Integrating Indoor Localization Systems Through a Handoff Protocol

Francesco Furfari, Michele Girolami, and Paolo Barsocchi

***Abstract*—The increasing adoption of location-based services drives the pervasive adoption of localization systems available anywhere. Environments equipped with multiple indoor localization systems (ILSs) require managing the transition from one ILS to another in order to continue localizing the user's device even when moving indoor or outdoor. In this article, we focus on the handoff procedure, whose goal is to enable a device to trigger the transition between ILSs when specific conditions are verified. We distinguish between the triggering and managing operations, each requiring specific actions. We describe the activation of the handoff procedure by considering three types of ILSs design, each with increasing complexity. Moreover, we define five handoff algorithms-based RSSI signal analysis and we test them in a realistic environment with two nearby ILSs. We establish a set of evaluation metrics to measure the performance of the handoff procedure.**

***Index Terms*—Bluetooth low energy, handoff, indoor localization, location-based services (LBSs).**

Adopted Symbols for Algorithm and Metric Description

Symbol	Description.
t_w	Time window for beacon analysis.
τ	RSS threshold used by the algorithms.
h	Hysteresis threshold.
t_{GT}	Transition time between two ILS.
t_{ET}	Estimated transition time between ILSs.
T_R	Time of reaction metric.
p_{eh}	Probability of early handoff metric.

I. Introduction

The potentialities of location-based services (LBSs) strictly rely on the possibility of estimating the position of a target in a seamless way [1]. This requirement represents a challenging task for a number of reasons. While for outdoor environments, global navigation satellite system (GNSS)-based techniques are well established, for indoor environments, it still exists the lack of a standardized technology and software interfaces enabling a device to self-localize or to be localized from the existing infrastructure [2]. Furthermore, the possible coexistence of heterogeneous indoor localization system (ILS) gives rise to the problem of switching from an ILS to a different one, and changing the localization technique [3], [4], such as fingerprint [5]. Indoor scenarios have evolved with the development of indoor localization technologies. To ensure continuous localization service, the conjunction between indoor and outdoor environments has been recognized as a key aspect that deserves further investigation.

However, in a broader context, any connecting area between different localization systems is regarded as a *seam*. Thus, seamless positioning techniques aim to provide localization services while users move across different environments.

A pioneering work in defining handoff methods for achieving seamless positioning is presented in [6]. This work addresses localization systems, covering both outdoor and indoor scenarios. It envisions a handoff algorithm that combines existing indoor and outdoor technologies to achieve seamless positioning. While recent works have already explored the transition between indoor and outdoor scenarios, our article uniquely focuses on the seamless transition among ILSs throughout the proposed handoff protocol. In addition, our modeling is more general and captures both outdoor and indoor transitions.

In this article, we focus on the last issue we mentioned, namely, the handoff (or handover) procedure that we introduce in [7] and [8]. The handoff procedure can be defined as a software routine designed to maintain connectivity with infrastructure and enabling the provision of a localization service, while a user moves indoor and/or outdoor. We first propose a macrodistinction between vertical and horizontal handoffs [9], then we define three possible scenarios describing how ILSs can cooperate and how such cooperation can impact the handoff procedure. We propose single, aggregated, and managed scenarios according to the level of cooperation. This work proposes for the first time a set of five algorithms, designed to trigger the handoff procedure. The focus is constrained to a proximity detection strategy, specifically centered on the analysis of received signal strength (RSS) from a device that broadcasts an ILS. We also propose two protocols to manage the handoff strategy, according to the selected use cases. We validate the proposed handoff solution by experimental evaluation of the proposed radio frequency (RF) handoff algorithms. In our experiments, we adopt Bluetooth technology to advertise the existence of an ILS. More

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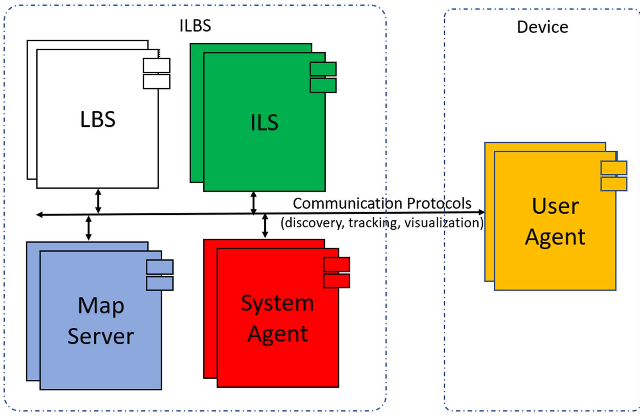


Fig. 1. ILBS hardware and software subsystems.

specifically, we adopt a number of Bluetooth tags advertising beacon messages at 2 Hz. We also employ a commercial smartphone to collect beacons and we run a median filter to elaborate the RSS value from the collected beacon messages. In turn, the adopted statistic is exploited by the proposed handoff algorithms. We reproduce 64 ILS's transitions, and we consider two metrics for the evaluation purpose: the probability of an early handoff (p_{eh}) and the time of reaction (T_R). The first metric measures the probability that an algorithm triggers the handoff procedure before moving from an ILS to the next one, while the second metric measures the time required by an algorithm to trigger the handoff procedure.

The rest of this article is organized as follows. Section II describes the reference scenario and it provides the definition of handoff. Section III describes the trigger phase, introducing five handoff algorithms. Section IV reports the managing phase of the handoff protocol, while Sections V and VI describe the proposed metrics and our experimental settings and results. Finally, Section VII concludes this article.

