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Seamless Mobility: Touchless Commuting

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Abstract

This project envisions the development of a prototype of a wireless "validation system" for public transportation that could replace the current smart card validation concept. This makes the process of using public transports more fluid and simple for the users, while reducing operating costs for the providers. The system relies on the users' smartphones to relay relevant contextual information, regarding the public transport usage.

One of the key focus points was the investigation of the existing communication wireless technologies, such as Bluetooth Low Energy, hardware and tools that could efficiently track the passengers' usage of the public transport. This represents an approach shift in public transportation – from checkin/checkout to be-in/be-out – which allows avoiding the former approach limitations.

The work also focused on exploring the possible scenarios of deployment, taking in consideration several factors such as cost, versatility of the technology and possibility of fraud.

The prototype was developed in the context of an actual public transportation system, in this case, Metro do Porto/STCP. Therefore, research was made on the current system to determine what was already implemented, what type of investment would have to be made and what would be the cost-benefit relationship. The similarity between this system and others around the world, allows the findings of this project to be a reference for future implementations of touchless commuting around the globe.

The field test's results make it possible to believe in a solution based on Bluetooth Low Energy, as long as the technology keeps improving, the developed solution is refined and the tests are continued in cooperation with transportation operators.

Resumo

Este projecto visa o desenvolvimento de um sistema de validação sem fios para transportes públicos, que possa substituir o atual conceito de validação com cartões inteligentes (*smart cards*). Desta forma, a utilização de transportes públicos torna-se mais fluída e simples para os utilizadores e, ao mesmo tempo, existe uma redução dos custos de operação. O sistema está dependente dos telemóveis dos utilizadores para enviar informação contextual relevante, sobre o uso dos transportes públicos.

Um dos pontos-chave foi a investigação de tecnologias de comunicação sem fios, como o *Bluetooth Low Energy*, hardware e ferramentas que pudessem eficientemente determinar o uso de um serviço de transportes por parte dos passageiros. Isto representa uma mudança na abordagem dos transportes públicos – do checkin/checkout ao estar/não estar – que permitiria evitar as limitações da primeira abordagem.

O projeto também focou a exploração de diferentes cenários de instalação, tendo em consideração fatores como custo, versatilidade da tecnologia e possibilidade de fraude.

O protótipo foi desenvolvido no contexto de um sistema de transportes públicos real, neste caso, a Metro do Porto/STCP. Assim, investigou-se de que forma este sistema funciona, para perceber o que estava implementado, o tipo de investimento que teria de ser feito e qual a relação custo-benefício. A similaridade deste sistema com outros à escala global faz com que os resultados deste projecto possam ser uma referência para futuras implementações de sistemas de validação sem interação.

Acknowledgements

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Rui Couto

“Start by doing what's necessary; then do what's possible; and suddenly you are doing the impossible.”

Francis of Assisi

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Abbreviations

B	Boarding
BLE	Bluetooth Low Energy
CTA	Chicago Transit Authority
GPS	Global Positioning System
IoT	Internet of Things
MP	Metro do Porto
NB	Not boarded
NFC	Near Field Communication
OS	Operating system
PB	Possibly boarded
PB2	Possibly boarded 2
PMA	Porto Metropolitan Area
POS	Point of sale
PT	Public transportation
PU	Possibly unboarded
RFID	Radio Frequency Identification
SDK	Software development kit
STCP	Sociedade de Transportes Colectivos do Porto
TAM	Technology acceptance model
UI	User interface

Chapter 1

Introduction

Public transportation (PT) is growing increasingly important in the context of modern societies. With the fluctuation of oil prices and increased traffic in highways, promoted by constantly growing cities, staying on time and saving up on moving, within our increasingly big urban centers, becomes heavily dependent of PT. With more than 20% of the world energy being spent on transportation, reducing the energy spent should be a key goal [1]. It's also important to motivate even more people to use public transports, especially considering the current and increasing migration of people to urban areas [2]. PT has a very big role in the promotion of urban mobility. Promoting its use reduces the number of cars on roads while it improves the efficiency of the public transport themselves [3].

PT services come at great price in terms of operations management: schedules, ticketing, flow management, fiscalization and maintenance are some areas that have a very significant impact on PT, and erode the profit margins of the operators. Designing a more efficient public transport network, where more seats are occupied, more often, can greatly reduce the total spending of each passenger and hence getting closer to achieving sustainable public transport [1]. One might argue that PT systems are made to help people rather than to make profit, since they are a public service [4], however if these services turn to profit or, at least, some of the expense needed to maintain them is reduced, the governments and the tax payers will be benefited.

In the context of this work, the focus will be on the ticketing operation. Currently, most worldwide PT operators work on a pre-payment approach: the user buys a ticket, either paper, or an electronic version, they show/scan/validate and they can then use the service. This approach is rather demanding for the consumer, which has to waste time, for example, learning how to work with the ticket purchase/usage infrastructure, buying the trip and validating the ticket. This small overview centers on the users point of view. Nevertheless, for the operators, the current ticketing infrastructures also represent large costs that erode their profit margins.

Besides representing large costs, the ticketing infrastructures are not providing relevant information that could be used to optimize the PT system network. Obtaining more information from the ticketing area could allow for the improvement of the PT system network efficiency by creating Origin/Destination (OD) matrices for passenger movement. These matrices are tables that describe the flow of passengers between various points in the transport network. This information could be very useful for the overall PT system planning – determining which routes need more attention and at what times, preventing the unneeded allocation of resources[1].

Recently, technological advances have allowed the adoption of powerful mobile devices and ubiquitous connectivity. This is triggering a change in the way that consumers interact with computers: the human-computer interaction paradigm is changing – the personal mobile devices are becoming portals to cloud-based repositories [5].

Studies of mobile commerce suggest that there is general consumer interest in the mobile ticketing services. The adoption rates, however, are slow due to complexity of transactions, lack of user-friendly mobile portals and slow connectivity. Further findings suggest that use context is determinant for the consumers' intention to use a mobile ticketing service [6].

This work tries to improve the ticketing infrastructure both for the user, promoting a greater adoption and simplicity, and for the operator, reducing costs and boosting revenues, achieved by, for example, increasing adoption rates.

1.1 Context

This work is included in Novabase's Seamless Mobility project. This project aims to create a set of solutions that provide PT users a smoother experience and reduced cost while focusing on the coordination effort required between the several parts that constitute a PT system. The base of the project is the existing technology and very good possibilities in terms of rewards: "Providing a radical multimodal integration is translated into more users, a higher usage rate and improved customer loyalty. For the non-conventional mobility services, Seamless Mobility can provide a network effect that makes them viable. For the industry of PT as a whole, it may provide the needed sustainability" [7].

This work will be developed in strict cooperation with the IBM-CAS laboratory. The laboratory mentioned is already responsible for some breakthrough in the area of mobile ticketing in PT services.

It will also be developed in coordination with PT operators – MP and STCP – with light rail and bus operations in Porto, Portugal.

1.2 Problems and Goals

According to Buehler, R. and Pucher, J., most definitions of sustainability include three dimensions: environmental, social and economic and, in PT, the emphasis has been on the environmental and social dimension. Ignoring the economic sustainability has been a huge mistake, as can be clearly proven by the state of many PT systems – low productivity, high costs and the need for large government subsidies [8]. *Metro do Porto* (MP) and *Sociedade de Transportes Colectivos do Porto* (STCP), two PT companies of Porto, Portugal are perfect examples of the previously described scenario. In the end of 2013, MP and STCP had high public debt [9]. This level of public debt has already hindered the expansion of the PT systems, which negatively affects the social dimension: a report, which presented the expansion plans of the MP light rail system lines, showed expansions scheduled to be constructed and working by 2012 [10]. These expansions, however, are not under construction. The economic scenario has completely halted all predicted extensions.

A paradigm shift is required to simplify the ticketing operation. A seamless way for the users to use the service without having to worry about trip planning or ticket purchase and validation and for the user to feel more motivated to use PT. And a way for the operators of the PT service to simplify the ticketing infrastructure - ideally shifting it to the client side - and to boost the number of passengers. This goal is already undergoing study and implementation. PT is making progress in order to provide more seamlessness, particularly in the areas of ticketing, transportation network design and institutional coordination. Operators and governments discussed, at a joint seminar of the International Transport Forum and the Korean Transport Institute in March 2012, and agreed on several policy-relevant conclusions, namely [11]:

- "E-ticketing provides great opportunities to users and operators, as well as governments;
- Bank account-based ticketing enables universal payments – nationally and internationally;
- Network design, when exploiting network economies, can give rise to 'virtuous cycles' for PT systems;
- The success of e-ticketing and network design depends on good institutional coordination".

The solution proposed, and thoroughly investigated in this work, tries to improve the current PT systems situation, while using modern technologic advances, by providing a remote and seamless way to track and pay for the usage of the transportation service. For this, a cloud-based repository would be used, to store and analyze the information that should be captured by the user's smartphones, which relay contextual information using an internet connection.

1.3 Document structure

This document is organized in several sections.

First, the state of the art covers: current PT ticketing systems, in particular, MP and STCP; wireless communication technologies used in the context of PT, with focus on the ones that seem more suitable to being used; the mobile services adoption theory and current mobile operating systems.

After the state of the art, the concrete problem is identified and a solution proposed.

After this, the solution implementation details are presented, including preliminary tests that support the implementation's decisions.

The next section provides a clear view of all the evaluation that was conducted for the developed solution.

Finally, the conclusion clearly provides a balance of the developed work, answering if the approach is feasible or not, while also identifying future steps and recommendations for the project.

Chapter 2

State of the art

This section presents the most significant theory in terms of public transportation ticketing approaches and current *modus operandi* of several, relevant, PT systems. New ticketing approaches, provided by the scientific community, are also analyzed and the wireless technologies currently being used are specified, in particular the ones that are more significant for this specific work.

Considering the connection between ticketing and mobile services some theory on mobile service's adoption and mobile operating systems is also presented.

2.1 Public transportation services today

Today's transportation services are very diverse and, considering a few exceptions, have very similar ways of operating, in terms of the ticketing operations: most are based in a pre-payment approach. The user buys the ticket, validates/shows it and he is then able to use the service. This approach has many disadvantages for the user:

- User learning curve with the vending infrastructure – Public transports are seen as an immediate service, being this aggravated by the fact that they are generally used to arrive at a destination in time. However, users, mostly the ones with advanced age are pressured to, almost immediately, learn how to use the vending infrastructures to purchase the service (in the form of the ticket);
- Time loss when buying and validating the tickets: the time wasted making the purchase itself is very detrimental to the customer experience, especially considering the overhead required for the payment processing. Together with this, one can also consider the lines formed, something very common on busy PT systems, both for the

purchase act but also for the validation of the tickets. These waiting points decrease user satisfaction;

- Planning with time – Some PT systems require the user to carefully plan the course, in order to buy the appropriate tickets for the journey. This is not only time consuming but also very restrictive for the user;
- Forgetfulness – Some PT systems don't have physical infrastructures in place that require the user to scan/validate in order to access the vehicles and, therefore, the users face the issue of forgetting to buy the ticket or even validate it. The users would then be taking advantage of the service and risking getting fined by the operator;
- Natural deterioration of the user hardware – the user generally has a card or a ticket that has to be maintained. That equipment deteriorates over time, requiring the user to exchange it, generally with a cost associated. Not only that, but it is not possible to predict when this equipment will fail. It can fail in the middle of a trip, when the operator is conducting fiscalization actions, leaving the user in the likelihood of being fined;
- Having to carry cash – it is not ideal, and sometimes not practical, for the user to be forced to carry cash, namely change, in order to buy a simple ticket. At the same time, it is not recommended that the user carries the, sometimes, huge amounts of money in order to pay for the subscriptions. In the first case, it is inconvenient and in the second, it is dangerous.

The PT operators also face some issues when following the current approaches:

- Electronic hardware for selling and validating tickets has to be secured and maintained frequently. Points of sale (POS) that aren't working are a big point of failure that cannot be excused with customer wrongful doing and has a doubled impact on the company revenues: no income from willingly paying customers and money spent maintaining/fixing;
- In the case of buses, the drivers may be responsible for selling the tickets themselves, which may translate in delays to traffic flow. Delays reduce customer satisfaction, which in turn, eventually, reduces revenue. On the other hand, it may also make the driver more exhausted and less focused on its primary function - driving;
- Most PT systems around the globe are very limited in terms of the amount of information they can collect. For example, in buses, it is very easy to know where the user entered, but very hard to know where the user exited [1]. Some systems do not force the user to "checkin" and "checkout", only relying on one of the operations to establish the usage of the customers. Deploying the infrastructures required to complement the remaining operations would be very expensive and, in some cases, even impossible;
- Having electronic POS requires staff that engage directly with the users, instructing them on how to use the POS. These members of the staff also require training. This

also may represent a weak link in the service value if we consider that that single employee represents the entire company. One bad experience with that employee may have effects in the entire company;

- Delays on service caused by the pile up of people trying to purchase and validate tickets/subscriptions;
- Costs related to POS. Supporting the personnel and the infrastructures is expensive.

Of all these problems, PT systems profits are incredibly reduced due to the need to work on the security and upkeep of the points of sale. The profits could also be increased if more information could be collected about the usage of the PT service by determining priority problems to solve in order to improve the overall efficiency of the network.

There are several types of PT systems around the world. In order to comprehend what already exists in terms of mobile ticketing in the context of PT, some PT systems will now be analyzed.

2.1.1 The Chicago Transit Authority ticketing approach

The Chicago Transit Authority (CTA) operates United States of America's second largest public transportation system. It provides service to the city of Chicago and 35 suburbs. It also comprehends about 1.7 million rides, on an average weekday. CTA has 1865 buses that operate over 128 routes that make up a total of 2179km. Buses make about 19,000 trips a day and serve 11,104 bus stops. On the rapid transit system, CTA has 1356 rail cars operating on eight different routes totaling about 361km of tracks. CTA trains make about 2,250 trips each day and serve 146 stations. CTA serves a population of 3.5 million and has an operating budget $1384.8 million. Farebox collections, non-farebox revenues and supplemental funding for operating expenses (through the Regional Transportation Authority) are CTA revenues sources [12].

Fare collection on the CTA system is made using *Ventra [13]*. *Ventra* is an open fare automated payment system. It represented a switch to a "tap & go" payment system versus the previous magnetic strip cards [13-16]. It uses RFID as the main technology [17]. There are several types of cards: the users' bankcards if they have the proper radio chips (just tap the card and have the amount withdrawn from your bank account); the Ventra card (a transit and prepaid debit card that can be used for transit and everyday purchases) and the Ventra tickets (special cards - for single-ride and 1-Day passes). There is also the possibility to pay using an NFC enabled smartphone with a mobile wallet app. With the implementation of *Ventra*, a significant increase in places to purchase or add value (money) to Ventra cards, in order to purchase fares, has occurred. The user simply "taps" the terminals and the amount is deducted or, if there is a subscription associated, the trip is deducted [13-16].

The open standards approach followed allowed to create a payment ecosystem that further aimed to reduce lines and waiting times [16]. It also aimed at providing a multi-modal system even when the users transferred between public transport modes, instead of making the user buy and keep many different tickets [18].

However, some problems emerged, with the use of the new system. Waiting times for Ventra's customer service call centers were pretty high [19] and lack of trust on the new service and problems using the online management system [18] even lead to the reinstatement of the ability to buy magnetic fare cards [20]. *Ventra* was also not able to deploy cards quickly (it took over 4 months to fade out the previous cards) [18]. There were also problems with the ability for the system to handle the rush hour loads – the card readers at 60 of CTA's 145 train stations failed and that resulted in 15000 free rides before the problem was fixed. The contractor was found liable and billed for the costs of the outage [21]. Other problems included multiple charges for a fare [22] and slow payments that were eventually resolved [23].

It is important to note that, even though the new system was aiming to improve customer experience and the service efficiency it had the opposite effect. The problems identified, when studying this small case study, should be taken in consideration when designing a shift in the payment approach on the PT area.

This system solves a few problems that were identified with the current pre-payment approach on PT. The user may forget purchasing the ticket, but he will not be able to ride, since most of the CTA network has turnstiles infrastructures and buses have drivers that will not let the user go through without scanning their card or buying a fare. The time loss when buying and validating the tickets is reduced, but not completely eliminated. The user is no longer required to carry cash, since the Ventra cards can be automatically refilled with cash from a bank account and credit/debit cards that have RFID technology are accepted.

The operator also has at least one more problem solved: the delays on service caused by the pile up of people trying to purchase fares. This problem is solved thanks to the online platform that allows the users to perform the fare purchase anywhere at any time. This could also minimize the amount of staff stationed at the electronic POS on stations.

However, a few problems remain. The users' learning curves with the electronic POS are still a huge barrier. Although the lines are smaller, the service is still not instant. Therefore, lines would still form. It is still required that the user plans his journey beforehand, in order to know what fare to buy considering he will travel a specific amount of time and make a certain number of transfers. The natural deterioration of the hardware is still an issue. For the operator, there still needs to be maintenance of the barriers/selling infrastructure; the bus drivers still have to sell cash tickets and the amount of information collected is still pretty scarce.

2.1.2 The London public transportation ticketing approach

London is a quickly booming city. Currently 8.4 million people live there. This number is expected to grow to 10 million in the 2030's. It is the Transport for London (TfL) responsibility to provide the sustainable growth of the city transport services. This organization is divided in three main units: surface transport, rail & underground and crossrail [24].

The surface transport unit oversees buses, cycling, river services, streets, Victoria Coach station, Dial-a-Ride and taxi & private hire. The rail & underground unit controls the underground and overground services, the Docklands Light Railway, the tramlink and the Emirates Air Line. The crossrail unit is a railway expansion, currently undergoing constructions, to link Maidenhead and Heathrow in the west to Shenfield and Abbey Wood in the east [24].

TfL's total income, in 2014/2015, is £10.9 billion, from many different sources (25% grant funding, 15% crossrail funding, 40% fares, 7% other income, 13% borrowing and cash movements). Of this amount, 61% is spent on running the network and 39% is spent on improving the services [25, 26]. The London Underground is considered the oldest rapid transit system in the world [27]. It has a length of 402Km [28]. The bus system is one of the largest bus networks in the world with around 8500 vehicles. More than 90% of the people living in London live within 400 meters of a bus stop [29].

In terms of fare collection, TfL has Oyster. Oyster is a plastic smart card that can hold pay as you go credit, Travelcards (subscription based and transport type independent) and Bus & Tram season tickets (subscription based only for Bus and Tram). This smart card can be used to ride a vast number of services within the TfL domain. Oyster can be recharged with cash and configured to be automatically *topped-up*. It can also contain travelcards (if they are meant to be used longer than a day) and bus and tram passes. The Oyster system allows a user to have different combinations on the card: money, passes and travelcard (ticket that can be put on the Oyster card and gives freedom to travel as much as the user wants on bus, Tube, tram, DLR, London Overground and National Rail services in London). It is able to work out which of them to use in order for the user to pay the minimum. There is also a web platform that allows the user to monitor what the card contains and the journey history, for example [30, 31]. Except on the bus and tram system, in order for Oyster to work properly, the user must touch the oyster card on a reader when they start a journey and when they end it (to correctly account for the usage of the transport system) [31]. This checkin works based on the RFID technology embedded on the cards [32]. Oyster works out the cheapest fare for all the journeys in one day so that the user never pays more than the daily cap [31]. In order to calculate this fare, the entire network is divided in concentric zones, around a specific center. The user may travel within one zone or crossing several zones, which affects the total amount to pay. The "tube", Docklands Light Railway (DLR), London Overground and National Rail services in London use the zoning system. The London Buses service does not [33]. The users can also pay using their contactless payment cards (debit/credit cards). The user is charged an adult-rate pay as they are using the fare system when using the contactless payment card, but the way the payment is made is different from using Oyster. This is because no credit is added before travelling. Instead the total cost of all the journeys that are made in one day is calculated at the end of the day and a single charge is made to the contactless payment card account [34]. TfL did not phase out the older paper tickets. It still sells travelcards in paper version that allow the user to travel as much as he wants, for a day, in most of the services of TfL. It also sells, in paper version, One Day Bus & Tram Passes, Single and return tickets, Group Day Travelcards and Paper season tickets and photocards [35]. NFC can also be used to pay in this PT system, using an NFC-enabled smartphone, with a wallet application, by touching the readers on stations with the smartphone [32]. This process is similar to the payment made with contactless payment bank cards.

Oyster was implemented as a response to three main challenges that London transport was facing, according to Weinstein [36]:

- "Improving revenue protection on the Underground system;
- Replacing the aging bus ticketing system;
- Increasing the flow of passengers through underground gates."

After being implemented, in phases, starting in 2003, Oyster introduced a series of new ticketing innovations, such as daily price capping ("automatically calculate the cheapest fare for all the journeys a customer makes in a single day") and auto top-up (customers using pay as you go can have their card automatically topped up with a specific amount when the balance falls below a specific limit). In 2009, 80% of all "Tube" and bus payments were using Oyster [36]. There were several advantages provided by Oyster, again, according to Weinstein [36]:

- Reduction of queues;
- Minimized cash handling/carrying;
- Revenue losses reduction;
- Higher processing of customers through the gates.

In sum, Oyster was a success for TfL [36].

However, it still has some shortcomings. The system requires users to checkout by touching the machines with the card, to complete a journey. However, TfL handles a lot of traffic. Checkout becomes almost impossible for commuters, which, sometimes, ignore or forget that step. This leads to penalty fares, maximum fare charges and even court prosecutions [37]. The time loss when buying and validating tickets is still present for the user.

The system has also been criticized for poor design, in terms of the interaction and the infrastructure. For example, many stations don't have barriers that remind the user to checkin/checkout, making them face penalties. The new vending machines and online platforms the users had to use also had a big learning curve. There were also issues with overcharging [38-40]. It suffered technical failure on some occasions. On March 2005 the system was unable to operate during the morning rush hour; barriers were left open and pay as you go fares not collected [41]. On July 2008, pay as you go cards were not being read correctly decreasing the confidence in the Oyster system [42].

Some security issues were also raised when in June 2008 researchers at the Radboud University, in the Netherlands, hacked an Oyster card [43]. This is deeply related to the constant need for the operator to keep maintaining and developing the infrastructures.

On the other hand, the multiplicity of paying hardware (both smart cards and contactless bank cards) has generated a set of other problems, namely, double charging due to *card clash* on passengers carrying the both type of cards [44]. At the same time, the operator still has to deal with delays caused by the pile-up on the readers, so the users can all checkin and checkout.

2.1.3 Metro do Porto & STCP case

Metro do Porto is the light rail network that serves the city of Porto and seven other municipalities. It was opened in 2002. The current network is composed of six lines, 81 stations, 67Km of extension. Most of the system is on the surface. In 2013 it had 56 million passengers and it owned 102 vehicles [45, 46]. Of these 102 vehicles, there are two main types:

- *Eurotram*

Figure 1 – Eurotram in Metro do Porto [47]

This vehicle reaches a maximum speed of 80Km/h and has a length of 35m. It has 80 seats. It has a low-floor design and it has an articulated design with three modules. A unit can be attached to another unit, making a double unit [48, 49]. The technical drawing shown below, does not allow to conclude the actual length of this vehicle type.

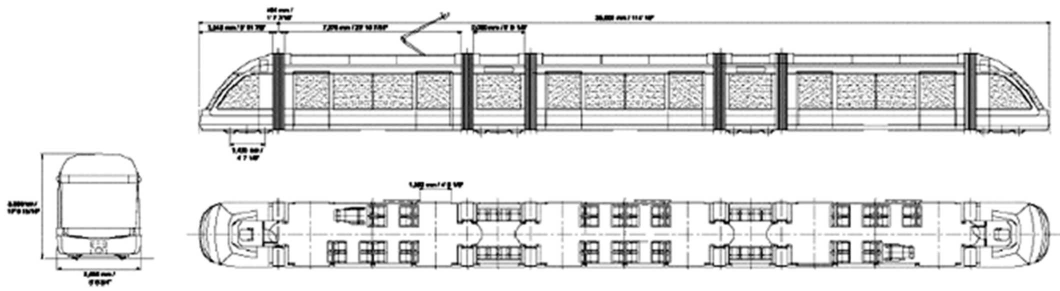


Figure 2 - Eurotram technical drawing

As such, further research has been done to obtain an approximate length. Google Maps was used to find an aerial view of the vehicles when used on the MP system.

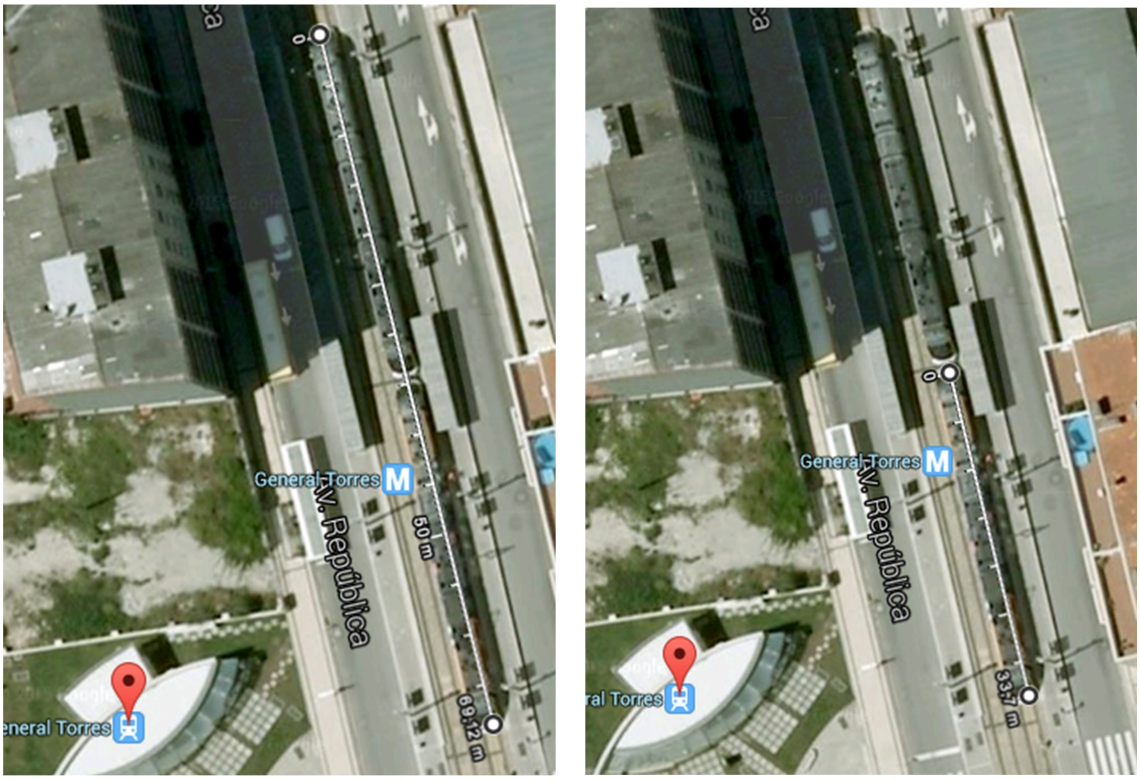


Figure 3 - Aerial view of Eurotram[51]

As seen in the above picture the approximate length for an Eurotram, double unit, is 69.12m while for a single unit the approximate length is 33.7m. In theory the single unit length should be half of the double unit length, but these inconsistencies are due to approximations made by Google Maps for the measurement.

- *Flexity Swift*

Figure 4 - Flexity Swift in Metro do Porto [52]

These are the most recent vehicles of the Metro do Porto fleet. They were introduced in 2009 and operate in the lengthiest lines. They are more comfortable and robust, compared to the previous model. They can reach a top speed of 100Km/h and they have 100 seats, making them slightly longer than the Eurotram version. They are also composed of three modules and can be coupled with another vehicle, making a double unit. A single unit has a length of approximately 37m [53, 54]. A double unit has approximately 74-76m.

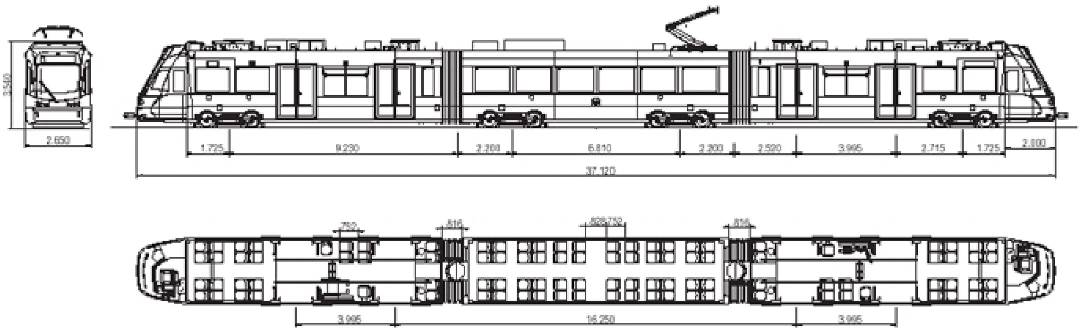


Figure 5 - Flexity Swift Technical Drawing [55]

After overviewing the current MP situation in terms of the network specification, it becomes important to overview MP's economic situation. At the end of 2013 the MP debt was of 3181 million euros, an increase of 16.8% in comparison with 2012 [9]. This public debt level is hindering the expansion of the network [10].

STCP (*Sociedade de Transportes Colectivos do Porto, S.A*. - in English - Porto Public Transport Society) is the company responsible for the management of bus and tram operations in Porto, Portugal. Most of the network is composed of bus routes, with a small portion dedicated to tram lines. In 2011, it served 900 thousand people in seven big municipalities. It had 81 lines (70 from the day and night network and 11 from the dawn network) covering

522Km (9Km is tram) and 2651 stops. It had 1438 workers and a fleet of 468 buses and 5 tram cars [56]. Of these buses there are several types currently being used [57]. Most of the buses are 12 meters long, with capacity for approximately 90 passengers (about 30 seated and 60 standing) either diesel or gas powered. There is also a small percentage of the buses that are double decked, articulated (18 meters length, gas powered and 150 passengers capacity) and smaller (similar to a van – less capacity, diesel powered and smaller length) [58-61].

More than half of the bus fleet operates on Compressed Natural Gas (CNG). In 2010 STCP had already exceeded the recommendation of reaching 54% of natural gas buses [58].

STCP, in comparison with Metro do Porto, had a debt of 397 million euros, in the same period (at the end of 2013), with an increase of 6.8% in comparison with the previous fiscal year [9].

However, this company has revealed an interest in innovating and improving customer experience when using their services. In 2014, an innovative system turned STCP in the first bus PT operator in Europe to offer free Wi-Fi access on their buses. STCP also belongs to the *Future Cities* project that is trying to turn the city of Porto in one of the most innovative. In this project, many vehicles of the Porto city (trash collecting vehicles and STCP buses) are connected in a network. This allows the collection of information throughout the city in order to improve energy consumptions, reduce the environmental impact and increase the management of roads and public transports [62].

2.1.3.1 Andante

Both STCP and Metro do Porto operate in a region that is called the Porto Metropolitan Area (PMA) [63, 64] and they use a smart card ticketing system called *Andante*. The price to pay depends only on the course and not the combination of transports used. The user is free to select the titles or subscription he wishes to purchase [64-66].

The smart card has two versions: a plastic one, for frequent use and a paper one for occasional use. The first type of card, called *Andante Gold* (GTML2 card) usually contains a subscription (unlimited travel for a period within a specific area) but may also contain simple trips. It costs 6€ and can only be used by one person. The second type of card, called *Andante Azul* (CTS Ticket), is meant for holding simple trips, of the same type, in limited amounts. It costs 0.60€ [64, 67].

The ticket types vary. The region covered by the public transports is divided in irregular areas that represent zones (this division can be seen in Figure 6). “Andante zoning system differs from most national and international multimodal ticket systems whose zones are concentrically defined. Such system benefits travelers within the city center and penalizes travels from the suburbs to the center as well as travels between suburbs. Andante zones are not concentric and were defined based on known travel patterns and local geography to develop a fairer system. The drawback of a fairer system, however, is additional complication.” [66]. However, each *Andante Azul* can only contain a specific type of journey in a variable amount

[66, 67]. This constraint has a workaround called the ClickZ service, which allows a user to purchase one additional ticket type, on a card, that will be used first, with higher priority [66, 68].

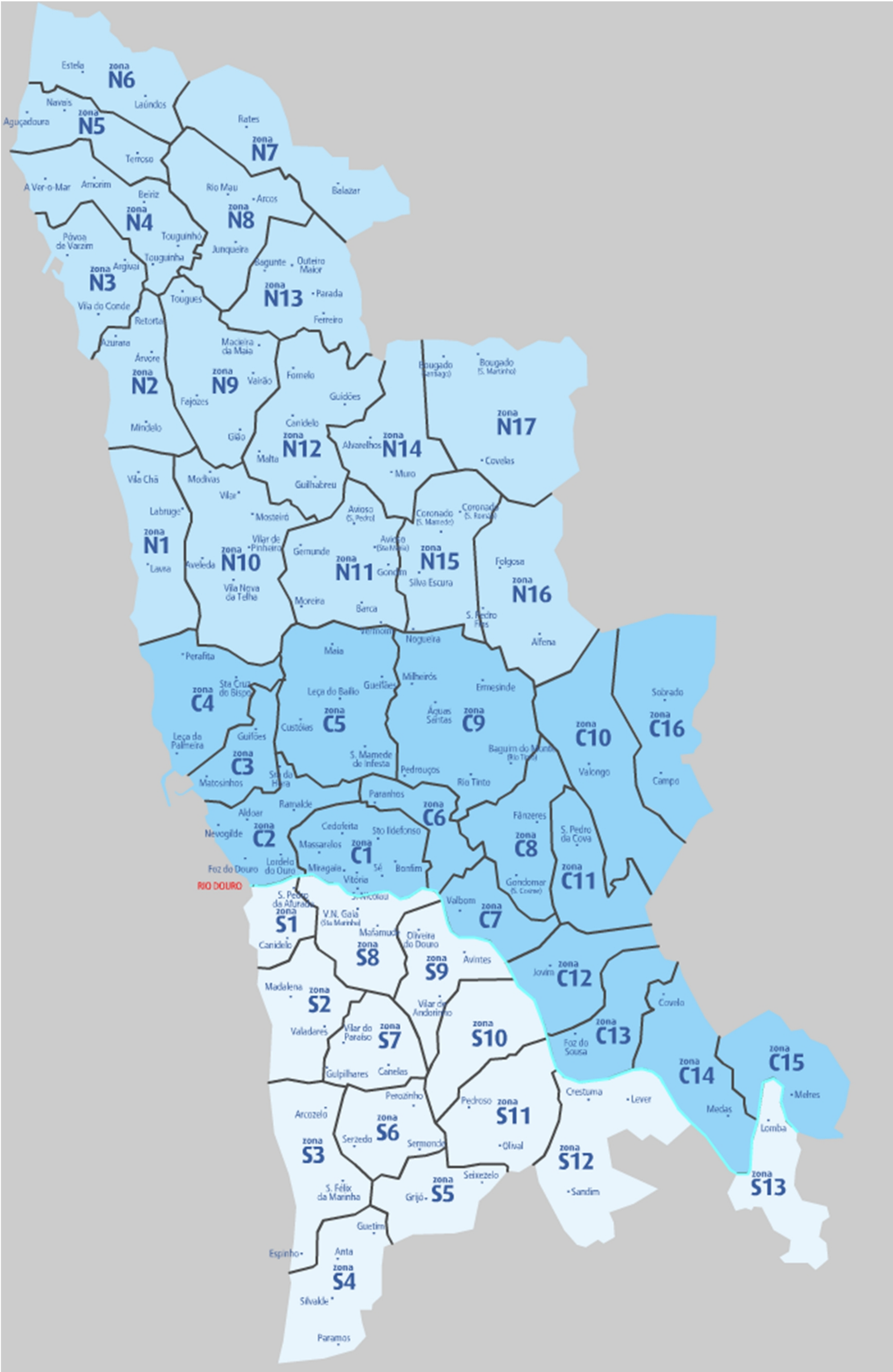


Figure 6 - Zones division [69]

The basic ticket type (and minimum) is a two zone ticket – Z2 and the maximum ticket type is a twelve zone ticket – Z12 [68, 70].

