any unrelated foreign objects in the airgap; this is clarified in Section 4.5. Finally, Section 4.6 illustrates the further requirements to be considered in the system's long-term evolution.

4.1 Scalability

The first identified key requirement is the scalability of this unit, meaning being able to increase its performance while decreasing its cost in response to a larger number of e-vehicles in the same platform. The wireless charging platform is meant to host at least 4 different micro-mobility vehicles, but this number could later be increased. Therefore, the CCU should comprise one circuit only on the transmitting side connected to each charging pad (PTU), instead of having redundant communications in a 1-to-1 implementation. Consequently, the CCU should employ a 1-to-many scheme, where the many are represented by the receiving circuits which are inevitably placed on each e-vehicle. Figure 7 describes the outlined system diagram.
It should be noted that the thesis utilises the terms *charging pad* and *PTU* as interchangeable; also, the acronyms CTU and CRU are defined to indicate, respectively, the individual transmitting unit and the receiving one which are comprised of the whole CCU.

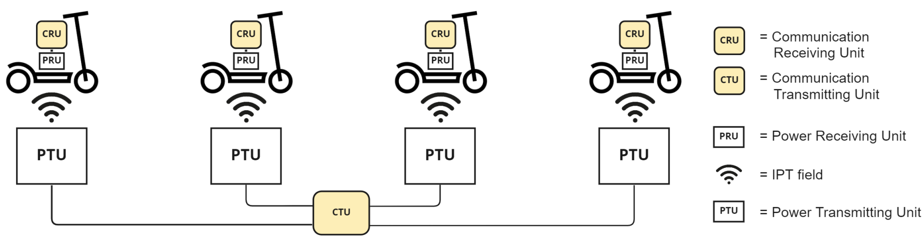


Figure 7: System diagram.

4.2 In-band vs Out-of-band

The most common wireless power technology deployed today uses what is commonly referred to as in-band communications, meaning the data and power signals are found together in the same waveform. The data being sent is typically piggybacked on the wireless power signal; however, this approach has several drawbacks which limit its implementation in different use cases.

Firstly, the data rate of the exchanged information is very limited in speed [18], which seriously restrains the amount of exchanged data. This might result in even danger, as the reactive time to a received alert is affected as well. For example, the Qi standard uses an in-band method, reaching a bit rate of 2kbps in receiver-to-transmitter communication, while only 200bps is achieved in transmitter-to-receiver one.

Secondly, the in-band method only allows 1-to-1 communication, associating a single transmitter only with a single receiver. This is not suitable for the presented e-scooter charging platform, as the redundant signal modulation and demodulation would increase cost and system complexity, thus decreasing the overall scalability. For example, the Qi standard comprises load amplitude modulation on the receiver side, and operating frequency shifting on the transmitting one. These also need Hardware (HW) capabilities that are currently not present in the Bumblebee [16] system.

Thirdly, the chosen frequency and type of information that can be sent are restricted according to international entities. This is necessary because the EM spectrum is limited and therefore divided by frequency bands to avoid interferences, which might be created by different signals coexisting in the same one. Furthermore, some regulations change depending on the area, so this type of communication might have to deal differently with each local agency.

On the other hand, an out-of-band communication scheme could instead overcome these limitations, making the implementation straightforward and universally accepted. Bumblebee [16] is a member of the AirFuel Alliance, which encourages the adoption of out-of-band technology. [66] Some existing licensed technologies would allow high-speed bi-directional communication, such as BLE, RFID, and UWB. Using one of these off-the-shelf solutions would respect the regulations and allow one-to-many communication independently of the power transmission, considerably simplifying the system HW. Indeed, in-band communication could cause the wireless charging technology to be regulated as a short-range radio device rather than an ISM device, leading to the technology needing to adhere to much stricter radio regulations.

4.3 Interferences and reflections

Interference is a fundamental nature of any wireless communication system, in which multiple transmissions often take place simultaneously over a common communication medium. This phenomenon can be compared to someone trying to hear someone else talking while a loud siren starts in the background: the increased noise results in a poor Signal-to-Noise Ratio (SNR) which makes the speech incomprehensible. Reflections also affect the reliability of wireless communications, decreasing their

throughput when the same signal is received over more than one path.
Interferences can be classified into different categories based on what causes them. Co-Channel Interference (CCI) happens when more devices are concurrently using the same frequency, whereas Adjacent-Channel Interference (ACI) is caused by signals which are next to each other in frequency. Moreover, Inter-Symbol Interference (ISI) occurs when the waveform that represents a symbol affects the subsequent one, and lastly, Electro-Magnetic Interference (EMI) is considered as the disturbance generated by any electrical component operating nearby whether via induction, electrostatic coupling, or conduction. [50]
EMI is of particular interest for this thesis as the CCU must coexist with strong EM induction fields. The operating IPT fields used to send electrical power could create distortion, altering the encoded messages, and eventually increasing the error rate. This has been confirmed by some tests run locally at Bumblebee [16] which showed this type of interference especially along the data cables and in the serial interfaces. Nonetheless, the interference intensity depends on different factors, such as the cable length and closeness to the coil, and it could be mitigated by improved shielding techniques.
Furthermore, the e-scooter charging platform is a very noisy electromagnetic environment as it provides many surfaces where the signal can bounce and cause reflections; also, the metallic structure of the e-scooter itself can generate a reflected signal. Reflections could result in signal distortion, randomly changing its variables and thus making it impossible to detect its content. This phenomenon is referred to as "multipath fading" and it is illustrated in Figure 8.

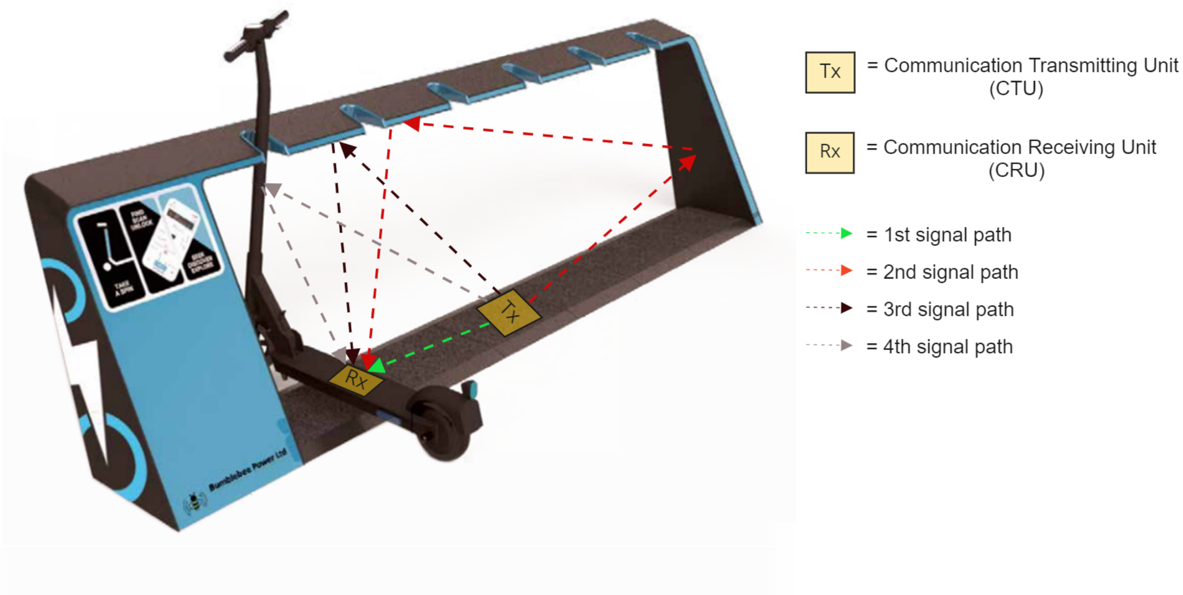


Figure 8: Possible charging platform structure designed by @Trueform [59] where some reflection paths are visualized.

When the same signal reaches the receiving antenna by numerous paths, these waves interfere constructively or destructively, as they arrive at the detector out of phase with each other depending on the traveled distance. Figure 8 shows the CRU above the standing area of the e-scooter for visualization purposes, even though it will be placed on the bottom part together with the Power Receiving Unit (PRU). Also, only a few of the many possible reflection paths are highlighted, and they would considerably increase when more e-scooters are placed simultaneously.
The out-of-band technologies mentioned in Section 4.2 were developed to be robust enough against the classic wireless interferences CCI, ACI, and ISI. Indeed, they usually deal with interference by coordinating users to orthogonalize their transmissions in time or frequency, or by increasing the transmission power and treating each other's interference as noise. However, this is not necessarily enough for the EMI and multipath fading expected in the scenario where the CCU must operate; then, further specific considerations are needed to evaluate the robustness of the adopted out-of-band protocol.

4.4 Localization

Since the aforementioned CCU needs to comprise a one-to-many communication for scalability reasons, the transmitter must know the receiver location to switch on the correspondent pad (PTU). Indeed, having only one unit connected to all the charging pads means the pad on which the receiver might be placed remains aleatory, even after a successful connection is established.
When it comes to detecting a device's position, the first logical solution would be the adoption of distance measurements, as it is found in the space domain as well. However, a distance measurement made by a single CTU might not be enough to solve this requirement. This problem is represented in Figure 9, where the green e-scooter comes in an empty charging station, but its relative position is undistinguishable from the red ones. The circle highlights how many locations would be possibly perceived using one distance measurement only, which here is calculated by the CTU placed in the middle of it. Unfortunately, pads 1 and 4 are equally distant from the transmitter thus the e-scooter position could be interpreted on both.

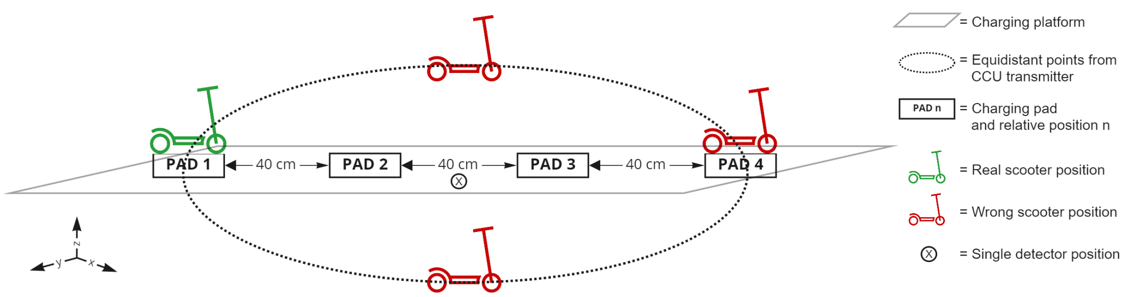


Figure 9: Localization ambiguity using 1 distance measurement only.

Moreover, the three-dimensional nature of this scenario does not restrict the detectable locations inside the charging platform; instead, an e-scooter could be somewhere else in the x-y plane (on none of the pads) and still have the same distance measurement. These considerations are then applicable wherever the transmitter is placed.
One distance measurement from the platform side would be enough only if the possible locations were restricted inside of it. However, the particularly noisy environment and the expected multipath fading could also affect the reliability of the distance values and make the localization process between the pads still hard, as they are meant to be placed only 40 cm from each other. For example, the Received Signal Strength Indication (RSSI) is notoriously compromised by multipath reflections. Ideally, distance measurements from more points would help to overcome the problem, for example using data trilateration as GPS does. Though, three different detectors talking to each other would be necessary for this implementation, with cost and complexity as the drawbacks. Also, given the low distance resolution of most of the modern short-range technologies, two detectors could be enough only if the sensing antennas had a two-dimensional beam pattern. This would allow to detect positions only along the vertical plane of the platform, thus avoiding symmetry misinterpretations of vehicles placed outside of it; still, cost and complexity would rise.
Furthermore, some mechanical sensors could be also considered as a solution; for example, detecting the pressure generated by the vehicle or inserting locks in the platform. However, Section 3.1 explains that extreme flexibility has been a key strength of the micro-mobility sector, thus it should be kept as much as possible.
Finally, the received voltage on the e-scooter can also be monitored to identify whether the energy is coming from the relative charging pad. This would involve the sequential switching of the connected pad, but some further considerations are needed. All the mentioned solutions could be complementary to each other.

4.5 Foreign Object Detection (FOD)

The FOD is a key feature of any WPT system, as it ensures a safety standpoint. A FOD system tries to detect whenever any object placed in between the airgap, such as coins and keys, is experiencing inductive heating effects due to the generated EM fields, to afterwards limit the temperature rise of these. This chapter presents some FOD solutions and highlights the one used by Bumblebee [16], to then delineate the CCU role related to this technique.
The main two FOD methods which have been developed are known as Power Loss Accounting (PLA), by Texas Instrument, and Power Loss Detection (PLD), by the WPC. They both evaluate a difference in the transfer efficiency to detect if a foreign object is present using in-band communication between the transmitter and the receiver. Nevertheless, Bumblebee [16] current implementation does not need this type of communication and works independently of the loading conditions, while the mentioned system experience problems if the foreign object and the receiver are simultaneously placed.

Bumblebee [16] system, presented in [5], exploits the signal response patterns of foreign objects on the transmitting side. A tuned wireless receiver would indeed behave as a resistive load, whereas anything else would appear as either a capacitive or inductive one. Therefore, a Field-Programmable Gate Array (FPGA) senses the drain waveform in the switching transistors of the transmitter through some Analog-to-Digital Converter (ADC) channels and makes the detection possible without talking to the receiver.
Furthermore, some other techniques could be possible using an extra coil, called a sense coil, and driving it at a slightly different frequency to monitor its transmitted power. Also, a camera could be placed in the system to record images of the airgap and evaluate whether a foreign object is present through some image processing. Nonetheless, these capabilities are not currently involved in the system thus they would require extra cost.
To summarise, the FOD current solution is more hardware related; however, the CTU needs to deal with the situation of a detected foreign object and make the system react accordingly. For example, the CTU could receive the FPGA output through an interrupt timer. Finally, when the object is detected, the system should either reduce the transmitted power or disable the WPT system until the foreign objects are removed.