II. Handoff Procedure

With the term *handoff*, we refer to a software procedure enabling a device to switch connections between different localization systems. In the context of indoor localization, an ILS is considered as one of the subsystems of the indoor infrastructure to which various connections are established, as illustrated in Fig. 1. The term handoff was initially used in the context of telecommunications networks, particularly in mobile telephone networks, it has assumed greater importance. Being borrowed from a different domain, it is fair to point out that there are differences compared to mobile telephony. In fact, the handoff concept applied to mobile telephone networks [10], [11] requires keeping connectivity across different base stations, so as to avoid any possible voice interruption during a call [12], [13]. When referring to a localization system, the handoff might also introduce a temporary disconnection from the localization system. Another remarkable difference between telecommunication and localization systems is that base stations are deployed contiguously, maximizing the spatial coverage of the broadband signal. Nevertheless, we cannot assume the same deployment for ILSs. More specifically, we consider that at least at the initial stage, ILSs cannot cover the whole indoor area, rather, only some regions are covered by any ILS. Consequently, when defining the concept of handoff for ILSs, it is important to take into account whether ILSs are contiguous or not.

We first distinguish between *horizontal* and *vertical* handoffs. In the first case, we assume the existence of a transition between localization systems that use the same standard. In our context, a standard addressing specifically the indoor localization domain would provide a set of guidelines, specifications, and protocols widely accepted and adopted within the industry; a common framework to enable interoperability, compatibility, and consistency across different technologies, products, and systems. Therefore, even if ILSs use different technologies, for example, radio positioning versus ultrasonic positioning, adhering to the same standard allows them to be able to interact, and a transition between them is a horizontal handoff. A different case refers to the transition from a localization system to a different one that is not compliant with the same standard. In this case, we consider a vertical handoff. In this last case, even the same technology is used, there would be no way to automatically interoperate, but specific adapters should be implemented to overcome the differences between the two systems. In this respect, the transition from the outdoor localization in which there are already well-established standards like GNSS [14], [15] to whatever standard will be adopted for indoor environment is to be considered a vertical handoff.

Both handoffs are important to ensure continuous and uninterrupted service for mobile users in different situations and environments. In our context, the goal of the handoff procedure is enabling a person to navigate *seamlessly* in the environments he or she is visiting. The objective is to minimize user intervention, who should not perceive differences in the transition between outdoor/indoor or indoor/indoor locations. In this work, we only focus on the horizontal handoff, assuming that the ILSs we are traversing adhere to the same standard as proposed in [7] and [8], which refer to as infrastructure for LBSs (ILBSs). In the next section, we recall the key concepts of this proposal.

A. Navigation Life Cycle

To address the current heterogeneity of ILSs and promote their interoperability, the central concept of our proposal is that ILSs should actively communicate their presence, both within the local environment (local advertisement) and on the Internet (global advertisement). This communication involves detailing their functionalities through a discovery mechanism with which ILSs can autonomously describe themselves by means of a metadata file, which we refer to as the ILBS descriptor. This descriptor enables user devices, such as smartphones, to interact with an ILS available nearby (in the case of the local advertisement), or with remote ILS on the web, similarly to an Internet search (in the case of the global advertisement). In case of the local advertisement, the ILS might exploit proximity-based technologies to advertise its presence, such as Bluetooth Low Energy, ultrawide band, or Wi-Fi. The ILBS descriptor describes a set of resources available for users. Among them, we mention:

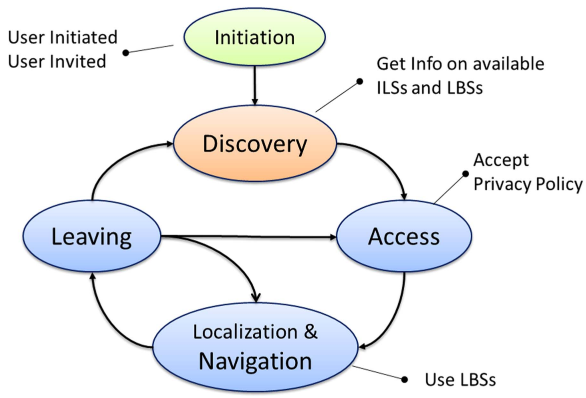


Fig. 2. Navigation life cycle executed by the UA.

1) a *map server* providing indoor maps of the monitored area; 2) information about the available *ILSs*, such as interfaces and protocols; 3) *LBSs* provided by the ILBS, such as a tour or booking services. The primary entities in this discovery process include the following.

1) System agent (SA): This is a software process that represents the information system and communicates the features (ILBS descriptor) of the smart environment equipped with one or more ILSs.
2) User agent (UA): This is a software component operating on the user's device, engaging on behalf of the user with the accessible ILSs/SA.

A graphical representation of the ILBS components is reported in Fig. 1. The navigation life cycle can be described with a set of states and transitions executed by a UA, as shown in Fig. 2. The *initiation* state can be triggered in various ways. In this work, we consider the case in which the initiation is triggered by the user, i.e., the owner of a smartphone willing to discover a LBS in the nearby. The user then triggers a discovery phase, which allows to locally look for an ILS. A possible implementation of the local search is based on RF technologies. In particular, the UA exploits such technologies to: 1) detect the presence of an ILS in proximity; 2) retrieve the ILBS descriptor providing information to access the ILS. In this respect, we consider the use of Bluetooth a viable technical solution. In particular, the EddyStone format [16] allows advertising URLs encapsulated in a beacon message. In turn, given the URL, it is possible to access the ILBS description as a, e.g., JSON file. The discovery phase ends when the UA retrieves ILBS descriptor. The UA then moves on to the *access* phase. During this phase, the UA requires to the user to accept/decline the privacy policies of the indoor environment [17]. The access phase is determinant for the correct use of the localization services and it could potentially introduce a slowdown in the handoff procedure, as an explicit user's intervention is required. Once the access phase concludes, the user can use the available LBSs, such as the *localization and navigation* services. The *leaving* phase starts when the user exits the environment. At this stage, the UA releases the resources acquired during the visit. The leaving phase is closely related to the handoff procedure, as explained in Section II-B.

