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Creating a Traveller Digital Twin: Bluetooth Low Energy for Fine-Granular Traveller Localisation

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Abstract. Using a traveller digital twin to collect real-time information can support future public transport features, such as personalised routing, automatic travel experience monitoring and real-time demand-based disruption management. For these features, reliable real-time information about travellers is crucial. This work describes how a Bluetooth Low Energy (BLE) setup can be employed to localise travellers during their journey and represent their status in a traveller digital twin. We provide an overview of existing BLE applications in the transport sector and present our BLE beacon setup. We perform a statistical analysis of the BLE beacons' signal performance in a test environment and present the results. We evaluate the performance of the BLE based traveller digital twin using real data acquired during a measurement campaign in the mentioned test environment.

Keywords. BLE beacons, traveller digital twin, intermodal public transport, journey milestones

1. Introduction

Digital Twins for Travellers (DTT) have been proposed as highly detailed digital representations of individual travellers along their journeys [1]. Knowing travellers' precise location in real-time is crucial for use cases like personalised routing [2], automatic travel experience monitoring [3], and real-time demand-based disruption management [4]. The DTT provides a trace for a traveller's entire journey. A journey consists of one or more trips; the travel mode for each part of the journey defines each trip. Additionally, crucial events during the journey can be conceptualised as milestones whose achievement determines whether travellers reach their destination on time. As such, having access to traveller attributes represented by a DTT can prove highly beneficial to traffic participants and transport providers.

However, many use cases for DTTs require a valid representation of the traveller's location, i.e., where a traveller is currently in relation to other real-world objects. If the

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represented locations are invalid, values in a DTT cannot serve as the basis for decision-making. Localisation often requires positioning as a first step, i.e., determining a traveller's coordinates within a frame of reference. The position must only be sufficiently accurate to choose the correct location among candidate locations. An ubiquitous means of positioning is GNSS (Global Navigation Satellite System). Unfortunately, GNSS is too inaccurate in many travel scenarios to discriminate between candidate locations. For example, a traveller might be unsure which of two opposite bus stops is correct. If the error of the GNSS signal is large, the uncertainty regarding the traveller's position is high. If the distance between the two bus stops is small, the position cannot be used to determine whether the traveller is at the correct stop.

We propose using Bluetooth Low Energy (BLE)-beacons in situations demanding the fine-granular localisation of travellers in real-time. BLE beacons are already employed in public transport (PT) systems as a means of automatic fare collection (AFC) [5]. At the same time, we can observe a lack of utilisation of real-time passenger information for disturbance management [6].

In this paper, we suggest a DTT architecture, specify how to set up BLE beacons for tracking travellers over the milestones of their journey and evaluate the setup in a field test. Section 2 discusses the core DTT architecture and the representation of a journey in terms of milestones and illustrates the need for valid localisation. Section 3 provides an overview of candidate technologies for traveller tracking and specifies the BLE-based setup. Section 4 reports the BLE setup's evaluation. Finally, section 5 concludes the article and outlines future work.

2. Traveller Digital Twin Architecture

Following the general architecture for human digital twin systems suggested by [7], a minimal configuration of such a system consists of a real-world twin that performs a task, a sensor and a digital twin. Task-relevant attribute changes in the real-world twin are detected by the sensor and mirrored in the digital twin, thus allowing inferences regarding the real-world twin's present and future state. A digital twin may help to achieve a system-related performance goal [9]. In this case, the digital twin part must reflect the real-world twin's current state in soft real-time, i.e., fast enough, so that the digital twin's state allows influencing the real-world twin in case of deviations from the performance goal. Such an influence requires an actuator in the real world. A common example of an actuator is a display providing travellers with information. If there is no need for real-time decision-making, other digital twin configurations may be restricted to an analytical

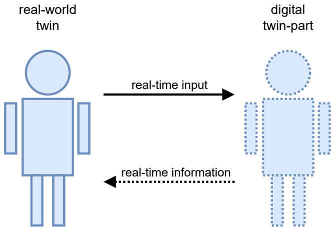


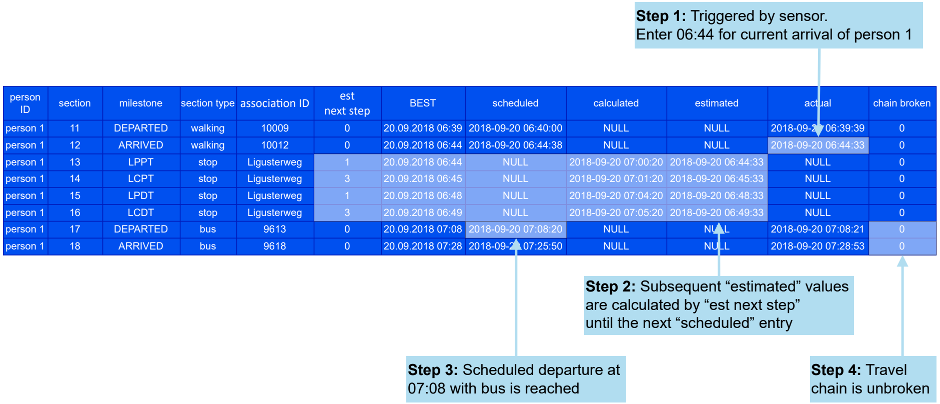
Figure 1. The digital twin configuration following [8].

purpose. These configurations do not incorporate (real-time) information from the digital twin part (dashed arrow in figure 1).

We adopt the digital twin concept to create a DTT. A DTT supports several features driving intelligent PT systems. These features include personalised PT routing, real-time demand-based disruption management and continuous travel experience surveys. The DTTs assist the transport company in real-time traffic management in everyday operations. Management decisions include vehicle holding, transfer coordination, and stop skipping. To apply these measures meaningfully, we divide a traveller's journey into discrete points along the route, so-called milestones.