4.6 Further requirements

This Section is covering all the requirements which Bumblebee [16] is yet to implement, but are considered vital for real-world deployment and form the prime subject of this thesis. Further experimentations will be carried during the internship project and eventually, a first solution will be presented for all of them depending on the time allowance.
These are:

- **Identification&Authentication**:
  Identification and authentication are necessary key features to recognize which vehicle is being charged and at the same time to avoid incompatible ones to receive power which might damage them. This compatibility detection is taken care of by the FOD too, as explained in Section 4.5. Even though Section 4.4 mentioned the usage of mechanical sensors, they would not be able to identify with absolute certainty a vehicle in the platform. Therefore, some parameters need to be advertised by the receiver to the transmitter for authentication, and a unique identifier is needed for the identification of the compatible vehicle.

- **Connectivity**:
  Connectivity is an essential part of any modern smart device, which is no longer confined locally but instead connected to the internet infrastructure. The two most common wireless methods to provide connectivity to a device are Wi-Fi and Sim data plan. The first one could result less practical for this scenario, as it works by providing a router that must be placed near each charging platform. The Wi-Fi router has a limited coverage area, and it needs to be connected

physically to a network access point. On the other hand, Sim cards have a limitless range when near a cell phone tower, which is largely distributed in city centers; however, Sim data plans can get expensive.

- **Remote control**:
  The most important feature of the remote control is the capability of switching on and off the transmitting circuits without touching any physical switch. Exploiting the connectivity, platform owners should be able to enable or disable the charging process when needed. Nevertheless, as explained in Section 4.4, the circuits should be turned on and off automatically as soon as a vehicle is parked inside the wireless charging platform.

- **Remote monitoring**:
  Remote monitoring is referred to the process of sending the locally collected data to a cloud system thus allowing statistics monitoring from everywhere. The statistics monitoring can be done through either a dynamic dashboard or a smartphone application. Key parameters to be monitored include information about the number of devices being powered at any given time and their relative state of charge; they are better delineated in Section 6.1. Moreover, the system parameters should be recorded to create reliable statistics about the platform usage and power transfer efficiency over time.

- **Over-The-Air (OTA)**:
  Over-The-Air (OTA) has been identified as a crucial CCU capability in the long term, as it would save cost and time. This feature would allow the firmware to be remotely updated into every CCU, without going locally to every already deployed unit. This is a common practice in the Internet-Of-Things (IoT) field where devices are not found in a fixed position but are instead quite free to move. This feature can be achieved once the connectivity is established.

- **Maintenance needs**:
  Finally, maintenance needs represent some Alert messages the CCU would have to send whenever a local check is required, as most probably some HW equipment needs to be repaired. Therefore, these messages would be generated from the exchange of key operating conditions. For example, whenever either voltage, current or temperature of any circuits rises too high for several times, it would mean the CCU is not able to deal with the problem by itself thus someone needs to physically go there.

All these requirements are considered critical by the author to improve the overall user experience and system efficiency. Furthermore, a CCU able to successfully comply with all of them would eventually enable new use cases for the WPT technology, not necessarily contained in the micro-mobility sector.

5 Comparison of candidate wireless technologies

A comparison of existing short-range wireless technologies was performed based on the use-case relevant features, which follow the requirements listed in Chapter 4. The identified candidates were found in Bluetooth Low Energy (BLE), Ultra-Wide Band (UWB), and Radio Frequency Identification (RFID).
Therefore, this Section provides a brief overview of each one, analyzing how their relative capabilities would apply in this e-scooter wireless charging platform scenario. Section 5.1 covers the BLE, which represents AirFuel choice, Section 5.2 explains the most recent technology, UWB, and Section 5.3 delineates an overview of RFID and its relative possible implications on the practical side. Nevertheless, the material presented in this Section is widely available in the literature. Hence, the major goal of this Section is not to contribute to research in wireless protocols, but instead to present a comparison of the three most suitable candidate short-range wireless networks for the presented scenario. Finally, this comparison and the following technology choice are found in Section 5.4.

5.1 Bluetooth Low Energy (BLE)

Bluetooth is a wireless Personal Area Network (PAN) technology jointly launched by five companies: Ericsson, IBM, Intel, Nokia, and Toshiba. They formed the Bluetooth Special Interest Group (SIG) in 1988, which now contains over 30.000 members at various levels of influence. This group developed the Low Energy version in 2009, aiming to realize wireless data communication between different electronic devices keeping low-energy consumption as the priority. [25] Bluetooth Low Energy (BLE), also known as Bluetooth 4 or Bluetooth Smart, is independent of classic Bluetooth and aims to become the best choice for novel applications, such as the IoT sector. Its synergy between good performance, low-power requirements and ubiquitous diffusion makes BLE an excellent candidate for the presented wireless charging scenario.

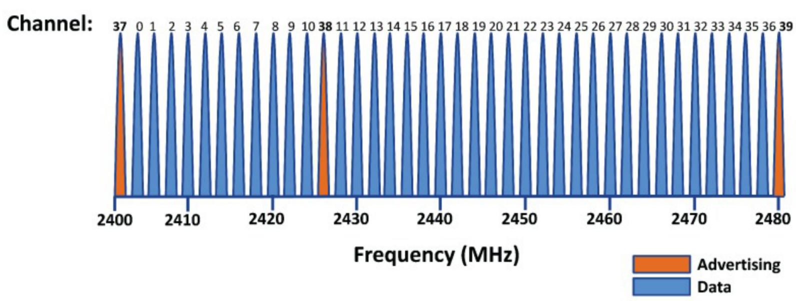


Figure 10: BLE channels. [58]

The fundamental operating principle is hereby described. A BLE device can detect another one by scanning its advertisement packets, but only after a successfully established connection communication can take place. Therefore, BLE devices can operate in two different modes: master and slave. The master is represented by the

first device, which also provides synchronization, whereas the second one is the slave, which advertises its presence.
This technology operates at precisely 2.4 GHz in the radio wave frequency and offers up to 1 Mbps data rate, which indicates the maximum transmission speed. The BLE protocol then operates in the Industrial, Scientific, and Medical (ISM) band, which is internationally reserved for different uses rather than telecommunications. Specifically, it works in the range of 2.4000 GHz to 2.4835 GHz, which is divided into 40 different channels; these channels' center frequencies are 2402 + k2 MHz, with k = 0, .., 39. Figure 10 shows that channels 0-36 are utilized for transmitting data, while the three remaining 37-39 are meant to transmit only advertisement packets. Channels are essential to coexist with other technologies operating in the same frequency band, such as ZigBee, Wi-Fi, and classic Bluetooth. The involved technique is called Frequency-Hopping Spread Spectrum (FHSS); BLE devices are always changing which frequencies they are transmitting and receiving on to avoid channel collisions. As soon as a slave connects to the master, it receives an address and a clock to calculate the frequency hopping sequence. This also helps to mitigate multipath fading, in terms of detecting the message content. [62] However, the BLE distance measurements are based on the Receiving Signal Strength Indication (RSSI), which is strongly corrupted by reflections thus making any values highly unreliable. Finally, the nature of the BLE communication protocol makes this solution to be efficient both in cost and energy consumption. Thus, the BLE Developers Handbook [26] considers it a leading candidate for the IoT sector, and many working solutions were already found. For instance, [27] delineates how to control and monitor household appliances through BLE, a smart plug, and an application implemented on Android OS.

5.2 Ultra Wide Band (UWB)

UWB indicates a modern name for a long-existing technology, first employed by G. Marconi in 1901 to transmit Morse code sequences across the Atlantic Ocean using spark gap radio transmitters. [31] However, the use of a large bandwidth and short pulse signals gained momentum only recently.
The peculiarity that makes this wireless technology different from all the other existing ones is, as the name itself suggests, the utilization of either a fractional bandwidth that exceeds 20% or an absolute bandwidth of more than 500 MHz. This implies the generation of very short pulses, which allow strong multipath immunity and precise localization accuracy; therefore, this technology is a strong candidate for the presented scenario as well.
Moreover, UWB operates at much lower power than traditional radio uses. The power use is so low that it is arguably indistinguishable from the ever-present noise floor of -41 dB/MHz, which defines the minimum constant level of interference every wireless device must deal with. [31] Nevertheless, these extremely severe power limitations do not permit a single pulse to go very far; therefore, the transmitter sends a train of pulses to represent a single bit of information. The received pulses are then added together, and the power of the accumulated signal rises above the noise level and

permits effective reception.
Figure 11 illustrates how UWB can coexist with other narrowband radio communication protocols: the huge bandwidth coupled with a very low power level makes it appear as background noise to others, thus immune to their detection and interception. The figure presents two licensed EM spectrum bands, Global Position System (GPS) and Personal Communications Services (PCS), and two unlicensed ones which are used by Bluetooth, Microwaves, Cordless phones, and Wi-Fi (IEEE 802.11).

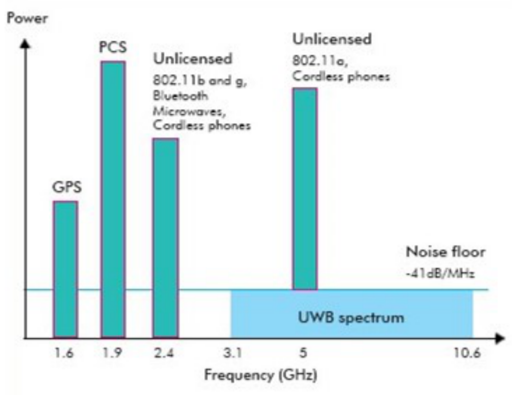


Figure 11: UWB spectrum.

Furthermore, the utilization of such a large bandwidth implies high data rates as, accordingly to the Shannon formula, the channel capacity (C_{cap}) is proportional to its bandwidth (B) in the condition of fixed Signal-Noise-Ratio (SNR).

$$C_{cap} = BWlog_2(1 + SNR) \tag{4}$$

It also provides enhanced ranging and multipath capabilities. Specifically, the distance resolution can be calculated following Heisenberg's uncertainty principle:

$$\Delta f \Delta t \geq \frac{1}{4\pi} \tag{5}$$

The IEEE 802.15.4 standard for the UWB physical layer, which has been released in August 2007, authorizes its use in 3.1-10.6 GHz and reserves at least 500 MHz for each channel. Then, knowing Δf = 500 MHz, a pulse width larger than Δt $\geq$ 0.16 ns is obtained. At the speed of light, this relates to a wavelength of:

$$\lambda = \frac{c}{f} = c\Delta t = 0.048m \tag{6}$$

This means different signals can be easily differentiated by the receiver as these pulses will overlap only when originated from sources closer than about 5 cm to each other. Here, a reflection from any object placed nearby is also considered a source. This number is just theoretical as it would be practically influenced by other factors; however, it indicates the UWB system can detect very accurate distances and it can be reliable even in highly reflective surrounding environments.
Another UWB intrinsic characteristic that detaches it from traditional wireless

techniques is the absence of a carrier wave. It transmits short impulses constantly instead of transmitting modulated waves continuously, avoiding the necessity of a crystal oscillator and modulation/demodulation blocks. [23] Then, UWB power requirements are low as UWB chipsets do not require intermediate frequencies, local oscillators, mixers, or additional filters. However, their battery life is limited by the techniques of back-end power consumption and pulse detection.
To summarise, UWB uses short-pulses, low-power radio signals to send large amounts of digital data over a wide frequency spectrum. It has recently attracted much attention for indoor wireless communications for its strong multipath immunity and accurate distance measurement, which are key requirements for the presented scenario.

5.3 Radio Frequency IDentification (RFID)

RFID has been introduced since the early 20th century to uniquely identify an object. The IFF (Identification Friend or Foe) system used the same principle to recognize the allied planes during the 2nd World War. [22] Then, it also represents an important candidate for the presented thesis scope.
An RFID system's basic working premise is that it consists just of an RFID reader and an RFID tag communicating by near-field inductive coupling, as mentioned in Section 2.1. The reader initiates a communication process by radiating an electromagnetic wave, which is intercepted by the tag. As a result, an induced current is generated at the tag, which activates the Integrated Circuit (IC) allowing for communication. The tag then uses phase or amplitude modulation on a predetermined frequency carrier to modify the digital signal and to communicate the data stored in its chip. The reader then transforms the binary-coded data received and sends it to the server for processing.

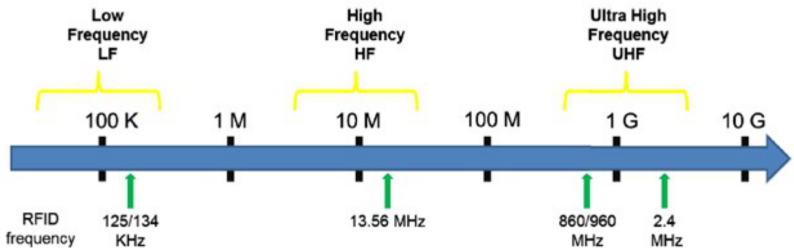


Figure 12: RFID frequencies allocation. [22]

RFID characteristics strongly vary depending on the frequency they adopt. Selecting the most adequate frequency is a function of both the current technological development, which is directly related to the system cost, and the properties of EM waves at those different frequencies. Figure 12 shows the different existing RFID systems: Low Frequency (LF) RFID, High Frequency (HF) RFID, and Ultra High Frequency (UHF) RFID.
LF RFID commonly uses either 125 kHz or 134 kHz as the frequency carrier. One

key characteristic of this frequency is the fact that the signal is less affected by metals and water; however, the read range consists of only a few centimeters, the system is expansive, and it comprises a low data rate. HF RFID operates at 13.56 MHz, which is internationally unlicensed as part of the ISM band. This is the most present in the market, as it comes with lower costs and dimensions, better communication speed, and a read range of up to 1 meter. Unfortunately, the signal is less robust against metals and water at these frequencies. Lastly, UHF RFID is newer compared to the other mentioned techniques and it adopts a method called backscattering instead of induction. It uses either the band 860-956 MHz or 2.45 GHz, which allows for having even smaller antenna dimensions, greater data rates, and a read range of up to a few meters. The main drawbacks are represented by its vulnerability to water and metal, which respectively attenuates and reflects the signal.