B. Handoff Operations and Scenarios

The leaving phase begins when the user has left the indoor environment. To this purpose, the UA must continuously check if the user is in proximity to an exit. This can be achieved by leveraging the user's position, proximity technologies, or a combination of location and proximity. The handoff confirmation for new services availability should occur only when an individual crosses the administrative threshold of the new environment. Our study of radio signals serves only as an initial step toward a full solution, which requires data fusion techniques typical of context-aware applications.

The handoff procedure requires the UA to perform the following two high-level operations.

1) *Triggering the handoff:* This operation consists of detecting the conditions required for the UA to activate a vertical or horizontal handoff when approaching an exit (see Section III).
2) *Managing the handoff:* This operation implements a set of steps required to: disconnect, connect, and access from/to an ILS in order to switch localization system and resources (see Section IV).

We distinguish among three possible scenarios in applying handoff procedures: *single*, *aggregated,* and *managed*. Their underlying architectures describe the degree of cooperation between ILSs and they represent the natural way of deploying and interconnecting these systems over time.

With the *single* scenario, we assume that ILSs do not cooperate, rather each of them is an autonomous system. The user's device is required to discover an ILS as soon as it gets in proximity to it. The user has to accept, at least on the first visit, the privacy policy before establishing a valid connection. This is the case of ILSs deployed in various buildings of a city, and typically for these systems the focus is on a seamless transition from outdoor to indoor. If there is no physical contiguity between the outdoor and indoor spaces, it becomes necessary to provide a description of the proximity area. This encompasses information needed to reach the indoor, such as details about stairs, elevators, and potential routes to reach the indoor space from the outside.

With the *aggregated* scenario, we introduce a further level of complexity. In this case, we assume that the description of different ILSs is aggregated into a unique ILBS descriptor and discovered by the UA at once. For example, this is the case of a wide shopping mall, equipped with two ILSs: the first covers the first floor, while the second provides localization services to the second floor. The ILSs may belong to different commercial entities, have been installed at different times and have different characteristics, but to provide a better user experience to the visitors who have just arrived at the large shopping center, all the information about the area is provided during the discovery process at the main entrance.

We also consider a third scenario, referred to as *managed*. In this case, we assume the existence of an authority managing and coordinating access to the indoor area. Similarly to the previous case, the user's device discovers all the ILSs at once, but a single authority is responsible for the localization policy. It authenticates and collects user consent, and provides an infrastructure

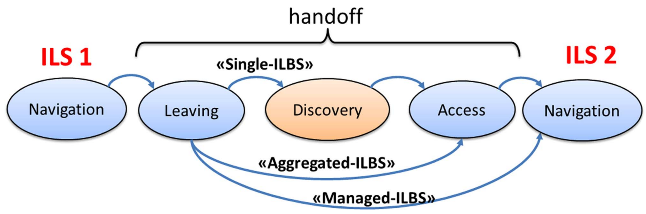


Fig. 3. Handoff life cycle from ILS_1 to ILS_1 showing the possible transitions.

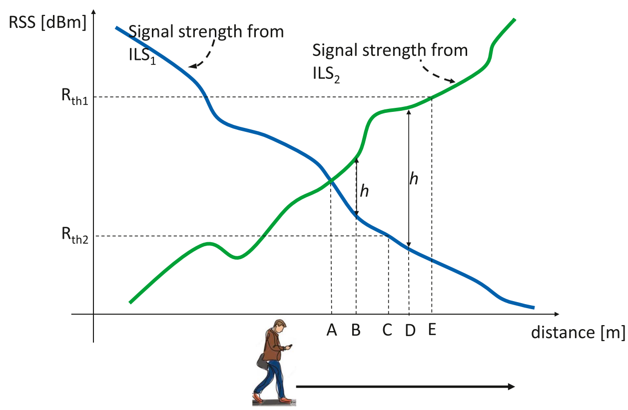


Fig. 4. Graphical representation of the RSS variation while moving from ILS_1 (blue line) to ILS_2 (green line). Points A,B,C,D, and E refer to the transition point from an ILS to the next one.

for machine to machine (M2M) communications between ILSs. This architecture is suitable for indoor environments in which it is required to control access to specific areas for security reasons, e.g., an airport terminal.

State transitions occurring for the aforementioned scenarios are shown in Fig. 3. In the figure, we consider the UA moving from ILS_1 to ILS_2. In the case of single scenarios, the UA should start every time a new discovery process. Instead, in the case of aggregated or managed scenarios, some states can be skipped since the information is provided upon entering the area.

III. Triggering the Handoff: RF Decision Algorithms

We now propose a set of algorithms designed to implement the triggering operation defined in Section II-B. These algorithms alone, as written in the previous section, cannot form a comprehensive solution to the problem. For instance, envision two adjacent floors in a building with completely overlapping signal strength, potentially leading to a misinterpretation triggering the handoff procedure. The inclusion of additional data, such as barometric pressure, becomes imperative to disambiguate such situations.

