An Internet-of-Things Enabled Connected Navigation System for Urban Bus Riders

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***Abstract*—A key challenge for rapidly growing cities of today is to provide effective public transport services to satisfy the increasing demands for urban mobility. Towards this goal, the Internet of Things has great potential to overcome existing deficiencies of public transport systems given its ability to embed smart technology into real-life urban contexts. In this paper, we show how this paradigm can be applied to the public transport domain and present the Urban Bus Navigator, an Internet-of-Things enabled navigation system for urban bus riders. UBN provides two novel information services for bus users: 1) micro-navigation and 2) crowd-aware route recommendation. Micro-navigation refers to fine-grained contextual guidance of passengers along a bus journey by recognizing boarded bus vehicles and tracking the passenger's journey progress. Crowd-aware route recommendation collects and predicts crowd levels on bus journeys to suggest better and less crowded routes to bus riders. We present the technical system behind the Urban Bus Navigator and report on results from an in-the-wild study in Madrid that indicates removed barriers for public transport usage and a positive impact on how people feel about bus journeys.**

***Index Terms*—Smart city, bus transport, navigation system, passenger detection, bus ride recognition, Internet-of-Things.**

I. Introduction

As cities continue to grow in size and population, new challenges arise for the design of urban mobility infrastructures. While public bus transport systems have the capacity to absorb large masses of urban travellers, their public image often suffers from a negative perception [1]. First, from a passenger's point of view, bus networks in dense urban areas are often considered as complex and difficult to navigate. Second, in contrast to private modes of transport, travelling on buses offers only a low level of comfort and convenience. Third, bus journeys lack a sense of personal control and ownership that is valued by car users [2]. To overcome these inherent weaknesses of the physical bus transport system, researchers increasingly turn their attention to digital technologies in order to improve the perceived quality of bus transport [3], [4], [5].

To fill this gap, the Internet-of-Things (IoT) provides great opportunities to improve existing public transport system by embedding smart technology into real world transport usage contexts. In particular, there is potential to design traveller information system which can foster a closer relationship between physical and digital travel experiences. There is empirical evidence that enhanced information availability and accessibility is an important factor for increasing readership and satisfaction with public transport services [6]. However, while existing transport information systems provide tools to help travellers plan an upcoming journey, there is no direct support available surrounding the information needs that emerge during their transport journeys. Despite the fact that real-world travel experiences shape the perception of public transport systems, current systems have no means to effectively assist travellers during their transport journeys when complex transport decisions have to be made.

In this paper we show how the idea of the Internet-of-Things can be applied to improve the experience of public bus usage and present the Urban Bus Navigator (UBN), a personalized bus navigation system with the ability to seamlessly interconnect bus passengers with the real-world public bus infrastructure. The UBN system is built upon a distributed IoT infrastructure which enables the passengers' smartphone devices to interact with buses in real-time and buses to sense the presence of on board passengers. Based on these mechanisms, UBN provides two novel information services for bus passengers: 1) micro-navigation and 2) crowd-aware route recommendation. Micro-navigation refers to fine-grained contextual guidance of passengers along a bus journey by recognizing boarded bus vehicles and tracking the passenger's journey progress. Crowd-aware route recommendation collects and predicts crowd levels on bus journeys to suggest better and less crowded routes to bus riders. Altogether, the UBN system provides users with a superior awareness of the state of the transport system and their travel options which translates into an improved public transport experience.

The Urban Bus Navigator system has been integrated into the municipal bus infrastructure in Madrid and is available to the public as a free smartphone app that has been used by hundreds of bus riders. In this paper, we present the technical components of the UBN system, give insights into user experiences from real-world field trials and share important lessons that we have learned in providing a connected transport application for bus passengers. Qualitative feedback from real-world bus users indicated reduced cognitive effort for managing bus journeys, increased motivation of using bus transport and better accessibility of travel information.

The remainder of the paper is structured as follows. In Section II, related work is discussed. An overview of the UBN system is given in Section III. In Sections IV, V, VI, we present the three key components of the UBN system. Finally,

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in Section VII, we report on results from the UBN system deployment and user trial in Madrid.

II. Related Work

Research on public transportation has traditionally focused on methods to improve the efficiency of the physical transport system. For instance, service scheduling is considered as an important problem for efficient bus transport operation [7]. However, Camacho et al. argue that this perspective is just motivated by the interests of transport operators and falls short of the information needs of passengers in the digital age [3]. Instead of resolving operational transport issues, they suggest to design passenger-centric information system that have the ability to improve the passengers' journeys.

A significant improvement of public transport information accessibility has been the development of mobile transport apps. OneBusAway is the first mobile app that brought estimates arrival times of buses on mobile devices [6]. The authors showed empirically that ubiquitous access to expected waiting times significantly increased satisfaction with public transport services. Meanwhile, numerous mobile transport apps have been developed for transport systems in many cities around the world. Some of these apps leverage on the built-in sensors of smartphone devices to provide personalization and context awarenes [8], e.g., by using GPS for suggesting bus stops in the surroundings of a user. This provides insight into the raw context of the user such as his current location, but does not capture a wider notion of transport context including the co-located physical transport system, e.g., the bus vehicle and bus line on which a user is riding.

Further, current mobile transport apps often rely on the transport information that is published by transport operators as open data, e.g., in form of the Google's General Transit Feed Specification (GTFS) [1]. This data encompasses a description of the transport network including routes, schedules and arrival times while qualitative travel information is missing as a basis for informed travel choices of transport users. Crowding on public transport system is a dimension of qualitative travel information that is known to have a big impact on travel satisfaction and cause a high level of stress and discomfort [9]. To identify crowd levels on public transport systems, some public transport agencies adopt automated fare collection system which can provide statistics about the number of passengers with digital boarding passes [10]. However, due to substantial investment costs these system are only deployed in selected cities and often lack integration with traveller information systems.

In absence of dedicated tracking infrastructure supported by transport authorities, crowdsourcing applications have been developed to acquire additional real-time transport information [11], [12]. The idea of these application is to allow transport users act in a collaborative manner and collect context data about about real-world transport conditions experienced during their journeys. For instance, Tiramisu enables bus passengers to use their mobile phones for manually sharing travel experiences, such as whether sufficient free seats are available on buses [13]. However, to sense real-time crowd information across large-scale public transport networks, fully automatic approaches are required which can operate without constant, manual interventions of transport users.