On the power requirements side, the only powered circuit is the reader since the tags work passively; this makes the RFID consume only a small amount of energy. Specifically, the paper [7] claims that compact UHF RFID readers can be integrated with mobile phones as they utilize no more energy than any of the built-in sensors on existing modern ones.

Finally, even though this technology is widely used, it is still immature from a security point of view. Classic security protocols are not applicable because of limitations in power consumption and processing capabilities in low-cost RFIDs. Therefore, a lightweight security solution that ensures confidentiality at low processing costs was not found yet.

Notably, active tags with an inbuilt battery exist in addition to the passive tags covered in this chapter. However, their necessary power requirements and relatively higher costs made them not considerable for the presented wireless charging platform.

5.4 Comparison

This Section is presenting a comparison between the wireless technologies presented in Sections 5.1 (BLE), 5.2 (UWB), and 5.3 (RFID). The purpose of this comparison is to choose the most suitable one accordingly to the requirements listed in Chapter 4 for a micro-mobility wireless charging platform.

The identified main features of each previously introduced protocol are resumed in Table 1: adopted physical layer IEEE specification, working frequency band, channels bandwidth and number, distance measurements accuracy, nominal range, maximum transmission speed, coexistence mechanism, and encryption technique. It should be noted that the coexistence mechanism is referred only to the coexistence with other narrow-band technologies; UWB uses a dynamic frequency selection between its channels (like FHSS) to avoid channel collisions with other UWB devices. Also, the European Telecommunications Standards Institute (ETSI) was taken as a reference for RFID channel bandwidth and number since it is not universally regulated.

The choice-making process below first discards the less suitable wireless protocol, to then evaluate a trade-off between the cons and pros of the remaining two candidates. This is presented with the same arguments for which the decision was taken during the internship. RFID is the one initially considered. Since this system has different features depending on the adopted working frequency, as described in Section 5.3, each one needs to be evaluated separately.

Table 1: Technical comparison of candidate wireless technologies. *[53], **[48]

Standard	***BLE***	***UWB***	***RFID***
IEEE specification	802.15.1	802.15.4z	802.15.4f
Frequency band	2.4-2.5 GHz	3.1-10.6 GHz	125/134KHz (LF) 13.56MHz (HF) 869/960/2.4GHz (UHF)
Channel bandwidth	2 MHz	500 MHz	200 KHz
Channels number	40	15	15
Localization accuracy	1 m	20 cm	3 cm *
Nominal range	10 m	10 m	10 cm (LF) 1 m (HF) 10 m (UHF)
Max data rate	1 Mbps	110 Mbps	10 kbps (LF) 200 kbps (HF) 4 Mbps (UHF) **
Coexistence mechanism	FHSS	Underlay noise floor	FHSS
Encryption	AES	AES	RC4

Firstly, LF RFIDs are limited in the nominal range (max 10 cm) which might be just enough for the presented scenario where the distance between transmitter and receiver is at least 7 cm. The tag would be placed underneath the e-scooter together with the receiving circuitry; it might be placed also in the vertical part of the scooter to reduce its distance from the reader. However, this last solution would further constrain the flexibility of the wireless charging system, eventually making the system tolerance to misalignment useless. Moreover, an LF RFID solution would employ an RFID reader for each pad; instead, the scalability system requirement, explained in Section 4.1, would take advantage of a single central transmitting unit able to detect all the receiving ones.
Secondly, HF RFID has a nominal range of about 1 m, which is still not enough if the central unit needs to simultaneously connect to all the receivers placed about 40 cm from each other. Furthermore, the adopted frequency of 13.56 MHz, is in the same unit of measure as the Bumblebee [cit] one, which is 6.78 MHz. Interferences would then be expected while these technologies share the same medium.
Thirdly, UHF RFID is the only RFID system that would be theoretically capable of connecting to all the receiving units and of locating their respective positions. However, in contrast with conventional RF communication links, [9] claims its performances are highly sensitive to multipath interferences and channel fading. Also,

the RC4 is the best encryption method that can be implemented with such low power requirements and process capabilities; this is considered much less secure than the Advanced Encryption Standard (AES) utilized by the other two candidates. Also, UHF RFID systems represent a rather new technology that has not been properly regulated yet. Different countries have established different frequency ranges for their operation, making the compatibility between systems more difficult. Consequently, RFID is the first technology to be discarded in this comparison.

The two remaining candidate choices are hereby evaluated based on their main features and behaviors in terms of various metrics; both of them do not interfere with the IPT link since they work at a much higher frequency range. In terms of security, both protocols have solid encryption and data protection mechanisms: BLE uses the AES with 16-bit Cyclic Redundancy Check (CRC), and UWB adopts the AES with 32-bit CRC. From the power requirements point of view, the BLE protocol consumes less amount of power than the UWB one, which leads to a longer device lifetime. [35] On the other hand, UWB is very suitable for applications that require a high data rate, but this is not a current key requirement of the presented implementation as sensors data does not require very long values for being represented. Other UWB strong characteristics are its high immunity to multipath fading and its carrier-less nature which avoids the need for modulation/demodulation blocks. Unfortunately, this last factor can also be considered a drawback as every carrier-less system has to rely on relatively complex and sophisticated signal processing techniques to recover data from the noisy environment. Moreover, UWB chips currently have higher costs than BLE ones, which represents a key factor in a realistic product deployment. The most complete available single-chip wireless transceiver is found in the Decawave DWM1001 module development board [49]; however, the product data and technical support are still being worked through. Then, the biggest critical UWB advantage remains its higher localization accuracy; nevertheless, as described in Section 4.4, three distance measurements are needed for efficient position detection. This threats the scalability requirement, especially considering the mentioned higher costs.

Lastly, BLE is a consolidated technology, robust and cheaper, which represents also the AirFuel choice. BLE is also able to mitigate multipath fading through its channel hopping algorithm, making it reliable even in this noisy environment.[63] However, BLE distance accuracy is based on the RSSI, which is notably corrupted in high-reflective surrounding environments.

To summarise, BLE seems the most adequate protocol for almost all the requirements presented in Chapter 4. BLE is relatively mature while UWB has just developed for 15 years and thus lacks market needs and suffers pricy issues. Unfortunately, the distance measurement is not doable with only the RSSI, even though some direction-finding capabilities were introduced to enhance BLE location services. [45] Therefore, a hybrid solution could be designed, inevitably incurring the risk of introducing more interferences to the already highly noisy environment. Alternatively, the receiver location could also be detected through a creative protocol that exploits the received voltage values of the individual e-scooter. This last option was considered the best one; therefore, a localization protocol that does not involve distance measurements is later explained in Section 6.3.

6 Implementation

This Section is covering the practical implementation of the already mentioned CCU, from the delineation of the key parameters, to the design of a localization algorithm and the protocols of the individual units.
Firstly, Section 6.1 provides a detailed resume of the identified parameters to be either passively monitored or actively controlled by the CTU. Secondly, the adopted HW is introduced in Section 6.2, highlighting its relevant specifics, components and peripherals. Afterwards, Section 6.3 presents the main contribution of this thesis, the localization protocol, along with its requirements and limitations. Then, the designed protocol is mostly explained in Section 6.4, as the CTU contains almost all the logic behind it, whereas Section 6.5 shows the CRU behavior. Both the individual units exploit a finite-machine state to illustrate how the system works in case of both a successful charging or the presence of any faults. Finally, Section 6.6 describes in detail the chosen bus protocol for communicating with multiple sensors through the same 2 lines (I2C) and the one for connecting the central unit with each PTU (CAN).

6.1 Key parameters

Key parameters were identified to allow an efficient system monitoring; these should be sent by the central unit to some cloud services for doing it remotely. Statistics would be created to understand how to system is working, thus improving it in the future.
These involve the state of the wireless circuitry before, during, and after the charging process; they are hereby resumed in listed Table 2. Row number 6 is highlighted as it is the only active parameter; the CCU can change it rather than tracking it.

Table 2: Key parameters.

n	Key parameter	*Description*	*Unit*
1	*Identification*	Unique identifier for each unit	-
2	*TX Power*	Transmitted power (PTU)	[Watt]
3	*RX Power*	Received power (PRU)	[Watt]
4	*Efficiency*	Efficiency of the WPT link	%
5	*Temperature*	Temperature of the coil	[°C]
6	*On/off*	Switch on/off the PTU	[bool]
7	*RX position*	Pad position on which the RX is placed	[1-4]
9	*FOD*	Foreign objected detected	[bool]
8	*Maintenance need*	In-situ check required	[bool]
10	*State of charge*	Percentage of full charge	%
11	*State of the battery*	Battery health state	[0-100]

The first parameter is identification: each CCU involved unit must have a unique identifier to differentiate it from the others thus correlating correctly its relative parameters. If each unit had a network interface controller, this could be done through the Media Access Control (MAC) address, which is a unique 12-character alphanumeric attribute. Nonetheless, on the receiving side, it would be redundant to create another ID when each e-scooter comes with a 4-letters one uniquely given by the e-scooter company, VOI. [61] Therefore, a hybrid solution is implemented, using the MAC address for identifying the CTU and the existing company IDs for the CRUs.
Then, the power being transmitted and simultaneously received is critical for understanding the wireless charging behavior. The recording of those values together with their time stamps allows for having solid data about it and eventually improve the system efficiency in the medium period, which also represents a key parameter. TX and RX power can be calculated respectively by measuring voltage and current before the transmitting coil and after the receiving one; their ratio then provides the efficiency value. Anyway, voltage and current are not enough hardware measurements; additional parameters to be monitored are found in the temperatures of the GaN transistors. Indeed, these values give a precious indication about the state of the charging: when they are too high, something is not working as it is supposed to, as these components are particularly vulnerable.
As previously mentioned, row number 6 is highlighted because the on/off parameter should not only be observed but also actively changed when the CCU protocol needs to be. Its value will be given to each PTU, and be represented in bool, meaning it can be either true or false.
Another key parameter is the receiver position, as introduced in Section 4.4, which correlates the position of the e-scooter with the PTU it is being charged from. Considering the minimum hostable vehicles by the developed charging platform, it can take a number from 1 to 4; the relative charging pad should have the same position number.
Moreover, an indication of whether a foreign object is detected is considered necessary, storing the value as a bool. As explained in Section 4.5, CTU receives the FPGA output through an interrupt timer and behaves accordingly when this field is true.
Unfortunately, not all the actions can be accomplished remotely, especially when the faults (over-voltage, over-current, and over-temperature) become recurrent. Therefore, the "maintenance need" indicates whether a local expedition is needed to physically check the platform and understand what went wrong.
Finally, monitoring the state of charge is considered crucial to follow the best battery charging profile. As mentioned in Section 4.6, keeping its SoC between 20% and 80% can strongly improve the battery's lifetime. On the other hand, the state of the battery allows to keep track of the battery's health state; each battery starts with a 100 and slowly deteriorates as time goes on. This deterioration period can be estimated by studying the relative charging profile characteristics, such as speed of charge and discharge, maximum achievable voltage, and many more. This estimation can be further improved during the platform deployment and allow to know when to safely remove a battery before any damage occurs.

6.2 ESP32 Development board

The ESP32 is a series of devices integrated with Wi-Fi and BLE and characterized by low-cost and low-power requirements; therefore, it represents an ideal solution for modern IoT applications. It is a system-on-a-chip microcontroller developed by EspressIf Systems, a Shanghai-based Chinese company; the ESP32-DevkitC was the chosen one after looking at the market availability. This is a complete development board, thus a different PCB could be designed in the future to keep only the necessary components and save space. However, due to its exceptionally small dimensions (54.4x27.9 mm), it is considered sufficient to prototype the CCU.
The key components of this compact board are:

- **ESP-32-WROOM-32**:
  A dual-core microprocessor that includes built-in antenna switches, RF balun, power amplifier, low-noise receive amplifier, filters, and power-management modules. More specific information about this module can be found in [55].

- **EN Button**:
  Reset button.

- **Boot Button**:
  Download button. It downloads the firmware through the serial port when pressed together with EN.

- **USB-to-UART Bridge**:
  Single-chip which connects the Universal Serial Bus (USB) and the Universal Asynchronous Receiver/Transmitter (UART) interfaces with a data rate of up to 3 Mbps.

- **Micro USB port**:
  This is the USB interface between the module and a computer. It provides a power supply to the board as well as communication.

- **5V Power On LED**:
  This led is ON when the USB or an external 5V power supply is connected to the board.

- **GPIOs**:
  The board has 36 different General-Purpose Input/Outputs (GPIOs). As described below, they can be programmed to enable multiple peripherals.