In Fig. 4, we show a user moving from ILS_1 to ILS_2. The user's device is able to detect the proximity with respect to an ILS, through RSS analysis. In particular, the signal strength of ILS_1 decreases as the user moves away from it. Similarly, the averaged signal strength of ILS_2 increases as the user moves closer to it. Given the example reported in Fig. 4, we propose five possible algorithms to trigger a handoff procedure. It is important to remark that all of the algorithms are based on the RSS analysis on a time window, namely t_w. More specifically, given a time window of length k seconds, each algorithm analyzes beacon messages collected in such a time frame. As detailed in Section VI, we set the Bluetooth tags to 2 Hz and we collect beacon messages by means of a commercial smartphone. Such a device collects data during the time window and it runs a median filter. We tested several settings for the length of the time window with the goal of exploring the limits and the potentialities of the Bluetooth technology. We report in Nomenclature the adopted symbols (see adopted symbols for algorithm and metric description).

A1 - Signal strength: The device triggers a handoff only if the signal of the new ILS (the arrival ILS) is sufficiently strong, i.e., greater than the threshold τ. In Fig. 4, the handoff occurs at position E, if the threshold τ is set to R_{th1}. The general idea of this algorithm is avoiding an unnecessary handoff when the signal from a newly discovered ILS is still inadequate.

A2 - Relative signal strength: The device compares all the available ILS's signals, and it selects the strongest value independently from the actual signal's value. The target ILS is selected on an averaged measurement of the received signals. Referring to Fig. 4, the handoff occurs at position A. This algorithm avoids too many unnecessary handoff when the current ILS signal is still adequate.

A3 - Relative signal strength with threshold: The device triggers the handoff only if the current signal (departure ILS) is sufficiently weak, i.e., less than a threshold τ and the signal value of the newly discovered ILS is greater than the current one. As shown in Fig. 4, the handoff occurs at position C because the RSS values for ILS_1 are below the threshold R_{th2} and RSS values from ILS_2 are stronger than those of ILS_1. As a result, A3 triggers a transition from ILS_1 to ILS_2.

A4 - Relative signal strength with hysteresis: The handoff is triggered only if the new ILS is sufficiently strong, given an hysteresis cutoff value, namely, h. In this case, the handoff occurs at point B, as shown in Fig. 4. This algorithm prevents the so-called ping-pong effect between two ILSs [18], which is caused by fluctuations in the RSSs from the available ILSs.

A5 - Relative signal strength with hysteresis and threshold: The handoff is triggered only if the current signal (departure ILS) level drops below a threshold τ and the target ILS is stronger than the current one by a given hysteresis margin. Referring to Fig. 4, the handoff occurs at position D, if the threshold τ is set to R_{th2}. This algorithm avoids an unnecessary handoff when the current signal is still adequate and the signal of the new ILS is sufficiently strong, given an hysteresis cutoff value, namely, h.

IV. Managing the Handoff Protocol

In this section, we introduce various categories of handoff, similarly to the well-known concepts in the field of telecommunication systems. To achieve this, we selectively adapt the terminology and principles from telecommunications to the ILS domain, emphasizing the aspects that hold relevance and applicability within the context of ILS. Before providing details of the proposed handoff protocol, it is essential to first distinguish

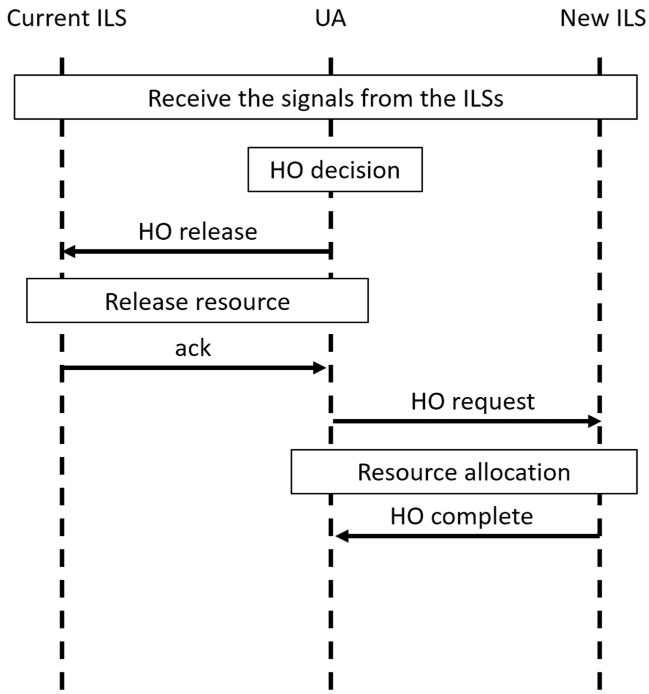


Fig. 5. Sequence diagram of the hard MCHO.

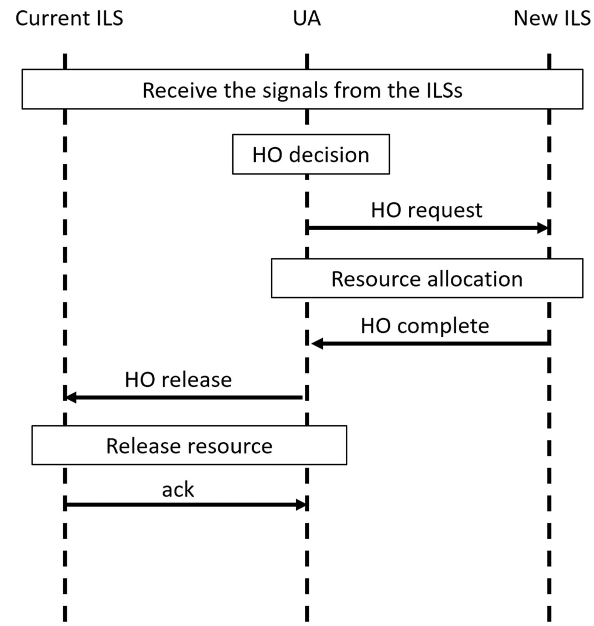


Fig. 6. Sequence diagram of the soft MCHO.

between three distinct types of handoff mechanisms. These handoff mechanisms are differentiated based on the level of control and decision-making assigned to the mobile devices, which significantly impacts the overall handoff system architecture. In particular, we consider:

1) mobile-controlled handoff (MCHO);
2) network-controlled handoff (NCHO);
3) mobile-assisted handoff (MAHO).