Current traveller information system provide support in singular travel contexts, e.g. before a journey is started, when searching for a close-by stop or while waiting for a bus. In order to offer continuous guidance for travel activities, the idea of navigation systems has been successfully applied in various mobility scenarios, in particular for pedestrians [14] and car drivers [15]. The equivalent of a navigation system for public transport systems is missing currently. There has been research into mobile phone based systems to detect the mode of transport of travelling users [16], [17]. These systems can differentiate bus ride activity from other transport modes by recognizing patterns in sensor data obtained from the user's mobile phones. However, a navigation service which constantly accompanies a public transport user and decides how to best provide support from start to end of his journey is yet an open research challenge.

III. The Urban Bus Navigation System

The Urban Bus Navigator (UBN) has been developed in cooperation with EMT Madrid [2], the Madrid transport organisation that operates the municipal bus system, in order to extend the capabilities of existing public bus transport information systems. Madrid's bus infrastructure encompasses a fleet of roughly 2000 vehicles that serve more than 200 bus routes with more than 4600 bus stops. The size of the city and the diversity of bus routes complicates travellers' transport decisions when it comes to navigating the city, especially as buses, in contrast to other public transport modes such as subways or trams, require frequent interchanges and are susceptible to incidents and temporary re-routing. In the following, we describe how we have enhanced the Madrid public transport system with Internet of Things features to uniquely address these needs.

A. Public Transport Information Needs

The UBN system has been developed in order to improve the satisfaction of public transport information needs. As public transport system cannot be physically controlled by users in the same way as private means of transport, access to relevant public transport information is a prerequisite to foster positive transport experiences. Empirical research suggests that travellers have specific information needs to make effective transport decisions [18]. To conceptualize this, Hörold et al. have developed a model of a public transport journey which encompasses tasks that passengers must be able to accomplish to use public transport such as trip planning, choosing from different routes, finding a path to a stop, alighting, transferring and dealing with transport disruptions [19].

To put this model in the context of bus transport, we analyzed bus journeys in Madrid and identified key decision

[1]The General Transit Feed Specification is available at https://developers.google.com/transit/gtfs.

[2]http://www.emtmadrid.es

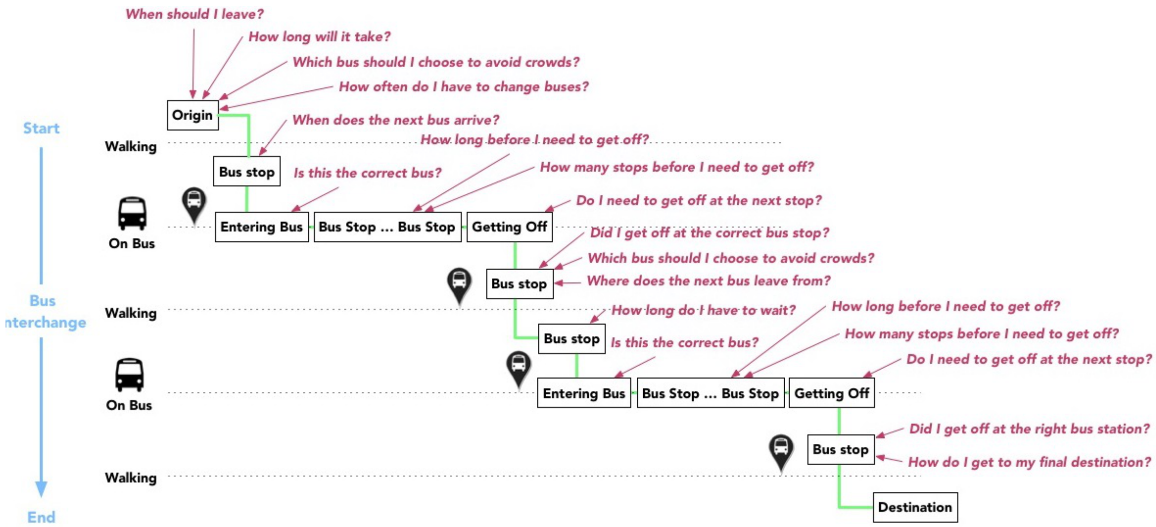


Fig. 1. Overview of the Contextual Information Needs of Bus Users from Start to End of Bus Journeys

points and associated information needs. Figure 1 gives an overview of our analysis. The diagram shows a bus journey from start (top) to end (bottom) where the passenger switches buses halfway through the journey. The rectangular boxes indicate key decision points during a bus journey such as boarding a bus, arriving at a bus stop, getting off from a bus etc. The text labels towards the right indicate passenger information needs associated with decision points. We refer to the decisions that passengers have to make during their journeys as micro-navigation decisions. Micro-navigation decisions are highly contextual: they depend not just on time and location but also on the traveller's transport mode (standing at a bus stop, riding on a bus etc.), the current travel context (specific bus the traveller is on, the associated bus line, estimated arrival times, etc.) and the upcoming tasks of a traveller (entering a bus vehicle, preparation for alighting, etc.). As highlighted in Figure 1 the variety and complexity of information needs demand a lot of focus and cognitive attention by travellers. Typical passengers have few problems making micro-navigation decisions as they can rely on their eye-sight, memory, prior knowledge, and general reasoning abilities. Disadvantaged users however - and this includes children, older people, tourists, novice users, people with poor eyesight, as well as people with impaired cognitive or physical abilities - require contextual help to make effective micro-navigation decisions. In absence of such help passengers can experience uncertainty and anxiety which may lead to reluctance to use public buses. But even non-disadvantaged users can experience stress making micro-navigation decisions, for example when in a rush, because of distractions or due to unfamiliarity with the environment, since using buses frequently requires travellers to acquire relevant trip information from their surroundings (e.g. sign posts, transport maps, information displays, etc.)

B. Design Rationale

Based on our understanding of traveller information needs we identified two key objectives for UBN. First, we conclude that support for micro-navigation decisions and contextual step-by-step guidance during the entire trip play a key role in shaping the public transport experience. Second, we determine that accurate crowd-level estimations for bus routes and recommendations of least crowded routes can bring significant benefits to bus passengers.

Current passenger information systems fall short of addressing these objectives. First, typical information systems focus on transport planning (with location and time being the only contextual factors taken into account), while dynamic information needs of micro-navigation tasks during a bus journey are not adequately captured. Second, state-of-the-art journey planners planners focus on optimizing hard objective measures such as travel time, but miss relevant contextual information that can influence the traveller's choice such as the crowdedness of a bus. We argue that the limitation of current transport information systems is rooted in their lack of inability of sensing and understanding the traveller's transport situation.

