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APPLICATION OF FUZZY LOGIC IN A SECURE BEACON–BASED GUIDANCE SYSTEM FOR PUBLIC TRANSPORTATION

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Promoting the use of public transport is increasingly urgent in our society, both to reduce traffic congestion, air pollution and stress levels, and to ensure the high level of mobility demanded by citizens. The lack of continuous on-trip assistance for public transport users discourages many travellers. Thus, the main objective of this work is to design a personal digital travel companion for outdoor location and event detection based on Bluetooth Low Energy, which can be used for intelligent transport technology. After analysing the functional requirements, the proposal is implemented as a mobile application for beacon-based event detection. The system includes an algorithm aided by fuzzy logic to determine the action to be carried out by the user at all times, being able to distinguish between different possible events when more than one beacon is detected. To defend the scheme against possible attacks based on beacon forgery or user tracking, the proposal includes different forms of authentication for data sent from beacons and data sent from the mobile application. The results obtained in simulations show that the proposed system is a viable guidance solution for public transport, including energy saving as one of its main advantages.

Keywords: public transport, guidance, location system, Bluetooth Low Energy, fuzzy logic.

1. Introduction

Massive population growth worldwide (7.9 billion in July 2021 according to most United Nations estimates (DAMADICS, 2021)) and its demand for travel in recent decades have caused many roads to become overcrowded. It generates serious mobility issues related to frequent traffic jams, consequent excessive air pollution and noise levels harmful to health. These problems are especially aggravated in cities, where there is a massive daily movement of commuters. Therefore, one of the greatest challenges of today's society is to improve people's mobility, from the point of view of the sustainability of large cities. To address this drawback, it is undeniable that the best solution relies on public transport.

Public transport must face a number of challenges to truly contribute to sustainable mobility of travellers. First, punctuality, travel time, and frequency of transport have a major effect on customer satisfaction with the service. Therefore, public transport must become a more optimized option for users, compared with private means. Very often we see that public transport and its schedules are not optimized, which causes delays for users. Another challenge is to balance the cost of transportation fares. They should be more profitable for commuters to use public transport rather than their own vehicles. Finally, the third challenge involves providing public transport with more user-friendly, convenient and customer-oriented features. This work aims to tackle this last challenge.

In large cities, many users may find it difficult

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to use the public transport network. Thus, the large number and variety of options and the usual saturation of transport lines generate confusion and stress in users. Among the most vulnerable user groups are the elderly, the visually impaired and tourists. In the case of the first user group, that is due to the fact that, with advanced age, cognitive and sensory abilities decrease, and this produces disorientation on public transport. This is an increasingly important problem because it is estimated that the percentage of elderly people will double by 2050, reaching 22% of the total population (United Nations, 2019). In the last case, that of tourists, the problem is due to the ignorance of the place and the problem system. On the positive side, cities are progressively incorporating technological elements and Internet of things (IoT) elements. They facilitate the interaction of citizens with urban elements, improving their quality of life (de Blasio *et al*., 2016). All the reasons listed above justify the need for the proposal presented in this paper, consisting of a system that allows users to be guided during their journeys via on public transport.

The designed system uses Bluetooth Low Energy (BLE) beacons for outdoor location and event detection, applied to public transport (Faragher and Harle, 2015; de Blasio *et al*., 2017b). It relies on a mobile application that is installed on users' mobile devices, allowing them to position themselves and detect events during their trip. Predefined events are detected through an algorithm based on fuzzy logic to determine what is happening during the journey. In this way, users can know both where they are with respect to the transport system, as well as what steps they have to take next. These could be either boarding the next bus or, the remaining stops until they have to get off the transport.

In this paper we present a prototype that has been developed as a concept trial for the proposed personal travel companion. It is based on a mobile application that notifies users of upcoming points of interest such as public transport stops, and alerts them when it is time to get off the vehicle.

The paper presents a guidance system for public transportation which uses BLE and LTE technologies. The assistance begins at the moment the user decides to take a bus, and ends when the destination is reached. In addition, the system considers the possibility that users take an incorrect decision. In this case, the system provides them with the corresponding instructions to correct the error and reach the desired destination. The proposed system is easy and affordable to deploy because BLE beacons are inexpensive and LTE is the most widely used wireless cellular technology today. Regarding security, this paper presents a system that tries to avoid different types of attacks. Specifically, beacon spoofing, man-in-the-middle on server connections, and user tracking are discussed. Finally, fuzzy logic is used to avoid situations in which a system with incomplete information may fail. In this way, the implementation allows correct identification of the events that are actually occurring.

The structure of the paper is as follows. In Section 2, some works related to the proposal are mentioned. In Section 3, the proposed system is described, including the reasons why it uses BLE, outdoor location and event-detection systems, and the fuzzy logic approach. Section 4 analyses the proposed system's security problems and their solutions. In Section 5, the results of the performed simulations are detailed. Finally, in Section 6 the paper ends with some conclusions and a discussion of future work.

2. Related works

In this section several related research publications are mentioned, classified into the following categories: public transport improvements, guidance systems, location solutions and proposals based on fuzzy logic. The methodology has been based on several comprehensive literature reviews from sources such as electronic databases and Google Scholar, focused on those four topics. Those reviews showed that, unlike all the selected works mentioned below, the assistance and guidance system proposed in this work is based on a location system designed for low consumption. This is thanks to the use of BLE and no other more resource-consuming technologies, such as the satellite-based Global Positioning System (GPS), the Universal Mobile Telecommunications System (UMTS) or Wireless Fidelity (Wi-Fi). For this reason the use of BLE becomes a great advantage on very long journeys. In addition, the BLE-based proposal is for outdoor location, which implies a different use than most BLE applications on location, which focus on indoor situations.

Although many of the proposals for outdoor location are based on GNSS technologies, there are numerous advantages to the novel approach proposed in this paper for using BLE technology for outdoor location:

- Unlike GPS, which can have areas of darkness in cities that prevent signal reception in places of high building density, the proposed decentralized, local-range architecture of BLE beacons does not have this drawback.

- The overall energy consumption of the proposed solution is low. The main reasons are as follows: BLE is a short range communications protocol, the transmitters or beacons are battery powered and their power consumption is in the range of 0.075–0.4 mW (Mackey and Spachos, 2019), the power consumption of BLE receivers is in the range of 8–10 mW (nRF5340, 2022).

- The personal digital travel companion is a standard application whose consumption is mainly determined by the hardware it uses, which in our case is the BLE receiver incorporated in the mobile phone or tablet. The highest consumption of the application is when the radio antenna of the BLE receiver is on, which causes a minimal increase in energy consumption, with baseline battery drain of 0.63–1.17% per hour on some Android mobile devices (Czurak *et al*., 2018).

- The location accuracy offered by this technology is high. In this sense, there are solutions that propose the combined use of GNSS and BLE (Luo *et al*., 2021).