In a mobile-controlled handoff, the mobile device is in charge of triggering the handoff based on the RSS analysis. Therefore, MCHO requires that the mobile device continuously collect and analyze RSS values. The NCHO operates differently. In this architecture, the ILS is in charge of determining if the mobile device is required to start the handoff procedure or not. Finally, with the MAHO architecture the current ILS directs the mobile device to measure signals from surrounding ILSs and to report those measurements back. The current ILS then uses these measurements to determine the need for a handoff. In this article, we assume an MCHO architecture. After the triggering event occurs, the UA is required to implement a series of steps necessary to: 1) disconnect from the current ILS; 2) connect to a new ILS; 3) access the new ILS to switch localization system.

We also consider two possible types of handoff procedures: hard handoff (HHO) and soft handoff (SHO), as shown in Figs. 5 and 6. In an HHO, the primary objective is to promptly release the resources allocated with the first ILS. The uncertainty during the leaving phase is minimal, and the acquisition of resources from the new ILS occurs only subsequently, or concurrently, with the release of the old resources.

Conversely, during an SHO the release of resources from the previous environment takes place only after acquiring the new resources. Consequently, there is a period during which both sets of resources are maintained. It is important to emphasize that effective management of resource release and acquisition is not only essential for the mobile device but also for the infrastructure, which must scale according to the number of visitors.

A. Hard and Soft Handoff Use Cases

In this section, we define the structure of indoor infrastructure and pinpoint specific scenarios that serve as starting points for addressing handoff procedures. To delve into this matter, we revisit some key concepts explaining the initial discovery phase of an ILS.

We first define three types of areas described by an ILBS: *administrative*, *coverage,* and *proximity*. The administrative area identifies the geographical region in which an ILBS is deployed and, generally, it corresponds to the building map. It is within these boundaries that resources are made available, and access policies are determined by the relevant authority. In Fig. 7, this area is delimited by the blue line.

The *coverage* area identifies the region covered by the ILS. Such an area varies according to the technology adopted by the ILS. As an example, a Bluetooth-based ILS might cover a smaller area with respect to Wi-Fi-based ILS exploiting professional WiFi access points. In the first instance, it delineates the region where a target can be located according to a specific localization technology, and indicates in which zones the system is announced. Please be aware that the coverage area is the sum of the coverage of the different available technologies and does not have a precise delimitation on the map like the administrative area. Therefore, the area is determined by the information published for the various access points and advertisement beacons located within the administrative area, such as position and power. In Fig. 7, it is represented by the sum of the blue circles.