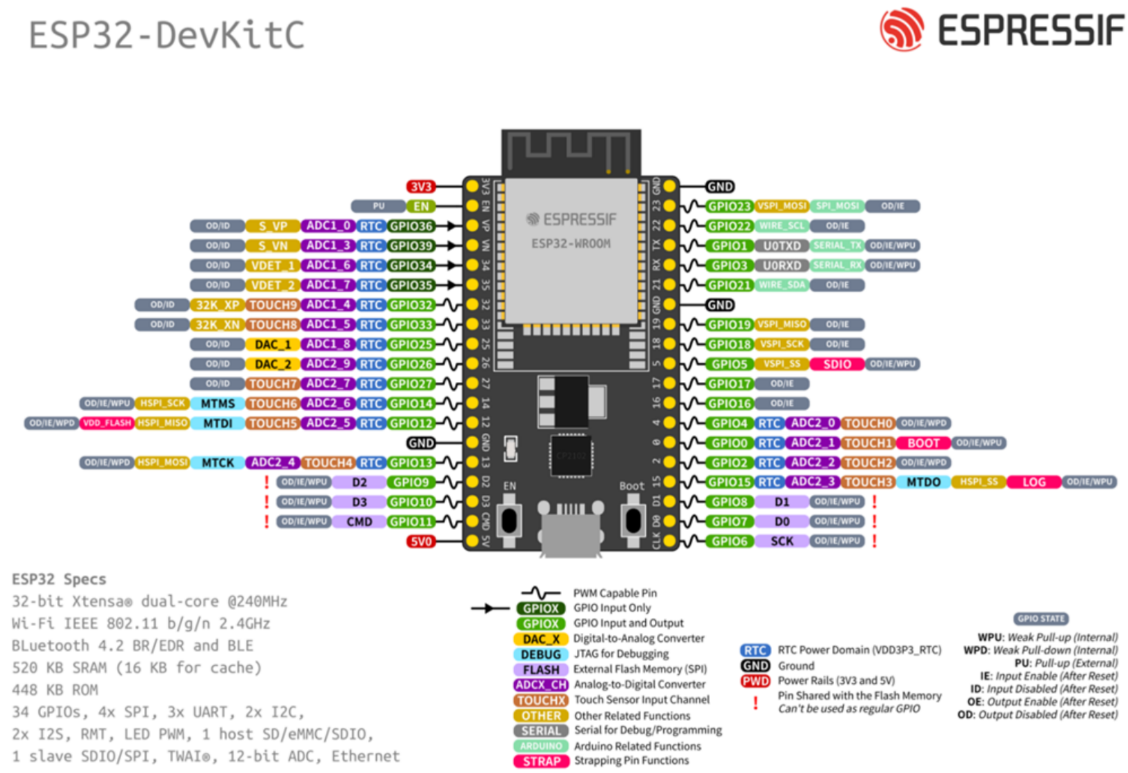


Figure 13: ESP32-DevKitC specifics. [54]

Figure 13 resumes the ESP32-DevKitC specifics; in particular, it reports the peripheral modes with which the GPIOs can be configured. The most important are mentioned here: capacitive touch, Analog-to-Digital Converter (ADC), Digital-to-Analog Converter (DAC), Inter-Integrated Circuit (I2C), UART, Controller Area Network 2.0 (CAN), Serial Peripheral Interface (SPI), Integrated Inter-IC Sound (I2S), Reduced Media-Independent Interface (RMII), and Pulse Width Modulation (PWM).
On the BLE capabilities, it is important to note that the maximum number of slaves allowed to be connected to a single master is set to 9. This is a physical limit set by the developed BLE controller interface.

6.3 Localization protocol

The localization protocol is the main personal contribution of this thesis, as it avoids the necessity of reliable distance measurement and it allows the use of the technology considered as the most suitable one: BLE. As explained in Section 5.4, BLE represents the best solution for almost all the key requirements presented in Chapter 4. Unfortunately, it lacks of an accurate location detection technique since RSSI values are notably corrupted by reflections in noisy environments. Therefore, this protocol aims to overcome this limitation, designing a localization algorithm that exploits the voltage measurements on the receiver side instead of distance ones. The designed protocol is resumed with a flowchart in Figure 14. The localization

process starts when a CRU is successfully connected to the CTU, which happens when the e-scooter is nearby the charging platform. Then, the CTU sequentially switches the pads on in a low-power mode and keeps checking for a reasonable amount of time whether the energy is received from the CRU or not. This time is initially set to 3 seconds, and the voltage threshold is 50V; they could both be adjusted accordingly during future tests. The protocol principle relies on the fact that when the voltage is received from the e-scooter, it means it is placed above the pad which is currently active. When this happens, the CRU position is correctly detected.
It should be noted that this sequential switching must not be done at full-power, because a vehicle carrying a damaged battery could be placed inside the charging platform. This damaged battery would receive power during the localization process of another one. Thus, the sequential switching should be done in a low-power mode to avoid sending a possibly harmful amount of energy to a damaged battery.

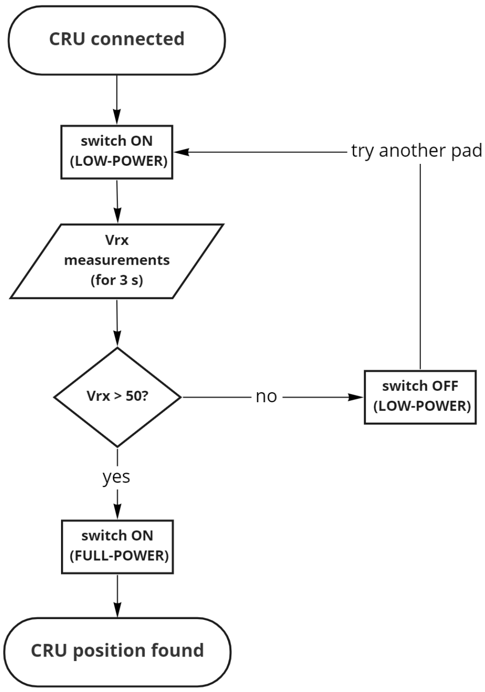


Figure 14: Localization flowchart.

The resulting basic behavior is illustrated in Figure 15, where the red lines indicate the e-scooter was not receiving the voltage when the relative charging pad was on. Finally, attempt number 4 makes the vehicle receive the power, therefore correlating its position with the relative pad number 4.
Nevertheless, not all of the required protocol features are represented in the flowchart of Figure 14. Some further characteristics are essential to assure efficient and reliable position detection without the involvement of distance measurements. Firstly, only one CRU can go through the localization process at a time to avoid misunderstandings. This is crucial as otherwise several pads could be simultaneously switched on, then no more assurance would be present about which is the one sending power to the CRU being checked. Moreover, the pads already enabled in full-power mode must not be

involved in the sequential switching anymore but left to their charging process. Another key feature to be added is a timeout which limits the time a CRU can be involved in this process, as other ones could be waiting to start it. No assurance about a successful detection is given in this scenario, as the e-scooter is not necessarily placed on one of the transmitting circuits even after a successful connection. As it is later explained in Section 6.4, the connection happens only within a range indicated by the RSSI value; however, the connected receivers can be just located nearby the platform, since RSSI is considered unreliable in this environment.

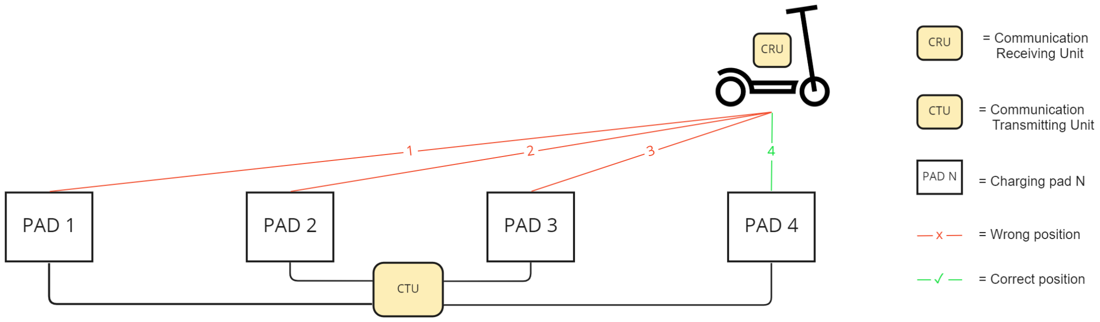


Figure 15: Localization protocol basic behavior.

To resume, this localization protocol exploits received voltage measurements and a sequential switching of the charging pads in low-power mode. Only one vehicle can go through the algorithm at a time, and a maximum timer is present to avoid infinite loops.

6.4 Communication Transmitting Unit (CTU)

This Section is going to cover how the CTU behaves, which essentially also contains all the logic behind the whole CCU. Therefore, a whole system picture is first given to later deeply analyze the CTU finite-state machine procedure. In addiction, considerations about the defined BLE service and characteristics can be found.
The BLE architecture, as already mentioned in Section 5.1, provides two different roles: the master and the slave. Here, the master is represented by the CTU while the CRUs are the slaves. Moreover, these roles can also be considered respectively host and peripherals, or even client and servers. The last ones are the utilized nomenclature from this point onwards since they are perceived as more intuitive by the author.
The server (CRU) advertises its existence, so it can be found by the client (CTU) through a scanning process; the connection is then established and the data contained in the server can be read by the client. This is also called point-to-point communication. Figure 16 shows the client maintains different bi-directional communication links with each server; the power link is mono-directional instead and it is physically provided by the PTU.
The NimBLE stack has been chosen for the BLE implementation, as it comprises smaller heap and flash requirements than others resulting in more lightweight. [56]

Each BLE service, characteristic, and descriptor have a Universally Unique Identifier (UUID), which is a unique 128-bit (16-bytes) number. The Bluetooth SIG specified some shortened UUIDs for all types, services, and profiles, including one for the WPT service. Then, this is used within CRU advertisements to connect only with these devices. The WPT Service UUID is 0xFFFE. [52]

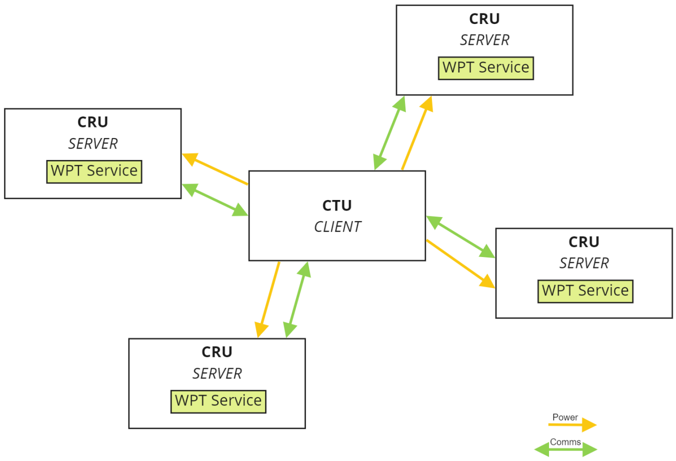


Figure 16: System architecture.

This protocol essentially contains 1 service and 2 characteristics. The service is mentioned above, whereas the characteristics are:

- **CRU Dynamic**:
  This is used by the CTU to read CRU dynamic values once the connection is established, mainly represented by the sensor measurements. Its identifier was generated using [24] and can be found below:

$$UUID = facb1764 - 2847 - 11ed - a261 - 0242ac120002 \tag{7}$$

- **CRU Alert**:
  Other than the READ permission, this characteristic has WRITE and NOTIFY permissions as well. In fact, this will be used by the CRU to send notifications of an Alert presence back to the CTU. Its identifier was generated using [24] and can be found below:

$$UUID = facb1a2a - 2847 - 11ed - a261 - 0242ac120002 \tag{8}$$

The basic state procedure is hereby described; it is also illustrated in Figure 17. Initially, the CTU starts in the CONFIGURATION STATE, where all the different modules required by the application are initialized, and a periodical timer begins to check for local faults. When the configuration is complete, it moves to LOCALIZATION STATE, the main state where the process stays in a busy wait loop. Here, the client scans for CRU that non only are advertising the WPT service, but are also placed within a few meters from it. This requirement is done by checking that:

$$RSSI < -80dBm \tag{9}$$

Therefore, the connection happens only with a CRU in the proximity of the charging platform, meaning within a distance of about 5 meters. Finally, when the localization process described in Section 6.3 understand on which charging pad the vehicle is placed, it transits to the POWER TRANSFER STATE where the wireless power transmission starts. The CTU then keeps reading the CRU Dynamic characteristic at least every 250ms, until it receives a CRU Alert Notification which can mean the charging is complete, or some sensor measurements are above the defined safety threshold, or the voltage is no longer received. In any of these cases, a disconnection occurs; when no CRUs are connected anymore, the CTU transits back to the localization state.
The voltage, current, and temperature of each PTU are periodically checked during the whole procedure. If a local fault is detected, the CTU goes into LOCAL FAULT STATE, where the relative power interface is disabled and the BLE stack is reset. On the other hand, a CRU-detected fault would send the CTU into REMOTE FAULT STATE, which disconnects the relative CRU and tries to check whether the receiver can recover by itself. It should be noted that both attempts, BLE stack reset and CRU disconnection, happen after a exponential waiting time when the fault is caused by an over-temperature, and a linear one otherwise. Indeed, the time interval could allow the circuits to be cooled down by the ambient temperature. However, after 3 failed recoveries, the relative power interface is constantly disabled and the maintenance need (described in Section 6.1) is set to true.