Fingerprinting-based location has to face some drawbacks that question its use under certain circumstances: signal noise produced by the continuous movement of people and objects, data collection conducted in the constant presence thereof, multipath fading, non-line of sight (NLOS) conditions, variable humidity conditions, signal strength variance between diverse devices, etc. Different techniques have been proposed to overcome these problems, such as recording fingerprints as signal strength ratios between pairs of emitters instead of absolute signal strength values, developing an automatic method based on mapping that avoids calibration by learning from on-line measurements, taking RSSI differences between each pair of transmitters instead of taking absolute values and taking the mean value, or the maximum of the mean value of RSSI for different receiver orientations (Kjaergaard, 2011; de Blasio *et al.*, 2017; 2018).

Finally, the use of fuzzy logic is an added value to avoid false positives, because variations in the intensities of different BLE beacons could cause the algorithm to generate false events.

2.1. Public transport improvements. In recent years, a great deal of research has been carried out to try to solve different challenges of public transport. Concerning punctuality and frequency, Gurmu and Fan (2014) propose a model based on artificial neural networks that can provide an accurate prediction of the frequency of travel times to give real-time information to both users and transport managers. Regarding travel time and transport speed, StreetsblogUSA (2021) proposes the consolidation of stops by studying their location and use. Besides, it advises streamlining routes by cutting deviations and eliminating duplicate routes, transit signal management giving priority to public transport and creation of fast transit lines. In order to estimate the travel time of the whole transportation network, Cao *et al*. (2022) give a system of linear equations which is constructed with the user equilibrium principle and observed data. With respect to travel costs, Pätzold *et al*. (2018) analyse what a cost-optimal public transport plan looks like, proposing three models in which public transport is benefited in terms of costs. Finally, in terms of convenience in the use of public transport, numerous studies to improve infrastructures (Dell'Acqua and Wegman, 2017; Lee *et al*., 2015), user feedback (Stelzer *et al*., 2016; Dridi and Kacem, 2004) and payment methods (Ferreira *et al.*, 2017; 2021) have been conducted. These works propose analyses and solutions to improve waiting times, transits, costs and infrastructures. None of them focus on what discourages many travellers from using public transport. One of the biggest drawbacks is the difficulty of using the public transport network in big cities. Unlike the previous works, this one proposes a system that assists the user of public transport, from origin to destination and throughout the journey.

2.2. Guidance systems. Numerous studies and proposals about guidance of people in public transport have been carried out. First of all, in the paper by Rathod and Khot (2016) a smart public assistance system is proposed for public transport, where travellers can use their smartphones to track transport or confirm the current and next stop with arrival times, among other functionalities. Second, Foell *et al*. (2014) present a mobile application for urban bus passengers, with the ability to recognize and track public transport using GPS and Wi-Fi. Also, for urban bus riders, Handte *et al*. (2016) present an IoT enabled navigation system that provides micro-navigation and crowd-aware route recommendation. Another study, by Barbeau *et al*. (2014), proposes a mobile application that works as an open source traffic information system. Zhang *et al*. (2011) present a multi-modal system based on GPS, which provides its users with information on transport, traffic, parking, etc.

The work of Czogalla and Naumann (2015) describes a system for indoor navigation in public transport transfer buildings based on smartphones. The system includes sensors, a camera, Wi-Fi, GPS, Bluetooth and inertial measurement units so that navigational aids collected from sensors provide en-route orientation. This proposal is focused on pedestrian indoor location while our approach would work both indoors and outdoors. Another related paper, by Christmann *et al*. (2008), presents a solution to accompany travellers in all steps of using local public transport, including a customized support system based on software and a client-server paradigm that employs GPS, UMTS or Wi-Fi.

The aim of all proposals presented in this subsection is the guidance of people in public transport using mainly GPS, UMTS and Wi-Fi. As we will see in the next subsection, these technologies have certain drawbacks.

This work proposal uses BLE technology, which is much less expensive both in consumption and in monetary terms regarding its deployment.

2.3. Location solutions. Concerning the location system, most of the research carried out has focused on indoor location. Zhu *et al.* (2014), Pu and You (2018), Faragher and Harle (2015), Lin *et al.* (2015) or Zhu *et al.* (2014) show systems based on beacons and BLE to locate users in places where GPS coverage is limited or null. Other works (Yang and Shao, 2015; Huang *et al.*, 2015) make use of different technologies such as Wi-Fi or radio frequency identification (RFID) for indoor location. However, when it comes to outdoor location, few alternatives to GPS have been proposed. Alnahari *et al.* (2017) show a study on the development of a location system, both indoor and outdoor, based on a network of wireless sensors with an average square error of 64.5 cm for indoor location and 123.0 cm for outdoor location. Mahyuddin *et al.* (2017) describe the concept and principle of each technique and explore several details of location techniques using Long Term Evolution (LTE).

BLE technology has low battery and data consumption but its biggest problems are a low signal range and availability. On the other hand, LTE has very high coverage and availability requirements; however, it has the drawback of high consumption of battery and data. For this reason, and unlike the previous works, we propose the use of a hybrid system. In this way, we manage to keep the best of both technologies. A particularly interesting case is the development of an application that uses a mobile device to help in the detection and avoidance of obstacles in real time for people with visual disabilities, to allow them to navigate independently in indoor environments, cf. Jafri and Khan (2018).

Another related work is the paper by Cheng *et al.* (2016), which describes a guidance system based on GPS, BLE beacons and near field communication technology. Castillo-Cara *et al.* (2016) developed a hybrid system that visually impaired people may use indoors/outdoors, based on the application of GPS and BLE technologies along with a mobile device. These papers show interesting results on the technologies used in our work, these being GPS and BLE. However, the scope is different since they focus mainly on people with visual disabilities. In addition, none of them contemplates their use as a means of transport.

2.4. Proposals based on fuzzy logic. Fuzzy logic has been widely used in different fields. For instance, Şen (2017) proposes a decision-making model employing fuzzy logic that can be used by business management experts. Moorthi *et al.* (2018) demonstrate the applicability of the fuzzy inference system to regulate the operations of water resource systems. More specific uses related to this work are described, for instance, in the works of Orujov *et al.* (2018) and Schott *et al.* (2017). The former presents experimental research of indoor location algorithms based on the intensity of the signal received from BLE beacons, as well as a proposal of two fuzzy logic systems for the location and selection of the best location method. The latter work proposes an indoor location system based on the inertial measurement unit, which is assisted by a fuzzy inference system. These works demonstrate the usefulness of fuzzy logic both within the scope of this paper and other study fields. In this specific case, it will be used to avoid false positives in event detection, based on different parameters. One of them will be the signal strength as mentioned in these works, but not only.

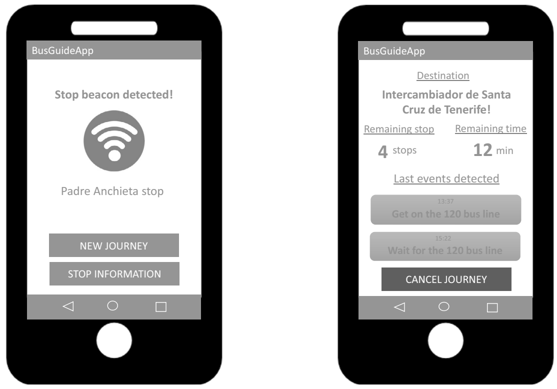

Fig. 1. Screenshots of the proposed mobile application.