If using a card that is valid for a month (season ticket/subscription), the user has to choose the zones in which he wants to travel and then recharge the smart card [64, 71]. This subscription ties the user to a specific course that goes through the selected zones. Any trip with that goes through other zones not subscribed is subject to fine [72].

If using an occasional ticket, the user must pay attention to the zone where the journey begins (the zone where the card is first used) and the zone where it ends [71]. With this type of ticket, the user can use, for a specific amount of time, any zone between the origin and destination. The user can even use only 1 ticket on the smart card, to return, if he respects the time limit of the ticket [72].

If a user wants to go to a destination that is in a zone in the immediate surroundings of the origin, or in the same zone as the origin, he needs a 2 zone (Z2) ticket [71, 73].

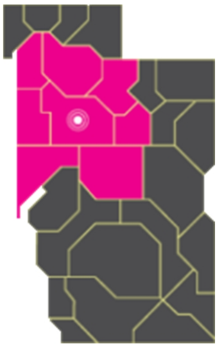


Figure 7 - Zone calculation example 1 [73]

The number of zones the user buys represents the number of adjacent zones that the user can use while travelling, starting the count on the origin zone. In figure 8, for example, the user starts in the zone with a white dot and, with a 4 zone ticket he can travel within the area presented in pink [68, 71].

Figure 8 - Zone calculation example 2 [73]

The user needs to plan his journey (determine what zones will have to be crossed between the origin and destination) to determine what type of ticket to buy for the *Andante* smart card [66]. This reasoning also applies to monthly subscriptions that provide unlimited use. In this particular case the user simply pays a specific, monthly, price based on the zones where he can freely travel (bypassing the zone counting strategy) [66, 74].

After planning the journey the user has to charge the smart card *Andante* accordingly [68]. There are several sale points across the network [75].

For the subscription users there is a big restriction with the Andante system. While the occasional tickets allow the user to use a range of zones (Figure 7, Figure 8), the subscription users are allowed an “axis” of zones where they travel without limits.

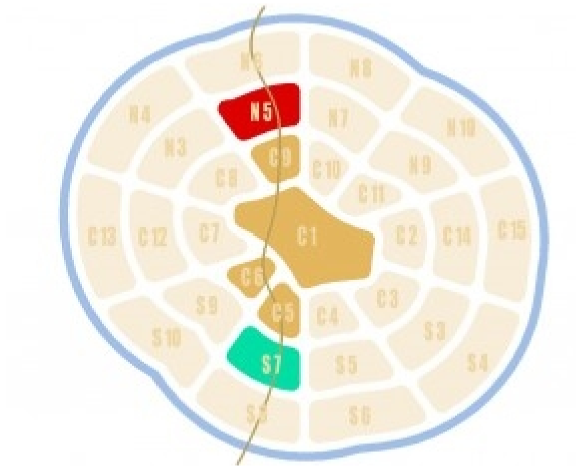


Figure 9 - Zones "axis" for a monthly subscription In green the origin zone, in red the destination zone [76].

If the user goes through a different set of zones, even though he has the same origin and destination, the operator could fine him. This is a significant limitation, considering that one of the *Andante* system main features is the ability to use different types of transport [65], with the same ticket. So, the user could use a different bus that passes by the destination point, but goes through a zone not covered in the subscription [76].

After having purchased the tickets/subscription the user starts the journey by validating on the yellow machines at the Metro do Porto stations (Figure 11) or in the buses’ entrance (Figure 10) [64]. A green light indicates that a valid ticket/subscription was used and that the user can board the transport vehicle. A red light indicates a problem and the user should not board in order to avoid fines. The user should validate every time he starts a journey and every time he changes the transport vehicle. The *Andante* card has to be maintained in order to work properly and to be used in a regular way [68].

Figure 10 - STCP buses' validation machines [77]

Figure 11 - Metro stations validation machines [78]

The validation process, equivalent to a checkin, is made using RFID [79]. There are control (anti-fraud) measurements in place based on human control [64].

In this system, however the users do not have to checkout. They only checkin, every time they board a vehicle, by validating. This means that the price of the transport cannot be optimized and reduced, for the user, and the information obtained is more limited, for the operator. At the same time, the physical infrastructures of Metro do Porto stations, such as the lack of barriers, and the STCP's buses structure, support that even if the checkout process existed, it wouldn't be very successful, since the users would leave the transport without validating, to avoid lines and because they would forget (much like what happened with Oyster). However, this lack of physical infrastructures also promotes the forgetfulness of the users when checking in, which may lead to fines. MP's new management company intends to deploy gates in most of the underground stations in an operation scheduled to cost 5 million euros, but that should cover only a small portion of stations [80, 81].

For the user, the *Andante* system has a complex learning curve, especially considering the zones calculation for determining the ticket type, which requires planning the course. There is also a time loss associated when buying and validating the tickets, at peak times [82]. The user also has to maintain the smart card, which may deteriorate over time. Carrying cash is also required in order to buy the subscriptions or the tickets for the smart card. There is no online platform that allows the user to, easily and securely, recharge the smart card.

For the operator, considering Metro do Porto and STCP, there needs to be a large investment in sales & validation infrastructures, in order to minimize lines and provide easy access to the service [82]. The STCP buses' drivers also are required to manually charge *smart cards* for each user that boards without one. This represents a possible delay on the entire route flow. The lack of a checkout process, due to the missing physical infrastructures e.g. barriers, limits the collected information by this PT system even more, preventing a complete and thorough operations management. The information that this operator collects was observed during a research grant, within the Seamless Mobility project [83]. The research grant allowed access to the Andante network validation/check-in data from 2013. It was possible to observe that the checkin information varies from the type of transport used:

- When performing the checkin in MP, the data collected is: the time, station (and zone it belongs to), user identification and ticket type - which provides the allowed zones, both for occasional trips and subscription variants;
- When performing the checkin in STCP, the data collected is: the time, station (which is only obtained from the vehicle technological infrastructure), line, direction, journey starting time, user identification and ticket type - which provides the allowed zones, both for occasional trips and subscription variants.

The collected information varies greatly between a system that shares the same ticketing system and intermodal approach, which eventually leads to arguments related to revenue distribution between the operators. It also limits the capability of the operators to infer relevant operational data.

The operator also has to support the costs of staff and informative publicity in order to simplify the entire process of ticket type calculation and purchase using the points of sale. The delays caused by lines to validate and purchase is unavoidable, due to the validation process implemented.

2.2 New approaches in public transportation

PT systems are getting more complex and being subject to new approaches that try to simplify their design and improve their operations. This sections overviews some of those approaches.

2.2.1 Mobipag STCP

The Mobipag STCP prototype is a project that was made for the Porto PT operators as a way to propose a ticketing solution that would require the least investment from the PT operators' point of view while obtaining the customers' acceptance. The forms of service delivery that require minimum investment from the PT operators are the ones that rely only on the customers' devices. As such, this solution is based on the customers' devices, on wireless communication technologies (Mobile network data – 3G/4G - or Wi-Fi) and on location providers, such as Global Positioning System (GPS) and network triangulation. Considering that the context is an open (ungated) system it was also important to guarantee the possibility of supervision of the ticket validity [84].

In this prototype, the purchase and validation of tickets would be made over-the-air (OTA), using Mobile Network Data (3G/4G) or Wi-Fi, and the location providers would allow determining the traveler position. The user would have a virtual wallet, on his smartphone, where he would be able to check the tickets he owns and select them for use. The purchase option would allow the user to directly buy a specific type of ticket (e.g. two zones, three zones) or to specify an origin and destination and have the type of ticket automatically calculated. The second option of purchase is a major improvement in the actual solution of Porto's PT services, given that it simplifies the process of pre-planning. This system also allows the user to have more than one ticket type in his virtual wallet, in contrast with the *Andante* smart card which only allows one ticket type in different amounts [84].

To validate a ticket, first, the costumer location is determined using the location providers. The system then presents a list to the costumer, containing the close stations where he can board a vehicle of the PT service. After selecting where he will board, the user is asked to select the ticket he wishes to use, from the tickets stored in his virtual wallet. The user then needs to select which bus line they will use (if we consider that different bus lines may have stops in common). This information allows the operator to determine which vehicle the customer boards, by crossing the information provided by the user with the time and vehicles on the road. After the ticket is validated, the customer can travel freely, within the ticket specified zone, for a period, presented on his smartphone. The user is notified when the journey time expires [84].

If a fiscalization officer wants to verify if a traveler has a valid ticket for a specific journey, the user can show the active ticket on the smartphone screen. The smartphone application would have security elements in the form of unforgeable watermarks and references that provide authenticity to the tickets [84].

The application would provide a vast number of other services such as checking the tickets balance, account movements, validation history, prices and maps and finding near stations [84].

2.2.2 Wireless detection of passenger trips

In order to improve a PT network efficiency, the operators should obtain and use Origin/Destination (OD) matrices to represent passenger movement. This matrix is a table that describes the flow of passengers between various points in the transport network (or alternatively between points on a map) [1].

The design of a PT network relies on the information provided by these matrices. Many decisions such as scheduling and driver assignment are based on that information [1]. The process of obtaining this matrix is very hard and expensive, normally involving human observation (to count the number of passengers over a number of days) [1]. The use of electronic ticketing systems has simplified the process. However, some PT systems do not have an end-to-end ticketing infrastructure (e.g. to record entrance and exit), for example, on the cases viewed previously, on buses, the entrance is recorded but the exit is not [1]. Metro do Porto only registers entrances and not exits. The problem of taking conclusions from an OD matrix based on origin-only data has been addressed by Zhao et al. in the analysis of Chicago Transit Authority rail system which collects origin-only information. Zhao et al. propose an approach based on the pattern of a person's consecutive transit trip segments [85]. But the analysis and proposal is based on some assumptions [1]:

- "There is no private transportation mode trip segment (car, bicycle, motorcycle) between consecutive transit trip segments in a daily sequence;
- Passengers will not walk a long distance to board at a different rail station from the one where they previously alighted;
- Passengers end their last trip of the day where they began their first trip of the day."

These assumptions introduce inaccuracies in the OD matrices. This approach also fails to take in account "one-way tickets, and passengers who do not have a permanent travel card" [1].

Zhao et al. approach to inferring Origin-Destination on PT systems, where only the checkin step occurs, was used and improved by Nunes, A. and applied to STCP's case [86]. A further improvement has been made by Couto, R. and Leal, J. in a research grant, extending the work to MP's case [83].

A growing city and expanding PT system affect the OD matrix over time, which turns it inaccurate of obsolete in a short period of time [1]. "An up-to-date OD matrix can help public transport authorities to better allocate their resources (drivers, buses, repair crews)" and developing a more efficient transport network [1].

Some solutions for providing accurate OD matrices have been designed. For example, the usage of cameras for automated head detection, pressure sensitive carpets or infrared sensing. But these solutions do not differentiate passengers and are expensive [1].

Kostakos has focused on the development of a system capable of capturing the passengers OD matrix automatically, by using Bluetooth hardware and passengers' Bluetooth-enabled devices with constant Bluetooth discovery as a mechanism to record passenger journeys. The combination of this information with the vehicles localization system allows to determine the stop where the users board and exit [1]. This system was prototyped on *Horários do Funchal*, the public transport operator in Funchal, Madeira, Portugal. The vehicles of the PT operator have an elaborate localization and ticketing system, which was in use prior to the study. Each bus has an on-board GPS system, digital odometer and door sensor, which provide the bus location at any given moment. Buses report their location using GPRS and this information is used on a central system that estimates when each bus will reach the next bus stop. These estimates are then provided to the bus stops displays, using a GPRS connection. The ticketing system on the buses also records information about the time when passengers boarded and the type of ticket purchased. The entire ticketing infrastructure is based on RFID [1].

The prototype included the use of a Bluetooth adapter, referred to as "scanner", installed near the exit area in the center of the bus. The installation required rewiring of the bus. "The scanner software is rather basic: it constantly issues a Bluetooth discovery request and records the results. According to the standard Bluetooth protocol, a Bluetooth device set to "Discoverable" mode must respond to the discovery request by transmitting its unique Bluetooth identifier (12 hex digits) and device class (6 hex digits). The scanner constantly issues the same discovery request, and constantly records the presence of the various devices it encounters (along with the date and time of each distinct instance a device was discovered). Using this approach, there is the additional benefit of not requiring any special software to run on passengers' devices. The only requirement is that passengers set their devices' Bluetooth adapter to "discoverable" mode [1].

After running the trial for a period, the datasets of information were correlated: Bluetooth data and bus localization data. This correlation allowed removing much of the noise from the Bluetooth dataset. For example, the scanner detected devices while out of service. Without the localization data, there was no way to verify if the Bluetooth information reflects passengers or not. With the localization data, it is possible to determine that the Bluetooth information appeared when the bus was out-of-service; therefore, the information could be discarded. If the scanner picked up devices outside the bus, even when in service, the system would discard the information, because it would be detecting a user entering and exiting the same bus stop. This system works assuming that the user does not turn on or off the Bluetooth, when inside the bus. In the end, it was possible to derive the passenger OD matrix for the lines that the prototype bus covered. Using this matrix it was possible to identify the most popular segment within the route, for example [1].

The main limitations identified in the mentioned prototype were the penetration of Bluetooth between the passengers (many did not have the technology on the smartphone and others had it deactivated) and the privacy implications associated, with the knowledge of the person location at any time (although these privacy concerns are already present in current PT systems) [1].

The system was proven to be very cost efficient, given the low cost of the hardware installed [1].

2.3 Wireless technologies in public transportation

Several wireless technologies have been applied, with different uses, in the PT context.

2.3.1 Radio frequency identification - RFID

Radio frequency identification, RFID for short, is a technology that allows the automated identification of objects and people. It can be viewed as a labeling measure that allows the detection of objects by computing devices. The basic concept includes an RFID tag, which is a small microchip designed for wireless data transmission, which is connected to an antenna. The RFID tag transmits information over the air, after request from a RFID reader [87, 88]. It also includes a reader, composed by one or more antennas (integrated or external), a radio interface, responsible for modulation, demodulation, transmission and reception; and the control system, which consists of a micro-controller, one or more networking interfaces and in some cases additional task and application specific modules, for example, digital signal or cryptographic co-processors [87, 89]. The role of the control system is to manage communication with the tag and interact with client applications [89]. Readers can be very versatile having their own processing power and internal storage, and even offering network connectivity [87].

RFID became successful mainly due to the way it operates: instead of having a tag creating its own transmissions, the tag modulates or reflects the electromagnetic field waves emitted by the reader to communicate. This allows the tag to be very simple, especially considering that the electromagnetic waves emitted by a reader can carry enough energy that can be used as a source of power, therefore eliminating the need for the tags to incorporate batteries. This makes the battery-less tags (passive tags being the correct denomination) cheap to build [88, 89].

RFID systems may vary in terms of applications and settings. They can have different power sources, operating frequencies, and functionalities. Depending on the settings considered the manufacturing costs, physical specifications and performance will vary [87].

The most common applications are item tagging, proximity cards for access control and contactless payment systems [87].

RFID is subject to interferences, especially when considering communication at a higher range [87]. It also raises privacy problems: the RFID tags respond to the readers without alerting the owners, especially in cases of high-range communication [88]. The RFID systems for access control and payment current face the problem of forgery [87].

Although RFID implements encrypting, the MiFare classic RFID chip, used by millions, had its encryption cracked in 2008 [90].

The *Andante* system, for example, overviewed in section 2.1.3.1, is based on RFID [79]. As such, it faces all these concerns and it has a huge infrastructure, demanded by RFID's complex architecture needs.

2.3.2 Near Field Communication - NFC

NFC is a radio technology that allows the bidirectional transmission of data over a maximum distance of 10cm and a maximum data rate of 424kB/s being based on RFID standards (in accordance to ISO/IEC 14443). The NFC technology works at a frequency of 13.56MHz [91-94] and its main usages are contactless transactions, accessing digital content and connecting electronic devices using a single touch [92]. NFC complements many consumer level wireless electronics by using key elements in existing standards for contactless card technology [92].

NFC inherited the active and passive communication modes. "In the active communication mode, both the initiator and the target use their own RF field to communicate. The target responds to an initiator command in the active communication mode by modulating its own RF field. In the passive communication mode, the initiator generates the RF field and starts the transaction. The target responds to an initiator command in the passive communication mode by modulating the initiators' RF field which is referred to as load modulation" [95].

In contrast with RFID chips in contactless smart cards, which provide a one-way communication channel, only sending information when requested, an NFC chip is a two way communication device operating on a message and reply concept [96].

An NFC device can operate in three modes: reader/writer mode, card emulation mode and peer-to-peer mode. The first mode means that an NFC enabled device can read and write data stored in a NFC compliant passive transponder. In the second mode, card emulation mode, an NFC device acts as proximity inductive coupling card (PICC). In the third mode, peer-to-peer mode, two NFC devices can carry out bidirectional communication to transfer arbitrary data. Most deployed services mainly use the reader/writer mode [93].

Mobile ticketing is considered one of the most promising applications of NFC [91]. As seen previously, this technology has already been applied, with success in Chicago and London PT systems.

Every NFC approach for public transportation ticketing requires investment in POS and NFC-reading systems and a large number of customers with NFC-enabled phones or a large investment on tickets with integrated NFC.

Concerning speed, security and usability NFC was found to be a good choice in comparison to more traditional payment services such s such as Interactive Voice Response, SMS, Wireless application protocol and one time password generator [84].

Despite the fact that NFC communication only works in low ranges, NFC still does not ensure secure communication [97].

Some vulnerabilities have been found in NFC, especially in the contactless transactions area. A team, at Surrey University, was able to receive a contactless transmission from distances of 45-80cm using unnoticeable objects. This is specially concerning if we consider that banks are starting to routinely issue contactless payment (NFC based) cards [98].

2.3.3 Wi-Fi

Wi-Fi is the common name of a wireless networking technology that provides wireless high-speed network connections and Internet by using radio waves. It is the trademarked phrase that means IEEE 802.11X. The definition of Wi-Fi, by the Wi-Fi Alliance is any "wireless local area network (WLAN) products that are based on the Institute of Electrical and Electronics Engineers' (IEEE) 802.11 standards". Wi-Fi works without physical wired connections by using radio frequency technology: a radio frequency current is supplied to an antenna and an electromagnetic field is generated that propagates through space. The base of a wireless network is the access point that broadcasts the wireless signal. Wi-Fi is supported by a several types of consumer electronics [99]. The typical range of this technology is about 46m indoors and 92m outdoors. Physical obstructions such as brick walls and metal frames reduce the range of a Wi-

Fi network. Wi-Fi operates in two different bands: 2.4GHz and 5GHz [100]. The first is used by other consumer gadgets, as such, Wi-Fi connections based on that band are more susceptible to interference [100]. Wi-Fi is known to have a large energy consumption, especially when compared with other wireless communication technologies [101-103].

Wi-Fi was used in the Mobipag STCP prototype as one of the needed technologies for the system to work.

2.3.4 Global Positioning System - GPS

GPS is a satellite-based navigation system composed of 24 satellites placed into orbit. These satellites circle the earth and transmit information. Receivers use the information transmitted to calculate their exact location. A GPS receiver must be locked to the signal of at least three satellites to calculate the 2D position (latitude and longitude) and to track movement. With four, or more, satellites the receiver can determine the user's 3D position (latitude, longitude and altitude). Once a position is locked it is possible to calculate a set of other information such as speed, bearing, track, trip, distance, distance to destination, sunrise and sunset time and more [104].

GPS receivers, nowadays, are very accurate. GPS satellites emit two low power radio signals, designated L1 and L2. Civilian GPS uses the L1 frequency of 1575.42MHz in the UHF band. The signals travel by line of sight, meaning they pass through clouds, glass and plastic but can't go through most solid objects [104].

Some factors can degrade the GPS signal and affect its accuracy [104]:

- "Ionosphere and troposphere delays;
- Signal multipath – the GPS signal is reflected off objects such as tall buildings or large rock surfaces before it reaches the receiver. This increases the travel time of the signal, thereby causing errors;
- Receiver clock errors;
- Orbital errors;
- Number of satellites visible;
- Satellite geometry/shading;
- Intentional degradation of the satellite signal."

GPS is a very slow communication channel – there is a need to reach "three or four satellites for an extended duration of 50 bits per second" [105]. There is also no time division as in other communication mechanisms, which means there is the need to constantly power the antenna while the communication lasts; while the GPS is on, the system cannot enter a sleep state. Mobile devices of today achieve their good battery life because they can aggressively and quickly enter into and exit from sleep states; GPS prevents entering this state [105].

Mobipag STCP prototype, discussed in section 2.2.1, besides using Wi-Fi, also uses GPS to determine the user location, when boarding the public transport. GPS is an expensive, and somewhat limited, technology to use in the context of PT [106].

2.3.5 Cellular network location (GSM)

Cellular towers are divided in three 120º sectors and they can determine in which sector a specific cell phone is and its approximate distance (by measuring signal strength and round-trip signal time). If the cell phone captures more than one tower at the same time, the ability to get the location of the phone is increased. The estimations of the towers are overlapped, reducing the error margin and improving the accuracy. Locations that have more cell towers closer to each other allow a more accurate estimation [107]. In many cases, triangulation is not even used. The user location is given simply with the result of one cellular tower, which may greatly reduce the accuracy [108, 109]. A good example of this is the story of a woman, which accepted a guilty plea for a murder, in which the main proof was that, according to the cellular network data, the woman was at the place of the crime. The evidence was, however, of poor quality. The tower data can place the mobile phone in a broad area, but it cannot pinpoint the location. To actually pinpoint a location, the "three-tower" (triangulation) method is required which cannot reveal past locations. The woman was released from prison 12 years later [108].

Although this example is a bit extreme, it proves that network location is not reliable enough to base an entire PT system. Especially considering that, when travelling in MP, most of the network has a poor cellular signal. New approaches to public transportation ticketing services are relying on this type of location data, even within the Seamless Mobility project. However, one cannot dismiss this technology completely. It can be used to support the current obtained location, using a more accurate method.

2.3.6 ZigBee

ZigBee is a wireless technology designed to use low-power digital radio for personal area networks. It operates on the IEEE 802.15.4 specification and it allows the creation of networks that require low data transfer rate (250 kbps), energy efficiency and secure networking (achieved with 128-bit cryptographic keys). It is applied in building automation systems, heating and cooling control and in medical devices. It was designed to be less expensive when compared with technologies such as Bluetooth [110, 111].

ZigBee has been overwhelmed by problems related to interoperability: the standard is not just a wireless transport mechanism; there is also a layer of software, on top of the transport mechanism, that allows the creation of profiles that interfere with different versions of ZigBee profiles. This makes it possible for two devices that have ZigBee to not be able to communicate, unlike Wi-Fi. ZigBee is mainly pushed in in-home sensors, by companies such as Comcast [112].

Initially there was an interest of using Bluetooth for sensor networks or M2M or Internet of Things (IoT). The creation of ZigBee was motivated by the high Bluetooth power consumption at the time, making it not practical for that purpose. ZigBee supports a much larger network with a lower data rate and much lower power chipset. The appearance of Bluetooth new standards took direct aim at the ZigBee market space, because it became much more suited for sensor network applications. "ZigBee works well in a home and light industrial environment, but fails in a heavily automated industrial environment. ZigBee can be easily jammed in a heavy industrial environment. BLE uses a frequency hopping spread spectrum that is inherently more robust to jamming" [113].

This technology has already been studied for application in PT systems. Lv and Hu [106] have designed a bus management system based on ZigBee and GSM/GPRS, which "implemented the basic functions of the intelligent public transport management system, such as monitoring the time of bus arrival, departing from the bus station and reporting stations name automatically". The stop monitor would be a ZigBee coordinator which could accept the request from other ZigBee devices (on buses) and identify them [106].

2.3.7 Bluetooth

Bluetooth is a wireless communication standard based on a radio system designed for short-range cheap communications. It is an IEEE standard: 802.15.1. Bluetooth defines a radio interface, but also "a whole communication stack that allows devices to find each other and advertise the services they offer". Bluetooth uses the 2.4 GHz band [114].

Bluetooth serves as the backbone for the IoT – "scenario in which objects, animals or people are provided with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction" [115, 116]; everything becomes connected to the internet.

The range of Bluetooth technology varies. The core specification requires a minimum range of 10 meters that can be changed, based on manufacturers implementations, to supply the needed range for a specific use case [117]. Range may vary depending on the implementation radio class [117]:

- "Class 3 radios – have a range of up to 1 meter or 3 feet;
- Class 2 radios – most commonly found in mobile devices – have a range of 10 meters or 33 feet;
- Class 1 radios – used primarily in industrial use cases – have a range of 100 meters or 300 feet."

The most common radio is Class 2. Bluetooth technology is designed to have very low power consumption. The specification allows the radios to be powered down when inactive (enabling some power saving) [117].

Bluetooth has short ranges and slow data transfer rates (the most recent specifications provide about 26 megabits per second) [118, 119].

Its possibilities have already been explored in the prototype for wireless detection of passenger trips, seen in section 2.2.2 of this document.

2.3.7.1 Bluetooth Specifications

Bluetooth has been subject to new revisions and specifications throughout the years. Version 2.1 + EDR increased battery life by up to five times and improved security (among others).

Bluetooth Version 4.0, also named Bluetooth Smart, brought the Bluetooth Low Energy (BLE) feature. After this version Bluetooth became very economical in terms of power and it became more flexible, allowing the creation of Bluetooth Smart sensors applications which allow to bring everyday objects like heart-rate monitors, toothbrushes and shoes into the connected world and have them communicate with application that reside on other Bluetooth Smart devices that consumers own [115]. BLE has two different radio-frequency channels: advertising channels – used for device discovery, connection establishment and broadcast transmission - and data channels – used for bidirectional communication between connected devices [120].

Bluetooth Version 4.1 improves consumer usability, boosts product developers possibility for innovations and extends the technology's vision for the IoT [115].

And finally, Bluetooth Version 4.2 improves the Bluetooth in terms of privacy, power efficiency and industry standard security while increasing the throughput speed and packet capacity [115].

2.3.7.2 Bluetooth beacons

Bluetooth beacons are devices used to broadcast signals (using the advertising channels [120]) and BLE (Bluetooth Core Specification 4.0 – Bluetooth Smart). In essence, the devices create a sphere around them, a zone in 3D space where their signal is present. These signals can be picked up by compatible smart devices. These devices transmitting the signal are powered by a fixed power source (e.g. USB power adapter, battery) [121].

A *beacon* consists of two parts: a broadcaster (beacon device) and a receiver (smartphone app, for example). The broadcaster is always advertising a constant piece of information, using Bluetooth 4.0 technology [122], while the receiver detects these messages, executing the necessary actions afterwards [123].

Businesses can setup Bluetooth beacons in their stores to broadcast different signals. The beacons allow specially designed apps to pinpoint if customers are in range and start events whenever they reach a specific area [122].

The broadcasting devices (beacons) only send data every fraction of second or so (advertising interval). The standard beacon message is composed by an UUID, a major and a minor value only. For example:

UUID: B9407F30-F5F8-466E-AFF9-25556B57FE6D
Major ID: 1
Minor ID: 2 [123]

The UUID is a unique identifier.

Considering the example provided by BeaconsSandwich: "*If Starbucks decides to deploy beacon sensors inside its store and make an app that can tell the user once they arrive at a specific store, they would define a UUID that is unique to their app and the beacons inside their stores. Inside the stores, they would place beacon devices and configure each of them to use a different "minor" value. For example, at the store A, they would place all beacon devices broadcasting the Starbucks UUID, major value 0, minor 1 near the door, minor 2 near the mugs display and minor value 3 near the cashier. At store B, they would use the same UUID, but major 1 and minor values according to the location inside the store. With the information broadcasted by each beacon, an app can detect the phones and tell how close (or far) they are from each of them and perform actions, such as display alerts to the user, offer discounts, turn lights on and off, open doors and so on*" [123].

Major and Minor values are integers from 0 to 65 535 [124, 125].

The radio signals transmitted have two main properties: broadcasting power and advertising interval. The greater the broadcasting power (can also be referred to as coverage, which represents the radius of the sphere example used above) [126] the more energy is applied to the beacons' antenna. The greater the energy applied, the greater the range at which receivers will be able to pick up the signal. The greater the broadcasting power the faster the battery will be drained. Changing the broadcasting power changes, the beacons' broadcast range. Receivers also receive the signal strength (RSSI) and use it to calculate the distance to the broadcasting beacon as well as estimating its location [127, 128]. The advertising interval defines how frequently radio signals are broadcast. The more frequent the broadcasts, the greater the chance the receiver picks-up the signal and also more data (samples) are collected, which can provide a more accurate distance estimation. Beacons can be set to broadcast very frequently, but that consumes a higher amount of energy [120, 129-131].

There are two main methods for a mobile device to interact with a beacon: ranging and monitoring [132].

Ranging provides a list of all the beacons in range and their approximated distance and it requires that the user is actively using the application [132]. This concept uses the RSSI -

Received Signal Strength Indicator – and measured power to infer the distance [131]. Based on this distance, the user may be in one of three predefined zones – far, near or immediate [133].

Monitoring enables the developed application to know when the smartphone is entering or exiting the range of a beacon; in iOS this feature works even if the application is not running [132]. On Android, for this feature to work, the application has to be running. It can be running on the background, however, making the user able to use other applications [134]. Monitoring was designed to perform periodic scans in the background: these periodic scans are defined by the scanning time (period of time the beacon finding will last) and sleeping/waiting time (period of time the beacon finding will be halted) [135]. A beacon region is created by a beacon and defined by its UUID, Major and Minor; the beacon regions can be defined in three different ways [136]:

- Only with the UUID – A region of this type consists on all the beacons with the same UUID (Major and Minor are ignored);
- With UUID and Major – all the beacons using a specific combination of UUID and Major;
- With UUID, Major and Minor – consists of a single beacon (Estimote Cloud prevents assigning two beacons with the same set of UUID, Major and Minor).

2.3.7.2.1 Bluetooth beacons comparison

In terms of beacons, the broadcasting device, there are several options. In the table below, six options are compared.

Beacon	Documentation/ Support	Security features	Battery life	Price	Extra observations
Estimote	A lot and easy to obtain [133]	- Requires login to alter beacon information [137] - Secure UUID (encrypted, rotating UUID, but Internet connection is required to decrypt) [138]	May vary from a month to 3.3 years [130] (**)	3 beacons – 99$ [139] (*)	- Sticker (smaller) version [139]; - Accelerometer and temperature sensors [139]; - Bulk editing (allows to change beacon configuration remotely, updating the beacons only when in range) [140, 141]; - Android Software Development Kit (SDK) incomplete when comparing to iOS SDK [142]; - iOS and Android configuration apps [139].
Gimbal	Not much		4 months (**) [143]	Simple version (smaller	- External power/battery status button w/ LED feedback [143]

				battery) – 5$ [144] (*) More complete version – 30$ [144] (*)	
Glimworms	Not much	PIN Code protected [145]		4 – 99€ [146] 100 – 9900€ [146]	- Only indoor use [147] - iOS configuration app only [148]
Bluecats	Not much	Secure mode: encrypted advertisement, only authorized apps can decrypt and interpret data [149]	(**)		- iOS only configuration app [150]
Kontakt.io	A lot and easy to obtain	- Requires authentication to edit beacon properties[151]; - Master and individual password to secure beacons [152]; - Further security improvements planned [152].	Up to two years [153](**)	3 – 81$ [154] (*) 50 – 1100$ [154] (*)	- Allows to delegate beacons to specific users, so they can change them [155]; - Provides online platform for editing beacons. The changes are synchronized when the configuration app comes within range of the changed beacons [151]; - iOS configuration app [156].
Bluebar beacon (BlueSense networks)	Not much	Requires login to alter beacon information [157]	Up to 15 months [158] (**)	26.80€ each unit [159](*)	iOS & Android configuration apps [157]

* excluding VAT, shipping and import charges. Better prices when ordering higher quantities;

** varies with transmission settings

Table 1 – Beacon comparison

2.3.7.2.2 iBeacons

iBeacons is the trademarked name that Apple chose for a technology that allows mobile apps, running on iPhones and iPads, to know how close they are to the Bluetooth emitter (beacon) [160]. The Apple iBeacon profile comprehends an advertising interval of 100ms and a signal/transmission power of -12dBm. The Apple iBeacon profile reduces the battery life of a beacon to 25% [161].

2.3.7.2.3 Bluetooth beacons uses

A lot of businesses and developers are comprehending the potential of the technology and are starting to take advantage to engage the customer more by delivering relevant and contextual interactions [121].