To address these issues, the UBN system provides the following key technical innovations:

- An IoT based distributed soft- and hardware system that connects bus riders' mobile devices with bus vehicles using short-range Wifi communication
- A micro-navigation solution to provide continuous trip assistance during bus journeys. This is realized by a semantic bus ride tracking scheme that detects the bus on which the passenger is currently riding and identifies fine-grained transport situations whenever they appear in a user's bus journey.
- A crowd density estimation approach to sense the number of passengers on buses. UBN monitors the wireless signals of mobile phones seen on buses to recognize bus passenger crowds and provides enhanced reality-aware bus route recommendation to avoid overcrowding on public bus journeys.

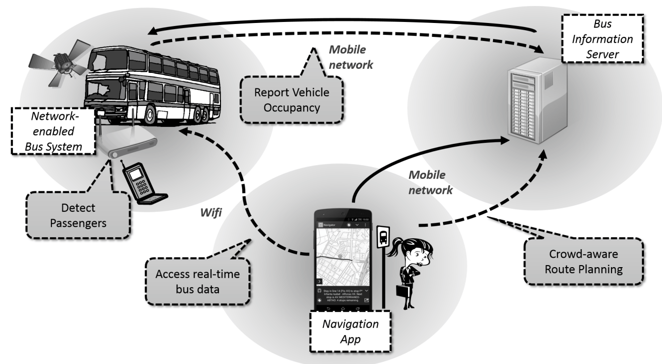


Fig. 2. The Urban Bus Navigation System

C. Internet-of-Things Architecture

The UBN is based on an Internet-of-Things architecture which involves a set of distributed soft- and hardware components which are tightly integrated with the bus system. The UBN system that has been deployed in Madrid is composed of three key components (see Figure 2):

- *The network-enabled urban bus system* with Wifi-equipped buses vehicles. Wifi is used to establish local networks for sharing bus data with the passengers' mobile phones. In addition, a crowd density estimation system has been integrated into the bus system.
- *The UBN navigation app* for bus riders. The UBN app is a smartphone application that is able to track a user's bus journey and support micro-navigation decisions by setting up connections to bus vehicles and recognizing on which bus and direction the passenger is currently riding.
- *The bus crowd information server* to collect real-time occupancy information from buses operating on different routes in Madrid. The server encompasses an enhanced transit route planning engine to recommend bus routes with lower predicted occupancy for avoiding crowds.

All three components of the UBN system are interconnected. Thus, UBN facilitates novel interactions (cf. dashed lines in Figure 2) compared to existing communication links found in state-of-the-art bus information systems (cf. solid lines). In particular, the architecture supports direct communication between the riders' mobile devices and bus vehicles as a way to design passenger-aware information services. In the following, we present each constituent component of the UBN system in detail.

IV. The Network-Enabled Urban Bus System

Traditionally, the computing and communication technology installed in buses is restricted to sense vehicle-centric data and communicate only with the transport operator. In this section, we describe how the information system deployed in the bus vehicles has been extended with subsystems to sense real-world bus journeys of passengers and enable sharing of bus data with their mobile devices in an ad hoc manner.

A. Ad-hoc Communication with Buses

The technical basis for the UBN system is the public bus transport system in Spain's capital that is operated by EMT Madrid. From an operational perspective, the bus system is similar to other cities. From a technical perspective, it resembles a state-of-the-art transport system. All buses are equipped with an industrial on-board computer system that is connected to external sensors, including a GPS receiver, and a 3G network interface to provide Internet connectivity.

Traditionally, the on-board computer system in the buses is a closed system to communicate with the bus operator only. For the development of UBN the bus system has been opened to communicate with mobile user devices co-located with the buses. To this end, the UBN system relies on the wireless access points inside the buses in Madrid that have been deployed to provide free Internet access to travellers. These access points are configured with a well-known SSID that announces the bus network uniquely in all buses in Madrid. We leverage on the availability of this short-range communication infrastructure by extending the on-board computer system with a web server and a corresponding web service to allow incoming connections from devices connected to the bus network. Upon request, the resulting system can then share the following information:

- *GPS Position*: The web service exports the current GPS position of the vehicle together with the vehicle id. The GPS information is used as basis for visualizations and computations performed by the mobile application.
- *Current Route*: To support navigation and to attribute the detected number of passengers to a particular route, the web service exports the current route name, id and direction along with a list of bus stops on the route.
- *Next Stop*: The web service also exports the id and name of the next stop of the bus along the current route. This information is derived from the bus position and integrates the state of the doors (i.e. whether the bus driver has opened the doors to let passengers enter and leave the bus) to compensate for inaccurate GPS positions and provide reliable next stop information.

B. Bus Crowd Density Estimation

The existing bus system has been extended with an embedded system for crowd density estimation to detect the number of passengers on a bus. For the purpose of bus crowd density estimation, we rely on the fact that Wifi-enabled devices carried by passengers are periodically sending out probe requests according to their their IEEE802.11 protocol operation in order to detect the access points that are nearby. In each vehicle, we therefore deploy an inexpensive off-the-shelf Wifi access point that acts as a network monitor to continuously capture transmitted probe requests. As the devices typically repeat their probe request on all available channels, it is possible to receive the probe requests of nearby devices by simply monitoring a particular channel. By keeping track of the MAC addresses of the devices transmitting the probe requests, it is then possible to count the mobile devices that are in the vicinity of the network monitoring hardware.

However, since the buses often move through densely populated areas with large crowds of people outside the buses, it is likely that many of the received Wifi signals stem from devices that are merely close to the vehicle but not located in the bus. To capture bus passengers only and remove any other entity from the set of detected devices, we enforce temporal and spatial filter criteria and observe if probe requests have been seen over a continuous spatial distance which implies that the device is moving with the bus. To this end, we associate the probe requests with precise time and position information obtained from the bus system. For each of the MAC addresses m contained in probe request frames, we keep track of the time t_m when the last probe request was received, the last position p_m of the bus at that time, as well as the total distance d_m for which it has been seen. The latter is computed incrementally by adding the distance between the last position and the current position $d_{m+1} = d_m + distance(p_m, p_{current})$ whenever a new probe request is received. Based on this information, we can estimate the number of devices in the bus as the sum over all m where $d_m > d_{th} \wedge t_m > t_{now} - t_{th}$.