2.1. Milestones of an Intermodal Journey

A person's journey involves multiple stages that we can divide into discrete process points. These points form the basis for milestone-based traffic management as proposed by [10]. Figure 2 illustrates this process. It depicts the intermodal journey of a single person. The person arrives at the bus stop *Ligusterweg*, possibly by foot, and takes a local bus to start his/her journey. Further information about the area is outlined in section 4.1. The first column contains the person identifier. The second column enumerates the sections of the journey. The milestones in the first and second rows of the third column refer to the departure of the person and his/her arrival at the bus stop. The subsequent abbreviations contain platform-related information explained in detail in [10]. The 6^{th} column *est next step* indicates in how many minutes we expect additional information for the next step of the travel chain. The column *BEST* holds the most reliable value selected from the subsequent columns *scheduled, calculated, estimated* and *actual*. *Actual* values contain measured time values and are, therefore, the most reliable ones. However, they also require sophisticated sensor infrastructure.



Step 1: Triggered by sensor.
Enter 06:44 for current arrival of person 1

person ID	section	milestone	section type	association ID	est next step	BEST	scheduled	calculated	estimated	actual	chain broken
person 1	11	DEPARTED	walking	10009	0	20.09.2018 06:39	2018-09-20 06:40:00	NULL	NULL	2018-09-20 06:39:39	0
person 1	12	ARRIVED	walking	10012	0	20.09.2018 06:44	2018-09-20 06:44:38	NULL	NULL	2018-09-20 06:44:33	0
person 1	13	LPPT	stop	Ligusterweg	1	20.09.2018 06:44	NULL	2018-09-20 07:00:20	2018-09-20 06:44:33	NULL	0
person 1	14	LCPT	stop	Ligusterweg	3	20.09.2018 06:45	NULL	2018-09-20 07:01:20	2018-09-20 06:45:33	NULL	0
person 1	15	LPDT	stop	Ligusterweg	1	20.09.2018 06:48	NULL	2018-09-20 07:04:20	2018-09-20 06:48:33	NULL	0
person 1	16	LCDT	stop	Ligusterweg	3	20.09.2018 06:49	NULL	2018-09-20 07:05:20	2018-09-20 06:49:33	NULL	0
person 1	17	DEPARTED	bus	9613	0	20.09.2018 07:08	2018-09-20 07:08:20	NULL	NULL	2018-09-20 07:08:21	0
person 1	18	ARRIVED	bus	9618	0	20.09.2018 07:28	2018-09-20 07:25:50	NULL	NULL	2018-09-20 07:28:53	0

Step 2: Subsequent "estimated" values are calculated by "est next step" until the next "scheduled" entry

Step 3: Scheduled departure at 07:08 with bus is reached

Step 4: Travel chain is unbroken

Figure 2. Example of next milestone determination by setting an **actual** time stamp.

In the depicted example, the person arrives at the bus stop on time. The scheduled arrival is confirmed by the *actual* value in the second row (*Step 1*). Based on this value, we estimate when the person approaches the bus stop and arrives at the platform (*Step 2*). These estimated values lead to the assumption that the person reaches the scheduled departure of the bus (*Step 3*) and the travel chain, therefore, is unbroken (*Step 4*).

2.2. Creating a Traveller Digital Twin

The DTT concept is not new to transport and mobility research. The authors of [11] adopt the concept for driver intention prediction. In [12], a motorway DTT is used for congestion avoidance. Furthermore, we can classify several real-time simulations as DTTs for analytical purposes. The authors of [13] map real-time traffic network data into the simulation environment SUMO [14]. The authors of [15] provide a real-time simulation framework for demand-responsive transport (DRT) simulation.

For our DTT, we integrate the milestone concept described in section 2.1 with the DTT concept. Thus, we define states the traveller passes throughout his/her PT journey. When starting a journey by PT, these states include arriving at the PT stop (possibly by foot), waiting for the PT vehicle, boarding the vehicle and leaving the stop inside the PT vehicle. Similarly, we can divide the journey's end into the steps of arrival at the stop using PT, alighting from the vehicle and leaving the stop. This work focuses on these two processes only, without considering interchanges. Measuring the steps in a unified way allows us to derive milestones of type *actual* and integrate soft real-time information into our DTT. We use BLE beacons at the stops and inside the vehicle to detect travellers and derive their milestones.

3. Using BLE Beacons to Determine Soft Real-Time Events of a Traveller Digital Twin

Real-time traveller tracking can be realised using several different technologies. These technologies typically also allow for indoor positioning. Therefore, they are often compared by their positioning performance. However, positioning performance is of minor importance for our use case because the information needs of the DTT consist of localisation (i.e. understanding where the traveller is in relation to the PT system) instead of absolute positioning. We also refer to this process as semantic traveller tracking. To account for, possibly, multi-level, underground stations, we are looking for an indoor-capable localisation approach. We also aim to minimise user interaction. Thus, we prefer Be-In-Be-Out (BIBO) capable technologies over Check-In-Check-Out (CICO) technologies. Technologies with low infrastructure requirements are preferred to ensure low implementation costs. These relevant features are summarised in table 1.

Table 1. Comparison of technologies for (soft) real-time traveller tracking.

technology	indoor capable	user interaction	implementation expense	service life
WLAN	**yes**	**BIBO**	electricity supply	-
UWB	**yes**	**BIBO**	**transmitter costs**	2 - 5 years
RFID	**yes**	CICO	electricity supply, RFID scanner	-
GNSS	no	**BIBO**	-	-
BLE	**yes**	**BIBO**	**transmitter costs**	**up to 10 years**

WLAN (Wireless Local Area Network) fingerprinting as a positioning method [16] is especially attractive in environments where the associated infrastructure is already installed. The technology is BIBO capable. WLAN routers require a power supply, which can be costly and cumbersome to install.

Ultra-wideband (UWB) wireless communication [17] can also be used for positioning. It is BIBO-capable and works indoors. UWB transmitters do not require electricity grid infrastructure, as batteries can operate them. A battery lasts 2 to 5 years, a decent service life.