For example, beacons can be used for resources tracking. On a restaurant, where servers are becoming equipped with Bluetooth enabled gear, to take orders, the usage of beacons could allow to correlate the customer satisfaction with the amount of time the server spent with the customer and to determine the most common paths and least visited areas in order to improve efficiency. The restaurant context is only an example. This concept could be applied to several different businesses [123].

The retail shop experience is also being improved with client receiving promotions as they walk inside the store and between store areas. The store can trigger remote events to get the customers' attention [123].

2.3.7.2.4 Bluetooth beacons limitations

Bluetooth beacons, especially when first introduced, had a series of limitations:

- Using the manufacturers' software allows anyone to alter any beacon of the manufacturer. One can simply change the values that the beacon is emitting, effectively rendering the beacon useless for the context it is used in [162];
- Anyone can have a beacon emit the same signal as another beacon (duplicating a beacon outside of its context) [162]. The CES Scavenger Hunt is the perfect example of the exploration of this problem. The purpose of the Scavenger Hunt was to use a proprietary app of CES to search for beacons. When they were found the application automatically updated the user progress. Afterwards, users that were not even in the location of the event, were able to determine the beacons content (UUID, Major and Minor) and replicate them, therefore completing the Scavenger Hunt without being present in the event [163];
- Lack of precision – Some providers highlighted that beacons had a lack of precision, when being used to guide customers through stores. The beacon signal can be affected by several factors [164].

The first problem is already addressed by some manufacturers that enabled a security feature that makes login required in order to alter a beacon [165].

The second problem has also seen some progress. Some manufacturers have implemented secure UUID which enables the rotation of UUID, within certain periods of time, that prevent the UUID from being replicated [138, 165]. At the same time, some manufacturers keep a database of UUIDs and only allow to a user to use a UUID that is not being used by anyone else [165]. However, this database is not transversal, which does not prevent someone from using a home-made or competitor device to emulate another beacon [166].

2.4 Mobile service adoption

The use of mobile, or e-tickets, in PT systems is context dependent: people generally use them when they run out of cash, are in a hurry or need the ticket unexpectedly or try to avoid queues [167]. According to Mallat et al. study's results [167], consumers are more receptive and able to use complex mobile services if these allow them to solve the type of problems identified previously.

The most relevant feature of mobile technology is mobility, which translates into "the ability of accessing services ubiquitously, on the move, and through wireless networks" and various types of devices. It is argued that computers need to be more seamlessly integrated in the use environment and in people's everyday lives so that they can actually become ubiquitous [167].

Another concept that is also very relevant, when discussing mobile commerce adoption and use, is use context. Studies conducted suggest that use situations have a significant impact on customer choice of products, stores and other purchase channels [167]. Dabholkar and Bagozzi [167] found that perceived waiting time and crowding were two factors that had a mediating effect on the use intention of consumer self-service technologies. Wendel and Dellaert [167] discovered "that consumer consider different media channels and require different benefits from them under different contexts".

Additional studies have focused on different contexts on mobile computing concluding that "technologies designed for mobile computing should be more flexible and adaptable to support tasks in altering environments" [167].

These results provide good insight needed to study the mobile ticketing adoption approach. Mallat et al. refer that "findings indicate that contextual factors affect consumer choice and selection criteria of mobile services depending on when, where and which services are used. Considering still that there are limited amount of typical and identifiable use contexts for certain mobile services it is recommended to try to identify them and evaluate their effect on mobile service adoption and use" [6, 167] .

Trust and risk have appeared as important determinants of electronic and mobile commerce adoption. In this type of services trust is important given that there is a spatial and temporal separation between the buyer and the seller and because the buyer is required to provide personal information. Siau and Shen postulated "that both perceptions on mobile vendor and on mobile technology are influential in trust formation"[167]. Perceived risk is also a determinant factor that could have negative effect on mobile commerce and technology adoption. In the area of mobile commerce, perceived risk is associated to the limitations in mobile networks (speed, connection and coverage), devices (small displays/keypads, limited power, limited memory) and the actual payment solutions [167].

2.4.1 Adoption factors on mobile payment services study

Mallat et al. [167] performed a research focused on the adoption factors of the mobile payments services. They applied this research to the context of the mobile ticketing service provided by Helsinki Public Transport, in order to determine which adoption factors were more relevant:

"*In 2001 Helsinki city Public Transport launched a short message service (SMS) based system for selling public transportation tickets. In 2004 close to 1,900,000 mobile tickets were sold and, at present, over 17% of all adult single tickets are purchased through the mobile channel. The tickets can be bought by sending a four character SMS to a premium service number. As a return message, the customer receives a single SMS ticket, which is valid for one hour on trams, subway, local trains, and certain ferries and buses. The ticket costs €1.90 and is priced lower than a single ticket bought in the vehicle and paid in cash. The tickets are billed through mobile phone operators' billing systems.* " [167]

The adoption factors considered are represented in figure 12:

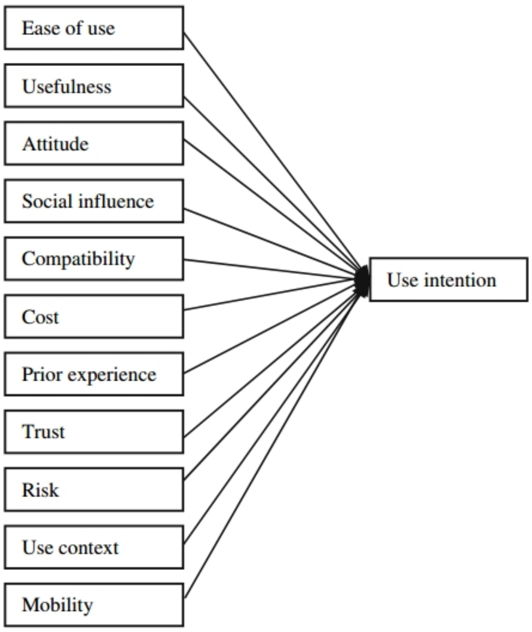


Figure 12 - Adoption factors studied [167]

The results of the study supported the effect of perceived technology characteristics on the intention to adopt mobile ticketing services. Ease of use and usefulness had a significant effect on the adoption decision, but still weak when compared to other factors, which makes one wonder if the TAM model may not be so widely applicable, as it has been found in many studies conducted in organizational environments. The best factors were prior experience and compatibility of the mobile ticketing service with a person's use of PT, mobile phones and general habits. Another very strong determinant was social influence, for example, other people's recommendation and perception of social acceptance. All the remaining factors, except cost, had a positive association with adoption decision. Cost, however, was not found a significant factor for mobile ticketing adoption [167].

2.5 Mobile operating systems

The smartphone world is very fragmented. There is a big variety of mobile operating systems running in the even more diverse smartphone hardware ecosystem.

In Q3 of 2014, the mobile operating system with the most market share was Android [168].

The two big players in the mobile ecosystem are, undoubtedly, iOS and Android [169]. This raises the question of which platform to target, when given limited resources.

Cross-Platform development frameworks, such as Phonegap and Xamarin, simplify the cross-platform development. The developer writes code once and that code is converted to functional code on each targeted platform. However, this solution falls short when there is the need to use very native functionalities, the need to handle large amounts of data or the need to include external dependencies [169].

Developing a native application – an application written using the platform code and technologies - takes a lot more work and investment [169] but is generally more stable and versatile. It is no longer a matter of which one to develop in, but more of a question on which one to develop first and planning the development for the remaining platforms [169]. This raises the question of which platform to launch first [169]:

- What are the current users (the passengers) using?
- What are the plans for tablet development? (iOS, for example, is stronger than Android in the tablet scenario);
- What is the developer team familiar with?;
- Is the application paid? – iOS users, for example, are more likely to pay for an application than Android users.

In this case, other variables apply. Such as, if there are any beacon technology limitations on either platform. When choosing the platform, the cost of equipments and technologies should also be taken in consideration. For example, developing for iOS requires a Mac computer, a phone and a developer's license which is somewhat expensive.

Chapter 3

Problem and solution proposal

This chapter explores the problem in more detail and provides a complete analysis of the solution proposal.

3.1 Problem

As seen previously current PT systems are facing several problems that even new approaches such as Oyster and Ventra are not solving completely.

The users are very tied to a pre-planning and pre-payment approach that demands a lot of input and interaction from them. There is no possibility of actually "using" the public transport without having to worry about lines, checking-in or even carrying cash. Basically, a user cannot simply walk in and use the service. These factors are decreasing the interest on the use of PT. In sum, it is not seamless enough for the user and it should be.

At the same time, operators are using a huge amount of their resources to improve and maintain ticketing systems that do not even provide them with enough information to improve other areas such as the network flow. Also, the ticketing systems decrease the interest of the users, due to their complexity, which reduces revenues even further, due to the loss of interest in using the service. These ticketing systems sometimes even delay the entire network: because they do not work, because they are congested and delay passenger processing or because they are not properly designed to handle a very sensible type of service such as public transportation.

The problem is providing an alternate ticketing system so that the passengers have a seamless usage, this being, using the public transport without worrying about checkin, checkout, pre-planning or pre-payment of tickets, in sum, improving customer experience. At the same time, part of the problem is assuring a new alternative allows to reduce the operators' costs in terms of ticketing infrastructure (ideally shifting a big part of the infrastructure to the passenger), reduce the delays on the system and, ideally, collect more information of the PT system usage, for the purpose of obtaining origin-destination matrices automatically, that allow the optimization of the network flow. Part of the problem is also the context where the problem is inserted. Considering that this work is directly related to two actual PT operators, any solution that is found has to answer to those operators' needs and restrictions. One of these restrictions is to find the most economical solution. At the same time, the same solution has to work seamlessly for both operators, as it currently works with the Andante system. It has to be an integrated and multi-modal approach for the both types of transport that the user can use – bus and light-rail/metro. Even though the solution is focused on the MP/STCP case, it must also be general enough to work with other operators, with the least changes possible.

3.2 Solution

When developing this solution other prototypes, such as Mobipag STCP prototype and the work done by Kostakos [170], were considered. A paper, explaining this approach, was also accepted for publishing [171] and is available for consult in Appendix I – Accepted paper.

The Mobipag STCP prototype envisioned a Wi-Fi/mobile network communication with a server where the virtual tickets were stored and where all the actions, such as buying new tickets and checking-in, were executed, but the technology used to determine the user location, GPS, as seen previously, is very energy demanding on limited powered devices. At the same time, GPS does not work consistently, being affected by several factors. One of the most serious factors that rules out its use in the proposed solution is the fact that it will not work underground or inside buildings, i.e. without line-of-sight. Considering that many stops on the Metro do Porto system are underground, or inside buildings, an alternative to GPS has to be found.

That is where Bluetooth (in particular the beacons) comes in and where it is possible to gather some input from Kostakos prototype. On this prototype a Bluetooth equipment detected the entrance and exit, on the vehicles, of passengers that had Bluetooth enabled on their smartphone. There was no actual correlation with the identity of the passenger, the system only served for statistical purposes in terms of identification of usage patterns. At the same time, the Bluetooth "scanner" that was developed required the rewiring of the bus. This meant additional costs in terms of installment. This would not be viable for operators, such as Metro do Porto and STCP, with a large fleet of vehicles.

This solution proposes the development of a mobile application that makes use of the Bluetooth beacons. The mobile application would require that Bluetooth was enabled, and would detect the user approximation to beacons in the PT network. The beacons can be easily installed anywhere, they are not expensive, especially when bought in large quantities, and they use Bluetooth Smart. They would be constantly emitting a Bluetooth message: a contextual message, informing the location; and the passengers' smartphones, with the application, would be communicating the location to a server, based on the beacons' broadcasted information. The use of Bluetooth, namely BLE, would reduce the impact on the battery life of the user's smartphone.

The number of beacons to deploy, their locations and cost estimates are overviewed in later sections. It is necessary to limit the transmission power of the beacons in order to control the range, avoid overlapping signals and save battery life. The message each beacon would transmit would vary, based on its location. Considering that beacons transmit an UUID, Major and Minor, as seen in section 2.3.7.2, the initial premise would be that the entire network would share the same and unique UUID; the Major value, an integer, would represent the location; and the Minor would provide further information. In order for the system to work more efficiently, the Bluetooth beacons' regions would be used, as explained in section 2.3.7.2, in association with the monitoring concept, that allows to determine when a user is in the vicinity of a region.

3.2.1 Overview

In order to completely understand the solution, the general view of the architecture must be analyzed. The proposed solution follows the design on Figure 13.

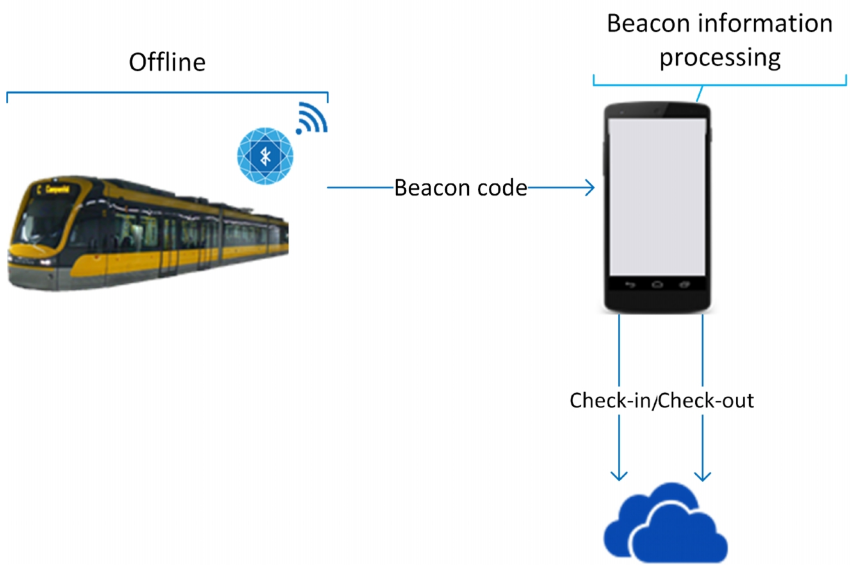


Figure 13 - Solution architecture [171-175] References include the diagram individual images (cloud, phone, vehicle and Bluetooth)

As said previously, beacons would be placed across the network; emitting a specific message depending on the location where they are installed. The smartphone application would detect proximity (via Bluetooth) to the beacons and send a request to the server, via Wi-Fi or mobile networks (taking advantage of the free Wi-Fi deployment trend, as seen on STCP's case) on PT systems, informing about the user location within the public transport system. The beacon code would be mapped to specific vehicles or stations. A mapping proposition is proposed in a later section of this document.

3.2.2 Checkin, checkout and assuring the correct usage

The solution proposed tries to maintain the steps that compose, generally, a trip: checkin, checkout and in transit. It tries, however, to do all these steps without user intervention. The steps depicted in Figure 14, in the form of a state diagram, represent the several steps followed using the proposed solution. The state diagram represents the most complex situation that could be faced: the beacon deployment is done in both vehicles and stops. However, this approach is still evaluated in further detail in the next section.

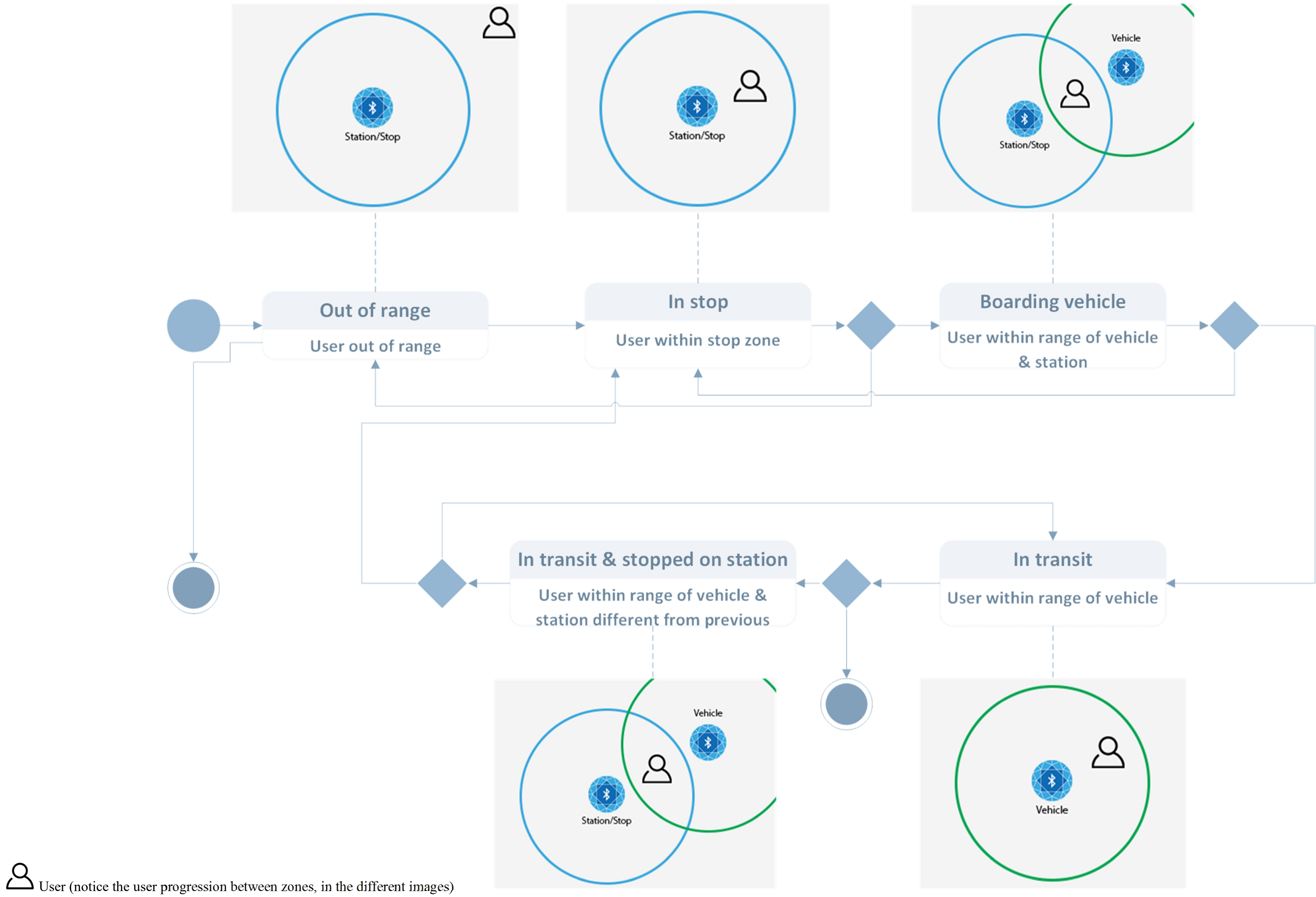


Figure 14 - State diagram of proposed solution [175, 176]

References include the diagram individual images (user and Bluetooth)

The application is running on the background. The passenger starts outside of the range of any beacon. When he approaches a station's beacon, crossing a region, the application detects this and saves this information. If he does not get closer to the stop, exiting the beacon range, it means it is just walking by the stop and the application discards the information.

If the passenger is in a stop region and the signal of a vehicle's beacon is detected, the application enters a state where it assumes the user is boarding. If the vehicle signal disappears and the region stop signal remains, the passenger did not board. If the stop signal disappears and the vehicle signal remains, the passenger is in transit. After this state, if another station signal is detected it means that a new stop was reached in his course.

When the passenger leaves the vehicle (the vehicle signal disappears) with a remaining station signal (checkout station) that, eventually, disappears a new state occurs - checkout.

If the application detects the signal of a vehicle (for example, a person is walking by a bus) it will check if there was a checkin. If there was not, the application verifies if there is a continuity to the bus signal (followed by the pick-up of stops signals) which may indicate the passenger boarded the vehicle in a place that is not a stop.

3.2.3 Beacon deployment

3.2.3.1 Beacon installation

In order to have a working system, based on beacons, they have to be installed in several key points of the PT network. These key points are the stations and the vehicles. This section discusses the advantages and disadvantages of each possible installment configuration.

3.2.3.1.1 Vehicles

This approach considers that the beacons are placed in the vehicles (buses and light-rail vehicles).

The following diagram details the steps in a solution based on this installment configuration.

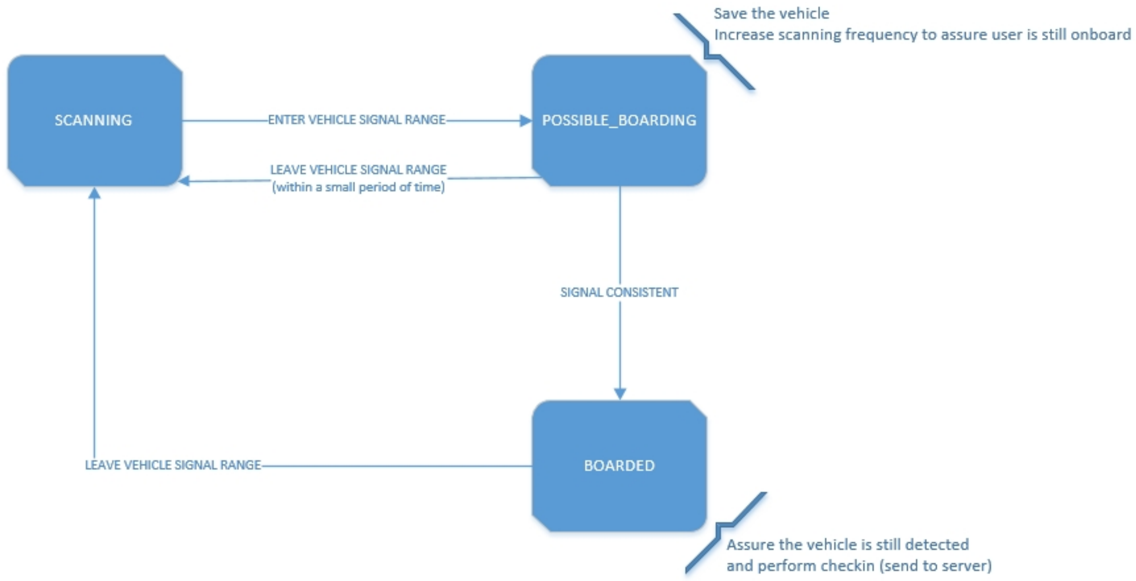


Figure 15 - Beacon installment (only vehicles) operation overview

First, the passenger smartphone is in *scanning* state, trying to detect a vehicle signal. When the user enters the signal region of a beacon installed on a vehicle a new state of *possible boarding* is reached. The detected vehicle is saved and the scanning frequency increased.

If the signal is consistent, during a specific timeframe, one can assume that the passenger boarded the vehicle. Afterwards, when leaving vehicle signal range, a timer is started, which will guarantee that the signal disappeared and that the passenger actually left the vehicle and stopped his journey.

This approach is subject to some problems. For example, it is not possible to determine the checkin or checkout point from the beacons information. To solve this, an external method to obtain the location would be required, such as:

- Access to the bus location, which may be private information, without an interface in place;
- Use of GPS signal from the user. This possibility raises additional permissions and security problems. It also has technical problems - GPS location can be slow and won't work properly underground (part of the MP transport operation is underground);
- Use of network location. Subject to flaws, especially if underground, when the reception is weak.

There is also the problem of conflicting vehicle signals (e.g. a vehicle passing by another). The application must be able to distinguish which is the vehicle the passenger is in. This can be solved by sampling: during the trip, the scanning frequency is higher and the application can make periodic checks on the vehicle that the user is in; if there is a conflict of signals, the one with no previous occurrences will be discarded.

This approach also can't handle with users walking by the vehicles. If the user is sitting in a station, without boarding, and a vehicle stops for a while, this can be considered a boarding by the software and will be charged to the user as a trip.

The two problems analyzed before can be minimized by using location data.

But, this approach is still based on timeouts, a bad method to follow, considering the variants associated to PT operations, such as delays.

In terms of cost, it is one of the most inexpensive installment proposals.

Metro do Porto has 102 vehicles and STCP has 468. For a bulk amount of 500 Estimotes, the price is 20USD per item [177]. This means that this solution would cost 2040USD to MP and 10000USD to STCP (excluding taxes, shipping, software development and installation/maintenance costs).

3.2.3.1.2 Stations

This second approach considers that the beacons are installed in the stations composing the MP and STCP networks.

The following diagram details the steps in a solution based on this installment configuration.

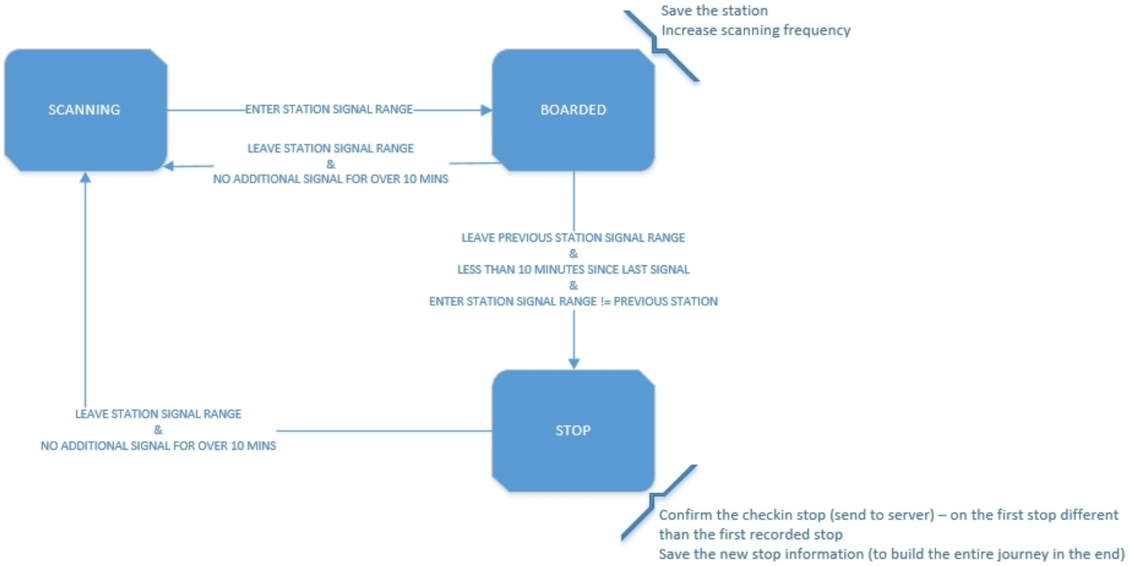


Figure 16 - Beacon installment (only stations) operation overview

First, in the *scanning* state the smartphone is detecting possible entrances in a station's region (created by the beacon signal). If the user enters a station's range, it goes to the *boarded* state. If the user leaves this region in a small period of time this means that it was just a passage and not an actual boarding, returning to the *scanning* state. If a new station is detected within a specific timeframe this means the user has actually boarded (entering a new state) and the final state change occurs when the user stops detecting a station for a long period of time (meaning the user left the PT system).

This approach, in particular this last portion, the checkout, is very susceptible to errors. A delay between stations might indicate a checkout when the user is, in fact, still in transit.

At the same time, this is a more expensive approach (for STCP, at least). In total, the number of stations of MP is 81 (rounding to 100 because most underground MP stations would require more than one beacon) and STCP total amount of stations is 2651. Considering that the price per beacon is still 20USD (it should be a little lower considering a bulk order five times superior to the previous scenario) this would translate to a cost of 2000USD for MP and 53020USD for STCP.

3.2.3.1.3 Vehicles and Stations

This third approach considers that the beacons are installed in the stations and vehicles composing the MP and STCP network. It is the most complex approach, and was briefly considered in section 3.2.2 - Checkin, checkout and assuring the correct usage.

The following diagram, summarily, details the steps in a solution based on this installment configuration.

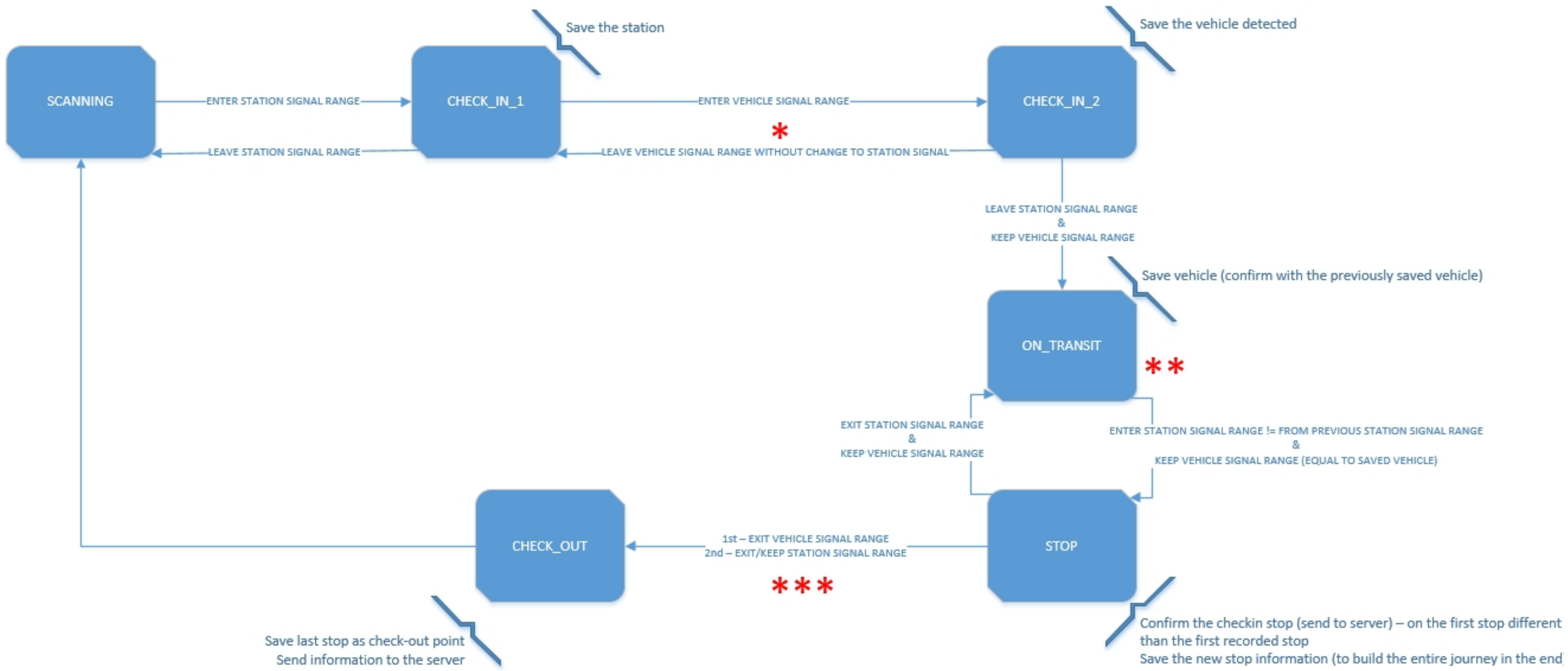


Figure 17 - Beacon installment (stations & vehicles) operation overview

First, in the scanning state, the smartphone is detecting possible entrances in a station's region (created by the beacon signal). After detecting the station signal, the smartphone is ready to detect a vehicle signal. If the vehicle signal persists while the station signal disappears, it is considered that the user is boarded. If the vehicle signal disappears and the station signal remains that means the user did not board that particular vehicle, but he may still enter another vehicle.

After entering a vehicle, and getting to the point where only that vehicle is detected, the next step should be the detection of a new station that is different from the first. If this happens a new, valid, trip is created. After this, a sequence of station detections should be created representing the course the user took. The user journey should be associated with one vehicle, but the user can pass by other different vehicles in his course. This can be solved since a checkin has only one vehicle associated (any other vehicles detected after the checkin can be ignored). If the user boards a vehicle while in the range of another vehicle the checkin has to be postponed until only one vehicle is detected (being that the checkin vehicle).

After the vehicle signal disappears, and a station signal still remains, one can start to assume that checkout happened (which is confirmed by the entrance on a new vehicle or by exiting the station). If the user loses the vehicle signal (when in between stations) the checkout is assumed in the station following the last detected one. If the user loses both the vehicle signal and the station signal the checkout is assumed on that station.

Red asterisks (*) in the image represent possible problems/requirements that need to be handled.

* Represents a situation where the passenger is within range of a station, and is entering and leaving several vehicles' range. This means the passenger is at a stop, while several vehicles are passing by. Only the vehicle the passenger leaves with is considered as a boarded vehicle;

** If the vehicle signal disappears, without a station signal, a timeout starts giving a chance for the vehicle to be detected again. If this timeout is not respected, a checkout is assumed using the last stop the user passed by. If conflicting vehicles' signals are detected and the passenger is in an ongoing trip, considering that at this stage a checkin point was already created, the new vehicles detected are ignored.

*** If when unboarding the station signal disappears before the vehicle signal, timeouts are triggered to handle this, and perform checkout using the last detected station. The same happens if the passenger remains in a station, with no vehicle, after a checkin. Ideally, the user should then leave the station, but, if the passenger stays in range of the station for a big period of time, the checkout is assumed on that station for safety purposes.

3.2.3.2 Beacon placement and broadcasting ranges

This section provides details on where to place beacons, within stations and vehicles, and how to configure them to obtain the maximum efficiency.

It is important to remind that beacons act as the center of a sphere, from where a Bluetooth signal is emitted, being the radius of that sphere the broadcasting range specified in the beacons' configuration.

3.2.3.2.1 Light-rail vehicles

The vehicles of the MP's fleet can be single units (35m and 37m long) or composed units (two single units attached, approximately 70-71m long and 74-76m long). Placing one beacon, near the connection point of two units would be possible, but vehicles are regularly uncoupled which would require changes in beacon placement. As such, one beacon per unit is required. The question is what is the best location for the beacon and with which broadcasting range.

Considering the Eurotram, if the beacon was placed in the front of the vehicle, the minimum broadcasting range required would be of 30m. A schematic of the beacon coverage for this situation is represented in the followings images.