3. Proposed system

The system presented here consists of a mobile application that uses BLE beacons and a fuzzy logic system to guide users through their journey on public transport. Before proceeding further, it is worth mentioning that this work is focused on a specific type of public transport, which is bus. However, the proposed system could be scalable to other types of public transport such as train, tram, etc.

The aim of this mobile application has been to help people travel by public transport. Besides, it is user-friendly, making it work well with smartphones. Since the number of people in Europe over the age of 65 will almost double from 85 million today to 151 million in 2060,[1] this proposal will allow them to travel safely and independently on public transport. The application has

[1] https://research-and-innovation.ec.europa.eu/research-area/health/human-development-and-ageing_en.

Table 1. Comparison of BLE with other closely related technologies.

Technology	Energy consumption	Range	Speed	Frequency
Bluetooth 3.0	Less than 30 mA	<30 meters	24 Mbps	2.4 GHz
BLE	Less than 15 mA	50 meters (150 meters in open field)	32 Mbps	2.4 GHz
Wi-Fi Direct	Related with range (>BLE)	200 meters	250 Mbps	2.4 or 5 GHz

been developed for the Android operating system, since it currently reaches the greatest number of users compared with its competitors (DeviceAtlas, 2018). Therefore, it will allow the system to be used by a greater number of users.

3.1. Functionalities. The main functionalities of the mobile application are the following: the application is automatically launched when it detects a transport stop; it can plan a journey providing the destination; it can make automatic payments; it can give instructions on how to reach the goal. Figure 1 shows the mobile application screenshots. The image on the left corresponds to transport stop beacon detection. At that time, the user has not selected the destination yet. In order to start a journey, the user must do so. When the user gets off of at the correct bus stop, the application is closed.

On the right, the image shows the screenshot corresponding to a user who is on an ongoing journey. It provides real-time information of the destination, remaining stops and a set of instructions to reach the goal.

The following subsections include a detailed explanation of the reasons for choosing BLE technology. Besides, they provide the description of the systems proposed to locate users on the trip and to know what type of event is taking place at all times.

3.2. Preliminary deployment environment. The scenario in which the guidance system will be tested is a local bus company called Global Salcai-Utinsa. It operates on the island of Gran Canaria (Canary Islands, Spain) and is one of the main transport companies there; it has a fleet of 308 vehicles operating on a transport network with 2686 stops, 121 different routes and 2395 daily routes. Every year, its vehicles travel around 25,000,000 kilometers, transporting 20,000,000 passengers with a fleet of 310 buses (Cristóbal *et al.*, 2018).

The most important elements are the user, the bus and the bus stop. Access to the bus is always through the front door of the vehicle, although the bus can be exited through either the front or the rear door. Hence, the transport beacons will be located in both doors. The bus stop always has at least one bus signal so the stop beacon will be located in it. In order to obtain real data, we will perform the evaluation in a bus station near the university. We will use one bus stop and one bus line, and we will use three different mobile phones: BQ Aquaris X, Galaxy A50 and Google Pixel. The first step will consist of ensuring correct mobile application operation for the three smartphones, since different parameter settings will be necessary depending on the specific device model. The second step will be to design a data structure to store the information of the stops and transport vehicles in a Firebase database, as will be explained in detail in Section 3.4. Finally, user app performance will be tested with people of different ages.

3.3. Bluetooth Low Energy. BLE 4.0 was introduced in 2009 as an extension to Bluetooth Classic. Improved versions, 4.1 and 4.2, were presented in 2013 and 2014, respectively, introducing greater data range, greater packet capacity and much higher-strength secure connections. Low-power devices that broadcast BLE signals are known as beacons. They are small and lightweight enough to be fixed to walls or other areas and can provide users with advanced services, i.e., ones that are directly related to the location. This is possible thanks to BLE protocols such as Google's Eddystone. These devices can exchange data with other devices in advertising mode, that is, sending message packets regularly to other listening devices, or in connection mode, that is, transferring data in a one-to-one connection (Dasgupta *et al.*, 2016; de Blasio *et al.*, 2018). In this work they are used as detection points in outdoor location and event detection systems. The main advantage of BLE is its low power consumption, which not only has a positive impact on mobile devices of users but also on the beacons themselves, making the autonomy of their batteries extend over time. In Table 1 we can see some of the main features of this technology compared with other very related technologies (Techspirited, 2021; 330ohms, 2021; World, 2021).

The information reveals that BLE stands out in its energy consumption feature, which is lower than for other technologies. In addition, the signal has a range such as to cover the dimensions of a bus and reach the stop beacons, allowing the detection of events during the journeys. On the other hand, in terms of speed, it is not an important feature in this system because it is only necessary to detect the signal of the beacons both for the location of the user and for the detection of events. Finally, it is worth mentioning that BLE 4.0 has been used in the implementation due to its widespread application, although the recently introduced Bluetooth 5.x versions with improved specifications are already available. The major features of Bluetooth 5.1, for example, are the ability to know the location of other devices and to identify the direction from which their signal is coming. All this is achieved by means of two key concepts: the angle of arrival and the angle of departure.[2]

3.4. Outdoor location system. The outdoor location system based on beacons proposed in this work allows users to be located during the journey, as well as shows them information related to their destination so that they can confirm that they are progressing properly on their routes. In Fig. 2, a scheme of the outdoor location system is shown.

BLE beacons send periodic broadcast signals every second that are uniquely identified by their media access control (MAC) address. On the receiver side, the received signal strength indicator (RSSI) is evaluated so that any value greater than -65 dBm indicates a beacon-receiver distance of less than 1 m. However, several papers on locations based on the RSSI from BLE beacons (Rida *et al.*, 2015; Faragher and Harle, 2015) indicate fluctuations in the RSSI and errors down to a meter, especially in real-world results, related to the presence of fast fading and to the orientation of the device as well as the user's hand position.

To save battery power, the timing of the BLE scans is organized so that during a 10-second interval a BLE signal scan is performed by the mobile application to detect any existing and known beacons in the vicinity. If a BLE beacon is detected, the scan interval is reduced to 1 s until the RSSI value reaches the defined maximum value of -65 dBm or passes a maximum peak.

Once the mobile application detects the presence of a beacon, through its MAC it makes a query to the server. This server has a database where each beacon is linked to a geolocated position, as well as other information of interest to the user such as the name of the stop, the lines he/she uses, the bus on which they are on, etc. For the system to function properly, a distinction is made between fixed beacons located at stops and mobile beacons located within public transport vehicles. The locations of the former are stored in the database, while those of the latter only provide information about the current line. Although the user's position between two bus stops is not necessary for the purposes of our system, an alternative location system could be used on the user's mobile device, such as GNSS or the mobile data network. This information is used to provide data about the next action they should take during the journey. Once the information required on the server has been retrieved, it is sent to the mobile application to inform the users.

This process is carried out periodically at a certain time interval so that the information shown to the user is continuously updated. When more than one beacon is detected, the one with the stronger signal received by the user is used.