Radio frequency identification (RFID) is a wireless data collection technology [18] that is used in some public entry inspection systems. It requires an RFID tag for the user and a scanner on the infrastructure side. The scanner needs a grid-based power supply. For the tag and scanner interaction, the distance between the devices must not exceed a few centimetres. The technology, therefore, supports CICO processes only.

GNSS are the first choice for global positioning. The technology supports BIBO and does not require any additional infrastructure or maintenance expenses for implementation. However, GNSS signal reception is degraded in challenging environments, such as urban canyons [19] and indoors [20].

BLE technology uses a set of beacons for indoor positioning. The beacons emit a BLE signal that most available smartphones can detect [21]. Measuring the RSSI allows for an approximate distance calculation [22]. The BLE beacons use a battery-based power supply and have a service life of up to 10 years. BLE technology allows for BIBO-oriented systems. With these features, BLE and UWB technologies have similar advantages. Indeed, UWB positioning is more accurate and has a more extended range. However, these features are not the focus of our application. Instead, our application benefits from the fact that BLE units are less expensive and generally longer living than UWB transmitters [23].

3.1. State of the Art

Looking at current applications of BLE beacons in the transport sector, we can distinguish the four main categories: AFC, (indoor) positioning, user information, and PT traveller tracking.

AFC can be CIBO-based [24], which leads the user to actively enter into a contract with the transport company (CI) but prevents him/her from extensive costs by automatically marking the end of the journey (BO). The majority of AFC systems are BIBO based [5], [25], [26]. Some works assess BLE-enabled AFC in a single vehicle [27], while others focus on the entire transport network [28]. The authors of [29] evaluate BLE performance against WiFi and NFC technology. The system suggested by [30] is commercially implemented by a transport company in Porto, Portugal.

BLE applications for positioning include the large field of indoor positioning [31], [32], [33], but also pedestrian outdoor positioning in environments challenging to GNSS [34]. The work of [35] suggests using BLE beacons to prevent accidents by notifying pedestrians on their smartphones when approaching a dangerous intersection. Another BLE application field is positioning and information for visually impaired people [36]. BLE also opens the field of tunnel positioning [37] and traffic tracking in case GNSS reception is degraded [38]. The work of [39] suggests detecting road vehicles by BLE and classifying them using the RSSI. The authors of [40] aim to inform detected road users about the traffic network state. Finally, BLE can optimise production processes in an underground mine [41].

Information-oriented BLE applications can enhance the in-location user experience. This can be customer-experience for retailing [42], touristic information as well as navigation for sightseeing [43] or safety-relevant infrastructure information in case of emergency [44]. Furthermore, BLE allows to estimate the occupancy of transport infrastructure, which enables real-time information about a road network [45], PT arrival time and congestion prediction [46], as well as crowd-sensing in PT scheduling and user habit analysis [47].

BLE-based traveller tracking supports micro-navigation and passenger guidance [48], which often is realised by a combination of different sensors [49]. The work of [50] provides a BLE tracking setup for school buses that prevent pupils from getting lost on their way to school. The authors of [51] estimate that many BLE beacons will be installed within the coming years and suggest applying shared usage for PT passenger tracking.

3.2. *BLE Beacon-Based Traveller Event Determination*

We propose a system setup with a single BLE beacon installed at each PT stop and inside each PT vehicle. As soon as the traveller enters the coverage area of a beacon, an application on his/her smartphone detects the signal and uniquely identifies the beacon with its MAC address. The traveller's device then registers the event *detected* for the identified beacon signal and transmits this information to our database. Thus, we know that a traveller has arrived at the stop where the event was registered. Figure 3 illustrates this process.

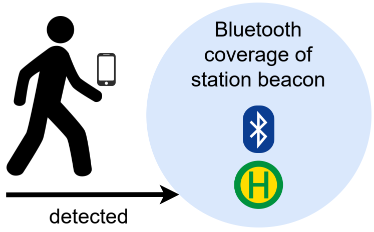


Figure 3. A traveller enters a station's BLE signal coverage area. We register the event *detected* in our database. Image composed of [52], [53].

When a PT vehicle approaches the stop where the traveller is located, his/her smartphone detects the vehicle's BLE beacon. We then write a *detected* event for the vehicle beacon into our database. For a traveller leaving the coverage area of a beacon, we consider him/her en route (*gone* event) as soon as the beacon signal is lost for more than 10 s. We use this method because signal reception might be interrupted even if the traveller is still within the coverage of the beacon. These short outages might occur as several environmental factors influence BLE signal reception.

Figure 4 illustrates the process of a traveller leaving the station in a PT vehicle. While the traveller and vehicle remain at the station, we have *detected* events registered for both station and vehicle beacons. When the vehicle (with the traveller on board) leaves the coverage area of the station beacon for more than 10 s, we receive a *gone* event for the station beacon while still detecting the vehicle beacon. Thus, the traveller must have boarded the vehicle and started the journey. Similarly, we can conclude whether the vehicle left the station without the traveller. The same principle applies to the alighting pro-

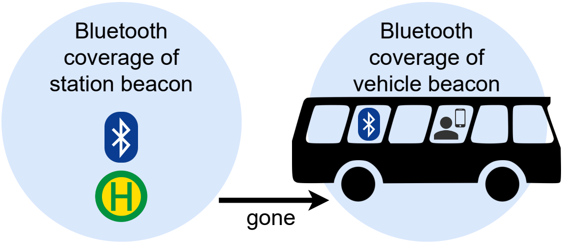


Figure 4. A traveller entered a PT vehicle and left the station's BLE signal coverage area. We register the event *gone* in our database for the station in question.

cess. We can detect a vehicle with a traveller on board approaching the stop/station and conclude whether the vehicle and the traveller left the station separately. The described setup can meet soft real-time requirements. The real-time capability thereby is limited by the registration time of the *gone* event.