Our previous experiments [20] indicate that 180 seconds is a suitable value for $t_{threshold}$ to identify new probe requests. For defining the spatial threshold, we consider that with typical Wifi hardware the transmission range does not exceed 100 meters and set $d_{threshold}$ to 300 meters in order to account for the fact that a moving vehicle might see an immobile device for twice the transmission range and to handle errors resulting from the incremental computation and imprecise GPS measurements. Any device that has been observed continuously for at least this distance is thus likely to travel with the bus. This also prevents bus travellers waiting a bus stop for other bus services to be counted as bus passengers. While the devices of these travellers may be visible for a significant period of time when vehicles are stopping, they will be detected as stationary devices and thus do not satisfy the distance threshold.

Based on this setup and processing, we are able to identify the set of Wifi-enabled devices that are traveling inside the bus by means of their unique MAC addresses. However, since this information could be used to identify the trips of individual users across the bus network over time, it could be violating the travellers' privacy. To mitigate this, it is possible to limit the privacy impact by either obfuscating (e.g. running the MAC addresses through a salted hashing algorithm) or aggregating the data. Due to our specific use case of crowd-level prediction, our system is using the latter approach whereby each bus only reports the total number of passengers per segment and not the individual identities of the Wifi-enabled devices. This ensures that the set of MAC addresses never leave the embedded system in the vehicle and thus, they cannot be used for further profiling of travellers.

V. Bus Crowd Information Server

In state-of-the-art transport information system all transport data is managed in central backend components. The bus navigation system adds two novel components to the backend system for making effective use of the available bus occupancy information. In the following, we describe how this data can be used to predict bus occupancy on future bus journeys and how these predictions can be integrated into a route planning engine as a means for optimizing travel comfort.

A. Predicting Bus Occupancy From Crowd Level Histories

Based on our crowd density estimation system installed in the buses, streams of crowd level information from across the bus network can be collected and stored on a dedicated crowd information server. As discussed previously, to protect the privacy of the passengers, with each crowd density report only aggregated occupancy information (i.e. timestamp, the vehicle id, the route id, the id of the network segment on the route as well as the estimated quantity of passengers) is transmitted. The idea is to use the crowd level histories as a basis for bus occupancy predictions to enhance the quality of contextual information available for trip planning.

To illustrate this, Figure 3 shows the variation of crowd levels on bus in Madrid between Sunday and Monday morning between 9 and 10 am. It can be seen that on Mondays, when urban travellers follow their work commutes, significant more passenger loads are observed than on Sundays. To facilitate predictions based on the available crowd level histories, we define a set of temporal and structural features that capture variations in bus ridership across the bus network with respect to time and route. Formally, each prediction is associated with a feature vector $< R, S_{orig}, S_{dest}, T_{day}, T_{hour} >$ with R denoting the bus route, S_{orig} and S_{dest} denoting the origin and destination stop on the route segment, T_{hour} denoting the hour (i.e. 0-23), and T_{day} denoting the type of day (e.g. 0 for Monday to Friday, 1 for Saturday, 2 for Sunday). To compute a prediction, we determine the average number of passengers over all past entries in the history for a given feature vector. Since such a prediction is computed for a specific day and time as well as bus route segment, it can be used to support passenger's travel planning. While we experimented with other aggregates, e.g. moving average, median, etc., we found a simple average value and the granularity of our chosen aggregation intervals to work best.

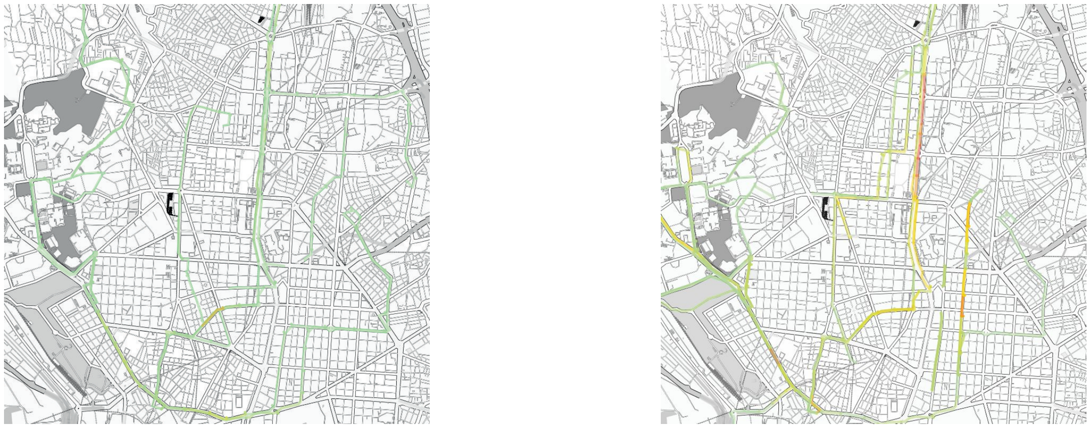
B. Least Crowded Route Recommendation

To make effective use of the bus occupancy information and enhance the state-of-the-art in trip planning, we have developed a custom transit routing engine to recommend most comfortable (i.e. least crowded) routes to passengers. The routing engine relies on GTFS data for the details on the public transport network (e.g. routes, stops, timetables, etc.)[3], OpenStreetMap[4] data for information about the street network and our bus occupancy predictions for insights into crowdedness of upcoming bus journeys. The engine fully supports the typical queries and constraints that can be specified in modern navigation applications (e.g. departure or arrival time, allowed vehicle types, walking speed, wheelchair accessibility, etc.) and is able to compute several direction alternatives. When integrating occupancy levels into the route computation step, it is necessary to address the following two questions:

1) How should the occupancy level be aggregated across multiple route segments?

[3]The transit data of EMT Madrid in GTFS format is publicly available at http://opendata.emtmadrid.es.

[4]More information on the OpenStreetMap project can be found at http://www.openstreetmap.org/about.



(a) Sunday Morning

(b) Monday Morning

Fig. 3. Visualization of Bus Crowd Density in Madrid on Two Different Days of the Week (9-10am)

2) Should the occupancy level be used to exclude routes or to rank alternatives?