3.5. Beacon-based event detection. In this work, an event is defined as an action that a user performs while on public transport. These events correspond to boarding public transport, paying automatically at the beginning of the journey, detecting a stop, getting off the transport after detection of a stop, etc. These events are controlled by a system based on beacons, which is responsible for launching the corresponding event when a specific beacon is detected. This system uses an algorithm that, through a set of conditions, manages to predict which could be the event that is occurring. However, event detection is not a completely deterministic operation. The variation in intensity generated by beacons' signals can provide different results in similar situations. For example, when the bus arrives at a stop, our mobile digital assistant will almost certainly detect both the beacon at the stop and the beacon on board the bus, which makes it difficult to distinguish, without further information, among different possible events: a passenger boarding a bus, a passenger arriving at a new stop on a journey already started, or a passenger getting off at a bus stop. For this reason, we propose a second subsystem based on fuzzy logic, which is in charge of inferring if the event proposed by the algorithm can really be taking place, using a dataset of nal intensities to deal with the issue of fluctuations in the RSSI and errors in estimated locations. Therefore, the system is able to detect the correct event using the proposed fuzzy logic system.

As in the case of the outdoor location system, the low energy consumption on users' smartphones thanks to the use of BLE technology is the main advantage of this system. In addition, as we will see in the experimental results section, the system provides greater precision to perform required actions during the journey. This could not be possible with other geolocation technologies like GPS, such as, the detection of a user who boards a means of transport to launch the automatic payment action.

Related to the operation mode, the event detection system, based on beacons, is initiated when the mobile application detects one or more of those. The application obtains the MAC from the beacons and sends it to the server. If the received MACs are registered in the system, the corresponding action is carried out using the proposed algorithm. Otherwise, it is discarded. On the other hand, a data set of 10 RSSI values (Bluetooth, 2021), from each detected beacon, is also sent to the server. The values of each data set are collected at an interval of 0.2 seconds and used to feed the fuzzy logic system. Once a beacon is detected, this interval is used to obtain a bunch of RSSIs. The challenge is to get accurate readings

[2]`https://blog.nordicsemi.com/getconnected/finding-your-way-with-bluetooth`.

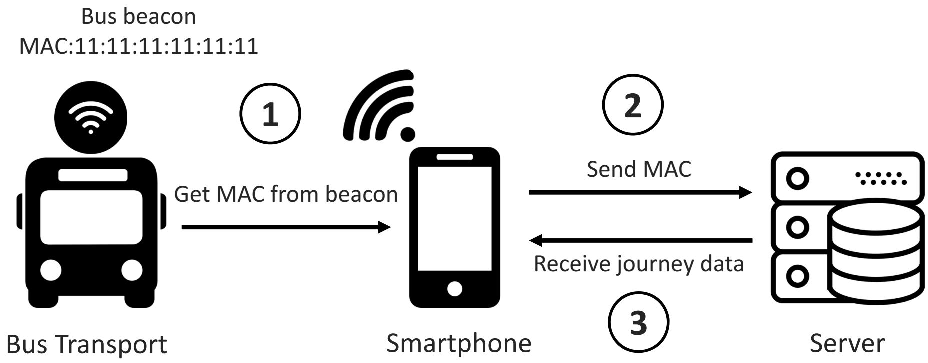

Fig. 2. Proposed outdoor location system schema.

of signal strength in a short period of time. Taking into account that the value of the RSSI depends on each manufacturer (Bluetooth, 2021), we need a set of values to translate them to linguistic terms and thus avoid a false positive. In addition, these data sets are sorted using the Quicksort algorithm (Hoare, 1962), discarding the two extremes to avoid possible peaks of intensity that could affect the fuzzy logic system. In Fig. 3 these steps are shown for a case in which two beacons are detected.

Once the data are sent to the server, it is first checked if the beacon belongs to some stop to the bus. In the first case, the user must select a destination in order to start Algorithm 1; at that moment the EXIST_JOURNEY variable is initialized as TRUE. In the second case, the server detects that the beacon belongs to some stop on the journey, if the user has started one. If the beacon does not satisfy either of these two possibilities, it is discarded and the mobile application will not perform any action. Otherwise, the algorithm is executed to determine the event that could be occurring. The pseudocode corresponding to the proposed algorithm is shown in Algorithm 1.

For simplification of the pseudocode, each event detected by the algorithm has been identified by an ID. Table 2 shows the meaning of each of them.

First, the algorithm checks whether he/she has just arrived at a public transport stop. Otherwise, if the user is already on a journey, the algorithm first checks whether the user is getting on or off the public transport vehicle. In the first case, automatic payment for the journey is carried out. In the second, it is checked if the user got off at a correct stop, at an incorrect stop, or if the end of the trip was reached. If the event detects both the beacon of the transport and that of a stop on the journey, the information of the journey will be updated to the user in the mobile application. The other cases contemplated correspond to the user leaving the BLE coverage during the journey, or errors that may occur during it.

Once the event has been determined by the algorithm, the fuzzy logic system is in charge of deciding if the event is finally taking place. In Section 3.6, the fuzzy logic approach is deeply detailed. Likewise, the tests performed to check the functioning of the event detection system using beacons, as well as the results, are shown in

Algorithm 1. Proposed event detection pseudocode.

```
if EXISTJOURNEY == FALSE then
  if STOPBEACON == TRUE then
    return 0;
  end if
  if (STOPBEACON == FALSE) & (TRANSPORTBEACON == TRUE) then
    EXISTJOURNEY = TRUE;
    return 1;
  end if
else if EXISTJOURNEY == TRUE then
  if (STOPBEACON == TRUE) & (TRANSPORTBEACON == FALSE) then
    if (isDestination(STOPBEACON) == TRUE) then
      EXISTJOURNEY = FALSE
      return 4;
    else if (isCorrectStop(STOPBEACON) == TRUE) then
      return 2;
    else
      return 3;
    end if
  else if (STOPBEACON == TRUE) & (TRANSPORTBEACON == TRUE) then
    return 5;
  else
    return 6;
  end if
else
  return 7;
end if
```

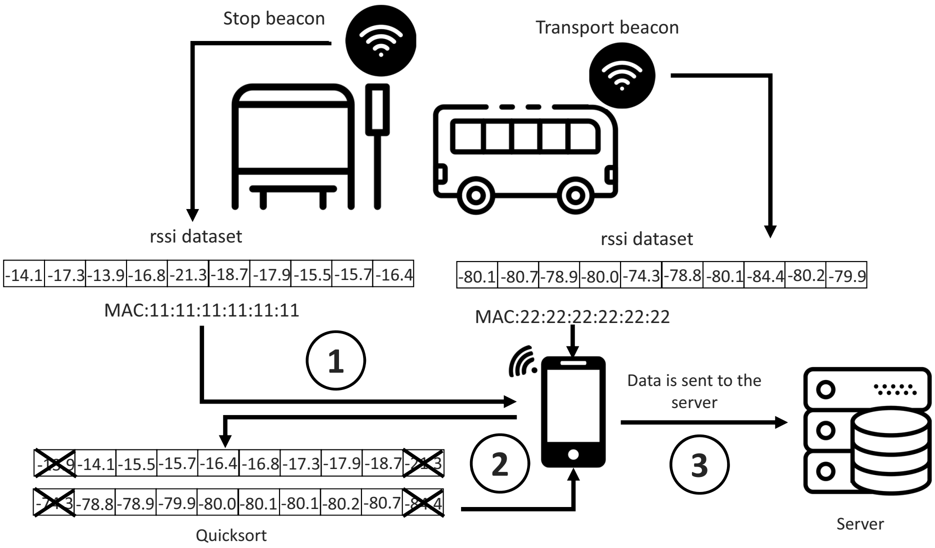

Fig. 3. Proposed beacon-based event detection system.