The described setup allows for semantic traveller tracking. We register the traveller's position at discrete points of interest. By avoiding tracking the traveller's GNSS position permanently, higher privacy standards can be met with lower effort. Indeed, one drawback of the proposed system is the lack of knowledge about boarding/alighting processes. This lack of knowledge is not likely to be resolved by GNSS integration because of the challenging GNSS signal reception in urban areas and inside the vehicle. Instead, we could gain information about the boarding process requiring a check-in when the traveller boards the vehicle (CIBO), as some AFC implementations [24] do. However, we adhered to the BIBO principle because it keeps user interaction at a minimum. Minimum user interaction is key to customer satisfaction and broad system usage.

We can compare our setup to the one implemented by [30]. The authors contrast two different architectural options. The first option is to equip all vehicles with a BLE beacon that dynamically transmits information. This results in higher transmitting requirements for the beacons but easier smartphone application implementation. The second option consists of installing the beacons at the stops/stations, which reduces the beacon's transmission requirements but leads to a more complex smartphone application [30]. We gain advantages from both options by installing beacons at the stops and inside the vehicles. Indeed, we need more beacons for this setup than for one of the options suggested by [30]. However, the added effort is limited, as beacons are affordable (approx. 30 € each), long-living and easy to maintain.

The BLE-based AFC implementation suggested by [5] uses a similar setup and concludes boarding/alighting processes by synchronising the BLE scans to the vehicle approach/departure to/from a stop. Our suggested setup eliminates the need to synchronise the BLE scans to the vehicle position, as we rely solely on the signal reception.

For continuous vehicle tracking, the integration of GNSS capabilities is beneficial. This integration is indeed planned throughout the ongoing system development, since GNSS works well in open-sky environments. The potentially challenging problem of regaining the GNSS signal after extended tunnel passages [24] is to be addressed in the future.

4. Empirical Evaluation of BLE Localisation

4.1. Method

We implemented a prototype of the described system in a residential district in Brunswick, Germany. The district compromises a local access street describing a circular route of approximately 2 km. It has one single connection to an adjacent main road. One bus line serves four stops in a one-way circular route along the access street. This bus line connects the district to the city's tram network via a local hub.

The simple setup of the bus line is perfect for an initial test run of our BLE-based semantic traveller tracking system. Within our test, we assume that the local bus line can be replaced by a small vehicle operating on a fixed route and serving the stops on a DRT basis. We equipped each of the four stops with a BLE beacon. The station beacons transmitted their signal at 4 dBm every 900 ms and could be uniquely identified by their MAC addresses. In addition to the existing stops, we defined a first/last stop in a parking area at the district entrance. This way, we avoid complicated interactions with PT vehicles at the local hub. Four instructed persons acted as PT travellers and were equipped with BLE-capable smartphones. The smartphones had our developed application for beacon detection installed, as described in section 3.2. Additionally, the smartphones recorded the RSSI of the received BLE signals with a sampling rate of 1 Hz. We used a Mercedes EQV van, as the DRT vehicle. The vehicle carried a beacon transmitting at 6 dBm every 900 ms.

To keep track of the measurement procedure, we applied a fixed schedule. First, all travellers were left at the initial stop while the vehicle departed idle on the circular route. It drove by the stop where the travellers were located without stopping. After another round on the circular route, the vehicle stopped again, and all travellers boarded. They then travelled to the next stop, alighted, and we restarted the process. This procedure simulates the basic possible scenarios (vehicle boarding, alighting and vehicle passing) within a transportation process.

4.2. Setup Validation with Statistical RSSI Analyses

The goal of our first tests was to ensure the basic functionality of the system. Figure 5 depicts the box plots calculated from the data of all travellers for every station. The box plots have been generated using Python's *matplotlib.pyplot.boxplot* function. The orange, horizontal line inside the box represents the median value. The whiskers extend to a maximum value of 1.5 times the interquartile range (IQR). The box plots indicate low skewness (below 1 for all of the stations) and only a few outliers. We can observe comparably high values (and scattering) at the stop *Sielkamp* and low values at the *first/last stop*. Most median RSSI values are between -70 to -80 dBm.

Indeed, these RSSI values would hardly permit data transfer [54]. However, the measured signal strengths are sufficient for our application, as they ensure signal detection. Lower RSSI values are associated with travellers approaching or leaving the station. Within our test setup, the distance between the transmitting beacons and the travellers was considerably high at the *first/last stop* and small at the stop *Sielkamp*, which is reflected by the measured RSSI values. We can explain the scattering of the RSSI values at the station *Sielkamp* by combining the short distance to the transmitting beacon at the stop and large

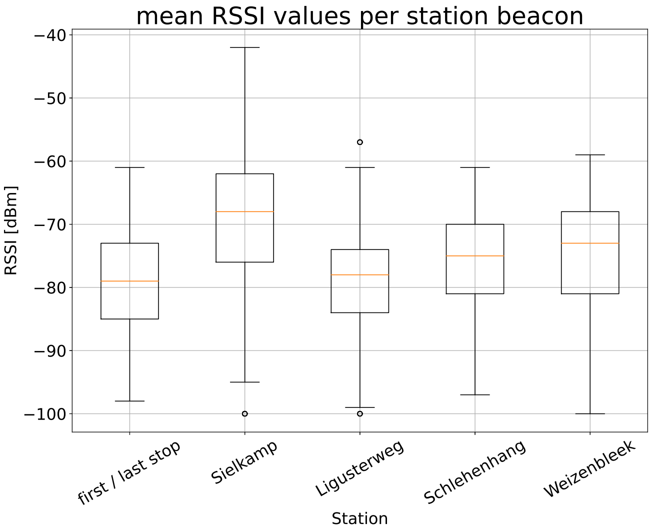


Figure 5. Distribution of RSSI values over all travellers per station.

distances during the approach towards the stop. The low skewness values indicate that the RSSI values are balanced and follow an approximately symmetric distribution. These assumptions are underlined by the low presence of outliers.