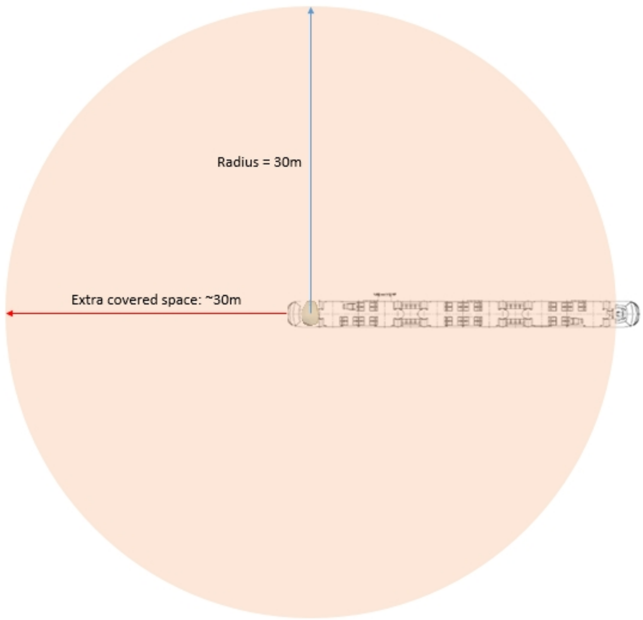


Figure 18 - Beacon coverage - in front of single Eurotram with 30m range [50] Reference includes the diagram individual image (vehicle technical drawing)

If talking about a single unit, a big portion of the beacon signal is wasted in the space in front of the vehicle. The backside drivers' cabin is also out of reach, but the extremities of the signal are covering a still usable passenger area. As so, further tests would have to be conducted to evaluate the signal coverage in these conditions.

An equivalent scenario happens when the beacon is placed in the back of the vehicle. The only difference is that there is a wastage of signal covering the region in the back of the vehicle.

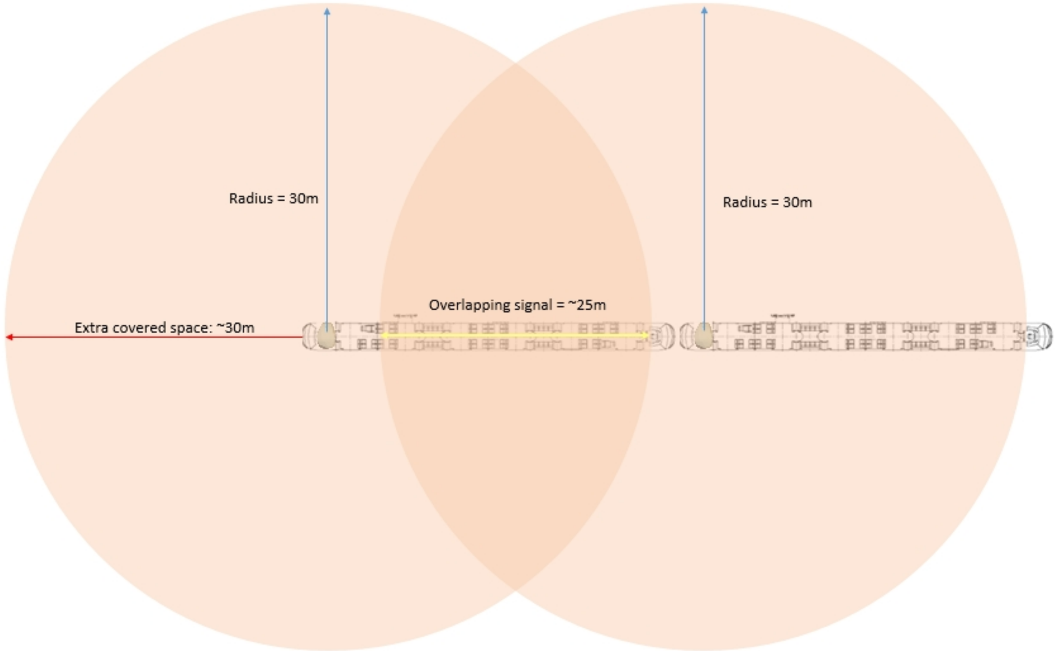


Figure 19 - Beacon coverage - in front of composed Eurotram with 30m range [50] Reference includes the diagram individual image (vehicle technical drawing)

When talking about a composed vehicle, the same coverage of unuseful space is made to the front of the vehicle. But also, one faces the creation of an overlapping zone of signals. Overlapping zones could increase the complexity of the solution development, and should be avoided, if possible. This new scenario is equivalent to placing the beacon in the back of the vehicle. The overlapping still occurs and the coverage waste happens in the space behind the vehicle.

When placing the beacon in the middle of the vehicle, two broadcasting ranges are possible – 15m and 30m. The first performs the coverage as shown in the following images:

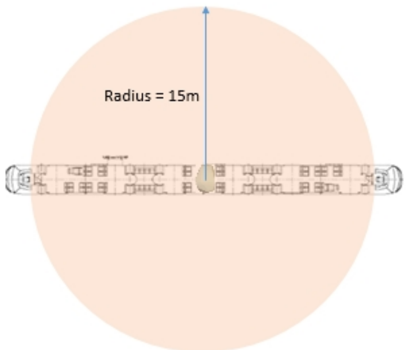


Figure 20 - Beacon coverage - in middle of single Eurotram with 15m range [50] Reference includes the diagram individual image (vehicle technical drawing)

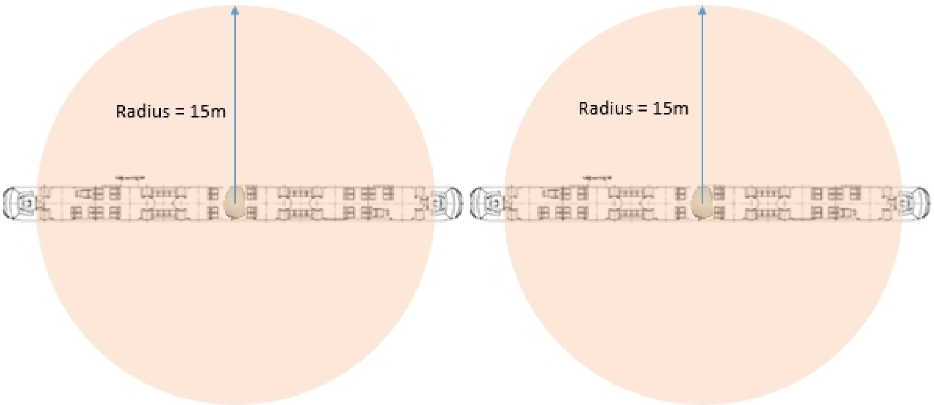


Figure 21 - Beacon coverage - in middle of composed Eurotram with 15m range [50] Reference includes the diagram individual image (vehicle technical drawing)

The 15m broadcasting range covers the entirely usable area of the passengers and partially the drivers' cabin. However, given that a portion of the passengers' usable area is in the extremities of the coverage, further tests should be conducted to evaluate the signal quality in these areas. This broadcasting range, for this type of vehicle, is the one where areas that don't require coverage are minimized.

When considering the Flexity Swift (the most recent vehicle in the MP's fleet) the scenario changes, but the problems of placing the beacon in the front or in the back of the vehicle remain, since unuseful areas would be covered. The beacon placement in the middle is still evaluated, for the 15m and 30m broadcasting ranges.

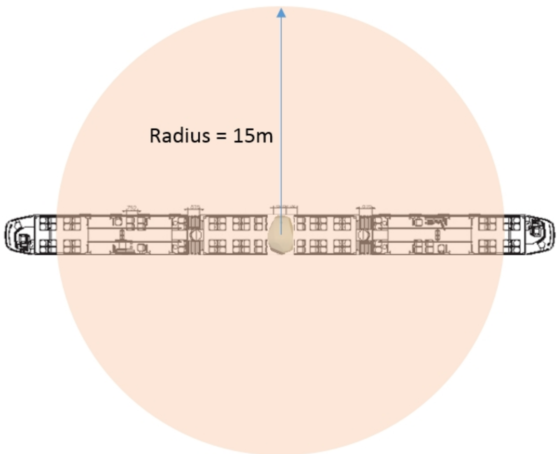


Figure 22 - Beacon coverage - in middle of single Flexity Swift with 15m range [55] Reference includes the diagram individual image (vehicle technical drawing)

For the 15m broadcasting range, a part of the passengers' usable area is not covered because this vehicle is longer and the drivers' cabin size is reduced to provide more passenger seats.

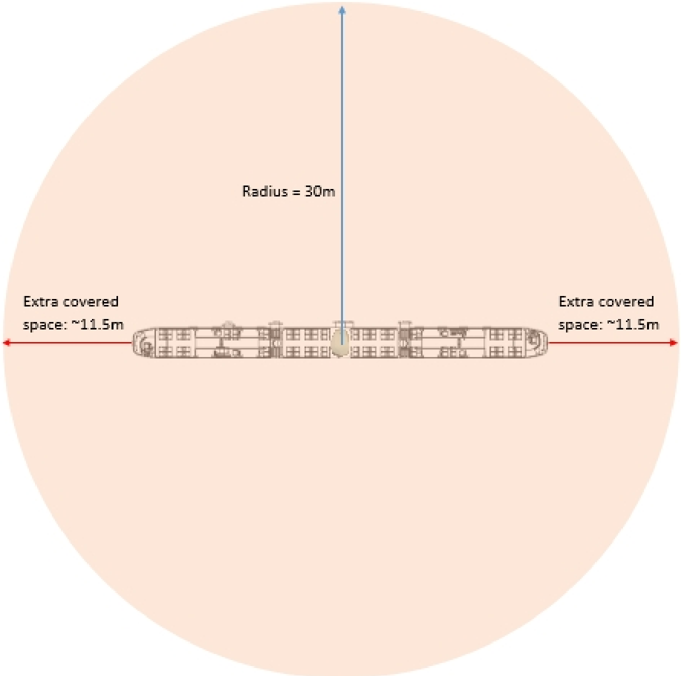


Figure 23 - Beacon coverage - in middle of single Flexity Swift with 30m range [55] Reference includes the diagram individual image (vehicle technical drawing)

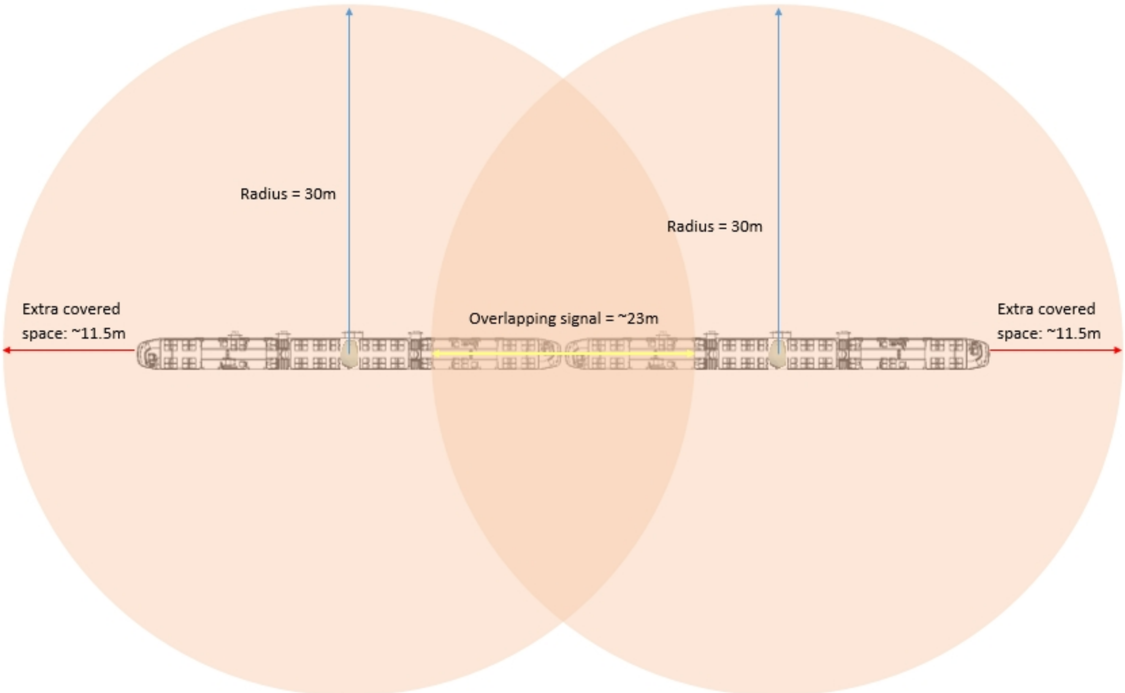


Figure 24 - Beacon coverage - in middle of composed Flexity Swift with 30m range [55] Reference includes the diagram individual image (vehicle technical drawing)

With a 30m broadcasting range, in case of a single unit, the vehicle is entirely covered by the beacon signal, however, there is a coverage of 23m unneeded space (half in the front of the vehicle and half in the back). For a composed vehicle, the amount of extra space covered is the same and there is the need to deal with overlapping zones.

3.2.3.2.2 Buses

Placing the beacons either on the front or back of the buses is not productive, following the analysis that was made for the light-rail vehicles. As such, several alternatives are analyzed in this section for different bus sizes and beacon broadcasting ranges, but the location considered for the beacon is always the middle of the bus.

For the smaller, 7.45m long buses, two broadcasting ranges are possible – 3.5m and 7m.

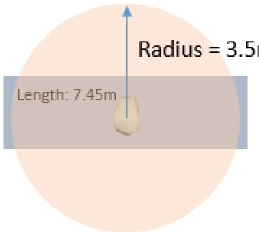


Figure 25 - Beacon coverage - in middle of 7.45m bus with 3.5m range

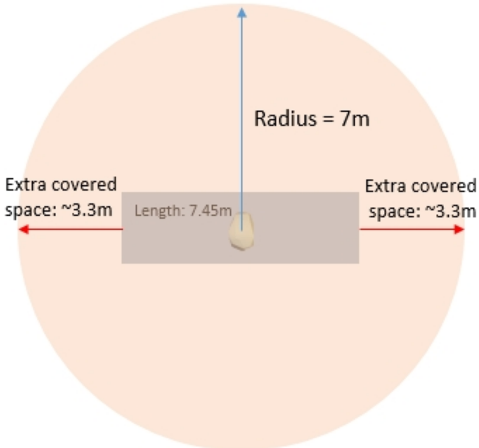


Figure 26 - Beacon coverage - in middle of 7.45m bus with 7m range

The 3.5m broadcasting range falls a little short on the required covered area. On the other hand, the 7m broadcasting range makes it so that some unneeded space is covered.

For the common length buses (12m) the ideal beacon broadcasting range is of 7m, with only 1m of additional space being covered.

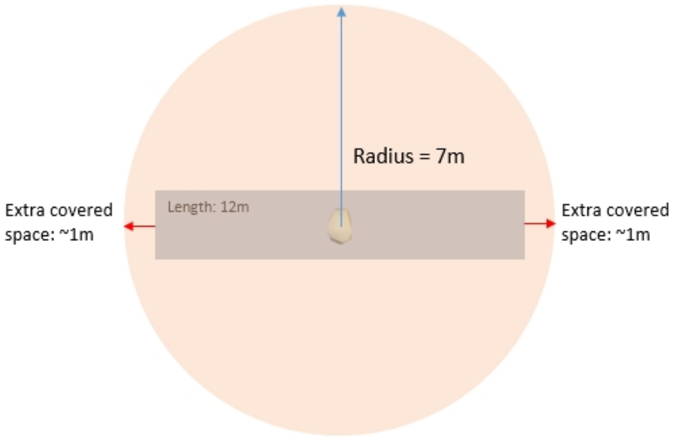


Figure 27 - Beacon coverage - in middle of 12m bus with 7m range

It's also important to note that the double decker buses (2 floors) are also 12m long. For this type of buses, further tests would also have no be made, prior to a conclusion on what the ideal beacon placement and broadcasting range.

Finally, the articulated buses (18 meters long) require a broadcasting range of 15m. In this scenario 6m of space in each end is covering unneeded space.

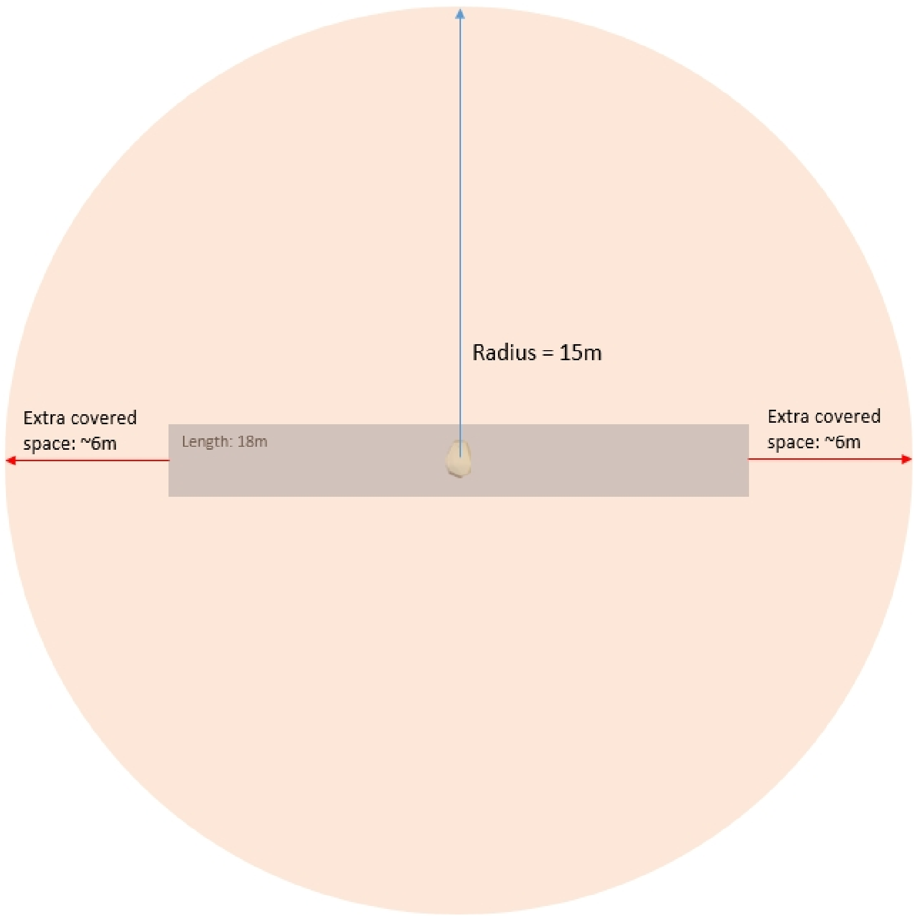


Figure 28 - Beacon coverage - in middle of 18m bus with 15m range

3.2.3.2.3 Light-rail stations

Light-rail stations within the MP network follow, approximately, the same design. The main platform is, roughly, 100m. The underground stations have a boarding platform of the same size but contain one or more additional top levels. The goal should be to provide complete coverage in the boarding platforms, ignoring any possible upper levels that do not provide direct entrance to the vehicles.

Figure 31 - Boarding platform length [51]

Figure 30 - Boarding platform track length [51]

Figure 29 - Boarding platform passenger area length [51]

A boarding platform is composed of two main portions, as can be seen in the following figure and based on the previous images.

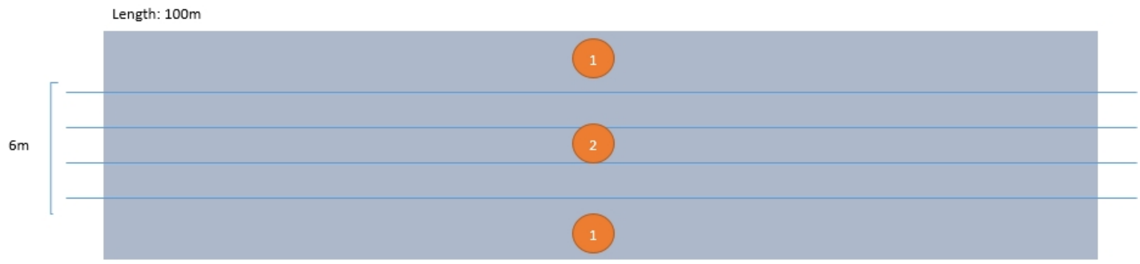


Figure 32 - Light-rail track layout

The first (1), is the boarding area where passengers board and unboard a vehicle. The second (2) is the track area used for the vehicles circulation. This track area size is standardized across the network. The boarding areas for the passengers could vary from station to station, but, in the following scenarios a vertical length of 2.5m is assumed, based on the previous observations.

One approach would be to place the beacon in the ceiling, in the middle of the station, but this would only work for underground stations and it would make beacon maintenance harder.

The ideal approach is to place a beacon in a wall/side of one of the boarding areas, as high as possible, in the middle of the station. For this, the minimal broadcasting range would have to be of 50m or 70m.

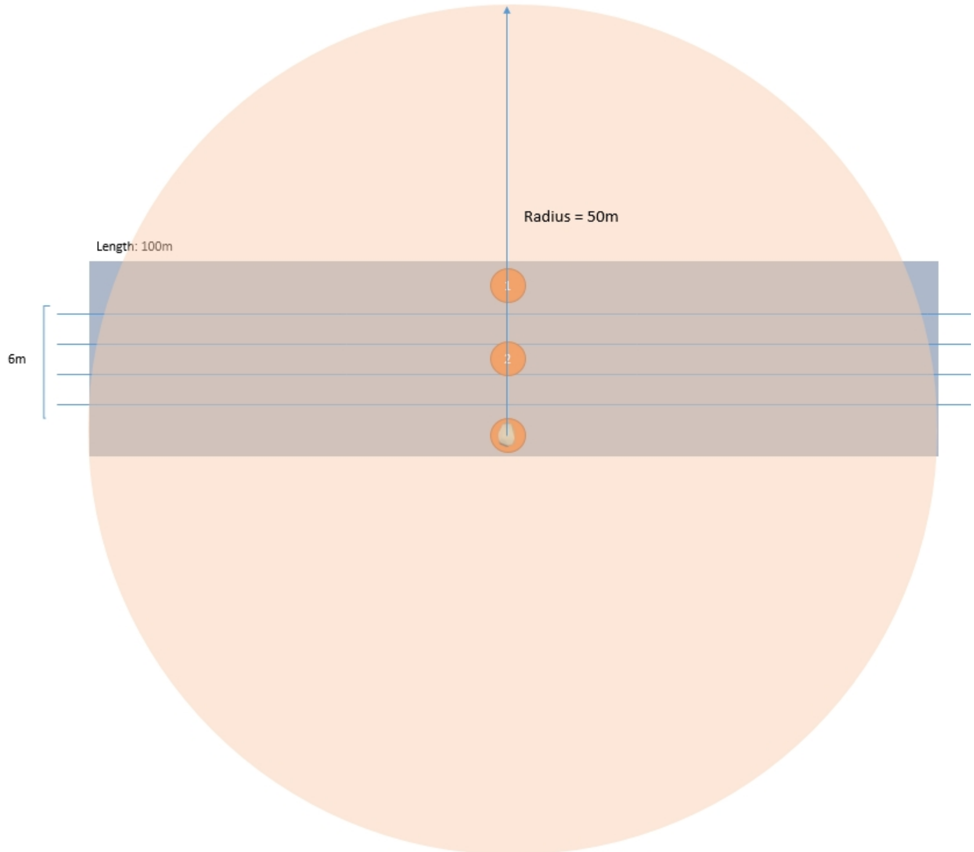


Figure 33 - Light-rail track coverage with 50m broadcasting range

As can be seen above, the broadcasting range of 50m covers most of the boarding platform. The boarding areas (1) have an estimated size of 2.5m. If this size is increased a higher area will become uncovered by the beacon signal.

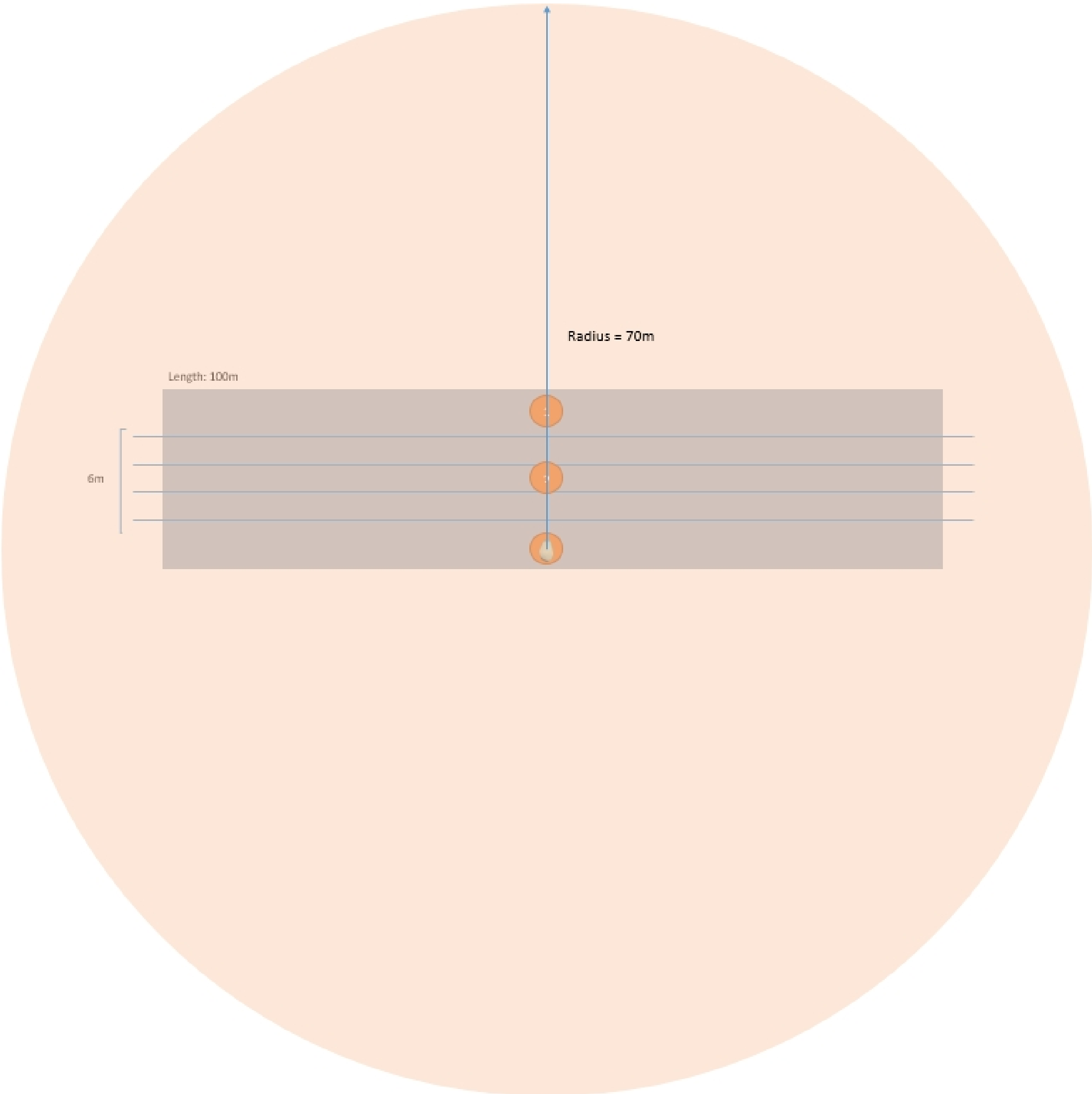


Figure 34 - Light-rail track coverage with 70m broadcasting range

On the other hand, a 70m beacon broadcasting range covers a wide area. Even though the boarding areas (1) are 2.5m in size they could still be bigger and be totally covered. However, there is the possibility of covering a lot more space than needed (especially relevant in overground stations).

In the MP stations, given the area that has to be covered, the fact that the users in the vehicles require the detection of the stations they pass by is not a problem.

3.2.3.2.4 Bus stations

Bus stations in the STCP's network are pretty simple. They consist, mostly, of a simple pole, with indications on the lines that pass by that location.

Figure 35 - Bus stop simple [178]

There are also more complex structures, with benches and timetables, shown in the following image.

Figure 36 - Bus stop with bench [179]

The only possible placement for the beacons in these conditions is the top of the pole (for the simple version) or within the station structure, ideally in the roof. The broadcasting range should be either 7 or 15 meters, in order to allow the passengers' smartphones to have time to detect the station as they get closer and in order for the passengers leaving on a specific station to be detected as well. It is also important that the station signal covers the vehicles that stop there, creating the overlapping that allows the several stations to be detected along the trip.

3.2.3.3 Beacon identification

Beacons within a fleet require a unique set of UUID + Major + Minor. Using the SDK, it is possible to monitor regions defined by wildcards, which means:

- It is possible to detect all regions if specifying no value to UUID, major and minor;
- It is possible to detect all regions of a specific UUID if determining the UUID value and no value for the major and minor;
- It is possible to detect all regions of a specific UUID and Major if specifying those values but setting the Minor as null;
- It is possible to detect a region, defined by a specific beacon, if specifying all the values for UUID, Major and Minor.

As seen previously, there could be situations where two or more beacons are required for the same object (station or vehicle). This means it becomes very important to try to make these beacons be identified as one entity instead of two (because in this scenario one would have to deal with conflicting signals).

The beacon identification should work as follows:

- UUID – the same for the entire network, basically representing both STCP and MP. Estimote guarantees unique UUIDs within all their beacons, meaning no one else can use this UUID when using Estimote beacons [137];
- Major – specifies one unique identity – either a vehicle or a station.
- Minor – specifies additional details (in the case of vehicles it could specifies the line they belong to).

3.2.4 Payment

With such a shift on the way public transportation systems' usage is measured, comes a shift in the payment mode. The goal is to charge the user on the amount of the service used, during a specific time frame. So, the user is only charged after using the PT system. This moves from the current pre-payment approach to a post-payment approach, like seen with the Oyster system.

At a specific time of the day, or week, ideally when the PT system is closed, the ticketing infrastructure, based on the collected information, calculates the amount the user has to pay. At the moment of register on the application, the user should provide an automatic method of payment (bank account, credit card, PayPal) or provide a piece of information that allows the operator to claim any owed amounts. The calculation of the due amount, however, contemplates several factors such as eventual subscriptions (season tickets) that the user might have or extensions of journey made beyond the subscription associated.

3.2.5 Limitations

The presented solution, still presents some problems.

First, the beacon signal could be replicated, making it possible to simulate a station or a vehicle. This could be bypassed using new security features that some manufacturers are implementing, such as Estimote's Secure UUID, that causes periodic changes of the beacon's ID - UUID, major and minor - so that it's broadcasting unpredictable, encrypted values – but requires internet connection for an authorized application to decrypt the data and get the correct beacon identification [180]. An easier solution could be to simply work on the situations that might pose a problem such as an individual trying to spoof the system by introducing several malignant beacons in the transport network, causing interference with native beacons. Some beacon's manufacturers already provide a database of used UUID's, meaning that they can't be used by more than one user. However, unless a common database of manufacturer's is created, someone could use other manufacturer beacons' to bypass this security feature [137].

A second limitation was identified in the previous one: dealing with multiple (conflicting and damaging) beacons' signals. For example, if within a trip (that is already associated to a specific vehicle) the passenger's smartphone starts detecting another vehicle signal, of the same type (bus or metro), while the original one disappears? What if two stations are detected at the same time while the user performs checkin?

Another limitation that could be dangerous is the detection of a trip when a passenger is simply nearby. For example, a passenger that has the application running, and is stuck in traffic behind a bus. In theory, the application should detect this user as going on a trip and charge him. This is a serious limitation that would negatively impact the customer experience and have a detrimental effect on the service adoption, because of the lack of trust. A good solution would be to, based on the user location, stop and start the service automatically or, at least, to have the user manually start and stop the service, although, the later could be considered a checkin/checkout and, therefore, an interaction with the public transportation service, something this project intends to remove. It's also important to note, that a good measure to avoid this is the correct configuration of each beacon, to avoid covering unneeded areas.

Fraud (using without paying) is a one of the bigger limitations, since it already affects current PT services heavily. This solution does not improve this limitation. The best way to solve this limitation is the usage of current methods, namely, fiscalization.

The battery is also an issue. Both for the passenger smartphone and for the beacons. This limitation has a tendency to become less worrying as times go by and battery related technologies improve. One approach would be to customize the beacon hardware: fit the interior of the Estimote beacon (the chip) in a larger case and provide a bigger power source, that can last longer.

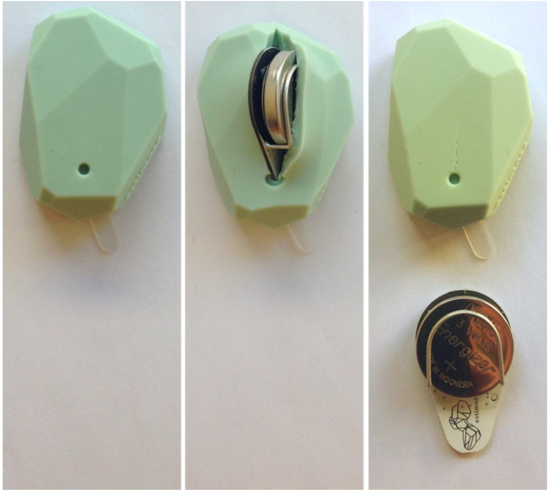


Figure 37 - Estimote beacons' structure [181] Opening beacon to get the actual hardware.

Figure 38 - Estimote beacons' hardware [182] The beacon hardware, with battery unattached.

Chapter 4

Implementation

This section starts by clearly pointing out the major implementation choices, based on the solution possibilities presented in the previous section. Later, it provides the technical implementation details while openly stating the major difficulties with this part of the project. During implementation, additional care was taken to try and reduce the impact of some of the limitations identified earlier; these implementation strategies are also analyzed.

4.1 Beacons' details

The beacons selected for the project were the Estimote beacons based on the comparison in section 2.3.7.2.1. In terms of quality/price relationship, Estimotes were close to Kontakt.io beacons; however, the fact that Estimotes have motion and temperature sensors was the decisive factor. These beacons have a big community of users, large documentation and are regularly updated. Estimote beacons also offer the secure UUID feature (when the decision was made, this was only supported in iOS, but planned for Android) - and the requirement of authentication to edit beacon settings.

It is also important to note that these beacons have a cloud-based platform that allows their management. Any configuration change is synchronized with the beacons when they are in range of a smartphone, with Bluetooth enabled, that has the official application installed and logged in with the account that is associated with the beacon [183, 184].

When the beacons arrived, their initial configuration was registered. As seen before, beacons have set of configured variables such as broadcasting power and advertising interval that have a direct impact on the beacon's battery life and discoverability, but also UUID, Major and Minor values that allow to unequivocally identify them.