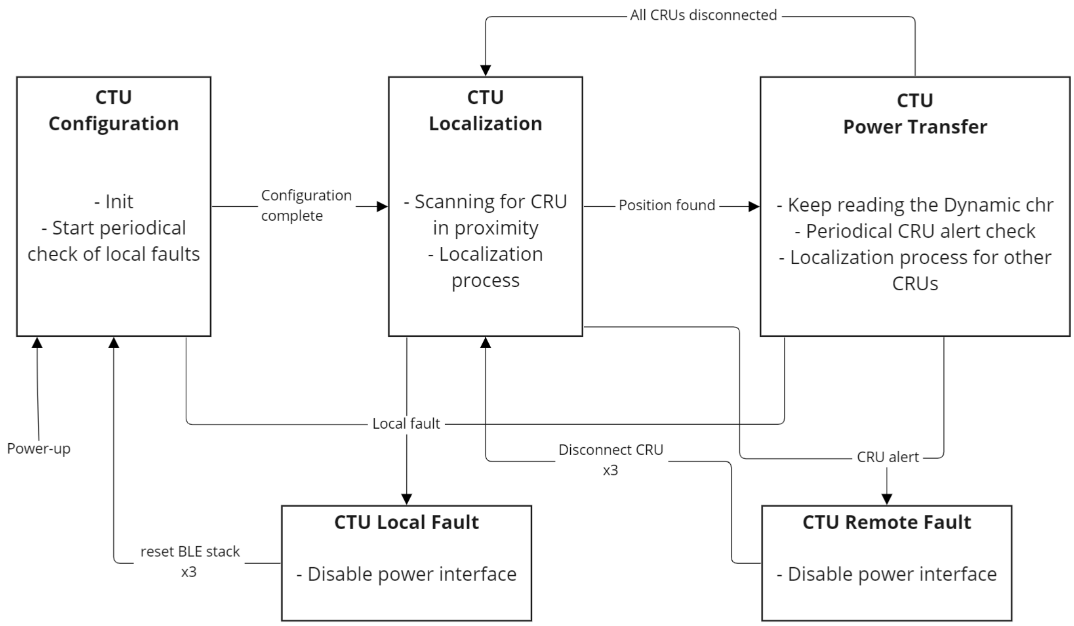


Figure 17: CTU finite-state machine.

6.5 Communication Receiving Unit (CRU)

This Section delineates the CRU behavior, which acts as a server answering to the requests made by the client. The CRU is integrated in each vehicle, and it is also responsible for measuring current, voltage, and temperature of the receiving side. Its finite-state machine is illustrated in Figure 18 and explained below.
The unit starts inside the CONFIGURATION STATE, which initializes the necessary application modules and advertise its presence until the connection is established by the client. It then moves to the POWER TRANSFER STATE only where it receives energy by one PTU in full-power mode,, which means its position was detected by the CTU. Afterwards, it comes back to the configuration state only when the charge stops, which is sensed through local sensor measurements. In addiction, the transition to the LOCAL FAULT STATE could happen anytime a fault is detected; the CRU is then disconnected, thus starting to advertise its presence again within the configuration state.

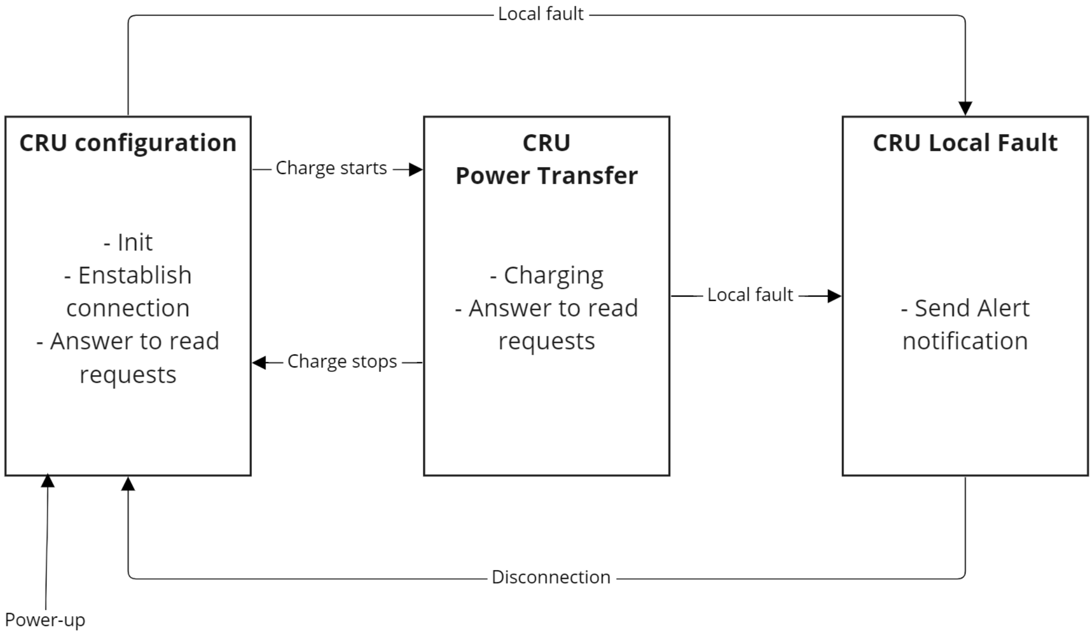


Figure 18: CRU finite-state machine.

Hereby the defined payloads, which are used by the characteristics listed in Section 6.4, are reported as in the coding implementation, which was made in C programming language:

- **Dynamic payload**:

```c
  // Union structure for sending float values over BLE payload
  union i2c {
    float f;
    uint8_t bytes[4];
```

```
    };
    // This contains elements necessary for dynamic payload.
    typedef struct
    {
        // Vrect value from I2C (4 bytes).
        union i2c          Vrect;
        // Irect value from I2C (4 bytes).
        union i2c          Irect;
        // Temperature value from I2C (4 bytes).
        union i2c          Temp;
        // CRU alert field for warnings to send to CTU (1 byte).
      uint8_t            Alert;
    } wpt_dynamic_payload_t;

```

- **Alert payload**:

```
    // Alert characteristic structure.
    typedef union
    {
    struct {
      // Charge complete field (1 byte).
      uint8_t            charge_complete:1;
      // Over-temperature field (1 byte).
      uint8_t            overtemperature:1;
      // Over-current field (1 byte).
      uint8_t            overcurrent:1;
      // Over-voltage field (1 byte).
      uint8_t            overvoltage:1;
      };
      uint8_t internal;
    } alert_field_t;
    // This contains elements necessary for alert payload
    typedef struct
    {
      alert_field_t      alert_field;
    } wpt_alert_payload_t;

```

Finally, it should be noted that the union structure called **i2c** is aimed to locate in the same memory address the I2C value in both integer and float formats. This allows to send the values using the defined NimBLE functions, which send integers, and then convert them back into decimal numbers (float).
Moreover, the same union structure is exploited in the Alert payload, where the field *internal* will become high when at least one of the other fields is set to 1 (*overvoltage*, *overcurrent*, *overtemperature*, and *charge_complete*). Therefore, *internal* will be set to the *alarm* field of the dynamic payload, making it possible to read the presence of an alert every time the dynamic characteristic is read by the CTU.

6.6 I2C and CAN buses

I2C is a serial communication bus that allows two or more devices to communicate with each other, using either the master or slave role. Normally, a bus has only one master and several slaves, which are differentiated by their unique addresses. The adopted communication speed is 400Kbit/s, which represents the I2C fast mode. The CCU comprises voltage, current, and temperature I2C measurements on each transmitting as well as receiving circuit. The chosen sensors were found in the *tmp112* [38] for voltage and current and in the *tmp100* [39] for temperature.
Figure 19 shows how only two lines are required by this technology: the Serial DAta (SDA), where the data transits, and the Serial CLock (SCL), which carries the master clock signal necessary for synchronization. The START condition happens when SDA transitions to the low state while SCL is high, then the master sends a byte (7-bit address + 1-bit READ/WRITE command) and waits for an ACK in response. This behavior goes on until the STOP condition, which occurs when the SDA transitions to the high state while SCL is high.

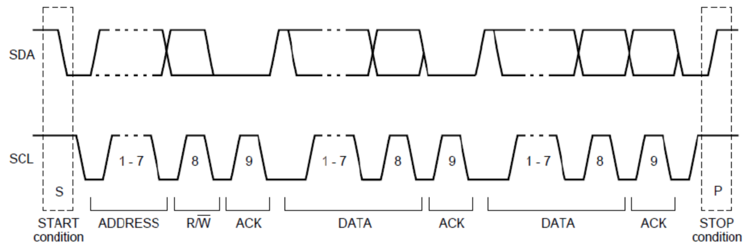


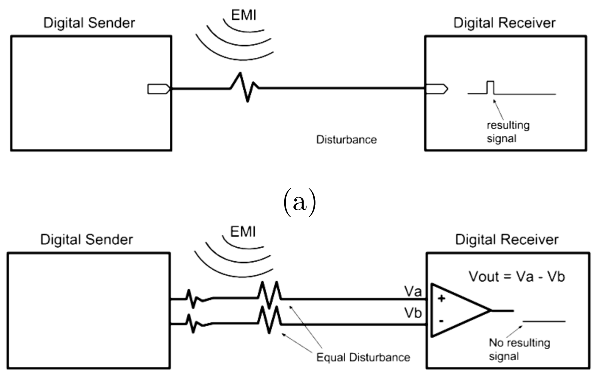
Figure 19: I2C timing chart. [51]

Nevertheless, I2C is a short-distance protocol since the master clock travels along the bus, and therefore it is particularly sensitive to external EM noise. Sensing the I2C lines with an oscilloscope in I2C mode, deconstructive interferences were found along the wired connections between the CTU and the PTUs. Figure 20a illustrates the scenario where the PTU is on but no PRU is placed above it; it can be seen how the SDA (blue line) and SCL (pink line) are successfully decoded even though they are not very clean already. Unfortunately, this changes in Figure 20b, where the PRU is receiving full-power from the PTU and the generated EMI along the cables makes the reception impossible.

(a) (b)

Figure 20: I2C lines without (a) and with (b) the IPT link.

Hence, the CAN bus was adopted for sending TX I2C measurements to the CTU, whereas the RX ones work reliably as they utilize short-wired cables to each relative CRU which then sends them to the CTU via BLE. The CAN bus is also responsible for the switching command transmission to each PTU;; these commands set to high state the input of a Solid-State Relay (SSR) for enabling either low-power or full-power mode.
The CAN protocol is also a serial communication bus for allowing more devices to communicate with each other's applications without a host computer, but it provides some more robust features than I2C. Firstly, only the data travels on the bus thus the clock is generated by each node; then, the detection of the correct bit time cannot be compromised by EMI. Secondly, it uses differential signal technology to transfer the data, which is much more immune to EMI. The difference between normal single signals and differential ones is highlighted below, where Figure 21a gets a disturbance on the receiver side whereas Figure 21b does not because the reverse polarity on the two lines nullifies the EMI.



(b)

Figure 21: EMI effects on single signal (a) and differential ones (b).

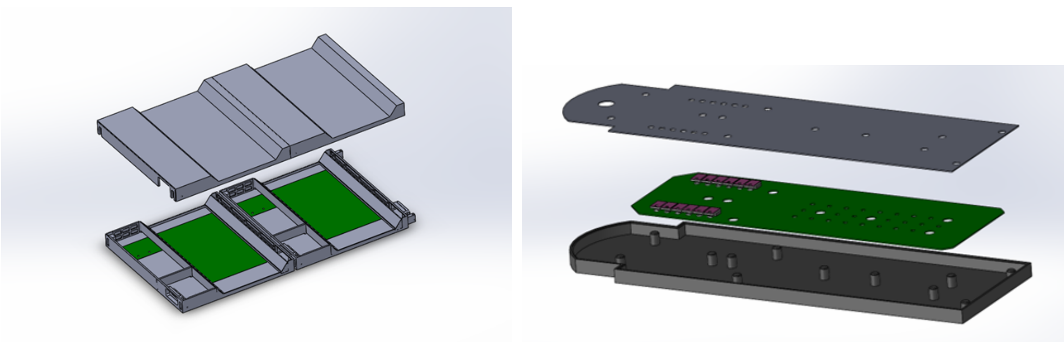
Figure 21b is true only under the assumption that both signals are equally affected by the noise, so the two wires need to be placed as close as possible to each other. In this thesis implementation, they were twisted together, and the required CAN transceiver and controller ICs to convert TTL logic in differential levels were respectively found in *MCP 2551* [44] and *MCP 2510* [43]. Furthermore, CAN bus uses the developed CRC approach for error detection, it can host many more devices than I2C, and the bit rate is generally faster as concurrent transmissions are allowed. Finally, the bus was implemented within a standard existing Ethernet cable as it provides improved shielding, and was connected to the ESP-32 configured interfaces. This bus worked reliably only when placed at least 40 cm away from the charging pads. In the future, other solutions need to be evaluated to make the CCU capable of working closer to the PTUs; however, this was not investigated yet as not considered the main focus of the thesis. More robust buses could be found in FlexRay or Ethernet; eventually, some auxiliary transmitting units could be also placed on each PTU and send the I2C measurements wirelessly over BLE or Wi-Fi.

7 Evaluation

This Section focuses on the analysis of the developed CCU features, described in Chapter 6, to assess their reliability according to the system requirements listed in Chapter 4. Not all of the requirements were accomplished due to the limited amount of time. Nevertheless, it can be said the CCU behaves as required, meaning it is able to react successfully to different users' behaviors around and within the wireless charging platform. The next steps would be to send the measured data to a cloud system and to define efficient post-processing procedures to allow remote monitoring and statistics collection. The author suggests the MQTT protocol as a lightweight solution for this purpose.
Section 7.1 provides the images together with an example output logs of the experimental setup, which utilised the current company prototype of a micro-mobility wireless charging platform. Section 7.2 defines the power requirements of each individual unit and their implications, then 5 basic evaluation scenarios are described and tested in Section 7.3, and finally, 5 complex ones are illustrated in Section 7.4.