Even though the interpretability of the skewness is limited, the symmetric characteristics of the distributions are a desirable development, especially considering that the RSSI values are influenced by various environmental factors. Such factors can be shielding effects caused by human bodies, antenna orientation and interference with other signals [5], [55]. The shielding influence of human bodies and the antenna orientation has already been studied extensively by previous works [5], [56], [57], [58]. Results show that shielding effects can influence data transmission in crowded trams or buses by 10 dBm [5]. Still, we consider this effect to be of minor importance for our application for two reasons. First, we rely on signal detection instead of the Bluetooth connection for data transmission. Signal detection is typically possible even if RSSI values are too low for data transmission. Second, the shielding effect will be much lower in a small DRT vehicle with fixed seats than in a crowded bus or tram.

Another influence on the RSSI is the orientation of the transmitting antenna, causing RSSI changes of 5 to 10 dBm [5]. To test whether the system works regardless of the antenna orientation, we did not make any restrictions on this parameter. The results indicate that stable signal detection is possible under the circumstances and user behaviour within the test environment.

The Bluetooth signal is close to the frequency band used for WLAN connections and, therefore, may suffer from interference [55] [59]. We performed a small interference test to ensure that our setup works in the presence of WLAN signals. The test suggests that we can receive the BLE signal without any deterioration.

Figure 6 depicts the development of the RSSI distribution within different distance intervals between transmitter and receiver. Similar to the tests performed under laboratory conditions by [5], we can observe lower RSSI values with increasing distance. Within 1 m distance, we can observe high (though considerably scattered) RSSI values with low

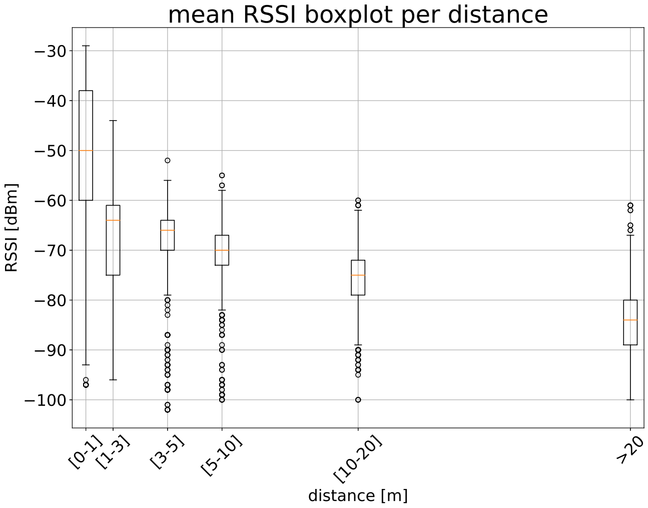


Figure 6. Distribution of RSSI values per distance interval. X-values indicate the distance range for the RSSI values.

skewness. In the $1-3$ m interval, RSSI values are right-skewed, while the presence of outliers is still low. In the $3-5$ m interval, we can observe lower the IRQ and many outliers at low RSSI values. The intervals of $5-10$ m and $10-20$ m follow this development. Within the interval >20 m, we can find the lowest RSSI values following a roughly balanced distribution with only a few outliers at the upper end.

The distribution inside the intervals below 3 m leads to the assumption, that a rough distance estimation is possible from these values. Indeed, the 95% confidence interval is $[0.15, 0.16]$ m in the $0-1$ m interval and $[1.75, 1.82]$ m in the $1-3$ m interval. However, the large IQR in the interval $0-1$ m impedes outlier exclusion. This effect might indeed be caused by waiting persons standing close together and thereby shielding the receiving device with their bodies. The small IRQ in the interval $3-5$ m can be explained by the low sample size, partially caused by the small interval. The sample size of the three remaining intervals is comparably large and stable. From the distribution inside these intervals we can conclude that the RSSI values at higher distances are generally lower and exposed to uncertainties.

Obviously, the varying sample size across the different intervals makes it hard to draw a generally applicable conclusion. Still, the distinction of whether the receiver is closer than 1 m to the transmitter is very clear from the RSSI values. Furthermore, the development of the RSSI in our setup exhibits strong similarities with the one derived under laboratory conditions by [5]. From our system validations, we can conclude that the proposed setup works well under the usage conditions in our test setup.

4.3. *BLE Beacon-Based Traveller Detection*

With the setup validation completed, we can apply the data to the use case of semantic traveller tracking. Semantic traveller tracking allows one to follow the traveller's travel chain. The travel chain one of the travellers followed during our measurement campaign (section 4) is depicted in figure 7. The suggested BLE beacon setup enables localisation at discrete points, i.e., at the stops and inside the vehicle. The traveller's position is listed on the y-axis, showing the stationary beacons below the vehicle beacon. The green colour of the vehicle row indicates that the vehicle beacon is detected at a station. We can conclude this information from the overlap with a stationary beacon signal. If no stationary beacon but only the vehicle beacon is detected, we can conclude that the traveller used the vehicle to move between stops. The red colour indicates that the vehicle passed the stop where the traveller was located without stopping. We can conclude this information from the short detection time. All stationary beacons are depicted in blue.

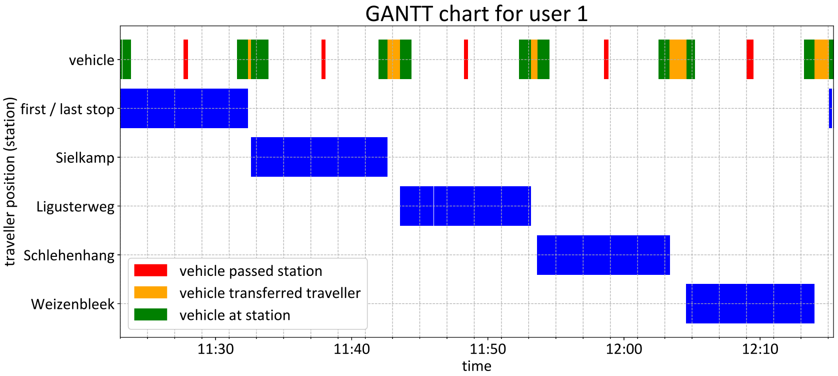


Figure 7. Digital twin of a traveller represented as GANTT chart. The traveller follows the schedule of our measurement campaign as described in section 4.1.