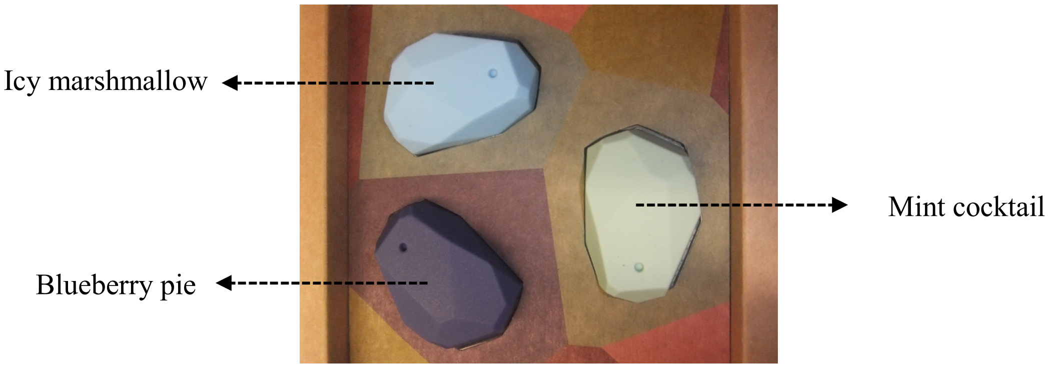


Figure 39 - Estimote beacons bought and used on the project

The beacons arrived with a broadcasting power of -12 dBm (maximum range of approximately 15m) and advertising interval of 950ms. These settings guaranteed an approximate battery life of 36 months, according to the Estimote iOS official application. Basic power mode was off and smart power mode was on. Secure UUID was disabled. The Operating System (OS) version was 2.2.

The default UUID for all beacons was B9407F30-F5F8-466E-AFF9-25556B57FE6D. The *Blueberry pie* beacon came with the major-minor pair of 47945-4540; the *Icy marshmallow* came with the pair 54223-9785 and the *Mint cocktail* with 9881-57199.

Whenever beacons were not used, their broadcasting range was set to the minimum (30 dBm – ~1.5m) and the advertising interval to the maximum (2000 ms). This maximized the batteries on the beacons throughout the project, being the estimated battery life on these settings of approximately 69 months.

All the initial beacon readings and changes were made using the official Estimote iOS configuration application, since it provides more details than the Android counterpart does (because the Android SDK is behind the iOS SDK in terms of development). The Android official application was not able to turn on/off the battery saving modes or read temperature and motion sensors, it did not require authentication to change beacons settings, such as UUID, Major, Minor, broadcasting range and advertising interval; and it didn't allow the activation of secure UUID. Considering that each beacon was registered to a user account, based on their UUID, Major and Minor, changing one of these values on the Android counterpart (which did not save the new settings to the Estimote server) made it so that the beacons would stop being recognized and adjustable on the iOS application. At the same time, since a beacon is unequivocally identified by the UUID, Major and Minor combination, these values have to be set uniquely between the beacon fleet (the application prevents the configuration of beacons with the same combination of values).

During the development, the Android SDK, Estimote's OS and Android's Estimote official application were updated. This brought new features to Android: authentication for changing beacon's settings (making it impossible to change beacon's settings without authentication and, therefore, solving one of the problems identified in section 2.3.7.2.4) and the possibility to enable Secure UUID and its usage with the Android SDK. Despite these updates, the Android SDK still is behind, in terms of development, of the iOS SDK.

The new update also brought new features such as:

- Motion UUID – make the beacon broadcast a different UUID when it is in motion;
- Flip to sleep – having the beacon laying down, rotated 180º, would make it stop broadcasting.

The possible values for the broadcasting range, obtained from the official configuration application, are presented in the following table.

TX POWER (DBM)	MAX DISTANCE (IN M - APPROX.)
-30	1.5
-20	3.5
-16	7
-12	15
-8	30
-4	40
0	50
4	70

Table 2 – Broadcasting ranges available

The beacons configuration and tests readings will be done using the official manufacturer iOS application [183].

4.2 Hardware tests (beacons)

4.2.1 Distance

In order to verify the technology reliability for the scenario considered, the first set of tests compared the real distance (between the beacons and the smartphone) with the estimated distance using the BLE signal.

4.2.1.1 Methodology

Two types of devices were used. An iPhone 5S, loaded with the official iOS Estimote app [183], and a Motorola XT926, loaded with the official Android Estimote app [185] and with the official Estimote demo application for Android [186].

To test this approach an open-space was used: a hall at the Faculty of Engineering of the University of Porto depicted in the following images. The hall is composed by two floors: one at ground level (Figure 41) and one at three meters high (Figure 40).

Figure 40 - Hall overview (first floor)

Figure 41 - Hall overview (ground level)

The main advantage of this location is the open space. It is similar to several bus and metro stations in Porto's PT network (Figure 42).

Figure 42 - Porto São Bento Metro station [187]

The test beacon was placed on the balcony of the first floor, three meters high. The smartphones were used at the normal usage level (about one-meter-high) which makes the height of about 2m.

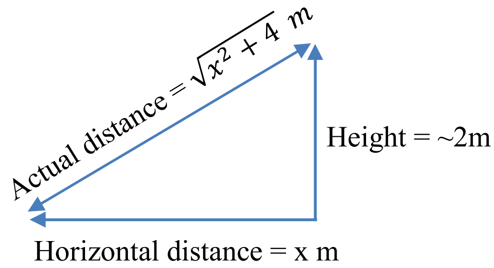
Figure 43 - Beacon placement and height overview

The several points were calculated based on the initial position of the beacon, along the hallway. Each floor square was about 1.2m in length, as such, crossing 10 squares would place one at 12m from the beacon. These measurements were confirmed using Google Maps and by using "reference" points to further get the exact locations to perform the measurements (see Figure 44).

Figure 44 - Test scenario layout [188]

Considering that each beacon is the center of a sphere and that the broadcasting range is the radius of that sphere: to calculate the actual distance of the beacon to a specific point in the hallway, it is necessary to apply the Pythagoras theorem.

The sketch represented below shows the basic calculations done, having in consideration the both dimensions (vertical and horizontal) of distance between the beacon and smartphone.



The tests were done in several different configurations.

For each chosen broadcasting range (7m, 30m and 70m), three advertising intervals were tested 100, 500 and 1000 ms (approximately). Measurements were also taken at the minimum horizontal distance from the beacon (0m), half the max broadcasting range and the max detected distance. So, for example, with the 7m broadcasting range, measurements were obtained directly underneath the beacon (0m horizontal distance, 2m vertical distance, 2m actual distance); at halfway of the beacon maximum range (3.5m horizontal distance, 2m vertical distance, ~4m actual distance) and at the maximum distance where the beacon would still be detected.

In this test, for each advertising interval – broadcasting range combination the estimated battery life remaining, on those settings, obtained using the official iOS Estimote app, was saved.

The data collected for this test is available on Appendix B: Beacon ranging (distance) and battery test results.

4.2.1.2 Results and analysis

The results of both tests are now compiled in graphs and analyzed in this section. The first set of graphs represents the estimated distance versus the real distance in several scenarios, for each platform – Android and iOS.

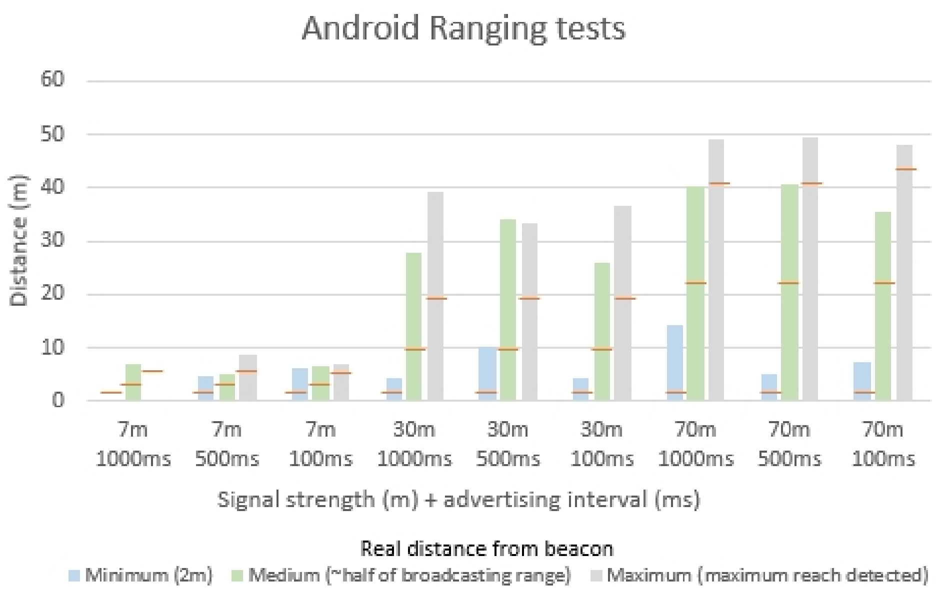


Figure 45 - Android Distance (ranging) results

Each group in the horizontal axis represents a signal strength and an advertising interval. Each bar represents the measured distance (the real distance is displayed as an orange horizontal bar crossing the column).

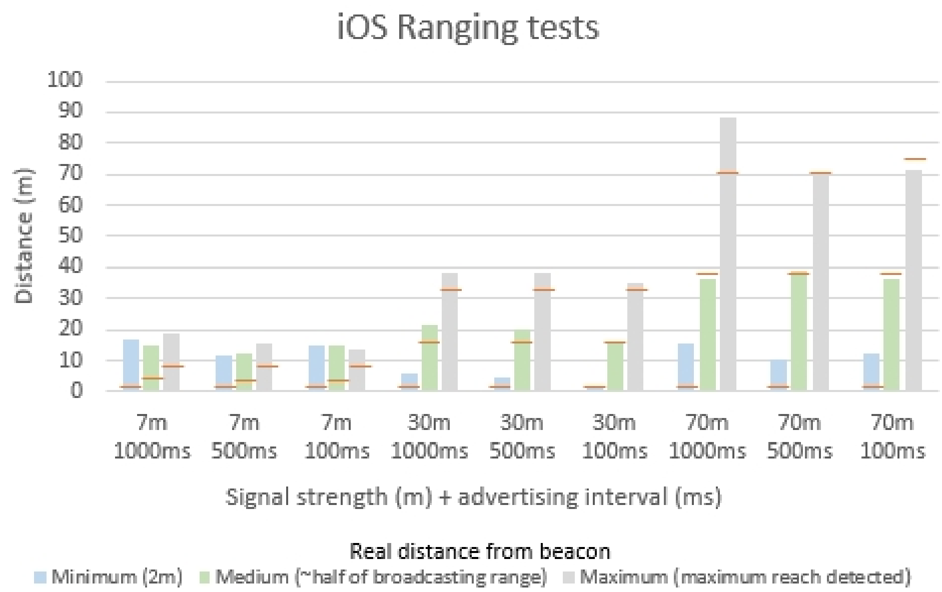


Figure 46 - iOS Distance (ranging) results

Each group in the horizontal axis represents a combination of signal strength and advertising interval. Each bar represents the measured distance (the real distance is displayed as an orange horizontal bar crossing the column).

These results were very irregular and did not accurately provide information, in line with previous tests executed by third parties [127, 128]. When the advertising interval was reduced the estimated distances improved slightly. The broadcasting range reach effect varied: on the 7m and 30m configurations, the signal was still detected slightly over that theoretical maximum (although the distance estimates were still not consistent or close to reality). However, when testing the 70m broadcasting range, the iOS counterpart detected the signal close to that limit, but the Android reading stopped at, about, 45m from the beacon.

4.2.2 Detection times

The second test executed measured the average time it takes for a smartphone to detect entering and exiting a region.

4.2.2.1 Methodology

In this case, the broadcasting range of the beacon was kept constant. However, the advertising interval of the beacon was changed (1000ms, 500ms and 100ms). The scanning and sleeping time of the smartphone application also varied from sleeping 20 seconds to sleeping 10 seconds and from scanning 5 seconds to scanning 1 second. Initial tests to determine what values would be best suited for testing showed that scanning periods inferior to 1s were not reliable (no beacon detection). This test was only conducted on Android, due to iOS licensing limitations. The beacon was kept at a fixed location. The smartphone would then be shifted from a position where it was inside the beacon region to a position where it was outside and vice-versa. The Android demo Estimote application has a module that shows, on screen, when the smartphone enters or leaves a selected beacon's region. A stopwatch was used to start counting the time, when the smartphone was being moved and to stop the time when there was a change in the application. The data collected for this test is available on Appendix C: Beacon monitoring test results (elapsed time for exit/entry detection).

4.2.2.2 Results and analysis

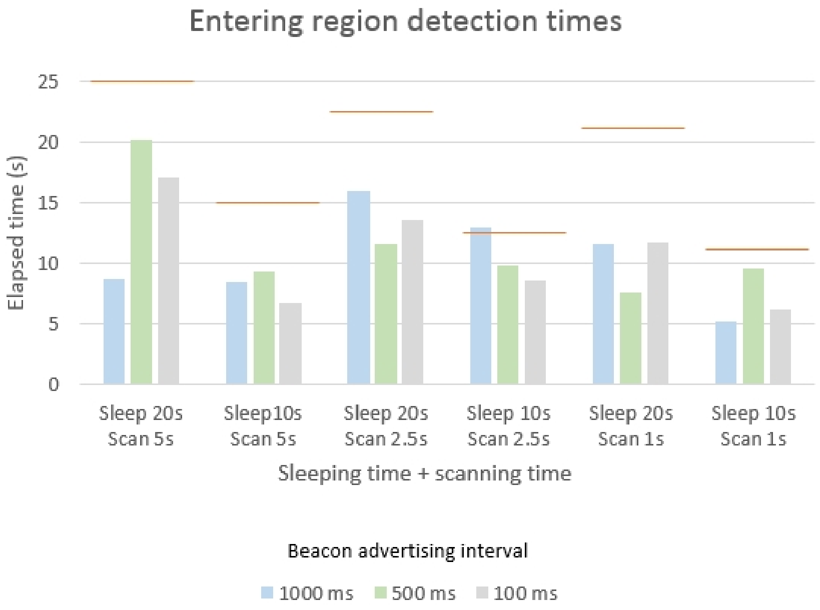


Figure 47 - Entering region detection times

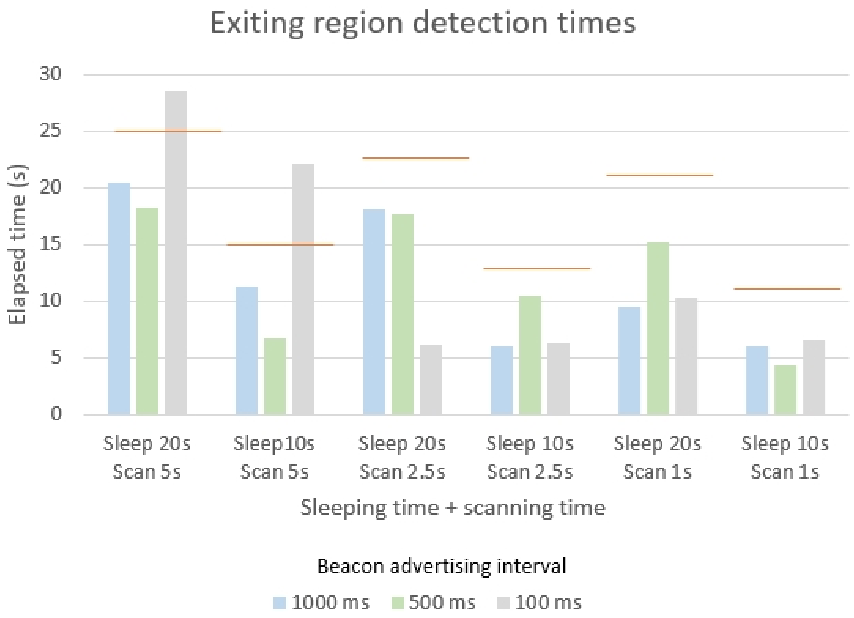


Figure 48 - Exiting region detection times

Each group of bars represents a scenario and each bar within that group represents the beacon advertising interval. The bar value is the time that it took for the entrance/exit to be detected, being the orange horizontal line the theoretical maximum value for that scenario [134].

These test results showed accurate zone detections, with several sleeping times and beacon advertising interval combinations: the maximum time it should take to detect an entrance/exit is the sleeping time + scanning time (represented as orange lines in the graphs). This theory was confirmed with the exception of three cases, two of them in the exiting test.

One should note that that scanning times inferior to 1s did not work reliably (no beacons were detected) and therefore, no test with a scanning interval inferior to 1 second was provided. It was also possible to observe that the scanning time should be greater than the beacon advertising interval to assure the maximum reliability.

It's also important to note that the response times for the detection of a region exit were worse.

4.2.3 Beacon battery life

4.2.3.1 Methodology

To obtain the values for the battery life of the beacons, an estimate was obtained from the iOS official Estimote application, for each broadcasting range and advertising interval considered in the Distance tests.

4.2.3.2 Results and analysis

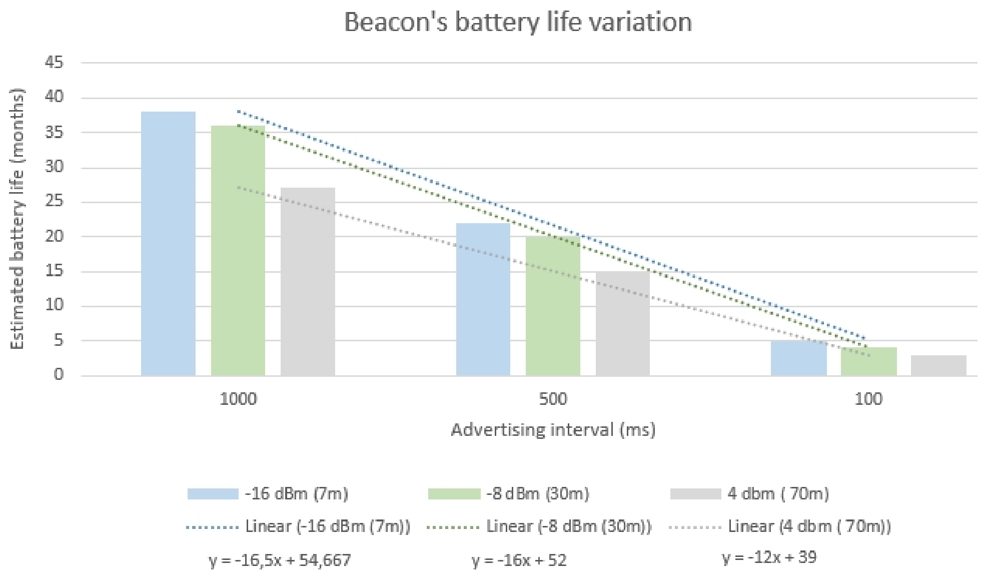


Figure 49 - Battery life estimates results

Each bar color represents a broadcasting range. Each group of bars represent an advertising interval. The column value is the battery life estimate in months for that specific set of characteristics.

In terms of battery life variation, the premise that higher advertising intervals (more frequent) and higher broadcasting ranges consume more power is true. The lowest battery estimate happens in an advertising interval of 100ms and the maximum broadcasting range. The rate at which the battery decreases less, when increasing advertising rate, is with a broadcasting range of 4 dBm.

4.3 Setup

The main approach to follow will be the deployment of beacons on both vehicles and stations. This proved to be the approach that assured more reliability for the entire system, even though being the most expensive.

Considering the test results on the previous section, some variables were defined for the development of prototypes.

The advertising interval of the beacons should be set to 500ms, since this value is good enough to assure a good reliability for the solution and a decent battery life for the beacons (from 15 to 22 months, according to the measurements – section 4.2.3 - Beacon battery life).

The scanning time, for the developed application, will be set to 1s and the sleeping time to 5s. This should assure, according to the results of the previous section, that the maximum time it will take to detect the entrance and exit of a region is 6s.

There are limitations in terms of hardware: there are only three beacons available, one that will represent a vehicle and the other two representing stations (starting point and exit point).

The value assignment strategy, uses the following values:

- UUIID: 64878A58–E456–4D5D—B472-16CDAABD392F - Estimote guarantees unique UUIDs within all their beacons, meaning no one else can use this UUID when using Estimote beacons [137];
- Major: partitioning to identify each vehicle and station type. A major between:
    - 10001 and 19999 - represents a MP's vehicle;
    - 20001 and 29999 – represents a STCP's vehicle;
    - 30001 and 39999 – represents a MP's station/stop;
    - 40001 and 49999 – represents a STCP's station/stop.

  The presented ranges allow to accommodate for each operators' infrastructure, even reserving space for new additions. The first digit allows to identify the type of vehicle or station while the remained four digits (sequential ID) allow to identify the vehicle or station number in the given type.
- Minor: can be used to obtain further information. In this specific case the minor is only assigned in a vehicle, to specify the line (if a vehicle does several lines, the driver would have to edit the beacon information when changing the bus heading).

For example: UUID: 64878A58–E456–4D5D—B472-16CDAABD392F; Major: 10001; Minor: * - Represents the regions defined by the vehicle 0001 of Metro do Porto. If the vehicle had more than one beacon (because it is composed), using this set of values would still identify all the beacons (since the last, most specifying element was still being ignored).

Testing vehicle and station conflicts became extremely difficult since it requires constant changing of beacon values. This means the focus was on providing a prototype that works under these restrictions, while planning and developing the actions to do in the extreme cases that can't be tested as thoroughly.

Android was chosen, for the development of the tracking application, because it has a big share of the market, because it does not require expensive hardware or licenses and because the developer is already familiar with the tools and technologies required for this platform. Besides these reasons, Android has the capability of creation of different types of components. The two most relevant here are Activities and Services. An activity "represents a single screen with a user interface" [189] while a service "is a component that runs in the background to perform long-running operations or to perform work for remote processes", not providing a user interface [189]. Since this project's goal is to remove most of the interaction with the user, and considering that having an interface is a form of interaction, the usage of services could be an approach to follow, considering it even allows users to use other features of the smartphone at the same time. This Android "feature" is not so easily replicable in iOS [190].

iOS limits the number of regions that can be monitored to 20 [136]. This is a big limitation, considering knowing which vehicles or stations, in specific, are in the vicinities of the passenger could be required to determine the complete, correct, course. Android allows the monitoring of an endless amount of regions.

The sleep/wait and scanning times values can be changed in Android, but in iOS probing for beacons occurs each second, and this is not adjustable [135].

The platform for development is Android Studio and a source control system will be used, to track changes and evolution of the code base.

The Android version required for the project is also subject to restrictions. Versions of Android inferior to 4.3 do not have Bluetooth Low Energy support [191], therefore, they will not be supported on this implementation.

4.4 High-level architecture

In order to comprehend the architecture behind the followed implementation, a deployment diagram, clearly displaying, how and where the system is deployed, is now presented and analyzed. Please note the similarities to Figure 14 that shows the solution proposal architecture.

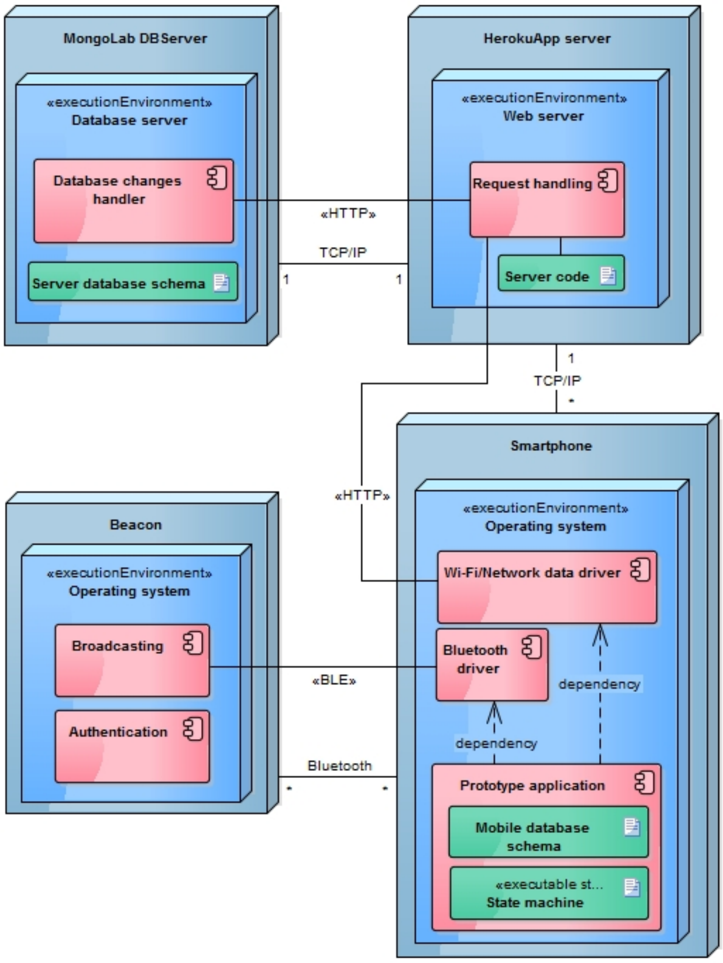


Figure 50 - Deployment diagram

This deployment diagram includes all the devices (dull blue boxes) that compose the system that was implemented:

- the database host – MongoLab [192];
- the server application host – HerokuApp [193];
- the smartphone;
- the beacon.

Each of these devices has an execution environment (bright blue boxes), the part responsible for the execution of software.

In the case of MongoLab it includes the database schema artifact (code that defines the data structure) and the database changes handler component, responsible for the read, write, update and delete operations in the database.

The HerokuApp's server execution environment contains the "request handling" component, that uses the "server code" artifact. The request handling component contains the methods that are made available for clients (the mobile application) to interact with the server.

The smartphone's execution environment is the operating system (in the particular case of this project, Android) which contains the Bluetooth drivers, Wi-Fi and Network Data drivers and the mobile application (the operating system contains more components, but only the relevant ones for this project are represented). This last component includes the mobile database schema artifact and a state machine (in practice, the developed code) while also depending on the Bluetooth drivers, for the beacon interaction, and the Wi-Fi/network data drivers for the connection to the internet and communication with the server.

The beacons' execution environment is the provided manufacturer operating system, that provides the basic functionalities for interacting with the beacons (broadcasting component and authentication component are mere examples of two possible components within this operating system).

The communication between the beacons and the smartphone is made using the Bluetooth technology, specifically BLE.

The communication between the remaining devices is made using TCP/IP which is, in essence, a stack that contains the communication protocols in which the Internet is based on. The specific protocol, within TCP/IP, being used is Hypertext Transfer Protocol (HTTP), a protocol oriented to request-response and suited for client-server communications.

4.5 Data models

4.5.1 Server

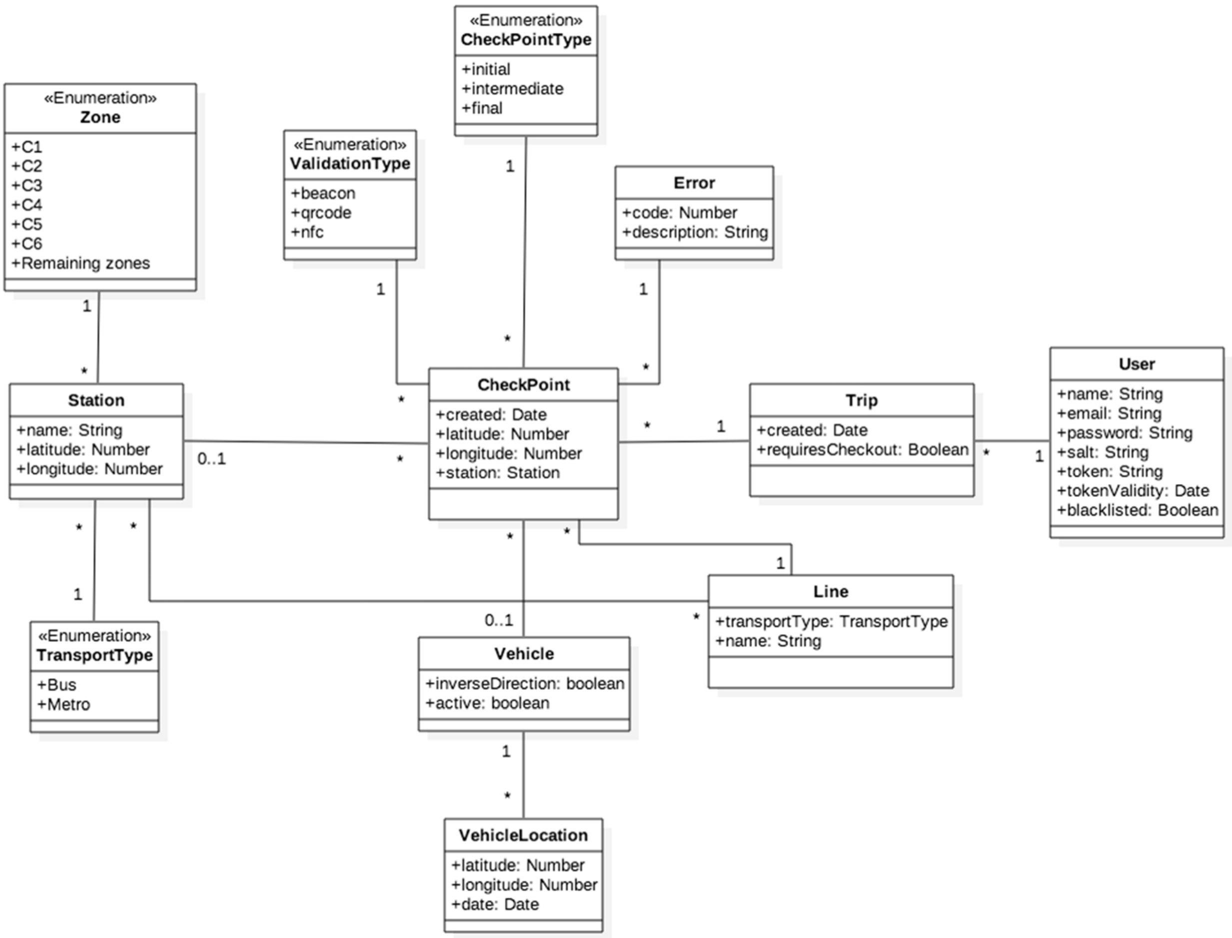


Figure 51 - Server data model

The data model for the server was designed in the most general way possible with the goal of working with a wide variety of validation types. This means that using beacons is irrelevant in the context of the data model; what matters is the information that has to be provided. As such, this data model was developed in cooperation with another MSc dissertation, also in the context of the Seamless Mobility project [194]. The difference between both thesis is the validation methods used.

The core of the entire model is the checkpoint. Checkpoints, ideally, one for the checkin and other for checkout, allow to determine the origin and destination of the user (composing a trip) and charge him based on that. A checkpoint is composed of several different components: the station where the validation occurred; the trip to which the checkpoint belongs; the type of validation (could be ignored, but was introduced to provide statistical information) and the type of checkpoint - could be checkin or checkout.

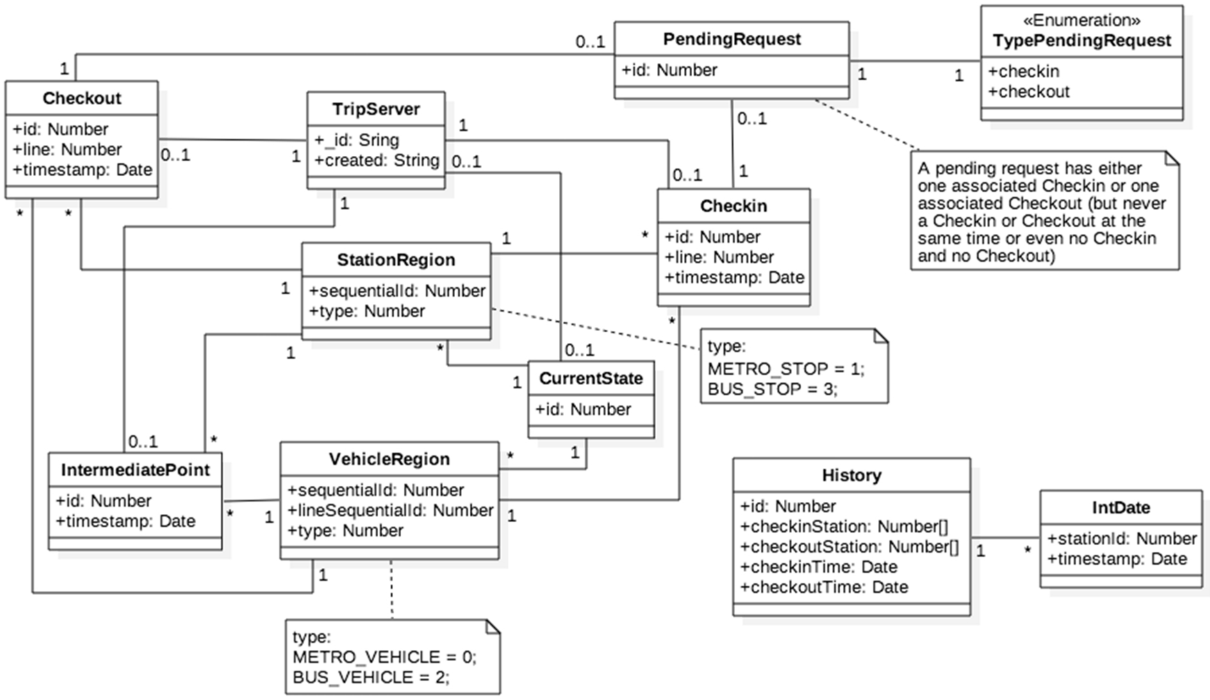


Figure 52 - Mobile application data model

4.5.2 Android

The data model for the mobile application envisioned, initially, the download of the complete information of stations, vehicles and lines. That proved to be an intensive task, especially when the application should start and be ready to work fast, given the public transportation context where it is meant to be used. As such, station, vehicle and lines' information is obtained on runtime, when needed – the sequential ID's are used to obtain the vehicle/station information from the server, considering that each vehicle and station have a unique sequential ID. It is also important to note that the application doesn't require the information it can get from the server to work, however, being able to obtain information from the server provides a more customized experience to the user.

At any time, the operation has a specific state, saved in the table CurrentState. The current state represents the current situation where the user is inserted (e.g. boarded, almost boarding), vehicles and stations that are in range and the ongoing trip (if any). The StationRegion and VehicleRegion tables are used to represent stations and vehicles that can be part of an intermediate point of the trip, a checkin or a checkout. The TripServer table represents a single trip, composed of a checkin, checkout and intermediate points. The pending request table stores any information that cannot be communicated to the server (either a checkin or a checkout).

The history table saves all trips information locally: it stores each trips' checkin, checkout and intermediate points. The server does not save intermediate points, as such, the user has access to his previous trips' intermediate points thanks to this table.