Regarding the first question, a method is required to combine occupancy levels that vary over the course of a bus journey between the start and end stop on a bus route. For the purpose of our work, we decided to aggregate the occupancy levels for the whole route by averaging the crowd levels associated with all segments traversed for a given trip. The reason for this is that the passenger's experienced overall comfort is more likely to be reflected by the overall level of occupancy. Nevertheless, our routing engine can easily be adapted to additionally include the likelihood of getting a seat when entering the vehicle. From an algorithmic point of view, the difference is merely whether the occupancy level of the first or more route segment(s) should be considered as underlying optimization criterion.

With respect to the second question, we decided to use the occupancy level for ranking as opposed to exclusion. Although the use of exclusion could result in a faster processing (since non-fitting routes can directly be excluded as part of the A* search), we did not intend to hide the routes with higher occupancy levels in order not to limit a traveller's choices artificially. Instead, we decided to rank and prefer route alternatives with regards to their expected occupancy levels. Ranking is performed using a variant of the A* algorithm [21] in order to find the 'best' route(s) within a multi-modal transit network consisting of walking and bus trip segments. We integrated the occupancy levels as an additional weighting factor during the A* route computation that ensures that lower occupancy route segments are explored preferentially given that other factors (e.g. duration, number of transfers, etc.) are similar. Towards this end, we add constant penalty values for higher occupancies to the overall weight which is used to order the traversal. By modifying the penalty value, it is possible to compute various trade-offs between bus crowdedness and classical travel metrics such as trip duration in order to suggest bus routes that can help avoid travelling in crowded buses.

VI. BUS NAVIGATION APP

On top of the connected bus infrastructure described previously, we have developed a smartphone application for bus passengers which can take advantage of it to provide a novel bus navigation service. The application supports real-time navigation of buses in Madrid by interacting with nearby buses and interpreting the sensed physical transportation context in relation to the trip goal of an individual bus passenger. In the following, we present the principle of bus navigation and describe the provided mobile user interface and supported navigation decisions.

A. *Micro-navigation*

Bus navigation is provided as a smartphone application with dedicated support for micro-navigation. Micro-navigation provides continuous guidance throughout all stages of a bus journey: before a user gets on the bus, during bus rides and when users get off the bus. While traditional bus travel applications focus on route planning, micro-navigation is much more fine-grained and covers a wide spectrum of information needs which appear directly in the context of an ongoing bus journey such as: "Is the bus that just pulled up at the bus stop the one I should take?", "On which bus am I riding?", "Am I on the correct bus?", "How long before I need to get off?".

Key to the support of micro-navigation tasks is therefore the ability of the navigation app to discover and connect to the physical bus infrastructure. To this end, the navigation app runs a background process that automatically tries to establish spontaneous Wifi connections to buses in the surroundings of the user. As a common SSID is used for the Wifi network in all buses, it is possible to enforce only connections with access points representing the bus vehicles (cf. Section IV-A). Whenever such a Wifi connection becomes available and is established, real-time vehicle status information can be queried to obtain knowledge of the route operated by the bus and the next stops along the route. For the purpose of bus navigation, the ability to connect to buses in real-time using local Wifi connections serves two important purposes: bus ride recognition and trip tracking.

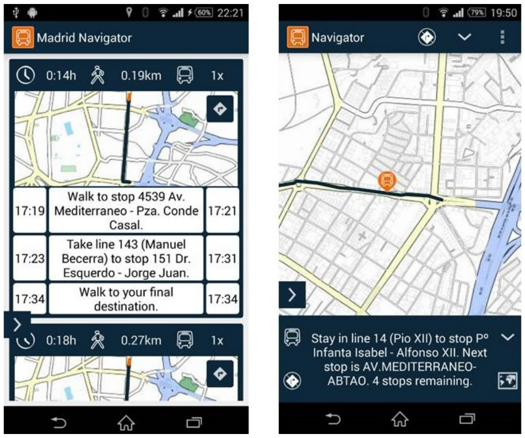


Fig. 4. Mobile User Interface of the Bus Navigation App

Bus ride recognition is implicitly enabled by the Wifi based connection mechanism. Since a Wifi connection setup requires a stable network signal of high quality which is available only inside or in close proximity of the buses, an active connection implies that the traveller is either on the bus or nearby to it. If the user leaves the bus and, as a result, the network signal quality drops, the connection cannot be maintained and is lost again. The change in Wifi connectivity can be easily detected on the smartphone and combined with suitable rescan triggers and timeouts to define a sensor for the user's current mode of transport and infer whether the user is riding a bus or not.

As the Wifi connection provides access to real-time data of the boarded bus vehicle, it can also be used to monitor the trip progress of the user. Such a direct connection between a user's smartphone device and the bus vehicle has not been supported by the first version of our navigation system [22]. Since this connection allows for periodically polling the buses on which the users are riding for their real-time status, the bus journeys of the users can be tracked based on information of the buses' current route and the next stops along this route. We use the vehicle data in combination with the user's trip plan to provide context-dependent navigation suggestions using proactive information provision that does not require any manual intervention by the user as discussed in the following.

B. Navigation Interface

The navigation app provides a set of of mobile user interfaces to interact with the user and display proactive travel information. The interfaces are designed to hide the the complexity of the distributed navigation system (i.e. interactions with buses and bus information server) and offer a seamless bus ride experience. Initially, navigation starts with a traditional trip planning interface: the user can plan directions from the current location to any other location in Madrid. Besides using common preferences such as shortest travel time, bus routes with low predicted occupancy levels can be retrieved (cf. Section VI-A). The user can visually inspect the direction information including predicted occupancy levels on a map and select one route for navigation.

Whilst navigating a bus journey, special information needs associated with each trip activity including walking and bus rides are supported. Navigation information is displayed on a dedicated interface that is composed of two parts: a notification area and a map area (Fig. 4). The map is used to help the traveller gain a geographic understanding of the journey. The current user location is shown and all travel segments involved in the journey are represented. Assistance for micro-navigation is provided via textual information that is displayed in the notification area below the map. By connecting to the buses and interpreting the user's trip progress in relation to the chosen travel plan, the following classes of navigation information are supported:

- *Walking*: If the app detects that the user is not on the bus, walking instruction are displayed to direct the user to the next bus stop where a bus needs to be entered.
- *Next Bus Departure*: If a user is approaching a bus stop whilst walking, information on the next bus departure is given including the route and direction of the bus supposed to be taken.
- *Prepare for Alighting*: If the user is riding the bus, the number of stops remaining is indicated before an alighting is required. This information is updated with each subsequent stop, and an alert is created before arriving at the user's planned exit stop.
- *Missed Alighting*: If a user is still found to be on the bus after he should have left at the last stop, a warning message is displayed with the option to replan the trip.
- *Wong Bus Alert*: If a user has entered a bus that is following a route other than the planned direction, an alert is created and a replanning option is offered.