The traveller starts his/her journey at the *first/last stop*. With the event *detected* registered at 11 : 23 in our database, we know that the traveller arrived at the stop, as described by the milestone concept in section 2.1. Initially, the vehicle was also present at this stop (first green vehicle bar) but departed shortly after the beginning of the test. A few minutes later, we can detect the vehicle beacon for approximately 30 s as the vehicle passes by the stop where the traveller is located (first red vehicle bar). At 11 : 31, the vehicle stops to pick up the traveller (first green part of third vehicle bar). From the combination of the persisting signal of the vehicle beacon and the signal loss of the beacon at the stop, we can conclude that the traveller boarded the vehicle and left the stop. Thus, following the concept in section 2.1, we can write a milestone of type *actual* for the traveller's departure. The vehicle drives to the next stop *Sielkamp* (orange part of third vehicle bar). As soon as the vehicle reaches the stop, the traveller alights from the vehicle, followed by the vehicle's departure. We can observe that the traveller keeps detecting the station beacon *Sielkamp* while the vehicle beacon signal is lost (the last green part of the third vehicle bar). Thus, the traveller reached the destination and alighted from the vehicle (arrival milestone of type *actual*). Following the scheduled measurement procedure for the remaining three stops, we can observe similar behaviour. Finally, the traveller reaches the *first/last stop* on board the vehicle.

As demonstrated, the suggested BLE beacon setup can keep track of a traveller's chain within our test environment. However, in some cases, we observe short signal outages. The stop *Ligusterweg* illustrates these outages. While the traveller waits at this stop, the blue bar is interrupted by several short white spaces. Since we thoroughly tested the Bluetooth signal connection, we assume a software implementation issue caused these outages. Depending on the configuration of the user's device, some background processes might interrupt the constant tracking of the BLE signal. These interruptions are, however, of minor importance for the system's overall functionality.

4.4. Discussion

We evaluated the suggested setup during a measurement campaign in a test environment. The setup performed well under the conditions described in section 4.1. Therefore, we assume it can be implemented at a reasonable expense in simple and limited real-world PT networks. Adapting the setup to more complex PT networks is feasible but might require further research and development.

We can summarise the measurement results as follows. The mean RSSI values in the order of -70 to -80 dBm indicate challenging conditions for data transmission but allow for stable BLE signal reception. The suggested setup does not suffer from WLAN interference. RSSI-based distance calculations work well within 1, possibly 3 m distance. Above these values, RSSI levels are lower, and distance calculations do not work reliably. We can perform semantic traveller tracking by concluding the milestones of a traveller's journey from the detected beacon. Tracking works even with small interruptions in signal reception, meeting soft real-time requirements.

Within the described environment, we evaluated different scenarios, such as boarding and alighting travellers and vehicle passing. The setup performed as expected for all tested scenarios. Semantic traveller tracking was possible under all circumstances in the test environment without outages. We, therefore, assume that adapting the setup for real-world conditions is feasible. The presented BLE-based semantic traveller tracking system enables us to *measure* the states throughout a journey and thus derive milestones of type *actual*. The suggested setup yields these values in soft real-time. With these soft real-time updates, we can refer to our system as a DTT with analytical purposes, following the definition in section 2. The system works regardless of short signal outages since the milestones are concluded from the time of the first signal detection and the time of the signal loss. At the same time, we can be sure that the system detected the correct beacons by distinguishing them by their MAC addresses. Faulty detection is unlikely. For more sophisticated localisation and traveller tracking, the suggested system could benefit from an integration of GNSS measurements. This is indeed one of the activities planned for the future.

5. Conclusion and Outlook

In this article, we describe the benefits and development of DTT using a BLE beacon setup for semantic traveller tracking. We use milestones to divide the traveller's journey into discrete points. Our suggested BLE beacon setup can measure these points. This enables us to integrate reliable soft real-time information into the DTT.

We present our setup and its implementation in a test environment. With the test setup, we performed and analysed RSSI measurements to validate the correct functionality of the system. Finally, we showcase the system's functionalities for an actual travel chain in our test environment.

Upcoming steps involve the fusion of GNSS measurement with the BLE beacon set-up to leverage shortcomings in both technologies. Furthermore, we plan to integrate our database into a suitable simulation environment. This environment allows the simulation and analysis of different transport management decisions following the principle of a *What-If Analysis*. Displaying the outcome of this analysis to the user in real-time establishes a feedback channel to the real-world traveller, a necessary element of a DTT.

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References

[1] Käthner D, Ihme K, Grunewald E. The More You Know: Digital Twins of Travelers; 2024. Manuscript accepted for publication.

[2] Borole N, Rout D, Goel N, Vedagiri P, Mathew TV. Multimodal public transit trip planner with real-time transit data. Procedia-Social and Behavioral Sciences. 2013;104:775-84.

[3] Nunes AJAD. A user collaboration model for urban passenger transport. Universidade do Porto (Portugal); 2016.

[4] Fang Y, Jiang Y, Fei W. Disruption recovery for urban public tram system: an analysis of replacement service selection. IEEE Access. 2020;8:31633-46.

[5] Narzt W, Mayerhofer S, Weichselbaum O, Haselböck S, Höfler N. Be-in/be-out with bluetooth low energy: Implicit ticketing for public transportation systems. In: 2015 IEEE 18th International Conference on Intelligent Transportation Systems. IEEE; 2015. p. 1551-6.

[6] Jevinger Å, Persson JA. Exploring the potential of using real-time traveler data in public transport disturbance management. Public Transport. 2019;11:413-41.