7.1 Experimental setup

This Section is presenting the adopted power units by Bumblebee [16], which is the company this thesis has been developed with. Their first wireless charging platform prototype was utilised throughout the tests made for the evaluation scenarios described in Section 7.3 and Section 7.4. An example output from the implemented code is also provided to explain how the assessment was done.
Figure 22a is showing 2 ground charging pads composition: the green parts represent the electronics and the transmitting coil (the bigger one), whereas the grey ones are the structured case. Therefore, this PTU setup does not require docks but just an e-scooter placed on it. On the other hand, Figure 22b is illustrating one PRU composition, which is attached underneath an e-scooter. Again, the green layer represents the electronics together with the receiving coil, and it is in the middle of a ferrite shit (above) and a water-resistant case (below).



(a) (b)

Figure 22: PTU (a) and PRU (b) composition.

The aforementioned PTUs were positioned together to form 4 different wireless charging places at a distance of about 40 cm to each other. Then, 4 e-scooters were retrofitted with a PRU. This led to the creation of a first 4-place wireless charging platform prototype which was utilised for the evaluation tests. Figure 23 shows it in full-mode, meaning all 4 e-scooters are being wirelessly charged. The platform was elevated just to allow an easier experimentation.

Figure 23: Wireless charging platform prototype.

Afterward, some example output logs together with their timestamps are provided to explain how the different scenarios were evaluated. Only the relevant part of the logs were kept for brevity reasons, and some colors are used to differentiate the different lines. Blue indicates the transition to a new state of the CTU protocol, explained in Section 6.4, green is used for information, orange for warnings and red for errors.
The unit is boot up so it starts in the configuration state and then transits in the localization one, where a discovery procedure is done every second. After about 24 seconds, an e-scooter comes near the platform so a connection is established. The CRU's services are checked to assess the presence of the WPT service, which is reported in the logs with a format composed of 32 hexadecimal digits.
The localization process thus starts accordingly to Section 6.3, and the CRU is found in position 3 through the reading procedures happening about every second. Therefore, the third charging pad is enabled in full-power mode, and the power transfer state is finally reached. After about other 23 seconds, the e-scooter leaves the platform. The third charging pad is switched off, the CRU is disconnected, and its relative peer structure is deleted to save space for new ones. Finally, the CTU transits back to the localization state, where it keeps checking for any e-scooter in proximity through the discovery procedures.
It should be noted that the desired software time gaps are only indicative because the presence of many concurrent processes slightly modify them.

[. . .]

— *Time: 0.013 s* —
I (79652) STATES: Power Configuration State

[. . .]

— *Time: 0.836 s* —
I (79652) STATES: Localization State

[. . .]

— *Time: 24.562 s* —
GAP procedure initiated: discovery; own_addr_type=0 filter_policy=0 passive=1 limited=0 filter_duplicates=0 duration=forever
— *Time: 25.524 s* —
GAP procedure initiated: discovery; own_addr_type=0 filter_policy=0 passive=1 limited=0 filter_duplicates=0 duration=forever
— *Time: 25.556 s* —
I (68084) BLE_CENTRAL: CRU found!
GAP procedure initiated: connect; peer_addr_type=0 peer_addr=ac:0b:fb:25:84:06 scan_itvl=16 scan_window=15 itvl_min=6 itvl_max=7 latency=0 supervision_timeout=32 min_ce_len=0 max_ce_len=0 own_addr_type=0
— *Time: 25.624 s* —
GATT procedure initiated: discover service by uuid; uuid=6455fffe-a146-11e2-9e96-0800200c9a67
– *Time: 26.549 s* —
I (65362) LOCALIZATION: Localization process starts!
W CAN_BUS: Enable charge on pad=1 in LOW-POWER
— *Time: 26.812 s* —
GATT procedure initiated: read; att_handle=16
— *Time: 26.824 s* —
GAP procedure initiated: discovery; own_addr_type=0 filter_policy=0 passive=1 limited=0 filter_duplicates=0 duration=forever

[. . .]

– *Time: 29.568 s*
W (78530) CAN_BUS: Disable charge on pad=1
– *Time: 29.595 s*
W (75530) CAN_BUS: Enable charge on pad=2 in LOW-POWER
— *Time: 30.127 s* —
GATT procedure initiated: read; att_handle=16
— *Time: 30.224 s* —
GAP procedure initiated: discovery; own_addr_type=0 filter_policy=0 passive=1

limited=0 filter_duplicates=0 duration=forever

[. . .]

— *Time: 32.681 s* —
W (78530) CAN_BUS: Disable charge on pad=2
— *Time: 32.785 s* —
W (77912) CAN_BUS: Enable charge on pad=3 in LOW-POWER
— *Time: 33.126 s* —
GATT procedure initiated: read; att_handle=16
— *Time: 33.224 s* —
GAP procedure initiated: discovery; own_addr_type=0 filter_policy=0 passive=1 limited=0 filter_duplicates=0 duration=forever
— *Time: 33.364 s* —
I (79638) BLE_CENTRAL: RECEIVED VOLTAGE GREATER THAN 50 V
I (79638) BLE_CENTRAL: CRU is in position 3
— *Time: 33.392 s* —
W (79646) CAN_BUS: Enable charge on pad=3 in FULL-POWER
— *Time: 33.402 s* —
I (79652) STATES: Power Transfer State

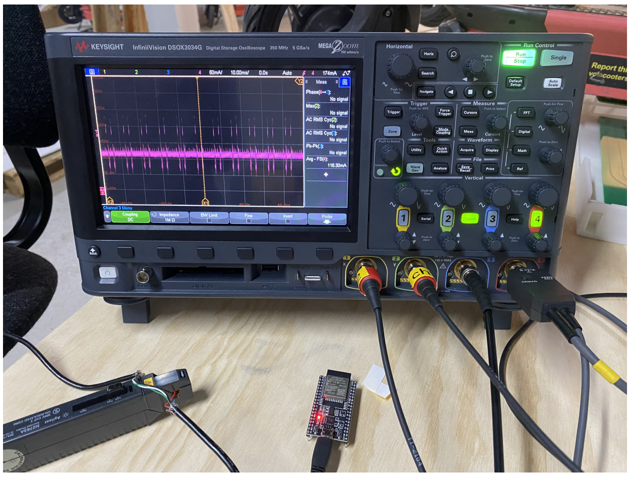
[. . .]

— *Time: 56.526 s* —
E (71638) BLE_CENTRAL: VOLTAGE NO LONGER RECEIVED
– *Time: 56.551 s* —
W (71642) CAN_BUS: Disable charge on pad=3
— *Time: 56.615 s* —
E (282555) BLE_CENTRAL: Disconnection with conn_handle=1
GAP procedure initiated: terminate connection; conn_handle=1 hci_reason=19
— *Time: 56.772 s* —
E (282577) PEER: Deleting peer with conn_handle=1; 0 peers remaining
— *Time: 56.902 s* —
I (79652) STATES: Localization State
— *Time: 57.485 s* —
GAP procedure initiated: discovery; own_addr_type=0 filter_policy=0 passive=1 limited=0 filter_duplicates=0 duration=forever
— *Time: 58.535 s* —
GAP procedure initiated: discovery; own_addr_type=0 filter_policy=0 passive=1 limited=0 filter_duplicates=0 duration=forever

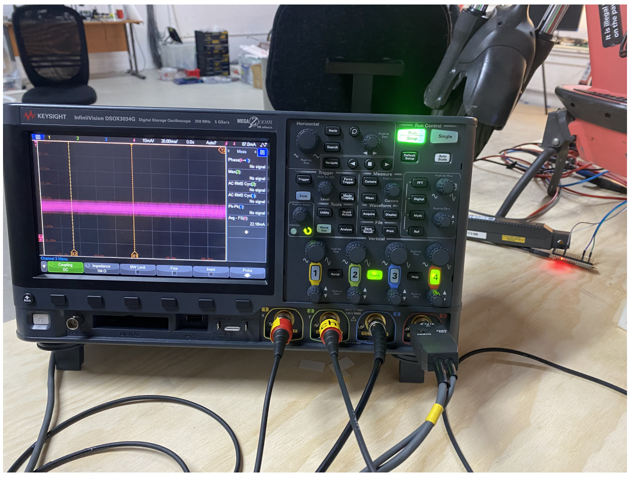
[. . .]

7.2 Energy considerations

The power consumption is a critical feature of each individual unit which is comprised of the designed CCU; nevertheless, it is much more crucial on the receiving side as the batteries inherently provide a limited amount of energy. Then, the following power considerations are presenting both CTU and CRU energy requirements, and mention a power-saving solution for the last one.
A current measurement was enough to calculate the consumed energy since the esp32 required voltage is fixed at 5 V. Therefore, a sensing coil was put around the supply wire and connected to an oscilloscope in order to obtain this parameter. Figure 24a shows the CTU average value, 118.39 mA, and Figure 24b indicates the CRU one, 22.18mA. Both values were obtained while the devices performed all their relative implemented functions. Also, it should be noted that these values respect the device datasheet recommendation for safe usage. [21]



(a)



(b)

Figure 24: Current measurement for CTU (a) and CRU (b).

The power consumption was calculated following the equation:

$$P[W] = V[V] * I[A] \tag{10}$$

This was then multiplied by the number of hours it is being used to get the number of Watt-hours $[Wh]$. The results are highlighted in Table 3 to understand the required energy of every single unit during a time span of a day, a month, and a year.

Table 3: CTU and CRU power requirements during different periods.

Unit	***P***	***P - daily***	***P - monthly***	***P - yearly***
CTU	0.59 [W]	14.21 [Wh]	426,20 [Wh]	155.56 [kWh]
CRU	0.11 [W]	2.66 [Wh]	79.85 [Wh]	29.14 [kWh]

As previously mentioned, the power requirements for the CTU are not considered as important as the ones of the CRU, because the first will be directly connected to the grid while the second is mounted on a moving object with limited battery capacities. Consequently, even though a daily **2.66Wh** is already a very low-energy requirement, it should be lowered in the future. For instance, a *sleep mode* would allow keeping only the device clock alive when the scooter is not around the platform, sending the advertisements only occasionally thus saving energy.

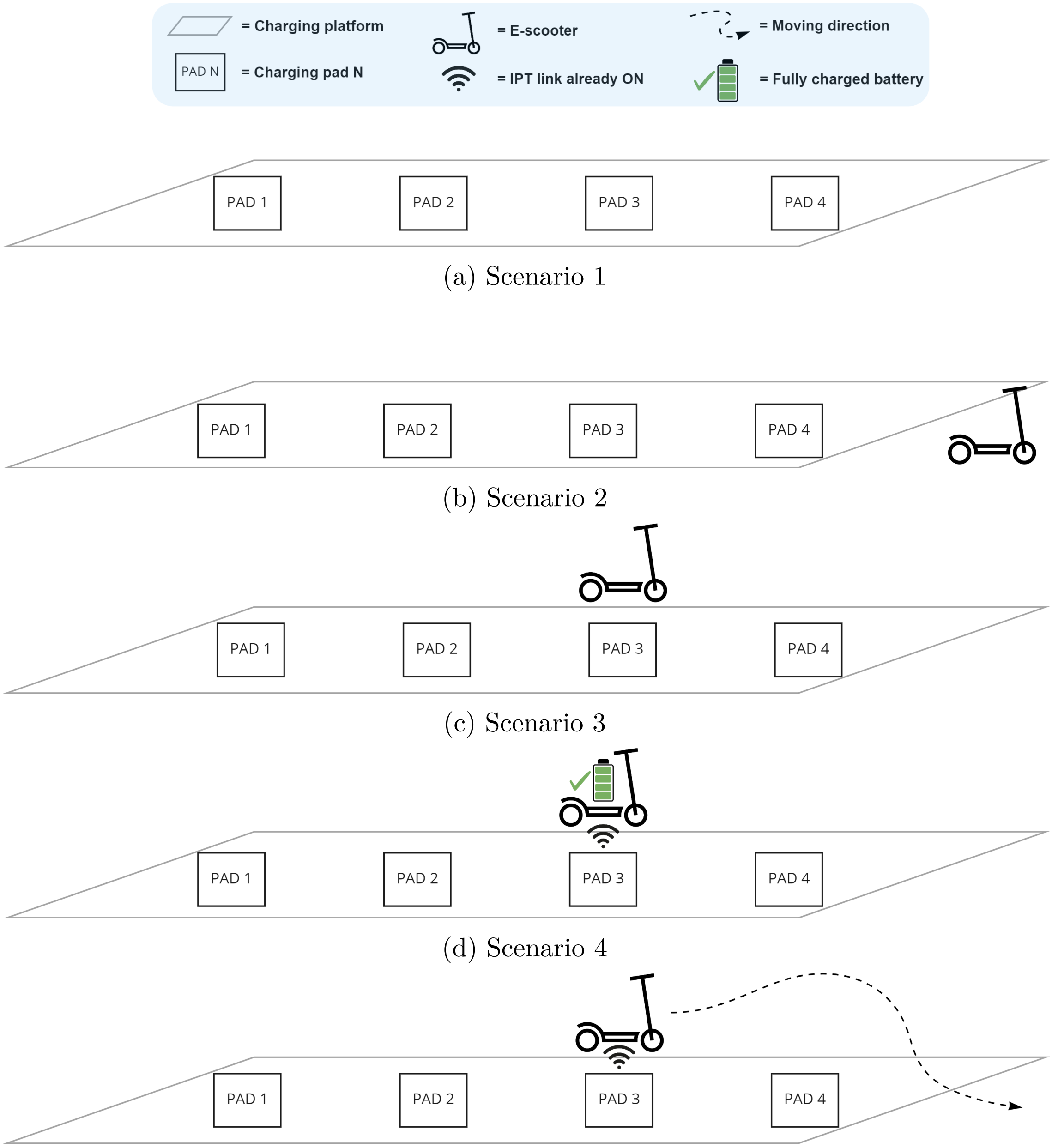
7.3 Simple evaluation scenarios

5 basic scenarios were identified to evaluate the unit basic behaviours. They are hereby described in Table 4 and illustrated in the relative Figures 25a, 25b, 25c, 25d, and 25e. These are considered the simplest circumstances the developed CCU must deal with; therefore, they were tested to assess whether the CCU reacted to them as expected by the protocol.
The number 1 can be considered the default wireless charging platform state: no vehicles are nearby. Here, all the PTUs are constantly off. Scenario number 2 involves one e-scooter placed in proximity to the platform, which might happen when the user completed the ride but he/she is having a chat with a friend before parking the vehicle. Then, the BLE connection between the CTU and CRU is established accordingly to Section 6.4 and the localization process switches sequentially the charging pads every 3 seconds in low-power mode, as explained in Section 6.3. However, none of them make the PRU receive any voltage. So, the localization timer (20 seconds) is triggered and makes the units disconnected for 2 minutes, waiting for the e-scooter to be moved. If it is still in proximity after this waiting time, the same procedure is repeatedly attempted until the position is found. It should be noted that the chosen times could be changed in the future, and the time gap after the disconnection

could be increased after every failed location detection attempt. Alternatively, an accelerometer sensor could be added to the system to make the reconnection happen only when the e-scooter is moved, avoiding unnecessary location detection attempts. The third scenario happens when the user correctly parks the vehicle on one of the charging pads. After the BLE connection establishment, the relative position is found as the received voltage is greater than the predetermined threshold, which is currently set to 50 V. Finally, the charging process starts in full-power mode.
When the charging process is complete and therefore the e-scooter battery is fully charged, the CRU detects a drop in the flowing current while the voltage stays high. This represents scenario 4, where the CRU sends a notification to the CTU which switches the relative PTU off and disconnects from the receiver. If the e-scooter does not leave the platform, the reconnection takes place after a reasonable time gap which is currently set to 2 hours.
Nevertheless, if the vehicle does leave the platform before the charging is complete, the CTU switches the relative charging pad off and removes the connection as soon as the received voltage no longer respects the mentioned threshold of 50 V.