Table 2. Description of events shown in pseudocode.

ID	Event description
0	Arriving at a stop without any journey having been selected yet.
1	Boarding public transport and automatic payment of the journey.
2	The user gets off at a correct stop of the journey.
3	The user gets off at an incorrect stop of the journey.
4	Arrival at the destination of the journey.
5	Updating information when a beacon of the journey is detected.
6	Warning of low or no coverage from BLE.
7	Error trying to detect the event.

Section 5.

The proposed implementation could be modified without much inconvenience to avoid connections with the server during the journey. In this scenario, a passenger going to a specific destination, by indicating it to the mobile digital assistant, would download all the information required by the app: information about the route, stops, beacon information linked to the route to be taken, etc., so that the system would simply require connectivity with the server just before starting the journey, and all the remaining processing could be performed on the user's device. This way of operating is especially useful in scenarios of low connectivity during the trip. Obviously, it has the disadvantage of more intensive use that would be made of the user's device, with all that this implies from the point of view of energy consumption.

3.6. Fuzzy logic approach. Fuzzy logic (Zadeh, 1988) is a methodology that provides a simple way to obtain a conclusion from incomplete input information. Unlike a deterministic model, where the same output will always be generated by the same conditions, fuzzy logic allows for a wider range of decision-making. In this paper, this mechanism based on the Mamdani fuzzy inference method is responsible for making the final decision about whether the event detected by the algorithm is actually occurring. This is because sometimes some beacons are detected in an uncontrolled way and could generate false positives. As soon as a beacon is detected, the mobile application reacts promptly. Unfortunately, it could provide an unmanageable number of actions that would be infeasible, especially if they are false positives. Some of them are related to the following:

- avoiding the app starts when the user passes next to a beacon stop;
- avoiding the app determines the end of a journey when the user is next to a beacon;
- avoiding the app sends information when the user is next to a beacon.

The developed fuzzy inference system for the evaluation of events consists of five variables that are detailed below. The system has one output that indicates the variety level to check behaviour of the app on the basis of input parameters, i.e., TRUE or FALSE. The system is tested by entering the input values to check whether the given input is a possible real event or not.

In general, a fuzzy inference system consists of three steps: the fuzzification method, the inference engine using a knowledge base, and the defuzzification method.

First, the fuzzification method transforms the crisp number inputs into fuzzy sets. To confirm the detection of an event, a total of five linguistic variables have been used:

- TYPE: Corresponds to the ID of the type of event detected, detailed in Table 2;
- N_BEACONS: Number of beacons that have been detected to determine the event being checked;
- RSSI_MAX_DIF: The maximum difference between RSSI intensities of all detected beacons. A low RSSI difference could indicate that the user or the environment (transport vehicles) is not moving, so it is possible to avoid duplicate events in the same period of time.
- BUS_BEACON_STATE: The maximum RSSI difference that exists in the beacon that is of transport type. This value indicates if the transport vehicle is moving with respect to the user. When there is more than one detected beacon of the same type, the one detected with the highest signal strength will be taken into account.
- STOP_BEACON_STATE: The maximum RSSI difference that exists in the beacon that is of transport stop type. In this case, the value indicates if the user is in movement with respect to the transport stop. Like the previous linguistic variable, when there is more than one detected beacon of the same type, the one with the highest signal intensity will be taken into account.

Each of these linguistic variables has associated linguistic terms that represent different meanings. In the case of the TYPE and N_BEACONS linguistic variables, their linguistic terms correspond to the values of the ID and the number of beacons detected, respectively. In the case of the RSSI_MAX_DIF variable, its SHORT, MEDIUM and HIGH linguistic terms indicate how large the difference in RSSI intensity is. Finally, for the BUS_BEACON_STATE and STOP_BEACON_STATE linguistic variables, the linguistic terms STATIC and MOVEMENT indicate whether the RSSI values remain static or not. In Fig. 4, a graphical representation of some fuzzy sets is shown for the linguistic variables of TYPE and BUS_BEACON_STATE as an example. These graphs have taken singleton and triangular form, respectively.

Because in fuzzy logic systems the variables are constructed from previous experience, the linguistic variables used, as well as the linguistic terms and the values assigned for each interval, have been selected according to the needs of the problem analysed. For example, for the RSSI_MAX_DIF variable, it has been taken into account that the value of the RSSI depends on each manufacturer (Bluetooth, 2021). This means that the ranges for each linguistic term cannot be extended further, as in some cases the RSSI range may be shorter, which could lead to false positives.

As an example of the fuzzification method, an entry of 20 for the RSSI_MAX_DIF linguistic variable is fuzzified as SHORT with a value of 0.43 and as MEDIUM with a value of 0.57. As an example of a singleton graph, for the TYPE linguistic variable, an input value of 1 is fuzzified as linguistic term 1 with its maximum value, while the rest of the terms have a value of 0.

Once the input crisp values have been fuzzified, the next step is the inference engine. This step simulates human reasoning using a fuzzified set of values and a set of rules. These rules are found in a knowledge base and are of the IF-THEN type structure. In Algorithm 2, a set of knowledge base rules are shown, where IS_EVENT corresponds to the output linguistic variable and whose linguistic terms are TRUE (the event proposed by the algorithm is correct) and FALSE (the event proposed by the algorithm is incorrect). If more than one rule is met,

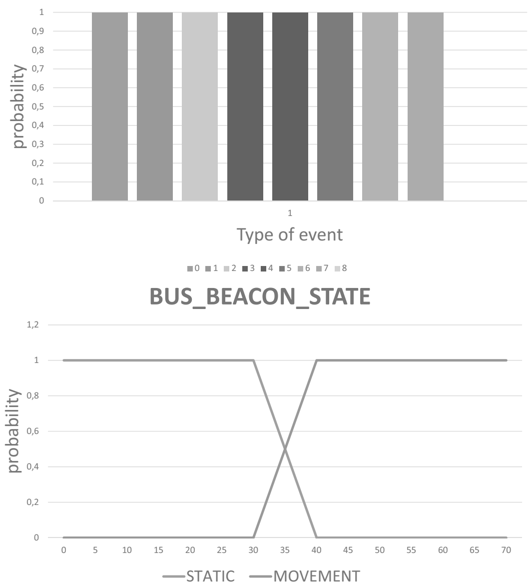

Fig. 4. Graphical representation of some of the proposed fuzzy sets.