Depending on the user's trip progress, relevant navigation information is selected from the options above and presented to the user. With each change in the bus vehicle status and the user's real-world context, the navigation information is re-evaluated and updated. This enables higher-level, semantic conclusions about the transport situation of the user (e.g., by delivering feedback whether a correct or wrong bus has been entered) which is more expressive than just time and location. In addition to providing textual output, the app is able to generate spoken navigation instructions using a text-to-speech engine. Combined with a pair of headphones, this enables hands-free use of the micro-navigation support during a bus journey and it simplifies bus usage by persons with limited vision capabilities.

VII. Deployment and User Study

The Urban Bus Navigator has been deployed in Madrid since July 2013 and was improved over two consecutive user trials in 2013 and 2014. Meanwhile the navigation app is available to the public and can be downloaded as free Android application from Google Play [5]. In total, 750 users have downloaded the app since it was first released. To analyse the impact of our navigation system in practice, we performed two types of evaluations which will be presented in the following: a technical test of the system effectiveness and a comprehensive user experience study in Madrid.

[5]https://play.google.com/store/apps/details?id=eu.gambas.prototype.navigator

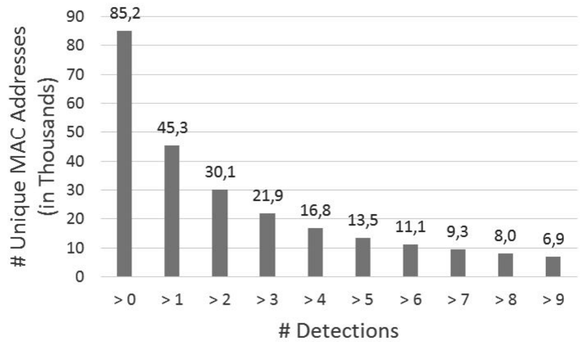


Fig. 5. Frequency of Detected Devices over 14 Day Period

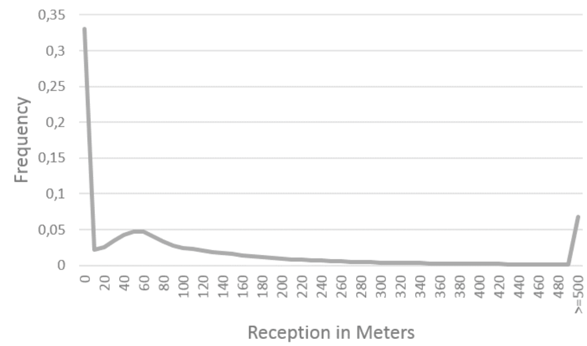


Fig. 6. Distribution of Spatial Distances of Wifi Access Points Detections

A. Technical Evaluation

For assessing the effectiveness of the operation of the crowd density estimation system in the buses, the ability to differentiate between people outside the buses and actual passengers on the buses is crucial. To analyse this problem in more detail, we monitored the probe requests observed in one bus operating in Madrid during a period of 14 days. For this purpose, an inexpensive commercial off-the-shelf Wifi access point has been deployed in that bus. The access point was running OpenWRT with libpcap and tcpdump to continuously capture the probe requests on one of the channels (see [20] for more details on the hardware setup).

During the observation time, the bus was operated for 224 (out of 336) hours and while it was operating, we logged all probe requests received by the monitor. To avoid duplicate detections of the same requests sent out multiple times, we limited the amount of logged probe requests to 1 request per MAC address per second. In total, the monitor logged 384874 probe requests from 85212 unique MAC addresses. Figure 5 shows the frequency of the detections of unique MAC addresses. Among the logged addresses approximately 40000 where only seen once and an additional 15000 addresses were only seen twice. These numbers clearly demonstrate the fact that a significant fraction of mobile devices were most likely not travelling in the bus. Instead, it is more likely that they were located at a bus stop or some where close to the street where the bus was driving.

To counter this effect, our proposed crowd density estimation system relies on a spatio-temporal classification mechanism to identify those devices that are moving with the bus (cf. Section IV-B). With this approach the idea is to identify stationary devices that do not follow the bus for a minimum time and distance and thus do not represent actual bus riders. To demonstrate the effectiveness of this classification, we constructed an evaluation scenario using only the Wifi access points (denoting a specific subset from all detected Wifi-enabled devices) that were detected by our Wifi monitor deployed in the buses. Since Wifi access points that are detected along bus routes in Madrid can be assumed to be stationary devices with a high likelihood, we tested if our approach is able to correctly them as non-bus riders based on the applied filter criteria. Figure 6 plots the distribution of the distances over which the access points were seen by the bus. As indicated by the figure, about 30% of the access points are only seen at the same position, 67% are seen for less than 100 meters and 90% can only be seen for 300 meters or less. The remaining 10% of access point sightings are forming a long tail (i.e. very low frequencies that can even reach distances in the order of kilometers). This can be explained by the fact that some access points captured by the bus are not deployed at a fixed position. Instead, they are mobile and traveling with the bus. Examples include smartphones with active Wifi tethering and access points deployed in nearby buses that share a common route segment.

Besides collecting past crowd level measurements, we aim to accurately predict the occupancy of buses on different bus routes in Madrid. To evaluate the accuracy of the predictions we have collected crowd level reports over a 7 month period between November 2014 and May 2015 as a baseline using three buses that were operating in the city. During this time, the buses where dynamically allocated to 28 routes, thereby, covering a significant part of the city. In total, the crowd density estimation system installed in these buses captured 63734 crowd levels for all segments of the routes on which the buses were operating at different times of day.

Based on this, we can use the dataset as a baseline to test the quality of the prediction by stepping through the reports in the order in which they have been generated. Thereby we use the previous reports $\{Report_1, Report_2, ..., Report_{n-1}\}$ as history for the next, i.e. $Report_n$. Then, we compute the prediction error by subtracting the passenger number in the report with the passenger number of the corresponding prediction. For our data set (with 63734 samples), this results in 45284 error values. For the remaining samples a prediction cannot be computed since the history does not contain an entry for the specific route, segment, hour and day (yet). The resulting average error lies at 5.1 passengers and the distribution is shown in Figure 7. Interestingly, finer aggregation intervals did not improve the prediction quality but significantly reduced the number of predictions. Similarly, separating Monday to Friday into separate days did not improve the result but considerably lowered the predictions and ignoring the day or the hour degraded the performance.