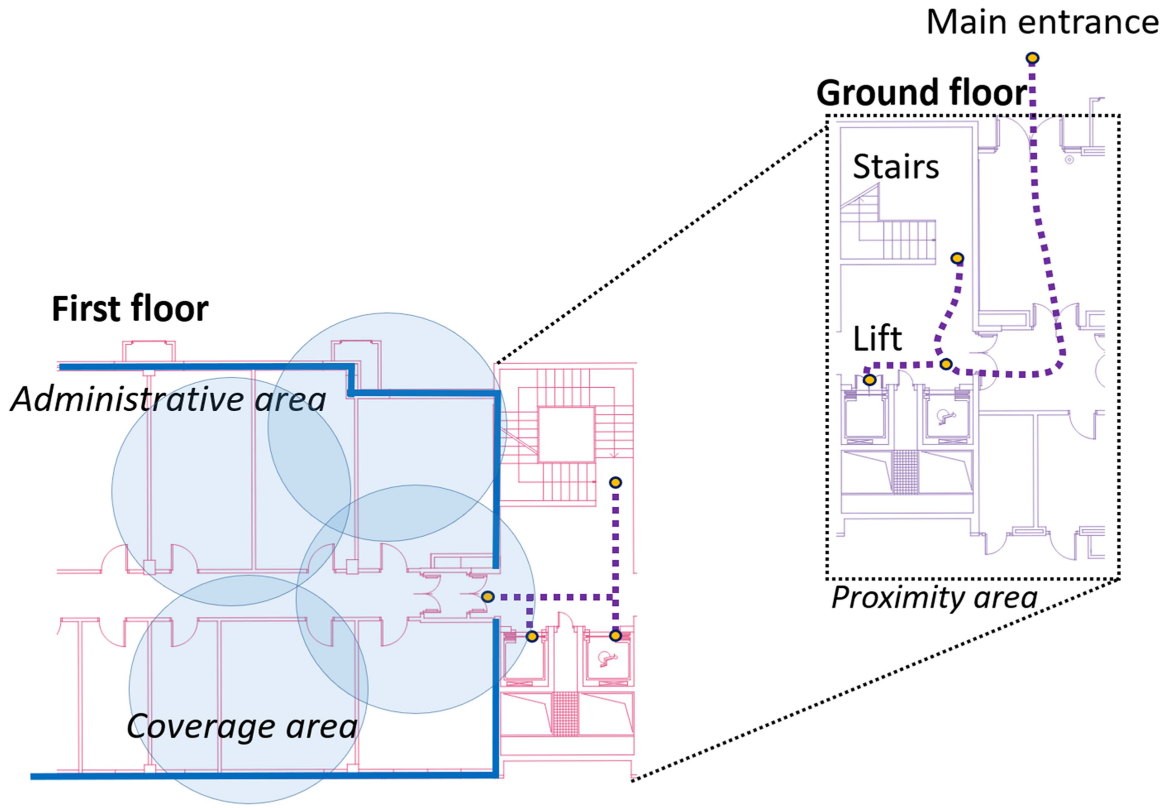


Fig. 7. Graphical representation of administrative, coverage, and proximity areas provided by the ILBS descriptor.

Lastly, the *proximity* area identifies the area right before entering the administrative area. More specifically, we introduce this concept to define a transition region necessary for moving from outdoor to indoor spaces. In this case as well, there is no precise delineation of this area, and it is determined by information such as recommended routes, guidance for stairs, or indications for elevators, all of which are present in the ILBS descriptor. This information, besides being presented to the user in textual form, can include details to enhance navigation, such as the number of steps, the level of the floor to be reached, the speed of elevator ascent, and so forth. Fig. 7 illustrates, as dotted lines, the routes from the ground floor to the first floor for reaching the administrative area.

The possible coexistence of ILSs leads us to also consider three possible ILS topology. More specifically, the distance between administrative areas and the extent of coverage areas are factors that influence the handoff procedure. We distinguish three cases: *far*, *contiguous*, or relatively *near* ILSs. With the *far topology* we consider each ILS independent and their administrative areas very distant from each other. Essentially, every shop is equipped with an ILS and radio sources used to determine the proximity are strategically deployed close the entrances. Such a deployment eases the discovery phase, and when the signal strength begins to decrease upon entering in the administrative area, it triggers the entrance. Upon leaving the indoor environment, an HHO is typically executed. In the absence of information about other near systems, all resources are released as shown in Fig. 5. The same technique based on the changing slope of the signal strength can be applied to detect the exit. After leaving the shop, the UA can remain in the discovery state for a certain period, but once a timeout occurs, the user needs to initiate the discovery phase again. This topology is depicted in the upper part of Fig. 8, it is typical of scenarios in which Single-ILBS are deployed in the city and two vertical handoff are usually performed in the transition from one ILS to another. This topology can also be found in large shopping centers, where no integration of the various ILSs has been carried out, but the other topologies are more suitable for the aggregated or managed ILBS scenarios.

Two ILSs with a *contiguous topology* are illustrated in the middle of Fig. 8. In such instances, the exiting environment seamlessly leads to entering the other, and both environments are equipped with radio sources that define their boundaries. Signals from the contiguous area are perceived when the user is still inside a different administrative area. In this case, an SHO solution is the most natural choice for implementation, as shown in Fig. 6.

The *near topology* is reported in the bottom part of Fig. 8. This case represents an intermediate scenario that might occur in large shopping centers. In these case, there exists a clear boundary between administrative areas, but the coverage areas of different ILSs may partially overlap. In this scenario, both solutions can be utilized, and various markers can serve as references: exiting an administrative area, overlapping coverage areas (indicated by red dotted lines), or the distance between administrative areas (marked by black dotted lines). The signal

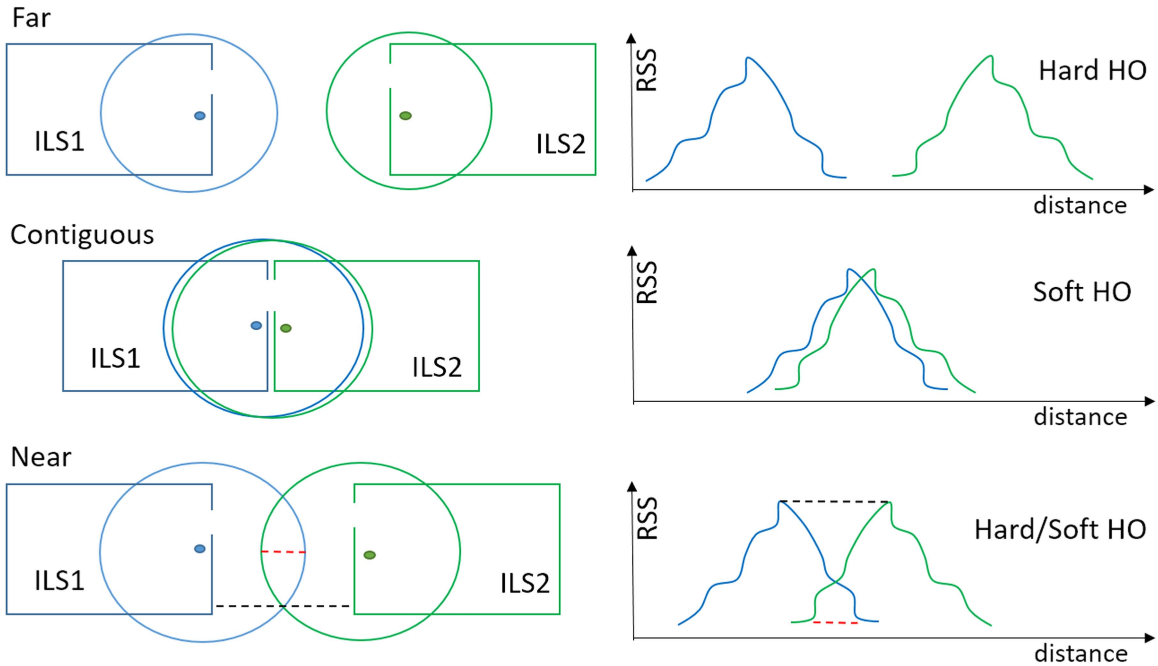


Fig. 8. Three possible topology for two ILS: Far, contiguous, and near ILSs.