Algorithm 2. Sample rule structure.

if $(TYPE == 0)$ & $(N\_BEACONS == 1)$ & $(STOP\_BEACON\_STATE == STATIC)$ **then**
  $IS\_EVENT = TRUE$;
end if
if $(TYPE == 2)$ & $(N\_BEACONS == 2)$ & $(RSSI\_MAX\_DIF == HIGH)$ & $(BUS\_BEACON\_STATE == MOVEMENT)$ & $(STOP\_BEACON\_STATE == STATIC)$ **then**
  $IS\_EVENT = TRUE$;
end if
if $(TYPE == 3)$ & $(N\_BEACONS == 2)$ & $(RSSI\_MAX\_DIF == MEDIUM)$ & $(BUS\_BEACON\_STATE == MOVEMENT)$ & $(STOP\_BEACON\_STATE == MOVEMENT)$ **then**
  $IS\_EVENT = FALSE$;
end if
if $(TYPE == 5)$ & $(N\_BEACONS == 2)$ & $(RSSI\_MAX\_DIF == HIGH)$ & $(BUS\_BEACON\_STATE == MOVEMENT)$ & $(STOP\_BEACON\_STATE == MOVEMENT)$ **then**
  $IS\_EVENT = FALSE$;
end if

all fuzzy sets are combined into a single fuzzy set using the fuzzy aggregation function AND.

Finally, the last step in the fuzzy logic system is defuzzification. This step is in charge of adapting the fuzzy values in crisp and accurate values again. This crisp value is in charge of determining finally if the event proposed by the algorithm is happening.

There are numerous methods that can be used to carry out this step, but it has been decided to use the center of maximum. It allows the typical numerical value to be the mean of the numerical values corresponding to the degree of membership at which the membership function was scaled. This method is identical to the Center of Area but with linguistic terms with singleton forms. The main advantage it provides is that a small change in input variables does not change the best compromise value for the output.

Once the final result is obtained, if it is positive, the event will be confirmed and the information necessary to execute the corresponding event will be returned to the mobile application. Otherwise, the event will be cancelled and will not be executed in the mobile application.

4. Security issues

This section describes security risks that could arise in the proposal presented in this paper, as well as security tools used to mitigate them. Specifically, three possible lines of attack are analysed: beacon spoofing, insecurity of server communication and user tracking.

4.1. Beacon spoofing. Beacons are essential elements in this proposal, since they allow the system to identify the stops and buses involved in the trips. Hence, a potential adversary could try to spoof the information provided by the beacons, which would cause a malfunction of the system, since, for example, it could lead users to unwanted destinations.

As has been presented in the previous sections, the beacons send their MAC to the server and, with this information, the stops or buses are identified. If this information travelled unauthenticated, an adversary could duplicate it on another beacon and provide information about an incorrect bus or stop. Therefore, the transmission of such information must be authenticated.

The standard authentication procedure for Bluetooth devices is developed according to a challenge–response scheme. There are several known beacon systems that try to avoid spoofing by using identifiers calculated with a cryptographic hash function. However, the need for synchronization makes this approach impractical for the proposal stemming from this study, where digital signature has been chosen as the basis for message authentication. BLE advertisement packets in the over-the-air signature transmission can only include a 2-byte header and a variable payload from six to 37 bytes. Thus, short signature lengths are necessary. That is why a short signature scheme has been chosen to sign beacon broadcast data. Specifically, the Boneh–Lynn–Shacham (BLS) digital signature (Boneh *et al.*, 2001), where signatures are elements of an elliptic curve group, has been applied in the proposal because, when compared with the well-known Elliptic Curve Digital Signature Algorithm (ECDSA), the BLS scheme requires only 160 bits. In particular, a 128-bit challenge is obtained from a combination of the 48-bit MAC address, a 48-bit timestamp, and a 32-bit random parameter. Timestamp in this context is only used to know if it is a new authentication or if someone wants to reuse another authentication message for a spoofing attack. That is, it is employed to force a different challenge sent from the server to the beacon. Once the mobile application receives this signed signal, signature verification can be performed and the verified message can be handled. The mobile application is also in charge of updating the public keys via a secure channel from a trusted key server. To reduce the computational and communication load, the mobile application can be configured to run message verification by random sampling.

4.2. Insecurity of server communication. In many applications, client-server communication takes place over the standard HTTP web protocol. In this protocol, when the application sends a request to the server, and the server answers; the information is sent and returned unencrypted. This means that an adversary could read the content of the communications through a man-in-the-middle attack.

The data that users and the server exchange can be confidential. This is, for example, the case of the username and password used to log in to the server. If an attacker can sniff this traffic, they could get to know information that allows privilege escalation and attack the proposed solution in different ways. Besides, this proposal sends information about the location of users, which can be considered sensitive data. Therefore, it is necessary to protect client–server communication so that privacy and trust are the most important aspects. This implies that the information must always travel between the client and the server encrypted.

Another important aspect is the authentication of the server so that the client must trust that the received information has been sent from the server with which they are communicating. Authentication prevents clients from communicating with malicious sites through deception. For this purpose, this work establishes the use of the TLS protocol in its highest version to protect client–server communications. The use of TLS allows for the application of the objectives of privacy and trust through encryption and authentication. By enabling TLS, the traffic between the client and the server is greatly strengthened and clients can use `https://` instead of `http://` to request content from the server.

4.3. User tracking. As mentioned above, one of the issues that users always worry about is the loss of privacy. This proposal sometimes uses the user's location so it might be thought that it is possible to locate users in real time. To solve this problem, in addition to the use of the aforementioned TLS protocol, an additional level of security has been added. In this case, pseudonyms that change frequently in non-fixed time intervals are used to identify users. However, since even despite changing pseudonyms the user could still be tracked if an adversary knows his/her potential start and end points, to cope with this situation, the proposed scheme applies the concept of fixed mixed zones to change pseudonyms. These mix zones have been defined in transport stops so that this makes it more difficult for an adversary to try to track a user. Thus, the mobile application changes its pseudonym after variable time periods in these defined mixed zones. Hence, this pseudonym update is communicated to the server through an encrypted and signed communication.

5. Experimental results

Two different case studies have been analysed to obtain experimental results. In both simulations, the viability of the event detection system using beacons has been verified with the proposed fuzzy logic approach. In the case of the outdoor location system, it has not been necessary to perform a simulation because its operation is based on a completely deterministic system. Given that the proposed outdoor location system is used to find the stops of the journey that the user is following, the system will identify the beacons via their MAC. Through a query to the server, the users can obtain all the updated information of their journey.

For the simulation of the event detection system, a total of two beacons were used, corresponding respectively to a stop and a transport vehicle. These beacons are located in such a way that they avoid all possible interferences, since the walls or other elements could cause the signal intensity to decrease.

5.1. First case of study. This case of use will be activated when the user gets off the bus, at a bus stop. The application must detect if it is the correct bus stop. If so, the application is finished. Otherwise, the user will be instructed on how to proceed. The technical details of how the application works are detailed below.