While we could use the predicted number of users directly as an output, we decided to further aggregate it by forming

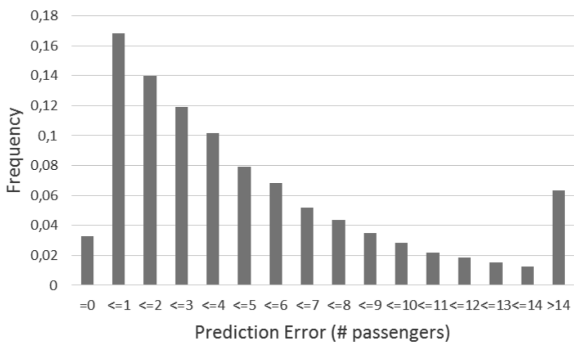


Fig. 7. Error Distribution of Bus Crowd Prediction

three classes of occupancy levels, namely low, medium and high occupancy. The relative class frequency is 42.8% for low, 42.1% for medium and 15.1% for high. Using the occupancy classes to classify the prediction, we get an exact match accuracy of 61.9% and a one-off accuracy of 98.4%. This means that in 61.9% the prediction will result in the correct class and only in 1.6% of the cases there a low occupancy will be predicted as high or vice versa.

B. User Experience Evaluation

The UBN system has been designed as a user-centric navigation system to improve the real-world experience of bus users while they are conducting bus journeys. In order to assess the implications of the UBN system, we therefore need to investigate its acceptance and perception among bus riders. To incorporate this, we conducted two user studies in Madrid focusing on user experience issues.

The first study was devised to collect quantitative feedback from a broad set of users of the UBN app. For this purpose, we adopted the Experience Sampling Method (ESM) and integrated a short questionnaire into the application to collect experience reports from the users ”in-the-wild”. The UBN application prompted users at key stages of their journey to rate their experience on a Likert scale (0 to 5 stars) with regards to various questions. The advantage of the ESM approach is that, even though feedback is limited in form of ratings, it yields in-situ experiences from the users as responses are triggered during or shortly after bus usage. In total, we received 350 ESM reports from the users.

One of the questions posed to the users was whether they consider the navigation feature to be useful. Here, 41% of the users agreed with the maximum rating of 5 stars, and an overwhelming majority of users (95%) rated the application usefulness with a 3 star or higher rating. We take this as evidence for the added value that the UBN system could provide. Similarly, we asked whether the navigation app made it easier for them to travel the bus network. Again, we received strong positive responses among the users as a high fraction of 93% agreed with a rating of 3 stars or higher. In order to evaluate the impact of the navigation feature on the user's transport behavior, we further asked whether they think that the application could motivate them to use public transportation more often. Here, the answer is again very positive since 36% of the users completely agreed with a rating of 5 stars and another 20% rather responded with a 4 star rating. While this shows that UBN system had a positive impact on the users' experience, understanding the motivations that are implied by the ratings required a qualitative study to interrogate the users' perceptions more deeply.

The goal of the second study was therefore to gain a deeper understanding of the subjective attitudes and specific feelings that the participants developed during the use of the application. To this end, we recruited 10 participants, 3 females and 7 males, with an age range from 23 to 46 (Mean=38, SD=9.3) and conducted semi-structured interviews after they had used the UBN app for approx. one week. With the help of a Spanish translator, we engaged the participants in a discussion about the specific situations they encountered when using UBN. First, the interview started with general questions about their transport habits, such as how often they conducted bus rides and for what trip purposes. Then, we asked more specific questions related to their individual experiences: How did you perceive the navigation support? Did the application change the way of how you feel about bus usage? Did the application make any difference to you? To inform the interviews, we instrumented the UBN app with logging code to track bus usage. This allowed us to create trip visualizations that revealed the journeys of the interviewees.

As part of the interviews we were interested to learn whether the participants' behaviours and feelings changed as a result from providing bus information through a series of reality-aware navigation suggestions. Several participants expressed positive experiences with regards to improved information accessibility. For instance, P1 explained: ”Whenever I come to Madrid I always need to check the signs inside the bus, and it takes time to read the moving text. This time I can check the screen on my mobile and look out the window. There is a monument, which I had read about it and I had gone past before, but never seen it. I discovered it accidentally”. It became evident that bus riders often need to gather required travel information from the physical environment, e.g., the displays in buses. With our application this information became directly accessible and visible on their personal devices. This allowed them to feel more relaxed and freed time and awareness for novel travel experiences.

The discussions further revealed that public transport use is influenced by perception of its complexity that can create preferences or avoidance behaviours. For instance, P2 said: ”I can't breathe properly in the subway, I prefers to use the bus, but buses are complicated ... Based on the nature of my job I always end up somewhere in the city, then I don't know how to get back home. I tried to find the nearest subway which is easy to understand ... I can do everything from beginning to end with this app and use buses. It's a combination of Google Transit and TomTom.” Compared to the subway system that has only a small number of lines and routes, bus systems are often regarded as the more complex transport mode. The uncertainties involved in bus journeys can result in high barriers of use. In this regard, it is interesting that a reference to a car navigation system was made. Although it was our design intention to translate the experience of using a car navigation system to public transportation, feedback indicated that users actually did experience UBN as a navigation system. The fact that the application is alive during a journey appeared to increase the participants' trust in the navigation support and to raise their confidence in using the bus system.

Another insight was the surprise many participants voiced about the variety of contextual situations UBN could handle during their journeys and that at occasions it would reveal crucial facts that users had overlooked. As P5 explained: "Once I was waiting for my bus to ride back home ... I started killing time and playing with my smartphone. Then I got on my bus and it told me you are on the wrong bus, I checked the bus and the app was right, very smart message". In that sense, the behaviour of the application was not only perceived as information to look at, but as helpful assistance to the cognitive processes that had to be carried out. Along similar lines, P9 stated: "Putting all these things together on a single screen means it can think instead of me". In particular, the participants reported that they felt the navigation has been tailored to their personal behaviours. These feelings emerged from the fact that travel information was provided through personalized notifications that shared a relation to their trip goals, for example by alerting about the number of stops left until the next alighting.