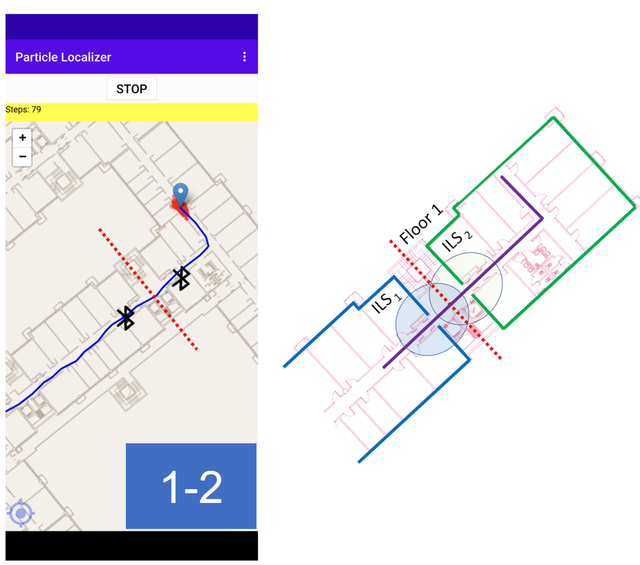


Fig. 9. Graphical representation of testing environment with two ILSs, the transition line is reported as red-dotted line.

trend for all three cases is depicted in the right part of the figure. The experimentation was conducted, drawing inspiration from the third case.

V. Evaluation Metrics

We refer to Fig. 9 to describe our reference scenario. In the figure, we show two ILSs each covering a specific region: ILS_1 covers the blue region, while ILS_2 covers the green one. The transition between the two ILS is represented as a dotted-red line. We propose below a set of evaluation metrics for measuring the performance of the handoff procedure.

1) *Accuracy - A:* It is possible to consider the handoff system as a classification task. The accuracy metric measures the algorithm's ability to correctly determine the necessity of a handoff. It is calculated as the ratio of correct classifications to the total number of trials.
2) *F_1 metric - F_1:* It considers both the algorithm's ability to accurately detect the need for a handoff (recall) and its precision in correctly executing the handoff when necessary.
3) *Probability of an early handoff - p_{eh}:* The probability an algorithm triggers the handoff procedure before the transition line between two ILSs. High values of p_{eh} indicate that the algorithm behaves proactively, differently the algorithm can be considered reactive as it triggers the handoff only after the transition line (red-dotted line in Fig. 9).
4) *Time of Reaction - T_R:* The time required by the algorithm to determine the ILS with respect to the transition line. This metric measures the triggering operation described in Section II-B. Given t_{GT}, the time of transition between two ILSs (red-dotted line in Fig. 9), and given t_{ET}, the time when the next transition is estimated, $T_R = t_{\text{ET}} - t_{\text{GT}}$. It is worth to note that T_R can assume positive and negative values. In the first case, the algorithm is reactive, returning the correct ILS only *after* the user crosses the transition line. On the second case, the algorithm behaves in a proactive way, *anticipating* the ILS transition.
5) *Time of Managing the Handoff - T_H:* The time required to manage the handoff procedure, as defined in Section II-B. This metric includes the steps described in Fig. 3. It is important to remark that, the time required to complete the handoff might be significant, therefore, an algorithm anticipating the handoff procedure, i.e., a proactive

algorithm, might mitigate the negative effect of significant values of T_H.

To further elaborate on the interconnection between the evaluation metrics, let us consider the following example. Suppose we have a specific handoff algorithm, and the measured values are A $= 1$, $F_1 = 1$, and $t_w = 3$ s. These values indicate that: 1) the algorithm successfully avoids unnecessary handoffs; 2) the procedure is accurate; 3) the handoff time requires 3 s to be completed. In this scenario, the optimal handoff procedure would involve $p_{\text{eh}} = 1$, signifying a fully proactive algorithm with a reaction time of $T_R =$ -3 s, effectively compensating for the 3-s management time. By setting $T_R =$ -3 s, the system becomes proactive and initiates the handoff procedure 3 s in advance, reaching the transition line. With $p_{\text{eh}} = 1$, the system always detects and predicts the need for a handoff, ensuring that all handoff procedures are completed precisely at the transition line.

VI. Experimental Settings and Results

We now detail the experimental settings that we use to test the handoff procedures in a realistic use-case. More specifically, we focus on the managed scenario described in Section II-B. In our experiments, the relevant information of both the departure and arrival ILSs is known a priori. In particular, the goal is to show how it is possible for an UA to trigger the handoff procedure. We assume a user moves in an indoor environment in which two ILSs are available. Each system covers a specific region, ILSs can be discovered with a wireless short-range technology, such as Bluetooth tags.