[7] Miller ME, Spatz E. A unified view of a human digital twin. Human-Intelligent Systems Integration. 2022;4(1):23-33.

[8] ULRICH F. DIE ERSTELLUNG EINES DIGITALEN ZWILLINGS: eine einfhrung in simcenter amesim. MORGAN KAUFMANN; 2021.

[9] Sjarov M, Lechler T, Fuchs J, Brossog M, Selmaier A, Faltus F, et al. The digital twin concept in industry–a review and systematization. In: 2020 25th IEEE international conference on emerging technologies and factory automation (ETFA). vol. 1. IEEE; 2020. p. 1789-96.

[10] Rudolph F, Grunewald E, Tremer D. Dividing Journeys in Milestones–A passenger (agent) trajectory reference. Transportation Research Procedia. 2023;72:2046-53.

[11] Kumar SA, Madhumathi R, Chelliah PR, Tao L, Wang S. A novel digital twin-centric approach for driver intention prediction and traffic congestion avoidance. Journal of Reliable Intelligent Environments. 2018;4(4):199-209.

[12] Kušić K, Schumann R, Ivanjko E. A digital twin in transportation: Real-time synergy of traffic data streams and simulation for virtualizing motorway dynamics. Advanced Engineering Informatics. 2023;55:101858.

[13] Oertel R, Krumnow M, Krimmling J, Wagner P. Microscopic real-time simulation of Dresden using data from the traffic management system VAMOS. In: 19th ITS World Congress; 2012. .

[14] Behrisch M, Bieker L, Erdmann J, Krajzewicz D. SUMO–simulation of urban mobility: an overview. In: Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation. ThinkMind; 2011. .

[15] Perera T, Gamage CN, Prakash A, Srikanthan T. A simulation framework for a real-time demand responsive public transit system. In: 2018 21st International Conference on Intelligent Transportation Systems (ITSC). IEEE; 2018. p. 608-13.

[16] Chen P, Xu YB, Chen L, Deng ZA. Survey of WLAN fingerprinting positioning system. Applied Mechanics and Materials. 2013;380:2499-505.

[17] Kshetrimayum RS. An introduction to UWB communication systems. Ieee Potentials. 2009;28(2):9-13.

[18] Nikitin PV, Rao K, Lazar S. An overview of near field UHF RFID. In: 2007 IEEE international conference on RFID. IEEE; 2007. p. 167-74.

[19] Xie P, Petovello MG. Measuring GNSS multipath distributions in urban canyon environments. IEEE Transactions on Instrumentation and Measurement. 2014;64(2):366-77.

[20] Puricer P, Kovar P. Technical limitations of GNSS receivers in indoor positioning. In: 2007 17th International Conference Radioelektronika. IEEE; 2007. p. 1-5.

[21] Dinh TMT, Duong NS, Sandrasegaran K. Smartphone-based indoor positioning using BLE iBeacon and reliable lightweight fingerprint map. IEEE Sensors Journal. 2020;20(17):10283-94.

[22] Paek J, Ko J, Shin H. A Measurement Study of BLE iBeacon and Geometric Adjustment Scheme for Indoor Location-Based Mobile Applications. Mobile Information Systems. 2016;2016(1):8367638.

[23] Accent Advanced Systems S. UWB vs BLE Beacons for indoor location; (accessed: 23.07.2024). Available from: `https://accent-systems.com/uwb-vs-ble-beacons-for-indoor-location/`.

[24] Pätzold K. Feldversuch eines bluetoothbasierten Check-In / Be-Out-Systems“ als Erweiterung von big bird Soest. Cubic Transportation Systems (Deutschland) GmbH; 2017. 0.94.

[25] Narzt W, Mayerhofer S, Weichselbaum O, Haselböck S, Höfler N. Bluetooth low energy as enabling technology for be-in/be-out systems. In: 2016 13th IEEE Annual Consumer Communications & Networking Conference (CCNC). IEEE; 2016. p. 423-8.

[26] Bitew MA, Muhammad A, Fandiantoro DH, Boedinoegroho H, Kurniawan A. E-payment for public transportation using BIBO method based on Bluetooth low energy beacon. In: 2020 International Conference on Computer Engineering, Network, and Intelligent Multimedia (CENIM). IEEE; 2020. p. 199-204.

[27] Jung K, Bermudez PB, Hwang H, Oh Y, Kwak J. Passenger's location estimation using Kalman filter for Beacon fare collection in a wireless low floor tram. In: 2018 International Conference on Electronics, Information, and Communication (ICEIC). IEEE; 2018. p. 1-4.

[28] Vieira E, Bartolomeu PC, Hosseini SM, Ferreira J. IOTApass: Enabling public transport payments with IOTA. In: 2020 IEEE 6th World Forum on Internet of Things (WF-IoT). IEEE; 2020. p. 1-6.

[29] Couto R, Leal J, Costa PM, Galvão T. Exploring ticketing approaches using mobile technologies: QR codes, NFC and BLE. In: 2015 IEEE 18th International Conference on Intelligent Transportation Systems. IEEE; 2015. p. 7-12.

[30] Ferreira MC, Dias TG, e Cunha JF. Is Bluetooth low energy feasible for mobile ticketing in urban passenger transport? Transportation Research Interdisciplinary Perspectives. 2020;5:100120.

[31] Ji M, Kim J, Jeon J, Cho Y. Analysis of positioning accuracy corresponding to the number of BLE beacons in indoor positioning system. In: 2015 17th International Conference on Advanced Communication Technology (ICACT). IEEE; 2015. p. 92-5.

[32] Faragher R, Harle R. An analysis of the accuracy of bluetooth low energy for indoor positioning applications. In: Proceedings of the 27th International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2014); 2014. p. 201-10.

[33] Chawathe SS. Beacon placement for indoor localization using bluetooth. In: 2008 11th International IEEE Conference on Intelligent Transportation Systems. IEEE; 2008. p. 980-5.