VIII. Conclusion

In this paper, we have presented the Urban Bus Navigator, a navigation system for bus passengers that has the ability to seamlessly interconnect bus passengers with the real-world public bus infrastructure. The UBN relies on a distributed IoT system comprising an embedded bus computing system, backend computing infrastructure and a mobile smartphone app to detect the presence of passengers on buses and provide continuous real-time navigation over the complete course of a bus journey. A several month-long in-the-wild study with bus users in Madrid highlighted that UBN is indeed experienced by passengers as true navigation system and conceived differently from existing mobile transport apps. Several positive experiences were reported by the study participants: reduced uncertainties and more relaxed travelling, better visibility and accessibility of travel information, and effective support for cognitive tasks required for bus journeys. The design of UBN is generic so that it can be adapted to any city that has a digital urban transport infrastructure similar to Madrid. All in all, UBN demonstrates the potential of the Internet of Things for delivering innovative urban transport experiences.

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References

[1] S. Stradling, M. Carreno, T. Rye, and A. Noble, "Passenger perceptions and the ideal urban bus journey experience," *Transport Policy*, vol. 14, no. 4, pp. 283 – 292, 2007.

[2] B. Gardner and C. Abraham, "What drives car use? A grounded theory analysis of commuters' reasons for driving," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 10, pp. 187 – 200, 2007.

[3] T. Camacho, M. Foth, and A. Rakotonirainy, "Pervasive Technology and Public Transport: Opportunities Beyond Telematics," *IEEE Pervaisive*, pp. 18–25, 2013.

[4] J. Hare, L. Hartung, and S. Banerjee, "Beyond deployments and testbeds: Experiences with public usage on vehicular wifi hotspots," in *Proc. of the 10th Intl. Conf. on Mobile Systems, Applications, and Services (MobiSys)*, 2012.

[5] S. Foell, R. Rawassizadeh, and Gerd, "Informing the design of future transport information services with travel behaviour data," in *Proc. of the Workshop on SenCity: Uncovering the Hidden Pulse of a City*, 2013.

[6] B. Ferris, K. Watkins, and A. Borning, "OneBusAway: A Transit Traveler Information System," in *Mobile Computing, Applications, and Services*. Springer Berlin Heidelberg, 2010, pp. 92–106.

[7] V. Guihaire and J.-K. Hao, "Transit network design and scheduling: A global review," *Transportation Research Part A: Policy and Practice*, vol. 42, no. 10, pp. 1251 – 1273, 2008.

[8] J. Raper, G. Gartner, H. Karimi, and C. Rizos, "Applications of location-based services: A selected review," *Journal of Location Based Services*, vol. 1, no. 2, pp. 89–111, Jun. 2007.

[9] B. C. Mairead Cantwell and M. O. Mahony, "Examining the Factors that Impact Public Transport Commuting Satisfaction," *Journal of Public Transportation*, vol. 12, no. 2, pp. 1–21, 2009.

[10] M. Trpanier, N. Tranchant, and R. Chapleau, "Individual trip destination estimation in a transit smart card automated fare collection system," *Journal of Intelligent Transportation Systems*, vol. 11, no. 1, pp. 1–14, 2007.

[11] A. Thiagarajan, J. Biagioni, T. Gerlich, and J. Eriksson, "Cooperative transit tracking using smart-phones," in *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, ser. SenSys '10. New York, NY, USA: ACM, 2010, pp. 85–98.

[12] P. Zhou, Y. Zheng, and M. Li, "How long to wait? predicting bus arrival time with mobile phone based participatory sensing," *IEEE Transactions on Mobile Computing*, vol. 13, no. 6, pp. 1228–1241, June 2014.

[13] J. Zimmerman *et al.*, "Field Trial of Tiramisu: Crowd-Sourcing Bus Arrival Times to Spur Co-Design," in *Proc. of Annual Conf. on Human factors in Computing Systems (CHI '11)*, 2011.

[14] S. Robinson, M. Jones, P. Eslambolchilar, R. M. Smith, and M. Lindborg, ""I Did It My Way": Moving Away from the Tyranny of Turn-by-turn Pedestrian Navigation," in *Proc.of the 12th Intl. Conf. on Human Computer Interaction with Mobile Devices and Services (MobileHCI '10)*, 2010.

[15] I. Skog and P. Händel, "In-Car Positioning and Navigation Technologies - A Survey," *IEEE Transactions on Intelligent Transportation Systems*, vol. 10, no. 1, pp. 4–21, March 2009.

[16] L. Liao, D. J. Patterson, D. Fox, and H. Kautz, "Learning and inferring transportation routines," *Artificial Intelligence*, vol. 171, no. 56, pp. 311 – 331, 2007.

[17] Liping Zhang and Gupta, S.D. and Jing-Quan Li and Kun Zhou and Wei-Bin Zhang, "Path2Go: Context-Aware Services for Mobile Real-Time MultiModal Traveler Information," in *Proc. of the 14th IEEE Intl. Conf. on Intelligent Transportation Systems (ITSC '11)*, 2011.

[18] B. Caulfield, M. O'Mahony, and S. Farrell, "An examination of the public transport information requirements of users," in *IEEE Transactions on Intelligent Transportation Systems (ITS)*, Sept 2005, pp. 78–83.

[19] C. M. Stephan Hörold and H. Krömker, *Advances in Human Aspects of Road and Rail Transportation*. CRC Press, 2012, ch. Identifying the information needs of users in public transport, pp. 31–340.

[20] M. Handte, M. U. Iqbal, S. Wagner, W. Apolinarski, P. J. Marrón, E. M. M. Navarro, S. Martinez, S. I. Barthelemy, and M. G. Fernandez, "Crowd density estimation for public transport vehicles," in *Workshop on Mining Urban Data (MUD2014), Joint Conference EDBT/ICDT*, Athens, Greece, March 2014.

[21] P. Hart, N. Nilsson, and B. Raphael, "A formal basis for the heuristic determination of minimum cost paths," *IEEE Transactions on Systems Science and Cybernetics*, vol. 4, no. 2, pp. 100–107, July 1968.

[22] S. Foell, G. Kortuem, R. Rawassizadeh, M. Handte, U. Iqbal, and P. Marrón, "Micro-navigation for urban bus passengers: using the internet of things to improve the public transport experience," in *Proc. of the First Intl. Conf. on IoT in Urban Space (Urb-IoT 2014)*, 2014.