The environment for the first tests is shown in Fig. 5, where the smartphone corresponds to the user and their location during the simulation.

The event to be detected is the getting off of the users at a correct transport stop during their journey. To do this, the first step in detecting the event is to identify and obtain the RSSI values of both beacons. The results are shown in Fig. 6. These values are then sorted using the Quicksort algorithm to delete the outliers. Although in this experimental case these values are very similar to the rest of the dataset, there are specific cases in which peaks of very high or low intensities could affect the fuzzy logic system.

Next, the MAC identifiers of the beacons, as well as their RSSI datasets, are sent to the server. There the first step is the identification of the possible event that

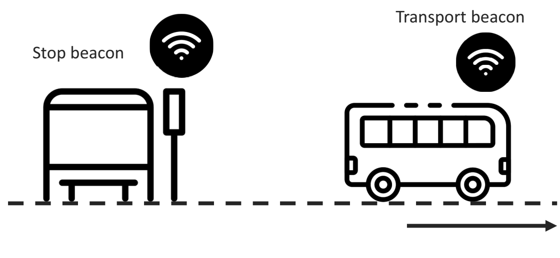

Fig. 5. Scheme simulation of the environment.

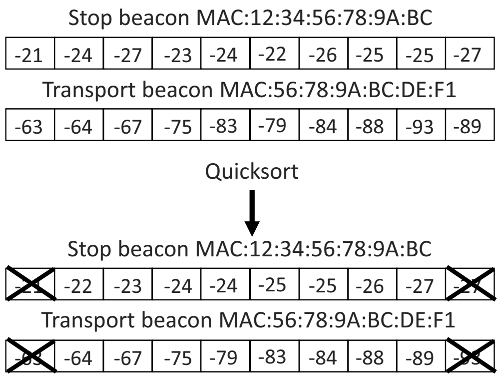

Fig. 6. Vectors of RSSI values taken for simulation.

Table 3. Input values in the fuzzy logic system.

Linguistic input variables	Values
$TYPE$	2
$N\_BEACONS$	2
$RSSI\_MAX\_DIF$	67
BUS_BEACON_STATE	5
$STOP\_BEACON\_STATE$	25

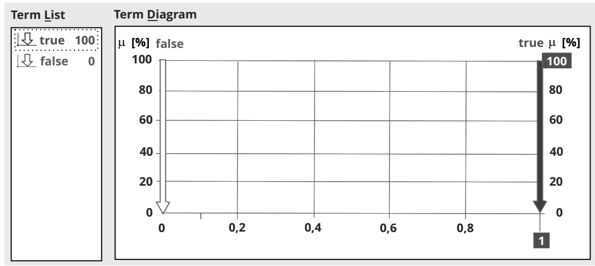

Fig. 7. Result of the fuzzy logic system for the current simulation.

Algorithm 3. Current rule executed in the fuzzy controller.

if $(TYPE == 2)$ & $(N\_BEACONS == 2)$ & $(RSSI\_MAX\_DIF == HIGH)$ & $(BUS\_BEACON\_STATE == MOVEMENT)$ & $(STOP\_BEACON\_STATE == STATIC)$ **then**
    $IS\_EVENT = TRUE$;
end if

is happening through the use of the proposed algorithm (see Algorithm 1). First, it checks that the user is actually making a journey. Then, it verifies that the beacon which corresponds to a stop is being detected with a high signal strength. Finally, it examines whether the beacon related to the transport vehicle is perceived with low intensity. This would be the normal control flow when a user gets off at a public transport stop. Finally, the MAC corresponding to the beacon of the transport stop is sent to the server. It is verified that it effectively coincides with a beacon associated with the target stop and, therefore, with the end of the journey.

Once the algorithm determines the possible event that is occurring, it is the turn of the fuzzy logic system. First of all, the input values of the different linguistic variables are prepared (see Table 3).

After introducing the input crisp values into the fuzzy logic system, these values are fuzzified and sent to the inference engine. The fuzzy controller rule that has been activated in the inference engine is shown in Algorithm 3. In this case, only one rule has been activated, but if there had been more than one, a fuzzy aggregation function AND would have been performed.

Finally, the defuzzification step converts the fuzzy output values into crisp values. As can be seen in Fig. 7, the result obtained gives the maximum probability that the event proposed by the algorithm is occurring. Hence, the event is accepted and the server sends to the mobile application all the necessary information to notify the user about the event on the journey.

The results of the simulations have been promising but only once the system is fully deployed in a public transport infrastructure can a broader view of the effectiveness of the proposed system in a real environment be obtained. For example, unlike other related works that use GPS technology built into the device (Zhang *et al.*, 2011), external factors such as weather, battery or time could affect the signal of the beacons and therefore event detection.

5.2. Second case of study. The second case of use presented in this work shows the support provided by the application during the user's journey to reach the final destination. The aim is to indicate whether the user is on the correct bus or not. During the trip the system will check whether the turned up beacons correspond to the expected stops for the selected route.

Besides, to test the operation of the application, as in the previous case, this section analyses three different states in which the application can be found, as well as the possible problems associated with the technology used. First, as shown in the previous section, the system receives information from two different beacons when the user is near a bus stop. Afterwards, the RSSI values are obtained and sorted using the Quicksort algorithm. Although the intensity of the beacon corresponding to the bus is, in general, greater than that provided by the stop, it is the information provided by the second beacon that allows the system to make correct decisions.

The RSSI values and the MAC information are sent

Stop beacon MAC:12:34:56:78:9A:BC

~~-27.0~~	-28.0	-29.2	-29.6	-30.1	-31.2	-31.8	-32.1	-32.5	~~-33.0~~

Transport beacon MAC:56:78:9A:BC:DE:F1

~~-33.0~~	-34.9	-35.7	-35.9	-36.0	-37.0	-37.4	-37.9	-38.2	~~-38.3~~

Fig. 8. RSSI values taken for simulation.

Table 4. Input values in the fuzzy logic system.

Linguistic input variables	Values
TYPE	5
$N\_BEACONS$	2
$RSSI\_MAX\_DIF$	65
BUS_BEACON_STATE	21
$STOP\_BEACON\_STATE$	60

Stop beacon MAC:12:34:56:78:9A:BC

~~-63.0~~	-63.4	-65.2	-72.6	-75.1	-84.3	86.3	-88.1	-90.2	~~-90.6~~

Fig. 9. RSSI values taken for simulation.

Algorithm 4. Current rule executed in the fuzzy controller.

1: **if** $(TYPE == 5)$ & $(N\_BEACONS == 2)$ & $(RSSI\_MAX\_DIF == HIGH)$ & $(BUS\_BEACON\_STATE == STATIC)$ & $(STOP\_BEACON\_STATE == MOVEMENT)$ **then**
2: $IS\_EVENT = TRUE$;
3: **end if**

to the services. With this information, once again, the server identifies the event that may be happening. The system checks that the user is traveling, but unlike in the previous case, the beacon corresponding to the bus is detected with a higher intensity and that corresponding to the bus stop, as we can see in Fig. 8, is detected with a lower intensity.