Table 4: Simple evaluation scenarios testing resume.

N.	***Fig.***	***Description***	***Expected CCU behavior***	***Outcome***
1	25a	No e-scooter nearby the platform	-All pads stay off	✓
2	25b	One e-scooter is placed nearby.	- BLE connection - Localization timer expires - Wait 2 mins and retry (repetitive)	✓
3	25c	One e-scooter is placed above a pad.	- BLE connection - Position found - Charging starts	✓
4	25d	Charging complete, and the e-scooter does not leave.	- CRU sends notification to CTU - Charging stops and disconnection - Reconnection after 2 hours	✓
5	25e	The e-scooter leaves during charging.	- Voltage not received - Pad switches off - Disconnection	✓



(a) Scenario 1

(b) Scenario 2

(c) Scenario 3

(d) Scenario 4

(e) Scenario 5

Figure 25: Simple evaluation scenarios.

To summarise, The CCU behaved as expected throughout all 5 identified simple evaluation scenarios, but time gaps can be further improved with the help of an accelerometer sensor.

7.4 Complex evaluation scenarios

This chapter is delineating other 5 evaluation scenarios, following the same structure as Section 7.3, which are considered complex as they involve more particular behaviors of both vehicles and users. They are resumed in Table 5 and illustrated in Figures 26a, 26b, 26c, 26d, and 26e.

Scenario number 6 deals with an unsuccessful positioning of the vehicle on the charging pad. Even though Bumblebee [16] offers greater tolerance to misalignment than other existing wireless charging technologies, as explained in Section 3.3, it still has limitations. These limitations could be removed by some mechanical structure which would help the vehicle to be placed in the correct position; however, the necessity to keep the system as flexible as possible is highlighted in Section 4.4. Therefore, it is not clear yet what the adopted structure will be. Nevertheless, the conducted test with the e-scooter placed in a slightly wrong position shows that the localization algorithm starts right after the BLE connection establishment, but the received voltage is not greater than the defined threshold of 50 V. Thus, the CCU behaves similarly to the scenario 2 as it keeps on trying to find the vehicle position. What could be added is a notification to the user to avoid this scenario; for example, a green led placed near the relative pad could tell when the e-scooter was correctly placed while a red one when it is not.

The seventh scenario complexity is because 2 vehicles are simultaneously in the platform, and it can be taken as a reference for what happens with 3 or 4 ones. It should be noted that even in the case of a simultaneous arrive of 2 or more e-scooters, the location detection is done with them sequentially to avoid misunderstandings accordingly to Section 6.3. Then, this scenario describes the procedure of a second vehicle placed on a pad while the first one is already being charged. The CCU behavior is similar to scenario 3, with the difference that the pad which is already charging on must not be involved in the sequential switching of the localization algorithm, but it should be kept in full-power mode throughout the second e-scooter location detection. Afterwards, 2 charging pads are on in full-power mode.

Scenario 8 describes the unusual but possible user behavior of moving the vehicle from one pad to another for any reason, for example, because the first spot is not comfortable for him/her. Here, the CTU would disconnect from the CRU as soon as the received voltage drops below the defined threshold, since the voltage check is continuously done even after the charging process starts. Consequentially, a reconnection happens and the new position is detected as in the simple evaluation scenario 3.

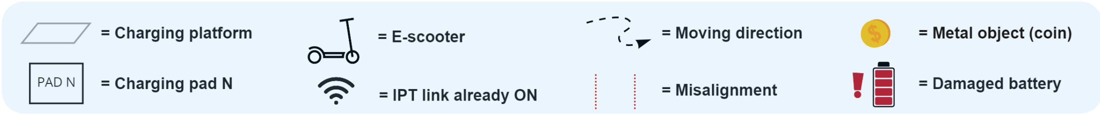
Then, scenario number 9 describes the presence of an e-scooter with a damaged battery on a charging pad. This could not be entirely tested as the faulty batteries conditions can be countless; however, the detection of an over-current by the CRU is expected, which then sends an alert notification to the CTU. This alert brings the CTU into the *REMOTE FAULT STATE*, as described in Section 6.4. Here, the CTU tries to disconnect and reconnect 3 times with a time gap of 20 seconds to check if the fault is recovered by itself. If not, an alert for local maintenance is sent out.

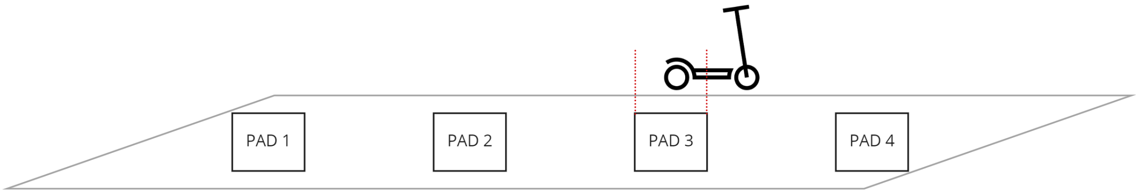
Scenario 10 happens in the presence of any metal within the IPT link; as explained

in Section 4.5, this is usually referred to as Foreign Object Detection (FOD). Here, the detection is done by the current company hardware implementation, so the CCU gets to know this presence just by an input pin connected to the output of the FPGA. The CCU then reacts disabling immediately the relative power interface and, similarly to scenario 9, disconnects and retries 3 times; if the object is still there, an alert for local maintenance is sent out.
It should be lastly noted the I2C measurements are updated about every 150 ms, and the BLE readings are done about every second. Then, the minimum system reactivity is about *1.15s*. This could be crucial to avoid misunderstandings generated by 2 or more vehicles swapping places with each other. However, this obtained reactivity can be considered faster than any manual swapping thus making the CCU reliable even in this critical presented scenario.

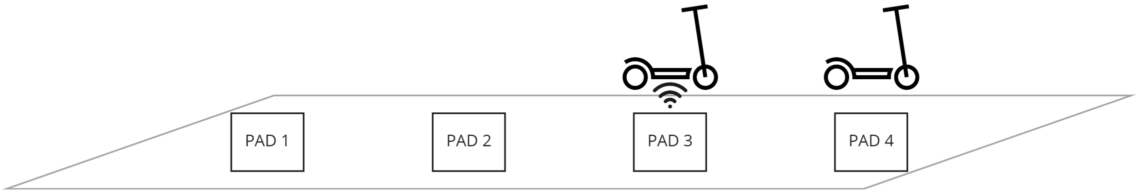
Table 5: Complex evaluation scenarios testing resume.
*To be further developed.

N.	*Fig.*	*Description*	*Expected CCU behavior*	*Outcome*
6	26a	One e-scooter placed in a slightly wrong position.	- Connection and localization starts - Received voltage not enough -Notification to the user	✓*
7	26b	One e-scooter is charging, and another one arrives on another pad.	- BLE connection - The working pad is not involved in the localization - Position found - 2 charging links	✓
8	26c	One e-scooter leaves a pad for another one.	- No received voltage - Disconnection and reconnection - New position found and charging on	✓
9	26d	One e-scooter with a damaged battery is placed above a pad.	- Overcurrent on CRU side - CRU sends a notification to CTU - Disconnection and retry (x3) - If not solved, disconnect permanently - Send alert for local maintenance	✓*
10	26e	A metal is placed within the IPT link.	- FPGA detects it and tells to CTU - Disconnection and retry (x3) - If still there, send alert for loc. main.	✓*

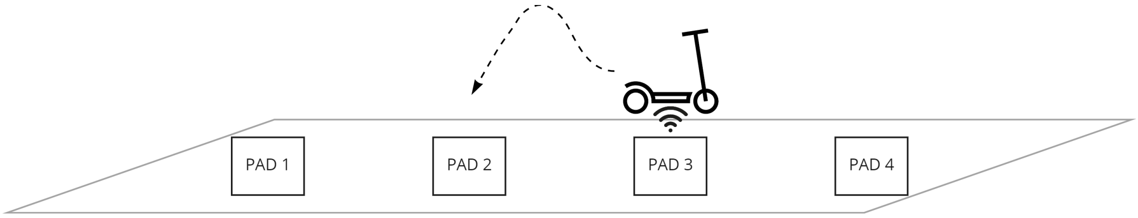




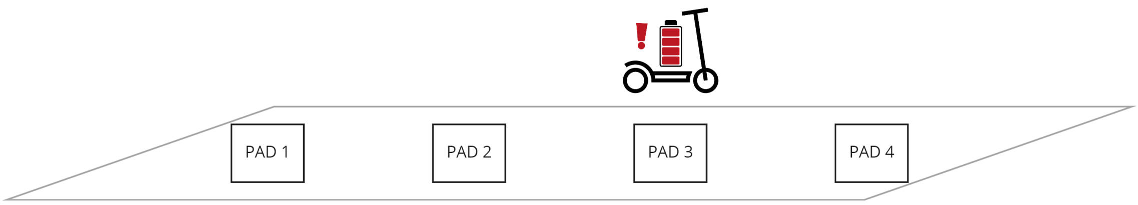
(a) Scenario 6



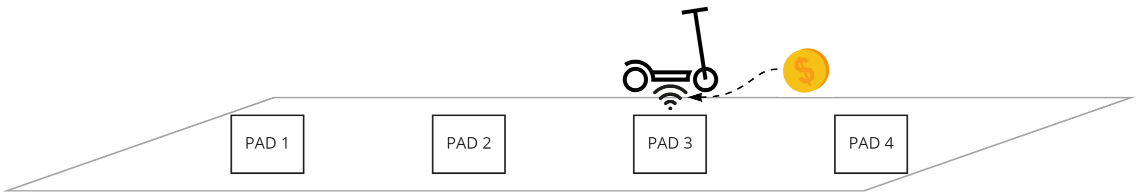
(b) Scenario 7



(c) Scenario 8



(d) Scenario 9



(e) Scenario 10

Figure 26: Complex evaluation scenarios.

To summarise, the CCU behaves as expected also in each of the 5 described complex evaluation scenarios. Further considerations about how to handle the vehicle misalignment, remote alert state, and local maintenance messages are needed for future improvements.

8 Conclusion

In this thesis, the aim was the design of a Control&Communication Unit (CCU) to be integrated with Bumblebee [16] wireless power circuity. Specifically, the mentioned unit had the purpose of enabling an automated and monitored wireless charging process for micro-mobility vehicles in shared schemes. The primary part of the thesis focused on the definition of the adopted technology this unit had to coexist with, and the delineation of the problems that the micro-mobility sector is currently facing. Therefore, the need of charging and parking those vehicles made clear how a wireless charging platform could ultimately be deployed in cities' streets as it would tackle both the mentioned issues. A technology comparison was carried between out BLE, UWB, and RFID protocols to choose the best candidate accordingly to the scenario's requirements. Finally, BLE was implemented through some ESP32 microchips following a client-server architecture; the single client was defined as the Central Communication Unit (CTU) whereas the multiple servers located on each vehicle were called Communication Receiving Unit (CRU). The main contribution of this thesis was the design of a localization algorithm that did not involve distance measurements thus making the system more scalable and cheaper. Key system parameters to be either monitored or controlled were defined, and a 5-finite states protocol was outlined for the CTU automated behavior in multiple conditions of the platform. Lastly, the CCU was tested by simulating some basic scenarios to assess its reliability.

The combination of this CCU and the company's wireless systems enables fully seamless parking of the e-scooter, which finally starts to be charged automatically without the need to plug any cable or activate any mechanism. The user experience is then enhanced as the user does not need to care about the charging process and he/she could be compensated by incentives for bringing the vehicle to these platforms. Nevertheless, it should be noted that the presented solution is just a prototype and the implementation may be continued. As mentioned in Chapter 7, the author suggests the adding of a *sleep mode* especially in the receiving units to not waste the limited energy the battery can provide. Also, the MQTT protocol is considered the best solution for adding remote connectivity to the system. For example, an MQTT broker could be implemented in Amazon Web Services thus enabling remote monitoring from everywhere. Furthermore, the utilized microchip came within a development kit which was directly adopted for its exceptional small dimensions. However, a new board should be designed keeping only the required components and eventually adding some others. For instance, the author suggests considering the addition of an accelerometer sensor to reduce redundant messages during the localization process thus saving energy. After a failed location detection attempt, a new one should happen only when the vehicle moves.