4.6 Server

This server was developed in cooperation with another MSc dissertation, also in the context of the Seamless Mobility project [194]. The difference between both thesis is the validation methods used.

To develop the server several choices had to be made.

The database was modeled using MongoDB, a NoSQL approach to designing databases. NoSQL means that the database was not modeled using SQL code and unlike SQL databases, that require the determination and declaration of a table's schema before inserting data, MondoDB's collections don't enforce document structure. MongoDB provides a more flexible data model, more scalability and better search possibilities [195]. After choosing this technology, the server chosen to host this database was MongoLab [192].

To develop the server, the framework Mean.js was used, being JavaScript the core language. It includes several technologies useful for the development of robust and scalable solutions.

The server provides authentication and authorization methods; reading methods to obtain information and methods to send information to the server.

The authentication methods allow a user to register and login, by providing an email and password. Considering that this project is a prototype no further information was required from the user. After logging in, the response includes an authentication token that has to be included in every request that the user performs, guaranteeing authorization. This token expires after a specific timeframe and is renewed every time the user authenticates.

The reading/consulting information methods allow to get a list of the stations, vehicles and lines or to get the information for a specific station, vehicle or line if providing an ID.

The methods for writing allow to request the creation of a checkpoint, which returns the checkpoints created and the associated trip.

The server also implements the determination of the user's closest station if coordinates are specified in the checkin or checkout requests.

4.7 Mobile application

To develop the mobile application, the software that allows to interact with the Estimote beacons was used – Estimote SDK. This software allows to detect when entering or leaving an Estimote beacon defined region.

Realm.io is a replacement for SQLite (the common solution for databases in mobile applications). Its main advantages are the ease of use, the fact that it is cross-platform, the speed and increasing support [196]. A big advantage is that database records can be manipulated as if they are high-level entities (objects) making it easier to perform the most common operations (create, read, update and delete).

The application developed consists of a main interface and a companion service. The companion service is responsible for detecting the passenger course (by determining entering and exiting beacon defined regions) and communicating with the server, allowing the passenger to perform other activities in the smartphone. The main interface allows the passenger to check ongoing and completed trips.

The basic interaction with the beacons is the detection of entrance and exit of a beacons' vicinity. As such, the initial approach was to design a mapping of all possible states where the application could be. It became evident that the ideal structure for a system like this is a state machine, represented in Figure 53.

Each state transition results from the entrance of a beacon vicinity, the exit of a beacon vicinity or the lack of state change for a long period of time. The states considered are divided in six major groups:

- Not boarded (NB) – represents all the states where the user is in range of beacons but it can't be concluded that he is trying to board;
- Possibly boarded (PB) – contains all the states that have all indications of a possible boarding by the user – cases in which the user is both in range of a vehicle and a station;
- Possibly boarded phase 2 (PB2) – embodies the states that would naturally follow a boarding stage (the case where the stations stop being detected, but the vehicle detected first in the previous stage still is – departure);
- Boarded (B) – symbolizes the set of states that follow a possible boarding, basically all the stops detected after the PB station(s);
- Possibly unboarded (PU) – contains the states that represent a possible exit from the vehicle, in a new station different that the checkin station;
- Checkout – after the verifications done on the PU states, actions are taken to communicate the checkout information to the server (or to save it locally if no internet is available) and to reset to the initial scanning state.

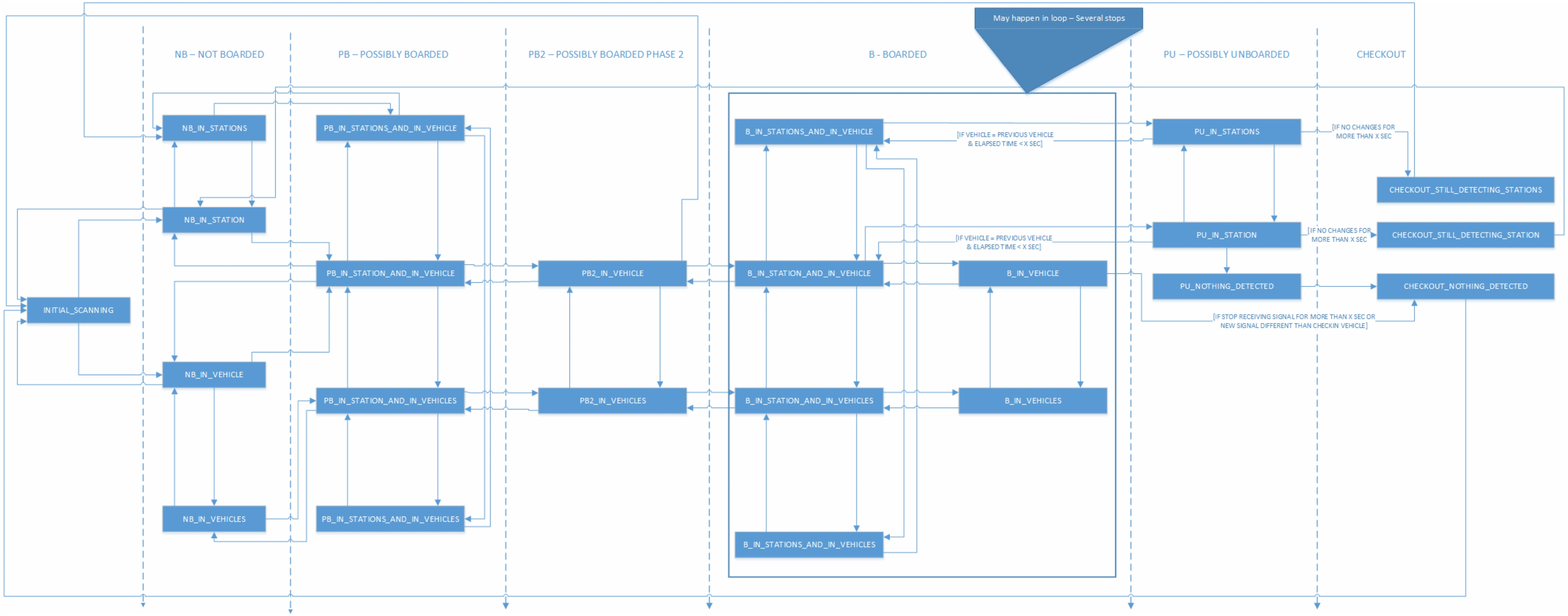


Figure 53 - Android State Machine

The entire process starts in the initial scanning state, where no vehicles or stations are detected. From this state the user can enter the vicinity of either a vehicle or a station, going to the respective states NB_IN_VEHICLE and NB_IN_STATION. If the user is in the vicinity of more than one unit of the same type, a transition occurs to either NB_IN_VEHICLES or NB_IN_STATIONS. When both types are detected (a vehicle and a station) the initial conditions for a boarding situation are met. As such, the user is on the PB set of states. These states represent a possible boarding situation but they can’t assure an actual ongoing trip (since a person can pass by a station and a vehicle without any intention to use the service). After the PB (probable boarding) states, the natural sequence for someone that is using the service is to leave a station while staying in a vehicle. This, again, can happen frequently if the user is not boarding, as such, this step is considered a second hint to an actual boarding (PB2 set of states). Naturally, the user should then stop at new stations (different from previous ones), and stay in the same vehicle (hence the loop present in the states composing the Boarded (B) stage). The fact that the user stops at a different station, while being in the original vehicle vicinity is considered enough evidence to consider this a usage of the service and to register a checkin (with the PB state station). When the signal vehicle is lost, and the user is still in the vicinity of a station, the possibility of an unboarding is considered - Possible Unboarding (PU). If a signal of the same vehicle is detected in a timeframe inferior to a specific number of seconds, the previous state is returned (the vehicle signal was momentarily lost). If, after being in a possible unboarding state, the user leaves the remaining station(s) the checkout event occurs. If the station is still detected after a specific timeframe the checkout is also considered (a good example of this situation is when the user switches transport at a specific station).

This complex state machine can be better understood when looking at Appendix A: Execution, which includes a graphical representation of an entire journey, with each state properly identified.

4.7.1 Features

The solution comprises of a complete set of features, presented here in order of priority:

- Detection of entrance and exit of beacon’s regions;
- Detection of checkins and checkouts, based on the articulation of several beacons detection (implementation of the state machine);
- Handling of abnormal situations (conflicts of signals, timeouts, Bluetooth deactivation or service deactivation in the middle of a trip);
- Offline registration of checkins and checkouts;
- Login and registration on the server;
- Communication of checkins and checkouts with the server;
- Synchronization of offline checkins/checkouts with the server;
- Notification system for specific, important states (checkin and checkout);

- Listing of all the trips done by the user;
- Local storage of intermediate stops;
- User interface that correctly shows the passenger the current state of the trip;
- Obtain station/vehicle information on runtime;
- Complement trip listing information with intermediate stops (if any exist locally, since the server does not accept intermediate stops) and type of ticket being used;
- Implement the possibility of changing the sleeping/waiting and scanning time while the app is running.

4.7.1.1 Solving limitations

In the previous chapter, when the solution was proposed, a set of limitations were identified. After being identified, the implementation steps had an extra attention payed to those limitations in order to identify possibilities for their removal or impact reduction.

Considering the first limitation, the replication of beacons and disturbance causing on the beacon network, there were several measures implemented:

- A simple approach for abnormal beacon detection is the usage of the user coordinates, on the checkin/checkout requests. This makes it so the server automatically assumes the closest station to those coordinates, disregarding the disruptive beacon signal;
- Estimote beacons brought a new feature, Motion UUID, that broadcasts a different UUID, Major and Minor when the beacon moves – this would make it harder to create a beacon that could disrupt the network, and would allow further development of the solution. This was not explored further since it was only introduced in an advanced stage of the development.

When handling the second limitation, which involves dealing with abnormal situations, such as conflicting vehicle signals, conflicting station signals or disappearing signals, a lot of attention was provided:

- If the user is not on a trip (no checkin made yet) and is in range of several stations, when he is about to leave the station after boarding a vehicle, he will detect the exiting of all the stations. The last station he exits from, if from the same vehicle type (metro or bus), will be the considered as the checkin station. Further improvement could have been made, by using the coordinates approach.
- If the user is not on a trip, and is in range of a station and several vehicles, the one that is considered as the checkin vehicle when the user leaves the station is the one that keeps the signal;

- When crossing several vehicles, in a trip, any vehicle that is not of the same type as the checkin station and vehicle (either bus or metro) or not equal to the vehicle associated to the checkin is ignored.

The third identified limitation, that contemplated the possibility of users being wrongfully charged, when simply passing by specific locations was not completely solved with this implementation. The best approaches would be the ones proposed in the original section: location based sensing and correct specification of beacon's broadcasting ranges.

Finally, the battery related limitations regarding the smartphone are solved by changing the waiting/sleeping time dynamically; when not in a trip, the sleeping/waiting times increase, making it so that the verifications happen less often and more battery is conserved. When the application detects an intention to use the PT service, the sleeping/waiting time is increased.

4.7.2 User interface

Although the user interface (UI) was not the main focus of this solution, it was also carefully developed and is now analyzed. It also helps comprehend the flow of the machine state.

When developing the UI, the most recent design guidelines in Android were used (sidebar, colors on main system bars, clash of colors, animations), having in consideration the compatibility with older devices.

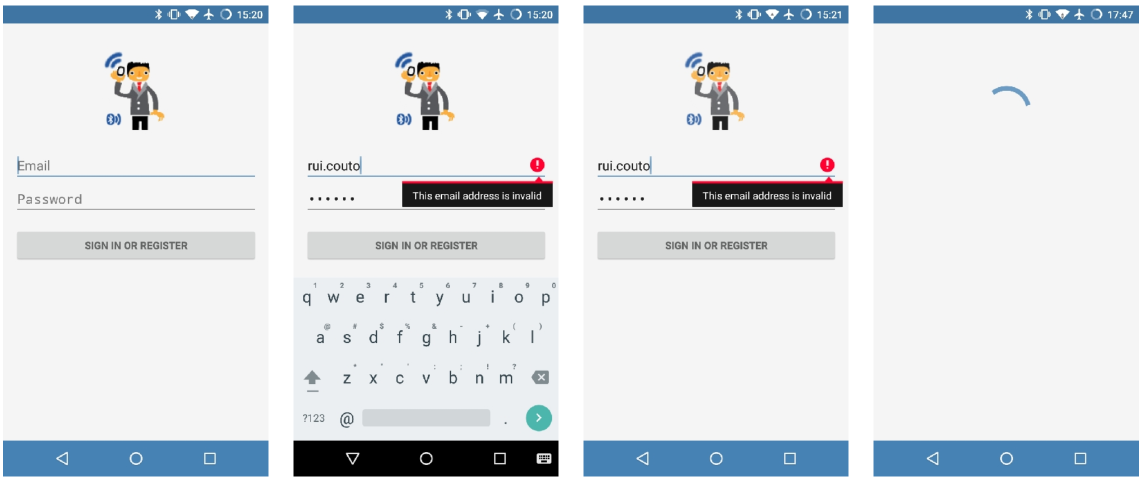


Figure 54 - Login UI

The login UI tried to automatically transmit to the user the identity of the application, the symbol of the supposed passenger, holding a phone that has blue waves coming out of it, that are associated with the Bluetooth icon. This interface changes to display errors and lengthy operations.

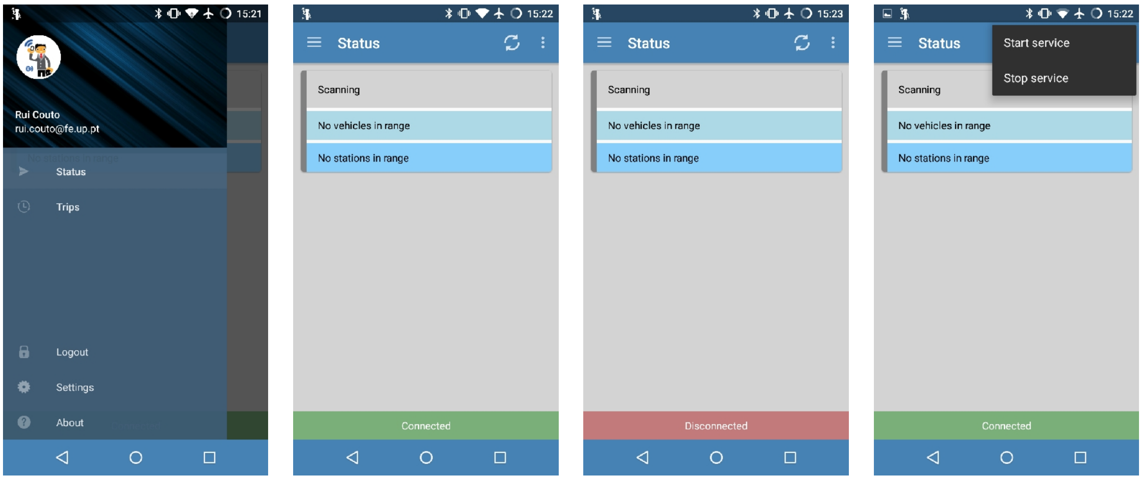


Figure 55 - Main UI

When opening the application, the sidebar is shown, presenting the user identification and the several options available to him. Selecting an option or sliding the sidebar to the left hides it. The main interface shows a card, with the information regarding the current state (including the vehicles and stations that are in range). In the bottom of the application a bar, either green or red, is shown, that presents, at any time the mode the application is working on (either connected to the internet or disconnected).

The top application bar shows the current fragment the user is viewing, in this case, “Status”. Also on that bar, to the left there is an icon that opens the sidebar. To the right, there are two debugging icons: the sync icon (that triggers the tasks responsible for synchronizing offline information) and the additional options item that provides a way to manually start and stop the service.

Figure 56 - Service notifications

As seen in previous sections, the application creates a service to perform the monitoring. This service creates several interfaces. First, there is a persistent icon on the Android top bar, where the time is displayed. Dragging down this bar, shows the name of the application and the current status. If clicked, the application main interface opens. The lock screen also shows the application information at any time, making the user able to check the application information without unlocking the smartphone.

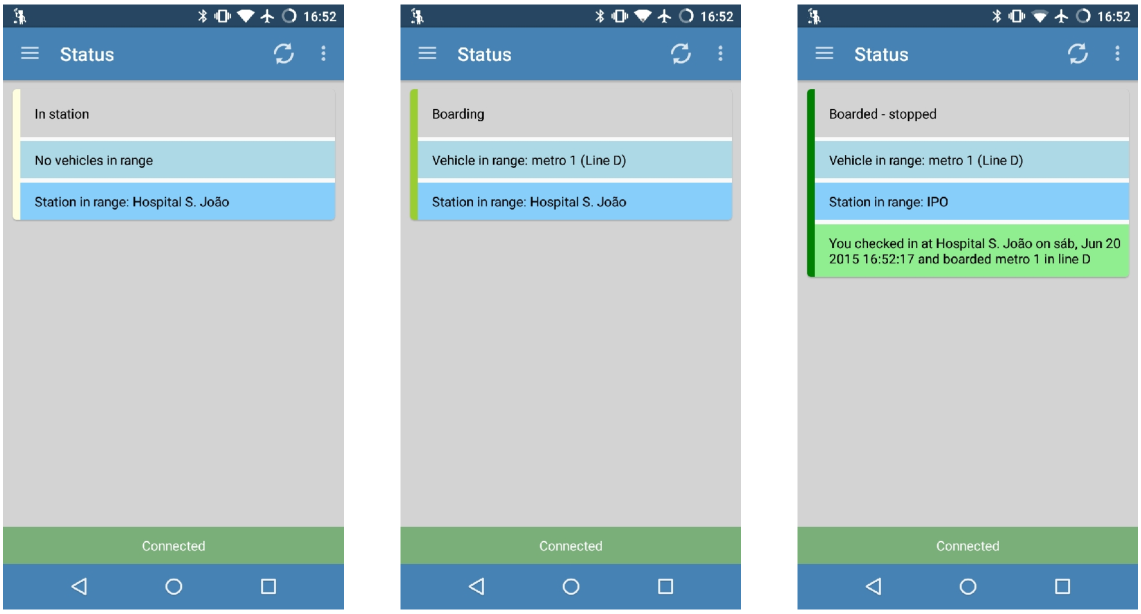


Figure 57 - Ongoing trip interface changes

The card shows the complete information regarding any ongoing trip. The left border of the card changes in color depending on the evolution through the state machine. The red color is used when there is an issue.

Figure 58 - State color variation

To completely understand the evolution of the interface, Appendix A: Execution shows the set of interfaces that comprise a metro trip from *Hospital S. João* to *São Bento*. The times presented are wrong, since this was a lab created trip. This should be analyzed together with the state machine presented previously.

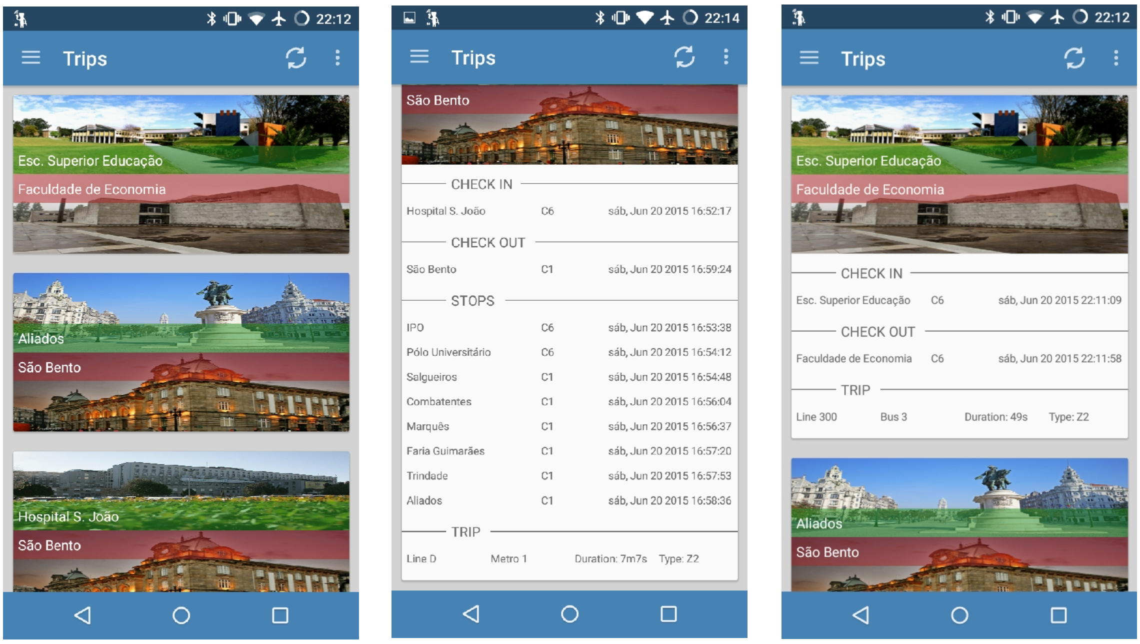


Figure 59 - Trips UI

If the user selects “Trips” on the sidebar, a new window is created, displaying a list of the completed trips by the user; each trip displays an image allusive to the checkin station (green) and the checkout station (red). Selecting a trip expands the box, providing further details for the trip, such as the zones of the checkin and checkout station, the intermediate stops (if they are saved locally), the line used, time duration, ticket type required and vehicle.

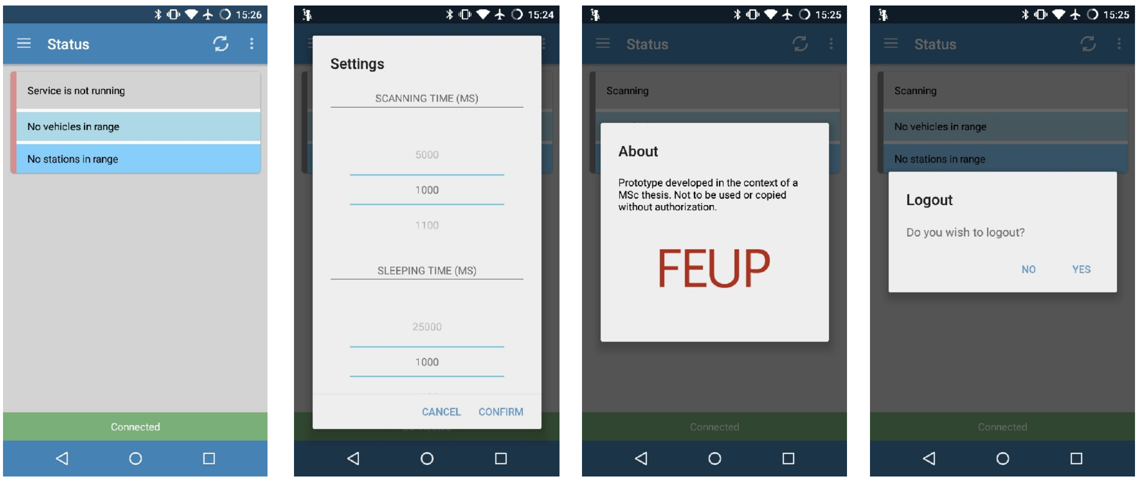


Figure 60 - Other user interfaces

When the service is not running, the main application interface also shows that information.

Selecting settings, in the sidebar, allows, for debug purposes, to change the scanning time and the sleeping/waiting times. The interface is a popup that comes over the current main activity. The about option brings up a popup as well, providing copyright information. The logout option allows the user to return to the login menu. The user has to confirm his intents.

4.8 Difficulties

The major difficulties when implementing this solution were the assurance that all offline data was correctly synchronized with the server. This meant that a series of strategies had to be put in place in order to deal with:

- The user performs the entire journey with an internet connection;
- The user performs the checkin with a network connection but later in the trip loses this connection;
- The user performs the checkin while offline, but later on establishes internet connection;
- The user performs the entire journey while offline.

The strategy followed, for each case was the following:

- Automatically communicate the checkin and checkout to the server when they occur;
- Communicate the checkin, obtain the generated trip information and use it for the remaining of the trip. Add the checkout to the database table that stores pending requests and implement code that detects changes in network connection and automatically tries to regulate pending requests when they exist and an internet connection is established;
- Generate an "offline trip", with a custom ID that clearly represents a trip that was created locally. Use a task to try to communicate the checkin to the server when a network connection happens; if the checkin is not communicated until the checkout happens, associate the checkout to the local trip and when the checkin is communicated update the locally generated information with the information from the server and then communicate the checkout; if the checkin is communicated to the server update every information associated to the generated local trip with the information obtained from the server.
- Communicate the checkin as soon as an internet connection is detected and update the information that exists locally with the information obtained from the server and then communicate the checkout.

The synchronization of the offline information lead to another problem which was concurrency (multiple attempts from different parties to access and manipulate a resource) between threads over the database. This was solved by having threads execute in the order they were started.

Chapter 5

Field tests

Considering the selected solution approach, including the beacon's choice, it became necessary to test the solution in order to draw conclusions on how well the it solved the problem initially presented.

5.1 Methodology

Using STCP's services, a bus trip was scheduled with a set of users to test the developed solution. The bus trip was scheduled between two close stations in the STCP network. The course is represented in the image below, being the topmost reference point the first stop (*Escola Superior de Educação* – of the same type as seen in Figure 36) and the bottom most point, with a red marker, the second station (*Faculdade de Economia* – of the same type as seen in Figure 35).

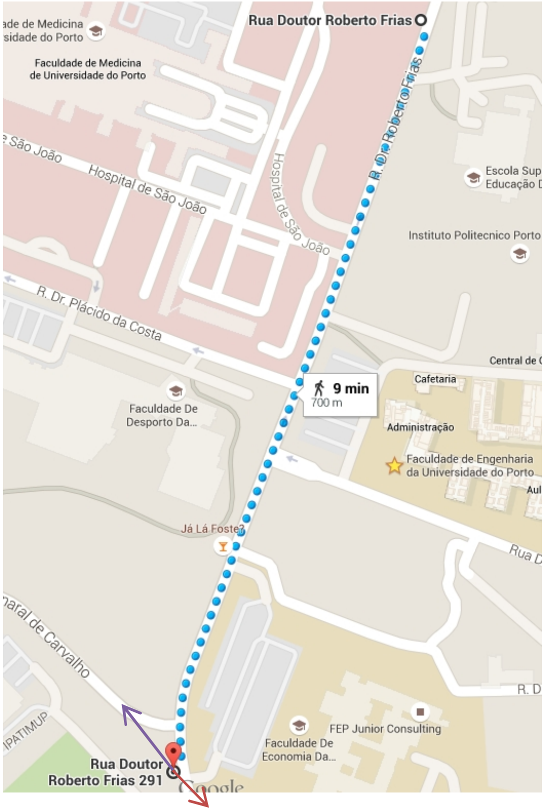


Figure 61 - Test course 1 [197]

The line that was used was line 300, connecting the stations *Circular Hospital de S. João* and *Aliados* [197]. This line's vehicles are 12m long.

A total of seven testers were selected to be part of the experiment, a sufficient number considering that Nielsen indicates that 5 testers are enough to discover most usability problems [198, 199]. The only restraint in their selection was the type of smartphone they would use. As seen in previous sections, Bluetooth Low Energy is a recent technology, that is only supported in Android versions superior or equal to 4.3, being this a decisive factor in the selection. After selection they were given precise instructions on how to perform the test (summarily: install the application, login, start the application when instructed) and were asked to fill in surveys before (Appendix C: Survey A – Before live test) and after the tests (Appendix D: Survey B – After live test) were executed. Their applications were configured for a scanning time of 1s and a sleeping/waiting time of 5s. They were also configured to write a file, in the phone's local storage, every time a new vehicle or station was detected or stopped being detected (every time there was a state change in the state machine). The log file also kept the user's login e-mail (which allowed for identification), the mobile phone model and the software (Android) version. These log files were collected once the test was complete. The test could be conducted online or offline; the internet connection was not a relevant factor (because the logs kept the information) and because it would make the selection process harder (since many people may not have mobile network data plans).

The beacons were set with an advertising interval of 500ms and a broadcasting range of 15m. As seen in section 3.2.3 - Beacon deployment, this broadcasting range could be considered as a waste for a 12m long vehicle, but it wasn't possible, in the course of this work, to perform measurement tests with STCP's vehicles and the beacons. As such, and considering that this solution relies on the fact that the station and vehicle signals overlap when a bus stops at a station, the safe approach was used, having a higher broadcasting range. Each beacon was also assigned a third-party keeper to assure the beacons were safe and to move them when needed.

The process was pretty straight-forward: the testers arrived at the departure station, waited for a bus of the specific line, boarded, conducted the trip until the destination station and then proceeded to unboard. After this they walked away from the destination station until the beacon signal was no longer detected (purple arrow in Figure 61). Considering that the vehicle's beacon could not continue the trip in the bus, it also was removed at the destination station, but it left the station in the opposite direction the tester's left and in the same direction as the bus, in faster pace (red arrow in Figure 61).

Figure 62 - Test execution

After this, the test was continued in a more controlled environment. The origin destination beacon was brought by its keeper to a closer location from where the testers were left in the previous step (without changing any settings).

The goal was to conduct the same trip, walking back, from the destination station, having the bus beacon keeper accompany the testers simulating a bus.

The testers went back to the destination station, where the vehicle beacon was already waiting. Then, the testers and the beacon walked the course in the following image:

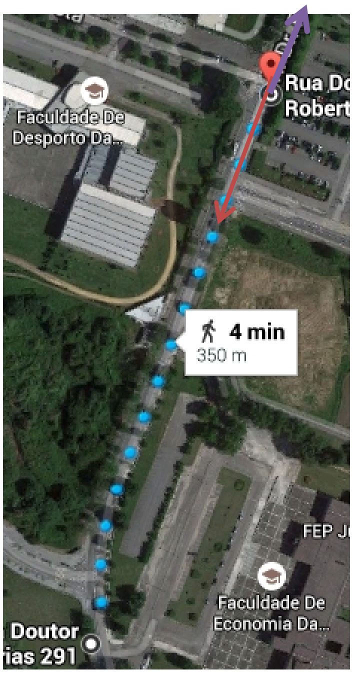


Figure 63 - Test course 2 [200]

After arriving at the destination point, marked with the orange marker, and considered to be the station *Escola Superior de Educação* (since the beacon was moved, but its settings weren't changed), the bus vehicle beacon keeper went back (red arrow in Figure 63), while the testers kept walking forward away from any station or vehicle signals (purple arrow in Figure 63).

In the end of this experiment, the application was stopped, everyone involved grouped back, the logs were collected, the surveys (to be answered after the test) were given to the testers and a small discussion occurred between the people involved.

5.2 Results and analysis

The selected testers had the following hardware:

Tester ID	*OS Version – API version*	*Phone maker and model*
Tester 1	5.1.1 – 22	Motorola XT926
Tester 2	4.4.4 – 19	Samsung Galaxy S3 4G GT-I9305
Tester 3	5.1.1 – 22	Google Nexus 5
Tester 4	5.0.0 – 21	Samsung Galaxy S5
Tester 5	4.3.0 – 18	Samsung Galaxy S3
Tester 6	4.4.2 – 19	Elephone P3000S
Tester 7	4.3.0 – 18	Samsung Galaxy S3

Table 3 - Tester's equipment

The results comprehend several sources:

- The results of the surveys;
- The collected logs – available in Appendix G: Field test's logs, with the user identification removed for privacy reasons;
- The discussion that happened after the test was complete;
- The observations made by the beacon's keepers regarding the testers attitude throughout the test.

The surveys' results made prior to the test Appendix D: Survey A – results) have the following distribution of results:

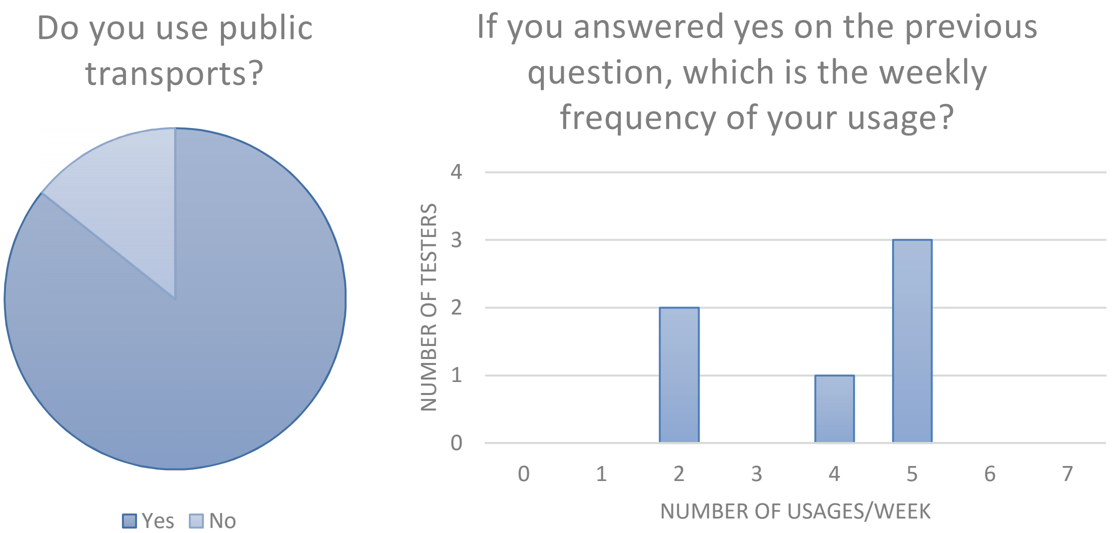


Figure 64 - Before field test survey - Questions 1 and 2 graphics

These results indicate that only one user does not use public transports, while two others use it with a low frequency and the remaining use it very frequently.

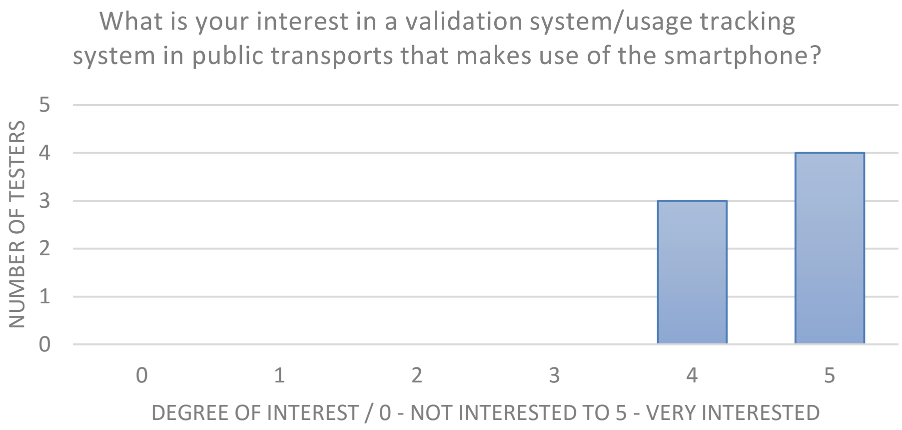


Figure 65 - Before field test survey – Question 4 graphic

All of the testers are interested in being offered a validation/usage registering system that makes use of the smartphone.