Following the steps of Algorithm 1, the system returns the value corresponding to updating information when a beacon of the journey is detected. In addition, with the MAC information of the corresponding beacon, the system can determine whether it is a correct bus stop beacon according to the line selected by the user or not. In this case, as mentioned before, with this information, the system can analyse three different cases that are summarized below:

1. It is a stop corresponding to the line selected by the user.
2. It is not a stop corresponding to the line selected by the user but it is on the correct route.
3. It is not a stop corresponding to the line selected by the user and it is not on the correct route.

The first and second cases are processed by the system in a similar way, as long as in the second case the bus does not stop because nobody wants to get off or are there no passengers waiting to get on the bus. After several tests, the obtained results are similar. The results of one of them are shown in Fig. 9.

Once the service applies the algorithm and returns the possible event that is happening, it is time to apply the fuzzy logic system. The values sent to the inference engine are shown in Table 4.

Also, in this case, a single rule has been activated as shown in Algorithm 4.

As in the previous case, the obtained results return a high probability that the event proposed by the algorithm is happening. Hence, the event is accepted and the server will send information to the application indicating that the user is on the correct bus.

A variation of this proposal that provides the same result even with different values is the one where the user is on the correct bus and the bus is stopped at a correct stop of the selected line. In this case, the table *Input values* in the fuzzy logic system will have a value, for the variable STOP_BEACON_STATE, between 0 and 30. This will indicate that the bus is stopped. The event will be accepted and the information returned by the server to the application will not generate any warning. It will indicate that the user is on the correct route.

Another situation corresponds to the second case presented. This test has also been done in the system and it has been verified that the results are satisfactory. Here, the bus is stopped at a stop located on the route established by the user. The proposal detects that STOP_BEACON_STATE and BUS_BEACON_STATE are in a static state, which will indicate that the bus is at a bus stop. However, this stop does not correspond with the line selected by the user. Therefore, the system concludes that the generated event is valid according to the fuzzy logic, but the information does not correspond to the correct bus that the user should have selected. In this case, the information sent from the server to the application warns the user that it is not the correct bus and that they should get off at the next stop.

Finally, we present the results for the third analysed case (it is not a stop corresponding to the line selected by the user and it is not on the correct route). It is important to realize that the event is valid because both the information received from the bus and that received from the stop correspond to data of a valid event. However, in this case, the stop is not on the user's chosen route. Hence, the information sent from the server to the application should warn the user that they are not on the correct route and should get off at the next bus stop.

Once the last two cases have been presented, where the user is on the wrong bus, the application itself can be used to find the closest bus stop corresponding to the correct line.

5.3. Problems associated with the technology used. One of the main drawbacks that has been detected in the technology chosen could be the speed of the vehicle. During the simulations, sometimes, packets from some stop beacons were not received. Specifically, and after performing the test cases, it has been found that when the vehicle speed is higher than 50 km/h it is possible that the beacons will not be detected when passing next to a stop. Although in urban environments this problem is not very significant, given that in cities traffic and speed limits in general do not exceed 50 km/h, it is a line of work that we can incorporate in future research.

The impact of materials around the beacon on the signal can produce disturbance. Besides, the orientation of how measurements are taken from the beacons can also change the results. Thus, the placement of the beacon nodes must be selected carefully. Another relevant aspect according to the experiments is the position of the mobile device with respect to the user's body. Disturbance may occur depending on whether it is held, for example, close to the body or is located in a pocket of the pants.

One more factor that should be studied in depth is the use of the proposed technology in the rush hour. At peak times, buses are full so it is necessary to analyse how this situation affects connectivity. The signal strength performances and range could be affected by the shielding of human bodies. We must take into account that the number of people who are in the place could significantly affect signal intensity, since up to 60% of the adult human body is water, and water absorbs radiation. For this reason, the RSSI value can be attenuated up to 10 dBm (Bahl and Padmanabhan, 2000; Kaemarungsi and Krishnamurthy, 2004; de Blasio *et al.*, 2017b). Therefore, future research in a real environment is required to assess the impact on the visualization of BLE beacons. In addition to this, it is important to note that the orientation with respect to reading devices, within a standard-sized bus, can cause the connection to be cut off.

Another disadvantage is the cost of beacons. Although their cost has decreased slightly in recent years, it still represents a great economic effort for transport companies to deploy these devices throughout their infrastructures, especially in big cities. However, this disadvantage is not a limitation since companies could gradually implement their use. For instance, companies could focus on those routes that may present a higher level of complexity for users or on lines without a large number of stops.

Finally, another problem with beacons is the inability to provide data that would allow companies to derive statistics. Knowing which stops are most frequented by users, which is the time when a certain bus passed by a certain stop and many other options are not possible only with the use of beacons. However, thanks to the employment of the proposed mobile application, this disadvantage can be eliminated. Every event generated by the user along their journey on public transport can be used by companies to offer better and more efficient services.

5.4. Discussion. The current employment of mobile devices by the majority of the population and the ease of use of mobile applications have been key factors in making the decision on developing the solution described in this work. Specifically, the proposed system consists of a mobile application that includes a novel location system based on BLE, which works in both outdoor and indoor environments so that it provides guidance as the traveller moves while using public transport. BLE technology requires very limited resources to operate, so one of the advantages of the proposed system is its low energy consumption. This has a positive impact on the mobile devices of users, especially when compared to the application of other technologies such as GPS, which consumes large amounts of energy. However, a possible disadvantage is the necessary investment that transport companies would have to make to provide the infrastructure with the required resources for the system to work. Although the only resources that are necessary are the beacons, and the cost of these devices is not high, perhaps the deployment in a large infrastructure could be seen as a drawback.

6. Conclusions

The need to increase ease of use is one of the main challenges in public transport because in certain situations and for some groups of people public transport can be very confusing. This work addresses the specific problem of guiding passengers within a public transport infrastructure, through the proposal of a digital personal travel companion application based on outdoor location and event detection.

In order to reduce the number of necessary interactions between the user and the application, the solution includes an alerting system based on context the system and personalization through the preferences and characteristics of the user. In particular, the proposal includes an event detection system based on beacons that, supported by a fuzzy logic algorithm, makes it possible to determine the user's most likely actions during the journey. These actions include predicting whether they need to access or leave a public transport vehicle, or whether a stop on the route is correct or not. Thus, the proposed system combines location-based services together with dynamic alert functions to offer passenger guidance and alerts. In addition, to further improve the customers' experience in the use of public transport, the proposal takes full advantage of event detection. Thus, once it has been detected that the passenger had entered a public transport vehicle, the payment for the journey is made automatically, which reduces the duration of stops, helping to make routes more efficient.

Since this is a work in progress, to improve event detection and reduce false positives, testing the system in a real environment will be essential. In addition, the application will be implemented for other mobile operating systems, such as iOS. A study of potential users will be useful to obtain valuable information on possible additional functionalities of the system. Finally, one of the most challenging research topics in the field of public transport is the implementation of a transnational system. It would allow uniform use of public transport across the borders of foreign countries to reach any destination without having to deal with complex maps with mixed ticketing and fares.

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