Moreover, the short-range wireless protocol choice could change in the next years based on the market availability and prices. In fact, UWB has some very strong features for this application, such as robustness to reflections and accurate distance measurements, which would enable the switching of the charging pads only when an e-scooter is placed above. The greatest advantage of UWB would then be the

avoidance of the sequential switching in low-power making the overall system more efficient.
Lastly, the future building of dense enough platform networks would increase micro-mobility vehicles' availability, decrease their operating costs by drastically cutting the swapping/charging needs, and aggregate the vehicles around these platforms. It should be noted that even though this thesis dealt with e-scooters, the advantages that the developed CCU enables could unlock new market possibilities for any other electronic device supplied by a battery. The indications that the battery State-of-Charge (SoC) provides can be used both for managing the safe operation of the storage system and for extending the battery lifetime by preventing over-charging/discharging. The state of the battery, delineated in Section 6.1, would give a precious indication of the battery's health state. However, this parameter still needs to be further developed to find the most suitable estimation method in the literature.

References

[1] Experimental researches in electricity. *Philosophical transactions of the Royal Society of London*, 122:125–162, 1832.

[2] A dynamical theory of the electromagnetic field. *Philosophical transactions of the Royal Society of London*, 155:459–512, 1865.

[3] Aqueel Ahmad, Mohammad Saad Alam, and Rakan Chabaan. A comprehensive review of wireless charging technologies for electric vehicles. *IEEE Transactions on Transportation Electrification*, 4:38–63, 11 2017.

[4] AirFuel. Airfuel - about. https://www.airfuel.org/about/, 2022. Accessed: 2022-29-07.

[5] Samer Aldhaher, Paul D. Mitcheson, and David C. Yates. Load-independent class ef inverters for inductive wireless power transfer. In *2016 IEEE Wireless Power Transfer Conference (WPTC)*, pages 1–4, 2016.

[6] Muresan Andrei, Brad Claudiu, and Ioan Vadan. Wireless power transmission — state of the art and applications. In *2019 8th International Conference on Modern Power Systems (MPS)*, pages 1–6, 2019.

[7] Marinos Argyrou, Matt Calder, Arsham Farshad, and Mahesh K Marina. Understanding energy consumption of uhf rfid readers for mobile phone sensing applications. In *Proceedings of the seventh ACM international workshop on Wireless network testbeds, experimental evaluation and characterization*, pages 51–58, August 2012.

[8] American Library Association. How it's developing. https://www.ala.org/tools/future/trends/micromobility, 2019. Accessed: 2022-29-07.

[9] Abdelmoula Bekkali, Sicheng Zou, Abdullah Kadri, Michael Crisp, and Richard V. Penty. Performance analysis of passive uhf rfid systems under cascaded fading channels and interference effects. *IEEE Transactions on Wireless Communications*, 14(3):1421–1433, 2015.

[10] Bird. Bird investor presentation. https://www.bird.co/wp-content/uploads/2021/05/Bird-Investor-Presentation.pdf, 2020. Accessed: 2022-29-07.

[11] John T. Boys and Grant A. Covic. The inductive power transfer story at the university of auckland. *IEEE Circuits and Systems Magazine*, 15:6–27, 4 2015.

[12] Marek Braniš, Gabriel Balint, Jakub Takacs, Matej Šulík, and Andrii Galkin. Shared electric scooters like a tool of a micro-mobility in cities. volume 2020-August, pages 631–638. International Multidisciplinary Scientific Geoconference, 2020.

[13] W.C. Brown and E.E. Eves. Beamed microwave power transmission and its application to space. *IEEE Transactions on Microwave Theory and Techniques*, 40(6):1239–1250, 1992.

[14] William C. Brown. Experiments involving a microwave beam to power and position a helicopter. *IEEE Transactions on Aerospace and Electronic Systems*, AES-5(5):692–702, 1969.

[15] Bumblebee. Bumblebee - airgap. https://bumblebeepower.com/applications/#airgap. Accessed: 2022-29-07.

[16] Bumblebee. Bumblebee - unplug the world. https://bumblebeepower.com, 2022. Accessed: 2022-29-07.

[17] McKinsey & Company. The future of micromobility: Ridership and revenue after a crisis, 2020.

[18] Wireless Power Consortium. Qi specification, communications protocol, 2021.

[19] Bern Dibner. History of electrical engineering andre marie ampere. *IEEE Power Engineering Review*, PER-4(2):15–16, 1984.

[20] Joseph Duruibe, Ogwuegbu C, and Jude Egwurugwu. Heavy metal pollution and human biotoxic effects. *Int. J. Phys. Sci.*, 2:112 – 118, 05 2007.

[21] EspressIf. Esp datasheet. https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf. Accessed: 2022-30-08.

[22] B. Fennani, H. Hamam, and A. O. Dahmane. Rfid overview. In *ICM 2011 Proceeding*, pages 1–5, 2011.

[23] Xin Gao and Lian Huai. Modern ultra-wideband communications: Recent overview and future prospects. *International Journal of Ultra Wideband Communications and Systems*, 4, 02 2020.

[24] UUID generator. Uuid generator tool online. https://www.uuidgenerator.net/version1. Accessed: 2022-27-08.

[25] Carles Gomez, Joaquim Oller, and Josep Paradells. Overview and evaluation of bluetooth low energy: An emerging low-power wireless technology. *Sensors*, 12(9):11734–11753, 2012.

[26] R. Heydon. *Bluetooth Low Energy: The Developer's Handbook*. Pearson Always Learning. Prentice Hall, 2012.

[27] Kyung Kwon Jung and Yong-Joong Kim. Design of smart monitoring system based on bluetooth low energy. In *2018 International Conference on Electronics, Information, and Communication (ICEIC)*, pages 1–3, 2018.

[28] Nemica Kadel, Wei Sun, and Qun Zhou. On battery storage system for load pickup in power system restoration. In *2014 IEEE PES General Meeting | Conference & Exposition*, pages 1–5, 2014.

[29] Aristeidis Karalis, J. D. Joannopoulos, and Marin Soljačić. Efficient wireless non-radiative mid-range energy transfer. *Annals of Physics*, 323:34–48, 1 2008.

[30] Sadeque Reza Khan, Sumanth Kumar Pavuluri, Gerard Cummins, and Marc P.Y. Desmulliez. Wireless power transfer techniques for implantable medical devices: A review, 6 2020.

[31] Rakhesh Singh Kshetrimayum. An introduction to uwb communication systems. *IEEE Potentials*, 28(2):9–13, 2009.

[32] Christopher H Kwan, Juan M Arteaga, Samer Aldhaher, David C Yates, and Paul D Mitcheson. A 600 w 6.78 mhz wireless charger for an electric scooter.

[33] Christopher H. Kwan, Juan M. Arteaga, Nunzio Pucci, David C. Yates, and Paul D. Mitcheson. A 110w e-scooter wireless charger operating at 6.78mhz with ferrite shielding. *2021 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer, WoW 2021*, 6 2021.

[34] Christopher H. Kwan, James Lawson, David C. Yates, and Paul D. Mitcheson. Position-insensitive long range inductive power transfer. volume 557. Institute of Physics Publishing, 2014.

[35] Jin-Shyan Lee, Yu-Wei Su, and Chung-Chou Shen. A comparative study of wireless protocols: Bluetooth, uwb, zigbee, and wi-fi. In *IECON 2007 - 33rd Annual Conference of the IEEE Industrial Electronics Society*, pages 46–51, 2007.

[36] Fanchao Liao and Gonçalo Correia. Electric carsharing and micromobility: A literature review on their usage pattern, demand, and potential impacts. *International Journal of Sustainable Transportation*, 16(3):269–286, 2021.

[37] Imperial College London. Wireless power lab. https://www.imperial.ac.uk/wireless-power/. Accessed: 2022-30-08.

[38] Imperial College London. Wireless power lab. https://www.ti.com/lit/ds/symlink/tmp112.pdf?ts=1658819738347&ref_url=https%253A%252F%252Fwww.ti.com%252Fproduct%252FTMP112. Accessed: 2022-30-08.

[39] Imperial College London. Wireless power lab. https://www.ti.com/lit/ds/symlink/tmp100-ep.pdf?ts=1662335088184&ref_url=https%253A%252F%252Fwww.google.com%252F. Accessed: 2022-30-08.

[40] Fei Lu, Hua Zhang, and Chris Mi. A review on the recent development of capacitive wireless power transfer technology. *Energies*, 10(11), 2017.

[41] H. Alan Mantooth, Michael D. Glover, and Paul Shepherd. Wide bandgap technologies and their implications on miniaturizing power electronic systems. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2:374–385, 3 2014.

[42] Juan Manuel and Arteaga Sáenz. Design of high frequency inductive power transfer systems for integration into applications. *Electrical and Electronic Engineering PhD theses*, 2019.

[43] Microchip. Can controller. https://ww1.microchip.com/downloads/aemDocuments/documents/APID/ProductDocuments/DataSheets/21291F.pdf. Accessed: 2022-30-08.

[44] Microchip. Can transceiver. http://ww1.microchip.com/downloads/en/devicedoc/21667e.pdf. Accessed: 2022-30-08.

[45] Pooneh Mohaghegh, Alexis Boegli, and Yves Perriard. Bluetooth low energy direction finding principle. In *2021 24th International Conference on Electrical Machines and Systems (ICEMS)*, pages 830–834, 2021.

[46] Society of Automotive Engineers. *SAE J2954: Wireless Power Transfer for Light-duty Plug-in/electric Vehicles and Alignment Methodology*. SAE International, 2019.

[47] Pashley. Pashley - about. https://www.pashley.co.uk/news.php. Accessed: 2022-29-07.

[48] Nicolas Pillin, Norbert Joehl, Catherine Dehollain, and Michel J. Declercq. High data rate rfid tag/reader architecture using wireless voltage regulation. In *2008 IEEE International Conference on RFID*, pages 141–149, 2008.

[49] Qorvo. Dwm1001 development board. https://www.qorvo.com/products/p/DWM1001-DEV. Accessed: 2022-26-08.

[50] Jeya Rajanbabu and Amutha Balakrishnan. Signal interferences in wireless communication. *Eurasian Journal of Analytical Chemistry*, 2019.

[51] Telelink semiconductor. Tsi i2c feature. http://wiki.telink-semi.cn/tools_and_sdk/Driver/doc/kite/html/md__project_1__table_of__content_09__t_s_i__i2_c__features.html. Accessed: 2022-30-08.

[52] Bluetooth SIG. 16-bit uuid numbers. https://btprodspecificationrefs.blob.core.windows.net/assigned-values/16-bit%20UUID%20Numbers%20Document.pdf. Accessed: 2022-27-08.

[53] Saurav Subedi, Eric Pauls, and Yimin D. Zhang. Accurate localization and tracking of a passive rfid reader based on rssi measurements. *IEEE Journal of Radio Frequency Identification*, 1(2):144–154, 2017.

[54] EspressIf Systems. Esp32-devkitc hardware reference. https://docs.espressif.com/projects/esp-idf/en/latest/esp32/hw-reference/esp32/get-started-devkitc.html. Accessed: 2022-27-08.

[55] EspressIf Systems. Esp32-wroom-32 datasheet. https://espressif.com/sites/default/files/documentation/esp32-wroom-32_datasheet_en.pdf. Accessed: 2022-27-08.

[56] EspressIf Systems. Nimble-based host apis. https://docs.espressif.com/projects/esp-idf/en/latest/esp32/api-reference/bluetooth/nimble/index.html. Accessed: 2022-27-08.

[57] Nikola Tesla. The transmission of electric energy without wires. *Society of Wireless Pioneers - California Historical Radio Society*, 1904.

[58] Jacopo Tosi, Fabrizio Taffoni, Marco Santacatterina, Roberto Sannino, and Domenico Formica. Performance evaluation of bluetooth low energy: A systematic review. *Sensors*, 17:2898, 12 2017.

[59] Trueform. Trueform - about. https://trueform.com. Accessed: 2022-29-07.

[60] Walter W. Massie & Charles R. Underhill. The future of the wireless art. *Wireless telegraphy & Telephony*, pages 67–71, 1908.

[61] Voi. Voi - about. https://www.voiscooters.com. Accessed: 2022-29-07.

[62] T. Watteyne, S. Lanzisera, A. Mehta, and K. S. J. Pister. Mitigating multipath fading through channel hopping in wireless sensor networks. In *2010 IEEE International Conference on Communications*, pages 1–5, 2010.

[63] Thomas Watteyne, Ankur Mehta, and Kris Pister. Reliability through frequency diversity: Why channel hopping makes sense. In *Proceedings of the 6th ACM Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks*, PE-WASUN '09, page 116–123, New York, NY, USA, 2009. Association for Computing Machinery.

[64] Wikipedia. Near and far field. https://en.wikipedia.org/wiki/Near_and_far_fiel, 2022. Accessed: 2022-29-07.

[65] WPC. Wireless power consortium - commercialized products. https://www.wirelesspowerconsortium.com/products, 2022. Accessed: 2022-29-07.

[66] Zhen Zhang, Hongliang Pang, Apostolos Georgiadis, and Carlo Cecati. Wireless power transfer - an overview. *IEEE Transactions on Industrial Electronics*, 66:1044–1058, 2 2019.