The criticism made to the current ticketing systems (obtained from the third, open, answer - Do you identify any ticketing problems in the public transportation systems you use? If yes, what are those problems?) is aligned with the disadvantages presented in section 2.1 - Public transportation services today:

- It can be hard to find locations that sell tickets;
- It's not pleasant to have to validate or physically purchase a ticket. Both actions are perceived as a waste of time;
- Having to validate season tickets is not good;
- It's complicated to get the correct ticket type and exchange zones on a ticket;
- There's a lot of line to purchase tickets in busy seasons (such as when there is a football game and in the beginning and end of each month);
- Too much fragmentation of the ticketing infrastructure (many systems, low interoperability);
- Magnetic cards with low durability and reliability;

The results of the survey made after the test (Appendix E: Survey B – results) can be seen in the following graphics:

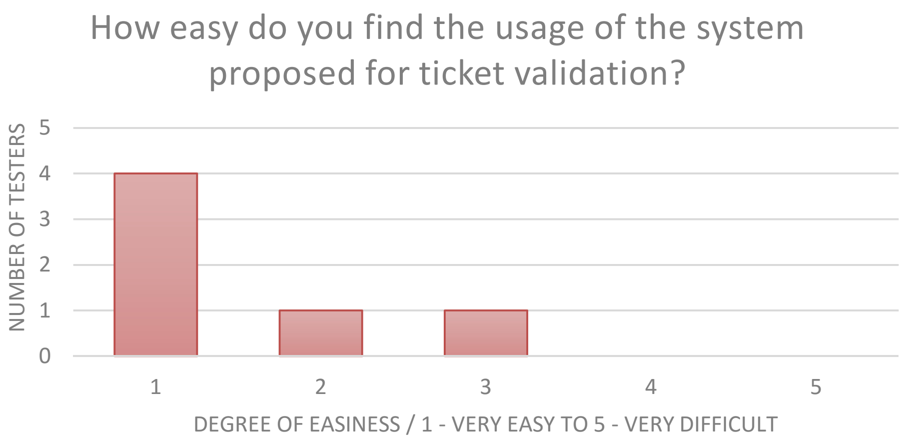


Figure 66 - After field test survey – Question 1 graphic

This first set of results shows that most testers find the developed solution easy to use.

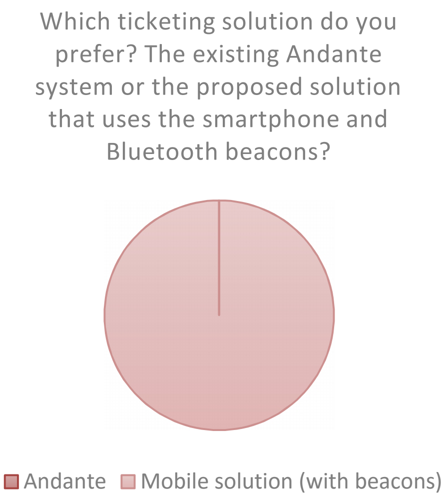


Figure 67 - After field test survey – Question 2 graphic

All of the users would prefer the mobile solution presented to them, rather than the previous approach being used – Andante.

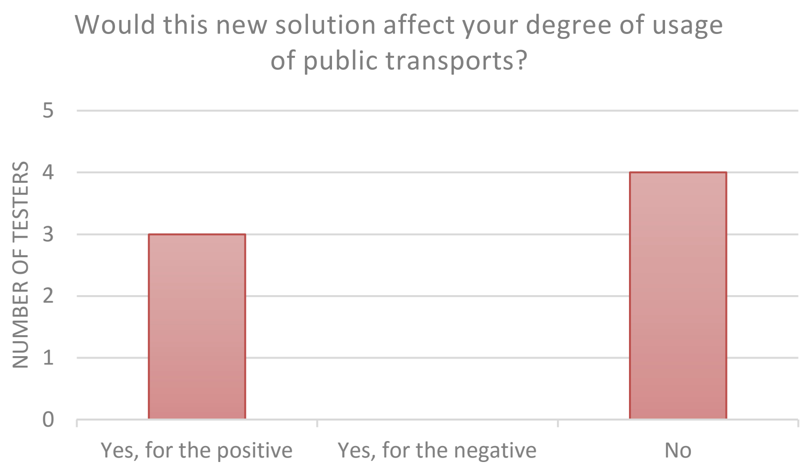


Figure 68 - After field test survey – Question 3 graphic

However, the degree of usage of public transports would not be increased, thanks to this solution, on four of the testers; which could be due to the fact that the simply don’t need to use public transports more often.

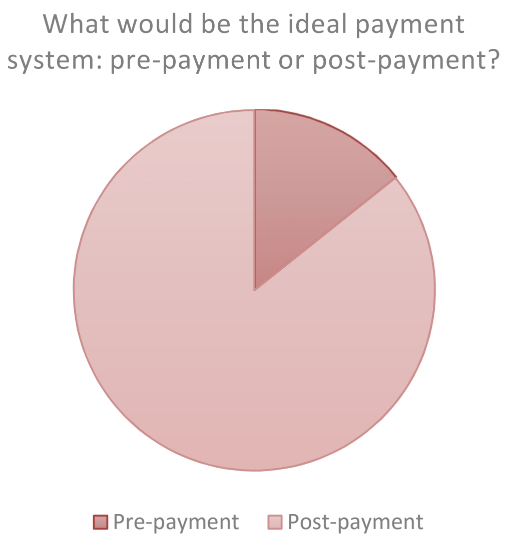


Figure 69 - After field test survey – Question 4 graphic

Only one tester saw the advantage of having a pre-payment approach with this solution; the remainder opted for the post-payment approach (in line with the payment method predicted for the proposed solution – section 3.2.4 - Payment).

In the open answer question - Do you have any suggestions for possible improvements of the developed solution? (suggestions related to user interface or robustness of the solution are not expected) - the only suggestion provided mentioned that the application should handle an automatic buying of tickets (which is part of the solution, considering the post-payment proposal - section 3.2.4 - Payment) and an automatic way for the application to start monitoring only when needed.

The logs, present in Appendix H: Field test's logs, show several different situations.

The green backgrounds are used to represent a normal and expected state. A sequence of green background entries, that abides to the state machine specified in section 4.7 - Mobile application.

If a green background entry is followed by an entry with yellow background this means there was an error, from which it was possible to continue execution, although the trip was lost. This happens with User 1 (2nd trip), User 2 (1st trip and 2nd trip) and User 6 (1st trip). In these cases, the smartphone stops detecting every beacon (even though they are still present) and restarts the state machine (as supposed) in the middle of a trip.

If a green background entry is followed by a red background entry it means there was an error, from which it was not possible to continue execution, which is the case of User 7 (1st trip) which experienced a phone reboot in the middle of the 1st trip.

When a green background entry is followed/intercalated with a light blue background entry it means that a beacon stopped being detected momentarily, but was rediscovered later on and the application was able to restore to the correct state.

In the log for User 5 (2nd trip) there is an orange entry that represents a timeout. The PU_IN_STATION state, in accordance to the machine state diagram (section 4.7 - Mobile application), surpassed a 120s timeout and automatically triggered a checkout (and considering the station was still being detected, it took the application back to NB_IN_STATION). This also reveals some inconsistencies in the time it takes for a smartphone to detect the exit of a region (which, according to the logs, seems to vary more than expected given the results for the hardware tests and the theory behind the sleep/wait and scanning times - section 4.2.2 - Detection times).

It's important to note that, given the logs, the best results (most green consecutive entries and most number of complete journeys – the ideal being two) are associated with the most recent smartphones – Nexus 5 and SM-G900F (Samsung Galaxy S5) – also containing the most recent Android software versions. This could mean that the Bluetooth drivers present in most recent Android versions are getting optimized. It can also mean the hardware is getting optimized and the technology is, as expected, evolving.

The discussion after the test also allowed to obtain useful information.

First, the users really appreciated the simplicity of the system and how it was done so "automatically". Then, in particular the testers in which problems occurred, expressed worry about what would happen if that happened when the system was being used.

Afterwards, testers asked how payment would work and what would happen if there was no internet connection. The first question was not answered to them, in order to avoid influencing the answers related to payment type in the survey. The second was explained as synchronization code that was run when an internet connection was detected.

This discussion also allowed to conclude that the reboot experienced by User 7 was unrelated to the application itself.

By observation, the following remarks can be made:

- Users were commenting the user interface, which according to them was well designed;
- Users were divided in two, distinct, groups: the ones that did the trip with the phone at hand at all times, checking the progress; the ones that kept their phone in the pocket and simply chatted with other testers throughout the journey;
- In the small number occasions when the application failed, users became visibly concerned and asked what to do.

Chapter 6

Conclusions

The initial proposal of this project, intended the creation of a wireless validation system, using Bluetooth Low Energy, in particular, beacons, that was reliable enough to replace current ticketing systems around the world and solve the problem of requiring too much interaction from the passengers, to use the public transport.

This lead to the exploration of the several concepts involved.

In particular, it's important to mention that ticketing approaches, in different public transportation operators and systems, don't vary much. The premise is the same: the user buys the trips; the user checks-in and the user checks-out (being this last portion optional in some networks). However, ticketing also involves the payment. Most systems continue working on the payment methods and the interactions with the user in this area, but disregard the portion of ticketing where the user is required to interact with the system in order to correctly use the service - the validation. As such, focusing on this area, that has been ignored for so long seems to be the correct approach.

Bluetooth, in particular its application with beacons, proved to be much more reliable and versatile than originally thought. And the technology is growing, with even more efficient usages of this type of devices. The internet of things is, indeed, a phenomenon, connecting everything and everyone in meaningful ways. This project is a great manifestation of this technology and how it can improve and simplify complex tasks; how it can provide the needed push to the so desirable seamless interaction age.

The initial proposal was ambitious, but it still was completed successfully. The solution proposed was validated scientifically [171] being that the first step for the creation of the prototype of a wireless validation system, using beacons and the Bluetooth technology. It's important to mention that in projects like this there is a need for a thorough understanding of the inner works of the underlying services, in this case the main context where the prototype was inserted - Metro do Porto and STCP -, and the technologies used. This knowledge potentiates the early identification of possible limitations and problems; the identification of these, early on, allowed one to better shape the scope of the project, and know if the solution would work and how could the ensuing steps improve the final result (by addressing the identified problems and limitations).

Given these results, one finds that the chosen approaches for beacon deployment and configuration were the right ones: the additional information delivered by the multiplication of reference points made the concept more reliable and reduced the number of limitations that would have to be faced.

The payment method was also subject to a new proposal. A complete post-payment approach, not new in the context of PT, but radical in the way that intends the complete removal of the pre-payment methods. Although the focus was the validation, such an alteration in this process would have to be associated with a radical alteration of the former. After all, they coexist in a bigger structure: the ticketing system.

Implementing the solution required special attention to provide a versatile solution. The server, for example, was developed to accept validations that occurred with beacons, smart cards, or even other validation methods. This was potentiated by the development of the server in cooperation with other MSc dissertation, making this versatility even more important. Scalability was also taken in consideration, in line with the type of data flow that is expected in a public transportation service. The architecture was simplified at the most, reducing unneeded layers.

The executed tests provided the needed verifications, taking in consideration the scope of what was developed.

The initial beacon hardware tests focused on the most important features, namely, determining the accuracy of the beacon's broadcasting ranges, determining the detection times and the beacon's battery life in different contexts. These initial tests were very relevant in the identification of possible limitations, but, in reality, they were even more determinant in the decision to carry on this line of investigation.

The field tests provided the "reality" that wasn't present in the laboratory: the distances, the timings, the people and the variability of situations. They were also essential to validate the solution, considering the project was presented, for the first time, to completely unbiased people. It's also important to mention that most adoption factors in mobile services, according to the findings presented in section 2.4.1, ranked well amongst the collected user data. The overall opinion was that the proposed solution was very compatible with a person's use of public transports. Almost every tester found the solution easy to use (in the surveys), while finding the solution useful, as per discussion results, due to it being so automated. Other factors were not so directly evaluated. Social influence, by observation, seemed to play a big part on the mindset of the testers, since they gathered when using the application, being those moments where more questions were raised. At the same time, when the application failed that left a dent in some testers that became increasingly worried about the risk of using the application. Trust was also decreased when users wondered what would happen if they were accidently detected or even if they had no internet connection. More than validating a software engineering project, this dissertation aimed at validating a new validation system concept, and this experiment provided that validation, considering that the users, generally, approved the approach. This approval was backed up by several, distinct, elements: surveys, discussions and contextual observation. The collected logs also showed that the application was robust, capable of handling most of the situations, failing in some minor cases.

Considering the problems that were initially pointed out on the current state of public transports, this solution would make it faster to buy and validate the tickets, no pre-planning would be required (you pay for what you use), the user would not forget to validate (the app would be always running), no more problems with degrading smart cards no need to carry cash. This solution learning curve cannot be assessed yet. The configuration steps were not the object of this investigation.

The operators would have the advantage of being able to gradually remove complex POS and security, optimize the flow of the network (no more lines and waiting times to perform validation) and provide higher customer satisfaction which could, in turn, increase the number of customers. The operator would also gather more information, since that with the new approach a checkout is always saved, even though there are no supporting infrastructures, like gates; while at the same time the amount of information collected between different transportation types would become the same (e.g. for the Andante system it would be possible to determine the line and vehicle when using MP). All of this, in the end, allows the operator to work more efficiently and spend less money.

Even though the solution was proven to work, it is essential to understand that it is far from perfect. This project is just the tip of the iceberg towards a completely seamless validation approach, that can actually be used in a real PT network. It is, nonetheless, a great push for the scientific community, in order to improve the technologies, get more internet of things concepts and push for the improvement of public transportation in general.

6.1 Future work

Future work includes the continuation of cooperation with operators, namely in terms of tests by performing additional evaluation of the beacons behavior in actual vehicles (light-rail and buses) and stations (considering that there was no possible timeframe that would work between the operators and this project's schedule), and additional, phased-out, trials as the solution gets refined. It's also important to discuss with operators the problem and solution proposed and use their expertise to further identify problems and limitations that couldn't be found before.

Developing fiscalization and configuration applications should also be point to consider. This project does not propose a solution to a big limitation: fraud. But it promotes the usage of the methods that have been proven to work to fight this problem: fiscalization. Creating a fiscalization application would be very easy and useful. The configuration application would also be very useful and smart in the context of PT. Considering that the beacon settings can be changed online, and then synchronized when someone running the application enters beacon range, the context of PT is ideal, considering drivers pass by several stations every day. Also, providing an application that performs dual function: fiscalization and configuration; allows employees to perform both functions.

The solution can also be refined, by fine-tuning the sleeping and scanning intervals and measuring and optimizing battery life.

The technology will also improve and this will mean analyzing and integrating new features in the solution e.g. Motion UUID.

The server could also be improved, by accepting intermediate stations, for example. This was not included in this project since the solution meant to be implemented should be similar to the existing infrastructure (and the existing infrastructure does not record the intermediate stops).

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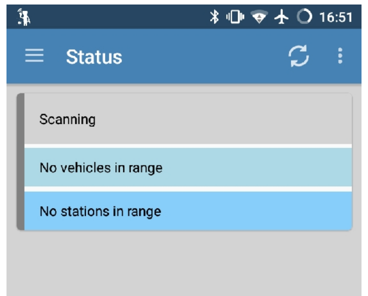
Appendix A

Execution



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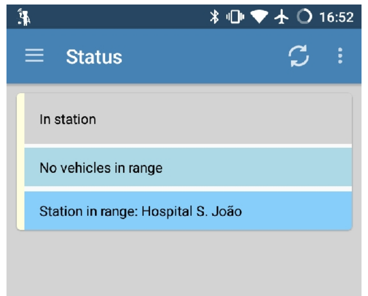

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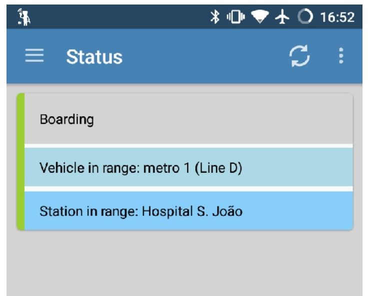
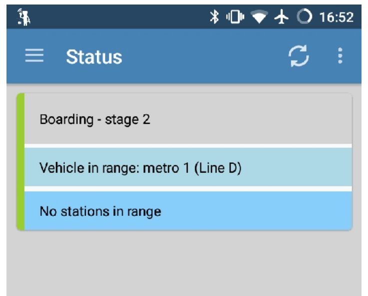
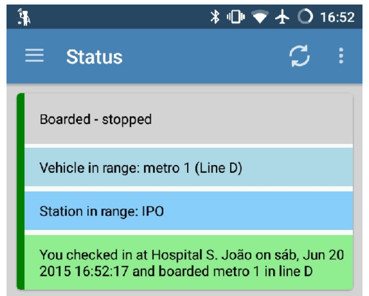


3 – PB_IN_STATION_AND_IN_VEHICLE



4 – PB2_IN_VEHICLE



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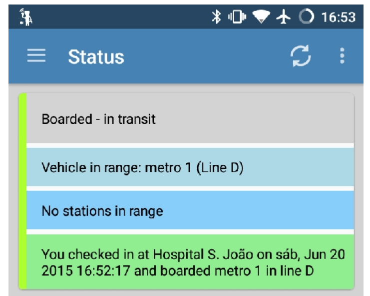
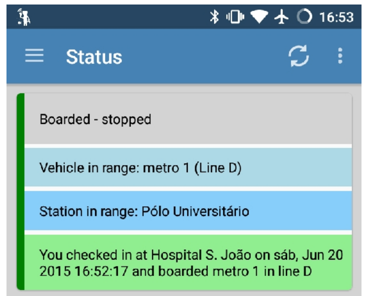


5 – B_IN_VEHICLE



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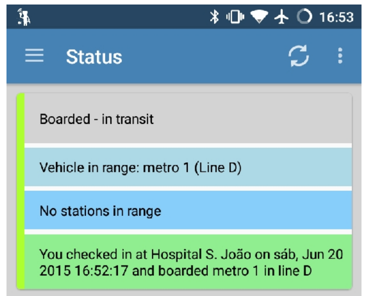
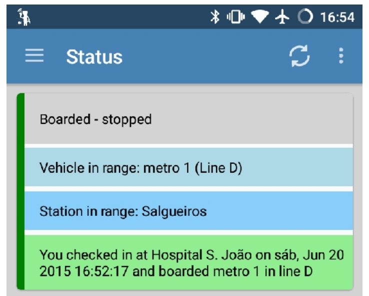
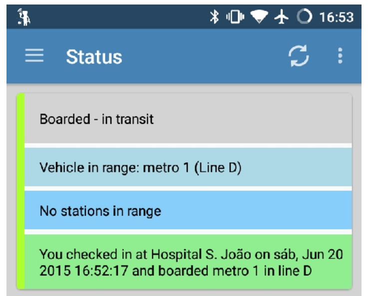


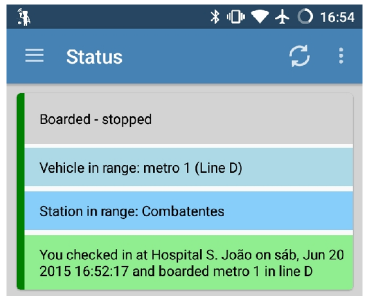
7 – B_IN_VEHICLE



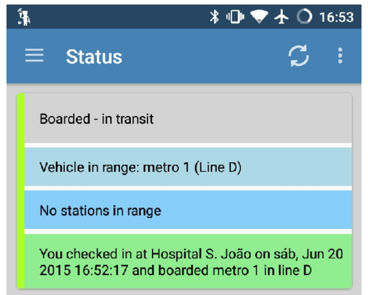
8 – B_IN_STATION_AND_IN_VEHICLE



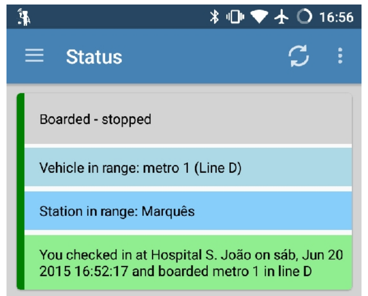
9 – B_IN_VEHICLE



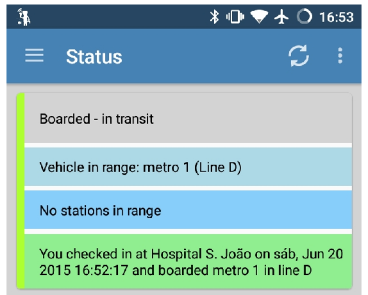
10 – B_IN_STATION_AND_IN_VEHICLE



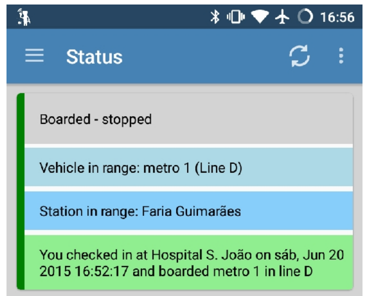
11 – B_IN_VEHICLE



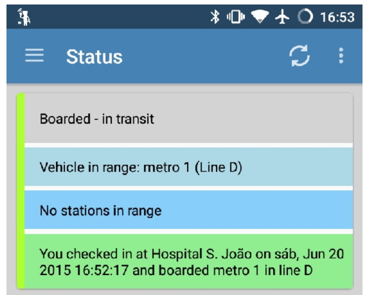
12 – B_IN_STATION_AND_IN_VEHICLE



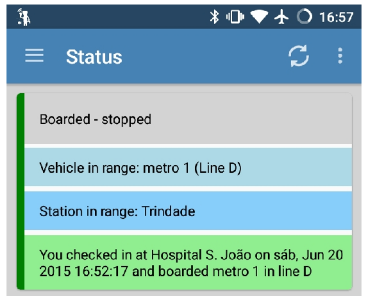
13 – B_IN_VEHICLE



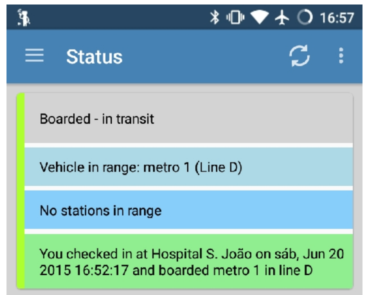
14 – B_IN_STATION_AND_IN_VEHICLE



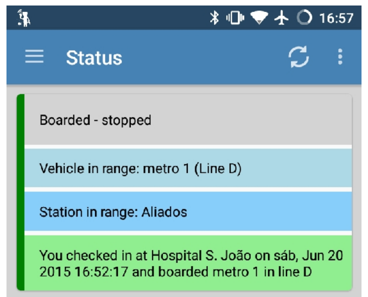
15 – B_IN_VEHICLE



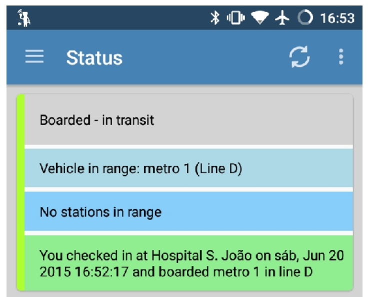
16 – B_IN_STATION_AND_IN_VEHICLE



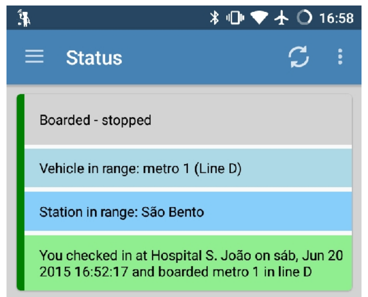
17 – B_IN_VEHICLE



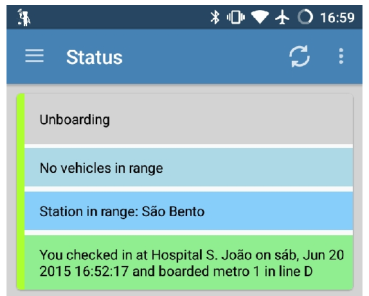
18 – B_IN_STATION_AND_IN_VEHICLE



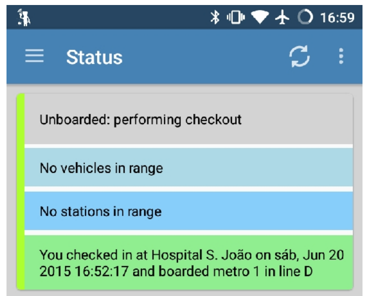
19 – B_IN_VEHICLE



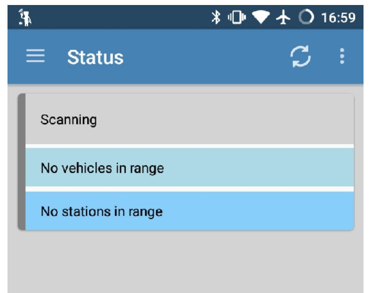
20 – B_IN_STATION_AND_IN_VEHICLE



21 – PU_IN_STATION



22 – CHECKOUT_NOTHING_DETECTED



23 – INITIAL_SCANNING

Appendix B

Beacon ranging (distance) and battery test results

B.1 iOS

Advertising intervals (ms)	Broadcasting Power											
	-16 dBm (~7m)				-8 dBm (~30m)				4 dBm (~70m)			
	Battery life (months)	Real distance (m)	Measured distance (m)		Battery life (months)	Real distance (m)	Measured distance (m)		Battery life (months)	Real distance (m)	Measured distance (m)	
1000	~38	Minimum detected Only height (2)	17	Avg: 17 SD: -	~36	Minimum detected Only height (2)	5, 7, 6	Avg: 6 SD: 1	~27	Minimum detected Only height (2)	8, 16, 17, 18, 19	Avg: 15.6 SD: 4.39
		Middle (~4)	13, 14, 16, 17	Avg: 15 SD: 1.83		Middle (~15)	17, 24, 23	Avg: 21.33 SD: 3.79		Middle (~35)	31, 29, 45, 38, 39	Avg: 36.4 SD: 6.47
		Max distance (8)	19	Avg: 19 SD: -		Max distance (30.4)	35, 42, 37	Avg: 38 SD: 3.61		Max distance (65)	85, 89, 91	Avg: 88.3 SD: 3.05
500	~22	Minimum detected Only height (2)	10, 11, 12, 13	Avg: 11.5 SD: 1.29	~20	Minimum detected Only height (2)	4, 5	Avg: 4.5 SD: 0.71	~15	Minimum detected Only height (2)	11, 10	Avg: 10.5 SD: 0.7
		Middle (~4)	12	Avg: 12 SD: -		Middle (~15)	18, 19, 20, 24	Avg: 20.25 SD: 2.63		Middle (~35)	37, 39, 41	Avg: 39 SD: 2
		Max distance (8)	13, 16, 17	Avg: 15,33 SD: 2.08		Max distance (30.4)	37, 39	Avg: 38 SD: 1.41		Max distance (65)	69, 71, 72	Avg: 70,67 SD: 1.53
100	~5	Minimum detected Only height (2)	14, 15, 16	Avg: 15 SD: 1	~4	Minimum detected Only height (2)	2	Avg: 2 SD: -	~3	Minimum detected Only height (2)	12, 13	Avg: 12.5 SD: 0.71
		Middle (~4)	15	Avg: 15 SD: -		Middle (~15)	12, 17, 19	Avg: 16 SD: 3.61		Middle (~35)	39, 38, 33, 34	Avg: 36 SD: 2.94
		Max distance (8)	9, 15, 17	Avg: 13.67 SD: 4.16		Max distance (30.4)	32, 34, 39	Avg: 35 SD: 3.61		Max distance (69)	69, 71, 74	Avg: 71.33 SD: 2.52

Height of beacon	3m
Smartphone usage height	1m
Avg	Average
SD	Standard deviation

B.2 Android

Advertising intervals (ms)	Broadcasting Power											
	-16 dBm (~7m)				-8 dBm (~30m)				4 dBm (~70m)			
	Battery life (months)	Real distance (m)	Measured distance (m)		Battery life (months)	Real distance (m)	Measured distance (m)		Battery life (months)	Real distance (m)	Measured distance (m)	
1000	~38	Minimum detected Only height (2)	Not detected	Avg: N/D (0) SD: N/D (0)	~36	Minimum detected Only height (2)	4.21, 4.57	Avg: 4.39 SD: 0.25	~27	Minimum detected Only height (2)	16.72, 11.87	Avg: 14.3 SD: 3.43
		Middle (3.5)	6.32, 5.55, 8.92, 7.27	Avg: 7.02 SD: 1.45		Middle (15)	33.82, 21.68	Avg: 27.75 SD: 8.58		Middle (35)	38.74, 40.87, 41.75	Avg: 40.45 SD: 1.55
		Max distance (10.1)	Not detected	Avg: N/D (0) SD: N/D (0)		Max distance (33)	39.25, 45.65, 32.50	Avg: 39.13 SD: 6.58		Max distance (45)	49.71, 50.24, 48.05	Avg: 49.33 SD: 1.14
500	~22	Minimum detected Only height (2)	5.1, 4.4	Avg: 4.75 SD: 0.49	~20	Minimum detected Only height (2)	7.76, 8.15, 14.54	Avg: 10.15 SD: 3.81	~15	Minimum detected Only height (2)	6, 4, 5.6	Avg: 5.2 SD: 1.06
		Middle (3.5)	4.4, 5.1, 5.55	Avg: 5.02 SD: 0.58		Middle (15)	19.72, 38.58, 43.71	Avg: 34 SD: 12.63		Middle (35)	39.24, 39.76, 40.54, 44	Avg: 40.89 SD: 2.14
		Max distance (10.1)	10, 10.07, 5.89	Avg: 8.65 SD: 2.39		Max distance (33)	39.25, 37.45, 23.40	Avg: 33.37 SD: 8.68		Max distance (45)	48.14, 50.88	Avg: 49.51 SD: 1.94
100	~5	Minimum detected Only height (2)	5.55, 7.27, 6.32, 8.92, 4.08, 4.67	Avg: 6.135 SD: 1.78	~4	Minimum detected Only height (2)	3.28, 5.10, 4.57, 4.21	Avg: 4.29 SD: 0.77	~3	Minimum detected Only height (2)	7.6, 9.48, 4.63	Avg: 7.24 SD: 2.45
		Middle (3.5)	7.15, 7.22, 5.55, 5.89, 6.32	Avg: 6.426 SD: 0.75		Middle (15)	19.78, 19.29, 33.82, 31	Avg: 25.97 SD: 7.52		Middle (35)	37.24, 36.16, 33.12	Avg: 35.51 SD: 2.14
		Max distance (10.1)	7.89, 5.89, 6.32, 7.15	Avg: 6.81 SD: 0.89		Max distance (35.40)	38.78, 35.90, 35.88	Avg: 36.85 SD: 1.67		Max distance (45)	46, 47.35, 50.24, 49.05	Avg: 48.16 SD: 1.87

Height of beacon	3m
Smartphone usage height	1m
Avg	Average
SD	Standard deviation

Appendix C

Beacon monitoring test results (elapsed time for exit/entry detection)

Advertising intervals (ms)	Sleeping + Scanning time											
	Sleeping - 10s | Scanning - 5s		Sleeping - 20s | Scanning - 5s		Sleeping - 10s | Scanning - 2.5s		Sleeping - 20s | Scanning - 2.5s		Sleeping - 10s | Scanning - 1s		Sleeping - 20s | Scanning - 1s	
1000	TEn: 6.254, 10.652	Avg: 8.453 SD: 3.11	TEn: 7.785, 9.542	Avg: 8.66 SD: 1.24	TEn: 11.64, 14.169	Avg: 12.90 SD: 1.79	TEn: 9.432, 22.256	Avg: 15.84 SD: 9.07	TEn: 4.474, 5.945	Avg: 5.21 SD: 1.04	TEn: 17.841, 5.231	Avg: 11.54 SD: 8.92
	TEx: 8.41, 14.205	Avg: 11.308 SD: 4.10	TEx: 24.42, 16.334	Avg: 20.38 SD: 5.72	TEx: 7.231, 4.608	Avg: 5.91 SD: 1.85	TEx: 11.138, 24.92	Avg: 18.03 SD: 9.75	TEx: 3.376, 8.601	Avg: 5.99 SD: 3.69	TEx: 6.622, 12.289	Avg: 9.46 SD: 4.00
500	TEn: 14.461, 4.130	Avg: 9.3 SD: 7.31	TEn: 25.632, 14.577	Avg: 20.10 SD: 7.82	TEn: 8.250, 11.354	Avg: 9.8 SD: 2.19	TEn: 5.388, 17.694	Avg: 11.54 SD: 8.70	TEn: 9.629, 9.324	Avg: 9.48 SD: 0.22	TEn: 5.533, 9.441	Avg: 7.49 SD: 2.76
	TEx: 5.691, 7.632	Avg: 6.66 SD: 1.37	TEx: 24.692, 11.630	Avg: 18.16 SD: 9.24	TEx: 10.842, 9.879	Avg: 10.36 SD: 0.68	TEx: 11.985, 23.181	Avg: 17.583 SD: 7.92	TEx: 4.557, 4.138	Avg: 4.35 SD: 0.30	TEx: 18.156, 12.256	Avg: 15.21 SD: 4.17
100	TEn: 7.527, 5.806	Avg: 6.66 SD: 1.22	TEn: 21.541, 12.621	Avg: 17.08 SD: 6.31	TEn: 4.744, 12.413	Avg: 8.58 SD: 5.42	TEn: 10.443, 16.589	Avg: 13.52 SD: 4.35	TEn: 6.356, 5.96	Avg: 6.16 SD: 0.28	TEn: 13.534, 9.760	Avg: 11.65 SD: 2.67
	TEx: 19.884, 24.221	Avg: 22.05 SD: 3.07	TEx: 30.908, 25.949	Avg: 28.43 SD: 3.51	TEx: 5.19, 7.248	Avg: 6.22 SD: 1.46	TEx: 6.618, 5.555	Avg: 6.09 SD: 0.75	TEx: 8.447, 4.532	Avg: 6.49 SD: 2.77	TEx: 5.132, 15.373	Avg: 10.25 SD: 7.24

Avg	Average
SD	Standard deviation

Beacon monitoring test results (elapsed time for exit/entry detection)

Appendix D

Survey A – Before field test

Solução de validação em transportes públicos usando o smartphone - Antes do teste

O objetivo deste inquérito é avaliar o interesse numa implementação de uma possível solução de registo da utilização de transportes públicos usando o smartphone e respetivas tecnologias móveis. Este inquérito antecede o teste ao vivo.