[34] Hasan R, Hasan R. Bluetooth low energy (BLE) beacon-based micro-positioning for pedestrians using smartphones in urban environments. Precision Positioning with Commercial Smartphones in Urban Environments. 2021:135-49.

[35] Schwebel DC, Hasan R, Griffin R, Hasan R, Hoque MA, Karim MY, et al. Reducing distracted pedestrian behavior using Bluetooth beacon technology: a crossover trial. Accident Analysis & Prevention. 2021;159:106253.

[36] Martínez-Cruz S, Morales-Hernández LA, Pérez-Soto GI, Benitez-Rangel JP, Camarillo-Gómez KA. An outdoor navigation assistance system for visually impaired people in public transportation. IEEE Access. 2021;9:130767-77.

[37] Brož J, Tichỳ T, Prokeš R, Štencek A, Šmerda T. Proximity Approach to Bluetooth Low Energy-Based Localization in Tunnels. Sustainability. 2023;15(4):3659.

[38] Khalid A, Memon I. Bluetooth-based traffic tracking system using esp32 microcontroller. In: Advances in Machine Learning and Computational Intelligence: Proceedings of ICMLCI 2019. Springer; 2020. p. 737-46.

[39] Lewandowski M, Płaczek B, Bernas M, Szymała P. Road traffic monitoring system based on mobile devices and bluetooth low energy beacons. Wireless communications and mobile computing. 2018;2018(1):3251598.

[40] Abbott-Jard M, Shah H, Bhaskar A. Empirical evaluation of Bluetooth and Wifi scanning for road transport. In: Australasian Transport Research Forum (ATRF), 36th. vol. 14; 2013. .

[41] Park S, Choi Y. Bluetooth beacon-based mine production management application to support ore haulage operations in underground mines. Sustainability. 2021;13(4):2281.

[42] Dudhane NA, Pitambare ST. Location based and contextual services using bluetooth beacons: New way to enhance customer experience. Lecture Notes on Information Theory Vol. 2015;3(1).

[43] Ito A, Hatano H, Fujii M, Sato M, Watanabe Y, Hiramatsu Y, et al. A trial of navigation system using BLE beacon for sightseeing in traditional area of Nikko. In: 2015 IEEE International Conference on Vehicular Electronics and Safety (ICVES). IEEE; 2015. p. 170-5.

[44] Hasan R, Hasan R, Islam T. InSight: A Bluetooth beacon-based ad-hoc emergency alert system for smart cities. In: 2021 IEEE 18th Annual Consumer Communications & Networking Conference (CCNC). IEEE; 2021. p. 1-6.

[45] Periša M, Cvitić I, Peraković D, Husnjak S. Beacon technology for real-time informing the traffic network users about the environment. Transport. 2019;34(3):373-82.

[46] Zorić B, Dudjak M, Bajer D. Predicting public transport arrival time and congestion based on BLE beacon crowdsourced data. In: 2022 IEEE Zooming Innovation in Consumer Technologies Conference (ZINC). IEEE; 2022. p. 81-6.

[47] Cianciulli D, Canfora G, Zimeo E. Beacon-based context-aware architecture for crowd sensing public transportation scheduling and user habits. Procedia Computer Science. 2017;109:1110-5.

[48] Ahola J, Heinonen S. Experimenting Bluetooth beacon infrastructure in urban transportation. In: 11th ITS European Congress, Glasgow; 2016. .

[49] Molina-Gil J, Caballero-Gil P, Quesada-Arencibia A, De Blasio GS. Application of fuzzy logic in a secure Beacon–based guidance system for public transportation. International Journal of Applied Mathematics and Computer Science. 2022.

[50] Sakphrom S, Suwannarat K, Haiges R, Funsian K. A simplified and high accuracy algorithm of rssi-based localization zoning for children tracking in-out the school buses using bluetooth low energy beacon. In: Informatics. vol. 8. MDPI; 2021. p. 65.

[51] Lahti J, Heino I, Kostiainen J, Siira E. Bluetooth beacon enabled mobility services and opportunities in public transit. In: 23rd its World congress, Melbourne; 2016. .

[52] Foundation W. Datei:Bluetooth.svg; (accessed: 23.07.2024). Available from: `https://de.m.wikipedia.org/wiki/Datei:Bluetooth.svg`.

[53] Foundation W. File:Smartphone icon - Noun Project 283536.svg; (accessed: 23.07.2024). Available from: `https://commons.wikimedia.org/wiki/File:Smartphone_icon_-_Noun_Project_283536.svg`.

[54] Li M. Understanding the Measures of Bluetooth RSSI; (accessed: 23.07.2024). Available from: `https://www.mokoblue.com/measures-of-bluetooth-rssi/`.

[55] Lin JR, Talty T, Tonguz OK. An empirical performance study of Intra-vehicular Wireless Sensor Networks under WiFi and Bluetooth interference. In: 2013 IEEE Global Communications Conference (GLOBECOM). IEEE; 2013. p. 581-6.

[56] Hiroi K, Shinoda Y, Kawaguchi N. A better positioning with BLE tag by RSSI compensation through crowd density estimation. In: Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct; 2016. p. 831-40.

[57] Etzlinger B, Nußbaummüller B, Peterseil P, Hummel KA. Distance estimation for ble-based contact tracing–a measurement study. In: 2021 Wireless Days (WD). IEEE; 2021. p. 1-5.

[58] Hoshi H, Ishizuka H, Kobayashi A, Minamikawa A. An indoor location estimation using BLE beacons considering movable obstructions. In: 2017 Tenth International Conference on Mobile Computing and Ubiquitous Network (ICMU). IEEE; 2017. p. 1-2.

[59] Narendra P, Duquennoy S, Voigt T. BLE and IEEE 802.15. 4 in the IoT: Evaluation and Interoperability Considerations. In: Internet of Things. IoT Infrastructures: Second International Summit, IoT 360° 2015, Rome, Italy, October 27-29, 2015, Revised Selected Papers, Part II. Springer; 2016. p. 427-38.