*Obrigatório

Costumas usar transportes públicos? *

○ Sim

○ Não

Se respondeste que sim à pergunta anterior, com que frequência semanal os utilizas?

Média de número de dias por semana que utilizas transportes públicos

	0	1	2	3	4	5	6	7	
Nenhuma vez por semana	○	○	○	○	○	○	○	○	Todos os dias da semana

Identificas algum problema no sistema de bilhética nos transportes públicos que utilizas? Em caso afirmativo, quais são esses problemas?

Qual o teu interesse num sistema de validação/registo de utilização de bilhetes em transportes públicos que utilize o smartphone? *

	0	1	2	3	4	5	
Nada interessado	○	○	○	○	○	○	Totalmente interessado

Validation solution in public transports using the smartphone – before the test

The goal of this survey is the evaluation of your interest in the implementation of a possible solution to register your usage of public transports, making use of your smartphone and the mobile technologies associated. This survey precedes the field test.

*Mandatory

Do you use public transports?

X Yes

X No

If you answered yes on the previous question, which is the weekly frequency of your usage?

0 1 2 3 4 5 6 7

Never Everyday

Do you identify any ticketing problems in the public transportation systems you use? If yes, what are those problems?

What is your interest in a validation system/usage tracking system in public transports that makes use of the smartphone?

0 1 2 3 4 5

Not interested Very interested

Appendix E

Survey B – After field test

Solução de validação em transportes públicos usando o smartphone - Depois do teste

O objetivo deste inquérito é avaliar o interesse numa implementação de uma possível solução de registo da utilização de transportes públicos usando o smartphone e respetivas tecnologias móveis. Este inquérito segue-se ao teste ao vivo, que deves ter realizado.

*Obrigatório

Como identificas a facilidade de utilização do sistema usado na validação de bilhetes? *

	1	2	3	4	5	
Muito fácil	○	○	○	○	○	Muito difícil

Qual a solução que preferes: o sistema Andante existente ou a solução proposta que utiliza o smartphone e beacons? *

○ Andante

○ Solução móvel

Esta nova solução afetaria o teu grau de utilização dos transportes públicos?

○ Sim, pela positiva

○ Sim, pela negativa

○ Não

Achas que o ideal para esta solução seria o pré-pagamento ou o pós-pagamento?

Pré-pagamento - terias de comprar o título antes da viagem; Pós-pagamento - recebias o valor a pagar periodicamente

○ Pré-pagamento

○ Pós-pagamento

Tens sugestões para possíveis melhorias à solução desenvolvida?

Não são esperadas sugestões relativas à qualidade visual ou robustez da aplicação desenvolvida

Validation solution in public transports using the smartphone – after the test

The goal of this survey is the evaluation of your interest in the implementation of a possible solution to register your usage of public transports, making use of your smartphone and the mobile technologies associated. This survey follows the field test, that you must have joined in.

*Mandatory

How easy do you find the usage of the system proposed for ticket validation?

1 2 3 4 5

Very easy Very hard

Which ticketing solution do you prefer? The existing Andante system or the proposed solution that uses the smartphone and Bluetooth beacons?

X Andante

X Mobile solution

Would this new solution affect your degree of usage of public transports?

X Yes, for the positive

X Yes, for the negative

X No

What would be the ideal payment system: pre-payment or post-payment?

X Pre-payment

X Post-payment

Do you have any suggestions for possible improvements of the developed solution? (suggestions related to user interface or robustness of the solution are not expected)

Appendix F

Survey A – results

Costumas usar transportes públicos?	Se respondeste que sim à pergunta anterior, com que frequência semanal os utilizas?	Identificas algum problema no sistema de bilhética nos transportes públicos que utilizas? Em caso afirmativo, quais são esses problemas?	Qual o teu interesse num sistema de validação/registo de utilização de bilhetes em transportes públicos que utilize o smartphone?
Sim	5	Nem sempre é possível ter uma payshop/loja andante perto e/ou disponível para comprar os bilhetes.	5
Sim	5	Ter de validar fisicamente antes de entrar (perder tempo), compra também ter de ser física.	5
Sim	2	Ter de validar passes mensais antes de entrar no metro / comboio.	4
Não			4
Sim	2	Perde-se muito tempo Muito complicado tirar o bilhete Tem de se trocar de zonas	5
Sim	5	Filas para comprar bilhete em "épocas altas" como dias de jogo do FCP e fim/inicio de cada mês	4
Sim	4	Demasiada fragmentação da bilhética (muitos sistemas, pouca interoperabilidade). Cartões magnéticos pouco duráveis e confiáveis. Bilhetes em papel pouco amigos do ambiente.	5

Survey A – results

Appendix G

Survey B – results

Como identificas a facilidade de utilização do sistema usado na validação de bilhetes?	Qual a solução que preferes: o sistema Andante existente ou a solução proposta que utiliza o smartphone e beacons?	Esta nova solução afetaria o teu grau de utilização dos transportes públicos?	Achas que o ideal para esta solução seria o pré-pagamento ou o pós-pagamento?	Tens sugestões para possíveis melhorias à solução desenvolvida?
1	Solução móvel	Sim, pela positiva	Pós-pagamento	compra automática de bilhetes era um bónus bem como economização na bateria (start/stop service automático e inteligente).
1	Solução móvel	Não	Pré-pagamento	
1	Solução móvel	Sim, pela positiva	Pós-pagamento	
2	Solução móvel	Não	Pós-pagamento	
1	Solução móvel	Não	Pós-pagamento	
1	Solução móvel	Sim, pela positiva	Pré-pagamento	
3	Solução móvel	Não	Pós-pagamento	

Survey B – results

Appendix H

Field test's logs

H.1 Tester 1

Phone info:

OS API Level: 5.1.1(22)
Device: vanquish
Model (and Product): DROID RAZR HD (XT926_verizon)

Time	State	Stations in range	Vehicles in range
Jun 16 12:01:20 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:01:29 2015	NB_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:08:06 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:08:27 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:09:55 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:10:35 2015	PU_IN_STATION	[Bus stop region 20]	[]
Jun 16 12:10:47 2015	CHECKOUT_NOTHING_DETECTED	[]	[]
Jun 16 12:10:48 2015	INITIAL_SCANNING	[]	[]
2nd trip			
Jun 16 12:10:48 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:15:00 2015	NB_IN_STATION	[Bus stop region 20]	[]
Jun 16 12:15:15 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:15:38 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:20:38 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:20:43 2015	NB_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:22:03 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:22:05 2015	NB_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:22:39 2015	INITIAL_SCANNING	[]	[]

H.2 Tester 2

Phone info:

OS API Level: 4.4.4(19)
Device: m3
Model (and Product): GT-I9305 (m3xx)

Time	State	Stations in range	Vehicles in range
Jun 16 12:02:01 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:02:03 2015	NB_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:08:00 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:08:21 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:10:07 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:10:09 2015	NB_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:10:09 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:10:33 2015	NB_IN_STATION	[Bus stop region 20]	[]
Jun 16 12:10:38 2015	INITIAL_SCANNING	[]	[]
2nd trip			
Jun 16 12:10:38 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:14:07 2015	NB_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:14:21 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:15:43 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:21:53 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:21:56 2015	NB_IN_STATION	[Bus stop region 18]	[]

H.3 Tester 3

Phone info:

OS API Level: 5.1.1(22)
Device: hammerhead
Model (and Product): Nexus 5 (hammerhead)

Time	State	Stations in range	Vehicles in range
Jun 16 12:01:14 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:01:22 2015	NB_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:08:16 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:08:26 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:09:48 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]

Jun 16 12:10:35 2015	PU_IN_STATION	[Bus stop region 20]	[]
Jun 16 12:10:47 2015	CHECKOUT_NOTHING_DETECTED	[]	[]
Jun 16 12:10:47 2015	INITIAL_SCANNING	[]	[]
2nd trip			
Jun 16 12:10:47 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:13:52 2015	NB_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:14:19 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:15:41 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:20:15 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:20:48 2015	PU_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:22:06 2015	CHECKOUT_NOTHING_DETECTED	[]	[]
Jun 16 12:22:07 2015	INITIAL_SCANNING	[]	[]

H.4 Tester 4

Phone info:

OS API Level: 5.0(21)
Device: klte
Model (and Product): SM-G900F (kltexx)

Time	State	Stations in range	Vehicles in range
Jun 16 12:01:32 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:01:36 2015	NB_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:08:20 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:08:33 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:09:52 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:10:36 2015	PU_IN_STATION	[Bus stop region 20]	[]
Jun 16 12:10:40 2015	CHECKOUT_NOTHING_DETECTED	[]	[]
Jun 16 12:10:40 2015	INITIAL_SCANNING	[]	[]
2nd trip			
Jun 16 12:10:40 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:14:04 2015	NB_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:14:18 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:15:43 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:20:01 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:20:48 2015	PU_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:22:25 2015	CHECKOUT_NOTHING_DETECTED	[]	[]
Jun 16 12:22:25 2015	INITIAL_SCANNING	[]	[]

H.5 Tester 5

Phone info:

OS API Level: 4.3(18)
Device: m0
Model (and Product): GT-I9300 (m0xx)

Time	State	Stations in range	Vehicles in range
Jun 16 12:06:07 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:06:08 2015	NB_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:08:15 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:08:30 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:09:51 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:10:36 2015	PU_IN_STATION	[Bus stop region 20]	[]
Jun 16 12:10:48 2015	CHECKOUT_NOTHING_DETECTED	[]	[]
Jun 16 12:10:49 2015	INITIAL_SCANNING	[]	[]
2nd trip			
Jun 16 12:10:49 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:13:55 2015	NB_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:14:18 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:15:44 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:20:11 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:20:22 2015	B_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:20:24 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:20:36 2015	B_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:20:45 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:20:55 2015	PU_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:22:55 2015	NB_IN_STATION	[Bus stop region 18]	[]

H.6 Tester 6

Phone info:

OS API Level: 4.4.2(19)
Device: c201v92ds_jbaol1_3m_ouya
Model (and Product): Elephone P3000S (P3000S)

Time	State	Stations in range	Vehicles in range
Jun 16 12:06:24 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:06:38 2015	NB_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:07:39 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:07:54 2015	NB_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:10:00 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:10:02 2015	NB_IN_STATION	[Bus stop region 20]	[]
Jun 16 12:10:11 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:10:31 2015	NB_IN_STATION	[Bus stop region 20]	[]
Service reset manually by the user (2nd trip)			
Jun 16 12:13:42 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:13:57 2015	NB_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:14:17 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:14:58 2015	NB_IN_STATION	[Bus stop region 20]	[]
Jun 16 12:15:20 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:15:41 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:20:33 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:20:44 2015	PU_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:20:48 2015	CHECKOUT_NOTHING_DETECTED	[]	[]
Jun 16 12:20:48 2015	INITIAL_SCANNING	[]	[]

H.7 Tester 7

Phone info:

OS API Level: 4.3(18)
Device: m0
Model (and Product): GT-I9300 (m0xx)

Time	State	Stations in range	Vehicles in range
Jun 16 12:01:32 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:01:58 2015	NB_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:08:15 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:08:23 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
User phone reboot			
Jun 16 12:09:28 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:10:39 2015	NB_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:10:39 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]

Service reset manually by the user (2nd trip)			
Jun 16 12:12:58 2015	INITIAL_SCANNING	[]	[]
Jun 16 12:14:18 2015	NB_IN_STATION	[Bus stop region 20]	[]
Jun 16 12:15:20 2015	PB_IN_STATION_AND_IN_VEHICLE	[Bus stop region 20]	[Bus region 3]
Jun 16 12:15:40 2015	PB2_IN_VEHICLE	[]	[Bus region 3]
Jun 16 12:20:12 2015	B_IN_STATION_AND_IN_VEHICLE	[Bus stop region 18]	[Bus region 3]
Jun 16 12:20:52 2015	PU_IN_STATION	[Bus stop region 18]	[]
Jun 16 12:20:56 2015	CHECKOUT_NOTHING_DETECTED	[]	[]
Jun 16 12:20:56 2015	INITIAL_SCANNING	[]	[]

Appendix H

Accepted paper

(Inserted in the following pages to preserve layout)

Exploring ticketing approaches using mobile technologies: QR Codes, NFC and BLE

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***Abstract*— There is a growing interest in integrating public transportation with the smartphone and mobile ticketing provides just that. To do so, different technologies can be used, such as Near Field Communication, Quick Response Codes and Bluetooth Low Energy. This paper explores the possibility of implementing a mobile ticketing solution, with focus on the ticket validation process, using these technologies. They are analyzed and compared at different levels and two possible approaches proposed. Both solutions are presented in terms of infrastructure and maintenance cost, as well as passenger interaction and benefit. The feasibility and performance of the technologies is analyzed and presented in the context of the proposed approaches. As a result, a mobile ticketing solution can be implemented using different technologies, and their choice depends on factors such as the available funds, the intended interaction level, performance and the size of the target audience.**

Keywords*— ble, bluetooth, qr codes, public transport, mobile ticketing solution, nfc

I. Introduction

Public transportation (PT) is growing increasingly important in the context of modern society. Constantly growing cities are making it very difficult to arrive on time and save up on moving, problems that can be solved using PT services. These type of services are not focused on profit [1] but they can be optimized in order to reduce costs.

The ticketing infrastructure is critical for the success or failure of a PT service. It is the main point of entry of revenue and also one of the main points of exit of revenue in the form of investment and maintenance. This paper focuses on exploring this component of the infrastructure within the context of the two major PT operators in Porto, Portugal: Metro do Porto – light-rail operator with 81 stations and 102 vehicles [2] – and Sociedade de Transportes Colectivos do Porto (STCP) – bus and tram operator with 2651 stops and 473 vehicles [3].

Recent technological advances have allowed the adoption of powerful mobile devices and ubiquitous connectivity. This is triggering a change in the way that users interact with computers: the human-computer interaction paradigm is changing – the personal mobile devices are becoming portals to cloud-based repositories [4]. There are several technologies that people can use to interact with their surrounding context by using their mobile devices, such as Near Field Communication, Quick Response Codes and Bluetooth Low Energy.

The focus of this project is to determine how these technologies and the inherent ubiquitous connectivity revolution can improve the ticketing infrastructures, namely the ticket validation.

This document provides an overview of the current ticketing system of the Metro do Porto and STCP operators. Then, an analysis and comparison between the technologies is presented, leading to two proposals for improving the ticketing systems. Next, technology performance tests are described and analyzed. Finally, the conclusion highlights the key factors of each technology and a discussion presents main benefits and ideal scenarios for the deployment of both proposals.

A. Porto's Public Transport operators

The main companies operating public transports in Porto are Metro do Porto and STCP. The multi-modal ticketing infrastructure is based on smart cards and is called *Andante* [5]. It is an ungated system, meaning that the user does not have to check-out, only check-in.

For the user, some disadvantages arise, such as requiring pre-planning, aggravated by an irregular division of geographic zones and confusing ticketing schemes, making it harder to compute origin, destination and type of ticket.

The operators, on the other hand, are required to maintain highly specialized and costly equipment, and are not able to collect important information such as checkout locations, which would indicate and store a complete user trip, instead of only an entry point.

II. Technology Study

The validation process using the smartphone can be made using different technologies. There are multiple existing solutions that aim to achieve this in an optimal way for both the users and the transport operators [6]. In the following sections, the technologies considered for the implementation of a mobile ticketing system are analyzed and compared.

A. Near Field Communication

Near Field Communication (NFC) is a short distance wireless technology, which comes embedded in some smartphones, that allows users to exchange information with a smart card or other NFC devices. A smart card is a card that contains a passive NFC chip that can be read by an active NFC device, which is called the reader. An NFC tag is, for instance, a small sticker containing an NFC chip, having stored data in it, that can be read or written by an active device.

The cost of this technology is not particularly high per piece [7], but it is the second highest cost technology presented in this paper. NFC has advantages like simple tag reading for a user, since they only need to unlock the phone and tap it on the intended tag, and the possibility of visually customizing the tags. It has the disadvantage of being a technology that is not available in every smartphone and not well known by the general public. This technology has been applied in public transportation before [6], with more focus on the touch-to-pay approach.

B. Quick Response Codes

Quick Response (QR) Codes allow the storage of information in a 2D barcode format, storing information both horizontally and vertically, thus carrying several hundred times more information than regular barcodes. These codes can be read by dedicated readers, or using smartphones as long as they have a camera and autofocus feature [8]. Also, QR Codes have the advantage of being easily created and can be printed using a regular printer, thus making the process of physical distribution not expensive. In fact, this process may be integrated in the workflow of existing schedules and maps at stops.

Similarly to NFC, QR Codes are also a technology that is mostly used to read a small amount of information from a code. QR Codes are the cheapest technology presented in this research since the maximum cost associated with it is the cost of printing paper.

Apart from its reduced cost, QR codes have the advantage of being supported by most smartphones [9], since only a camera with autofocus is required, and being more accepted by the general public [10], since they are widely used (e.g. magazines, advertising). One of its disadvantages is the fact that the reading process might be slower than NFC tags, since apart from unlocking the phone, the user also has to open the application and point the camera to the code. Also, the level of visual customization is more reduced than NFC tags.

C. Bluetooth Low Energy

Bluetooth is a wireless technology, that exchanges data over short distances using radio transmissions [11]. The most recent Bluetooth standard is called Bluetooth Smart, or Bluetooth Low Energy (BLE); it has several advantages over the traditional standard, such as lower power consumption and enhanced range [12, 13], and it is being adopted by the recently released smartphones. Another type of device that implements Bluetooth Smart technology is a beacon: a small device that periodically emits a Bluetooth signal, containing information, that can be picked up by another device that is scanning for Bluetooth signals [14]. When using specific tools, provided by beacon manufacturers, to develop a mobile application, it is possible, using the beacon signal, to determine the approximate distance to the beacon – called ranging – or to determine when the smartphone enters or exits the beacon's vicinity - called monitoring [15]. Beacons are more expensive than the previously presented technologies, having an average cost 60 times higher than the NFC most expensive counterpart [16], per unit. There are also lower cost options [17]. Beacons have the advantage of not requiring the user to interact with the smartphone in order to receive the signal being emitted, and also the fact that the information can be received at longer distances than NFC and QR Codes. Apart from the price, the biggest disadvantage is the fact that beacons require a power source, increasing installation/maintenance costs.

D. Comparison

The following table compares the technologies presented above:

TABLE I. TECHNOLOGIES COMPARISON

Technology	Price per unit	Advantages	Disadvantages
QR Codes	Very cheap	• High availability • High acceptance	• Higher user interaction • Lower customization
NFC	Cheap	• Visual customization • Low user interaction	• Lower availability • Not well-known
Bluetooth	Costly	• Long distance reception • No interaction needed	• Power source needed • High cost

Summing up, Bluetooth has the advantage of being more user friendly and automating the process of ticket validation, since it does not require interaction from the user, but has a higher cost of deployment. QR Codes on the other hand have a lower cost but require the highest level of interaction with the user. NFC tags are slightly more expensive than QR Codes, and cheaper than Bluetooth beacons, but the interaction process is more pleasant.

III. PROPOSED APPROACHES

Now, two possible approaches for a mobile ticketing system, in the context of Porto's public transportation system, are presented and discussed. Each approach uses different technologies: the first uses either QR Codes or NFC, due to their use case similarity, and the second uses of BLE and beacons. The focus of the presented approaches is the ticket validation process and the solutions account for the possibility of having check-in and check-out steps.

A. *Approach 1 – Near Field Communication / Quick Response Codes*

As aforementioned, the first solution uses QR Codes or NFC to implement the validation process, since both technologies consist of storing a piece of information that is actively read by a mobile device. The solution is described using QR Codes, but the implementation based on NFC tags is very similar and they may in fact complement each other. The check-in codes, or tags, will be placed inside the vehicle itself, requiring the reading process to happen while travelling. As a result, using the bus case as an example, each bus can have a number of codes (for example, 3 codes) placed inside, where the user would simply be required to read one in order to perform the validation step, namely the check-in step. In this solution, the check-out step is optional, and the user may pre-configure or choose at the time of check-in the ticket type being used: zone ticket or automatic ticket (postpaid solution – where the user is charged on his associated credit card).

When the automatic ticket option is chosen the check-out step is required, and the amount that is charged to the user is calculated from the route of the trip. In order to perform the check-out step, each station will have a check-out code with that specific purpose, thus identifying the station where the user finished the trip. Location data can be used to assess the user's real location, so that the system can verify if the user is indeed in a certain station.

Fig 1. First approach architecture [1 2 3 4 5]

B. *Approach 2 – Bluetooth Low Energy*

The second solution uses beacons and the monitoring concept presented previously. This solution envisions beacons to be placed at the stations of the network and inside the vehicles. Each beacon transmits a message that announces the vehicle / station type (light-rail or bus), the operating lines and identification. First, the user enters a station, which is detected by a smartphone application. If the user boards a vehicle, the entrance in the vehicle's region will also be detected. After boarding the vehicle, the user will be entering and exiting station range, while remaining in the vehicle range (stopping by the several stations in his course). If the user exits the vehicle region and the station region (therefore the user is no longer within the range of any beacon) the check-out is assumed. This flow allows to determine the entire course of the user: the check-in, check-out and intermediate points.

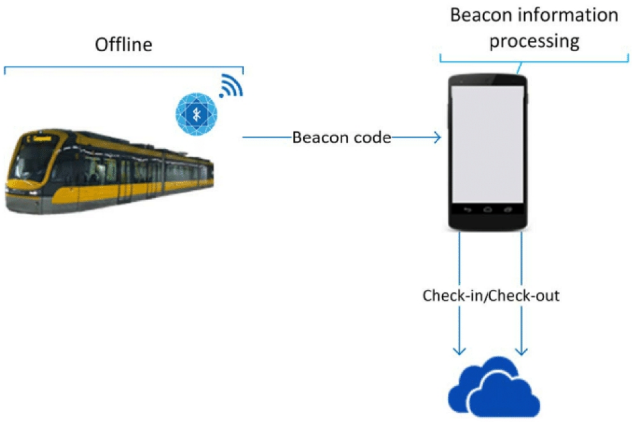

Fig 2. Second approach architecture

IV. METHODOLOGY

This section presents the testing methodology that was used to evaluate each technology's performance. Since each of them works in a different way, each experiment will be described separately. Every technology was tested in the same Android device.

A. *QR Codes*

In order to analyze the performance of reading a QR Code, the speed of the reading process had to be measured and evaluated. This process was reproduced under different circumstances, to replicate plausible public transport scenarios. Also, the two QR Codes that were used to perform the tests were printed in a white sheet of paper, one of them measuring 5.82cm x 5.82cm and the second one doubling this size. These dimensions were used to fit existing infrastructures, such as buses or stops.

One of the factors that is prone to influence the reading of a QR Code is the ambient light available at the moment. In the tests, ambient light is measured in *lux*, which is the unit that measures the amount of light received by a sensor. Two

[1] https://www.iconfinder.com/icons/99345/skydrive_icon
[2] http://smartcompanion.projects.fraunhofer.pt/
[3] http://ipsisnet.blogspot.pt/2012/12/metro-do-porto-pretende-reduzir-50-dos.html
[4] https://pt.wikipedia.org/wiki/Esta%C3%A7%C3%A3o_de_Baguim
[5] http:// NFCtags.com

other factors that might influence the reading process are the size of the QR Code and the distance at which the code is read. Movement can also influence this process however, at this stage, it was not considered in the tests.

In order to evaluate the performance of QR Code reading under these conditions, both codes were placed under different illumination conditions. Finally, the two codes were also read at different distances so that the influence that this factor has on the process could be determined. To perform the reading, an Android application, making use of an open source library based on Zbar[6], was used.

B. NFC

Similarly to QR Codes, the main aspect that should be evaluated when analyzing the performance of NFC tags is the speed of the reading process. However, the factors that influence the reading of NFC are not the same for the reading of QR Codes. On NFC, the most important aspect that should be tested is the material separating the reading device and the tag. In order to do evaluate this, the same NFC tag was read with different materials in between. The first test was performed without any material, the second was performed using a 1.5cm plastic piece in between, the third a 3cm wooden surface and the last was performed on a 7cm thick double-glass window. A message was written in the tag and the default tag reading Android application was used.

C. Beacons

The beacons used for testing were the Estimote beacons[7]. To test the beacons' performance an open space, simulating a wide station, was used (it wasn't possible to schedule real tests in the stations with the PT operators). A beacon was placed 3m high (Fig. 3 – left) and the readings were made in several locations along a 120m long corridor (Fig. 3 – right). The corridor was sectioned according to the distance from the beacon's location. The goal was to compare the real distance between a device and a beacon with the calculated distance (using the Received Signal Strength Indicator – RSSI – and Measured Power [18]). The readings were made using iOS and Android, with Estimote's official application for each platform[8 9]. This test scenario included the variation of the broadcasting range (broadcasting power intensity that translates to the maximum distance the signal can reach – coverage) [19] and advertising interval (the frequency in which packets are sent) [18, 20, 21, 22]. Samples were registered and then an average calculated.

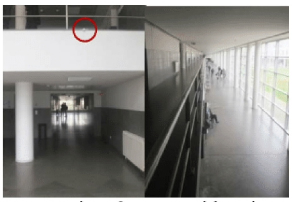

Fig. 3. Beacon placement view & test corridor view

[6] https://github.com/dm77/barcodescanner
[7] http://estimote.com
[8] https://itunes.apple.com/pt/app/estimote/id686915066?mt=8
[9] https://github.com/Estimote/Android-SDK/tree/master/Demos.Asd

An alternative test was executed with beacons – consisting on the measurement of time elapsed until the smartphone detects entry and exit of a beacon region – proximity detection [19]. The execution of this test required the demo application, provided by Estimote. Due to development limitations on the iOS platform (licensing requirements), these tests were performed on the Android platform only. However, given the different levels of development, the Android platform is expected to reveal worse performance than the iOS, thus covering the worst scenario. This test varied with the beacons' advertising interval but also with the smartphones' scanning and sleeping times [23]. Two samples for each variable scenario were taken. Then, the average between those samples was calculated. According to the documentation [23], a smartphone will detect the entrance on a region, in the worst case, in a complete cycle (sleeping time + scanning time).

V. Results

The results from the executed tests are now presented and briefly analyzed.

A. QR Codes

The reading speed of the QR Codes in different light levels was quite regular, not varying much when different illumination levels were present. It was however possible to determine a minimum level needed to perform the readings. This level is 4 lx, and it corresponds to the minimum lighting level needed for the reading process to be performed successfully. When the codes were in an environment in which the illumination was lower than this value, the codes were not read successfully. This might be a challenge in bus stations at night, with low lighting, requiring an extra light source, such as the phone's flash. In addition, the two codes that were used were read at different distances and it was determined that the maximum distance that the smaller one (5.82cm x 5.82cm) could be read, is approximately 0.5m (M=589.5ms SD=232.6ms). As for the bigger one, this distance is approximately 1m (M=502ms SD=18.4ms). In this case, the consequence of doubling the size of the code, resulted in doubling the maximum distance at which the code can be read. Also, when the code is read nearby, the reading process might be inconclusive, therefore the minimum distance for successful reading is dependent on the code size. Fig. 4 shows a chart presenting the average reading speed of the two codes, at different distances. In the cases where a column is not shown, the reading failed.

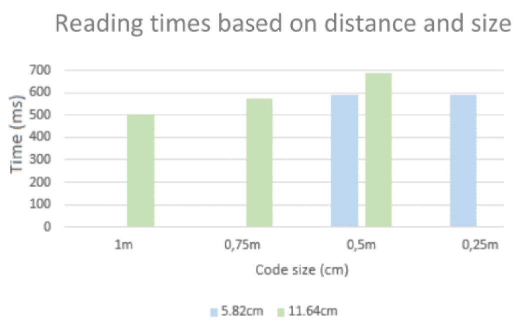

Fig. 4. Reading speed of the QR Codes, based on distance and size

Finally, in order to analyze the reading speed under different illumination levels, in the valid lighting conditions (>= 4 lx), three different levels were used: high (~ 80 lx), medium (~ 20 lx) and low (~ 5 lx). The codes were placed and read in different locations, that provided the Android light sensor with these values. Fig. 5 presents the average results of these readings, in which only one column was used to represent the values under the previous conditions, for both code sizes.

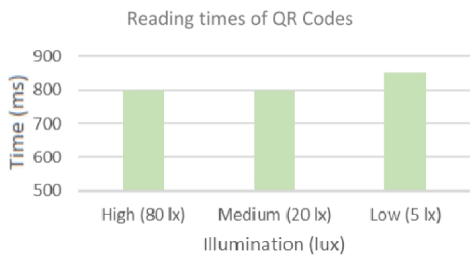

Fig. 5. Reading times of the QR Codes, under different illuminations

It is possible to conclude that the reading speed is approximately the same under different illumination and distances. This shows that when appropriate conditions are met during the reading process, stable reading speeds can be obtained. The results only account for the moment in which the camera is being pointed at the code, assuming the camera and the application are on.

B. NFC

In similarity with the QR Codes, the reading speeds that were achieved while performing the reading of NFC tags were stable. When reading the tags using the described materials, similar average reading times were obtained, with the exception of the glass test. In this test, due to the properties of the barrier, the mobile device could not read the code. Fig. 6 presents the average results of these readings.

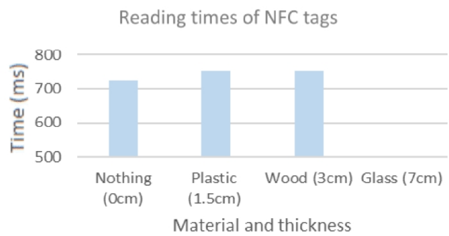

Fig. 6. Reading times of the NFC tags

It is possible to observe that the bars shown in the chart are almost at the same level, except the last one that does not show any value, considering that the reading failed.

C. Beacons

The distance calculation method used by beacons has shown several limitations in previous work [24, 25]. The results of the distance tests had the same outcome, with the distance estimations being inaccurate. As a result, the approach presented relies on the monitoring (proximity detection) method. This method detects entering and exiting a defined region and, given the relevance, the test results corresponding to this method are presented in more detail. The results showed accurate zone detections, with several sleeping times and beacon advertising interval combinations: the maximum time it should take to detect an entrance/exit is the sleeping time + scanning time (orange line), which was mostly confirmed (the theory only failed in ≈5.6% of situations in the entering detection test and ≈11.1% of situations in the exit detection test). Scanning times inferior to 1s were not reliable. The scanning time should be greater than the beacon's advertising interval to assure reliability.

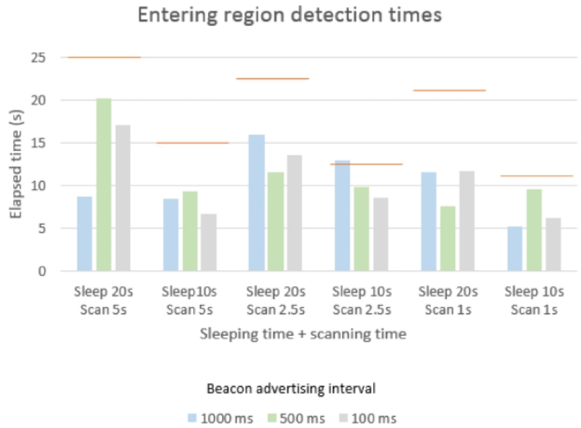

Fig. 7. Entering region detection times

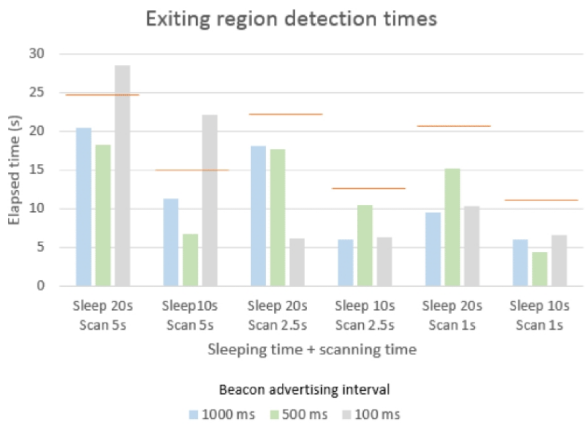

Fig. 8. Exiting region detection times

VI. Conclusions

These technologies offer different ranges of advantages to both the operators and passengers, providing services with different costs, interaction needs and visual customization levels. If the operators want to provide their users a service that requires the least interaction possible, BLE and beacons should be chosen, at the expense of a higher maintenance and investment cost. On the other hand, if a system with the lowest infrastructure costs is to be implemented, then QR Codes or NFC should be chosen, with QR Codes having the clear advantage of having a lower cost and NFC having a more pleasant interaction with the user. This comparison is one of the major contributions of this paper and it can be used to support the decision of which technologies to use in similar contexts.

The results allowed to conclude that QR Codes and NFC may easily be applied to mobile ticketing solutions in public transportation, especially considering the good reading speeds, robustness and level of maturity, in which a trade-off between cost and ease of use should be considered. However, QR Codes carry more restraining factors than NFC tags due to the conditions present in transportation stations. In some cases, it might be dark in the station, and as such methods to address these conditions are required. One solution for this is the usage of flash present in the smartphone for dark environments, or by producing larger codes. Finally, as for NFC, from the tests that were performed, it can be seen that this technology works well with the expected materials being found in stations, like plastic.

As for the use of beacons (and BLE) it is possible to determine that it is feasible but can be enhanced and made more reliable as the technology improves. Currently, beacons could not be used reliably if an estimated distance is required, but may be used when knowing if a user is nearby is enough (given the detection time results).

The proposed and analyzed approaches make use of the considered technologies and have the possibility to revolutionize the ticketing infrastructure, as it exists today, providing a contribution for the public transportation area. These approaches allow users to gain more control over their trips and use a more customized and user-friendly process while allowing operators to avoid installing and maintaining complex and expensive infrastructures and to collect more information.

Future work consists on implementing prototypes of the approaches and later test them with users in a real context.

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