Moreover, we assume that the UA knows in advance the optimal settings of the proposed algorithms, namely the threshold and the hysteresis values to apply to the estimated RSS values. These assumptions can be readily generalized: ILSs may rely on technologies distinct from Bluetooth examined in this study, such as Wi-Fi or UWB. Moreover, contiguous ILSs might employ different radio signals, with one using Bluetooth and the other utilizing UWB or Wi-Fi. The generalization is grounded in two key assumptions: first, that ILSs are self-describing, meaning each environment declares the type of radio technology it employs, and additionally, each environment can provide information on the optimal parameters setting. This information guides the UA during transitions between environments. The second assumption is that the UA adjusts its behavior based on the obtained description. For instance, it decides whether to activate or deactivate radio interfaces and selects the most suitable algorithm for triggering the transition; if the radios are of different types, i.e., Wi-Fi versus Bluetooth, employing algorithms based on the hysteresis parameter might not be meaningful, but algorithms based on the threshold could still be applicable. Similarly, if the radio offered by the new environment is incompatible with the device's radio interfaces, adaptability becomes crucial. This adaptability is essential, and in large environments equipped with distinct ILSs, it can be planned in advance after receiving the ILBS descriptor of the shopping mall.

To this purpose, we select as testing environment our research institute, namely ISTI-CNR located in Pisa. We identify a 20-m long corridor of 1.8 m width and 3.1 m height. The corridor is characterized by offices both on the left and right side, as reported in Fig. 9.

ILS_1 covers the West side of the corridor, while ILS_2 covers the East side. The transition point between the two ILSs is a relax area, and it is denoted with a red-dotted line in Fig. 9. The area covered by the two systems is delimited by Bluetooth beacons. In particular, we deploy two Bluetooth tags at 1.8 m from the ground and 6 m from the transition line reported in Fig. 9. Tags advertise iBeacon messages at 0 dBm and 2 Hz as the advertisement frequency. Tags are small units powered by a CC2420 battery produced by GlobalTag.

A. Data Collection and Evaluation Metrics

Data are collected with a commercial smartphone, namely, Google Pixel Pro 6 provisioned with the `ParticleLocalizer` Android application [19], [20]. The application is designed to collect and log Bluetooth beacons and the application also estimates the user's position, showing the followed path, as reported on the left side of Fig. 9. Please note that we adopted a commercial smartphone for the data collection so as to reproduce a realistic condition. According to our experience, the maximum number of beacon messages that can be collected in a time window depends on the software library provided by the operating system, e.g., Android API. As a general consideration, given a Bluetooth tag set to 10 Hz, we cannot expect collecting ten beacon messages per second, as the software procedure used to scan for beacon messages provides some limitations.

Tests are executed by some users holding a smartphone in hand and walking with a speed of approximately 1.1 m/s, the user acts as follows:

1) he/she moves from ILS_1 to ILS_2;
2) he/she moves from ILS_2 back to ILS_1.

The adopted smartphone logs some information related to the received Bluetooth beacons:

1) timestamp of reception (Unix timestamp);
2) MAC address;
3) major and minor numbers;
4) RSS value in decibel units.

Furthermore, we label the ILS's transitions (ILS_1 to ILS_2 and vice versa) with the handoff ground truth (GT), reporting the timestamp of a transition. More specifically, each time the user moves from an ILS to the adjacent one, we record the transition's timestamp. Such information can be used to compare the output of the implemented algorithms with respect to the GT. The format of the GT is the following: <timestamp, ILS_x>, where ILS_x identifies the destination ILS. On the left-side of Fig. 9, we show an example of the path followed in testing the aforementioned transitions. The blue line shows the followed path, the pin icon shows the current user's position and the Bluetooth icon denotes the location of the Bluetooth tag delimiting the ILS. The figure also shows on the bottom-right corner the button to log the GT. In particular, every time the user moves from ILS_1 to ILS_2 or vice versa, we logs the transition's timestamp.

Our dataset comprises 64 transitions from ILS_1 to ILS_2 and vice versa, with a total of 108.562 collected beacon messages

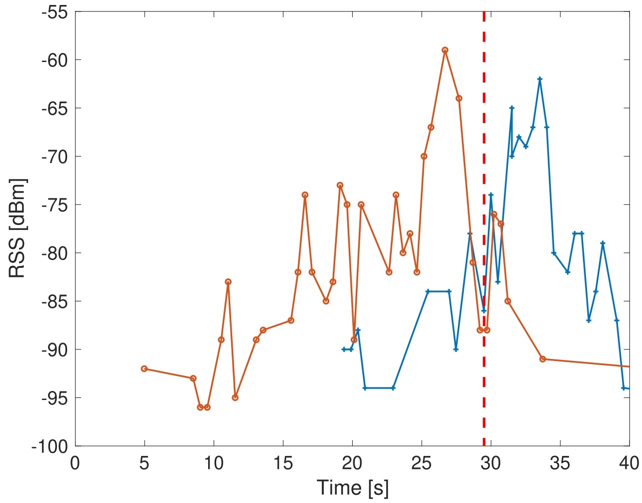


Fig. 10. RSS fluctuation while a user approaches the ILS transition line (red-dotted line).

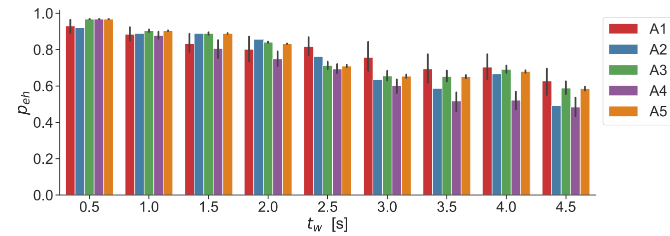


Fig. 11. Probability of an early handoff, p_{eh} by varying time window t_w. Vertical black bars show how the probability varies for a specific algorithm.

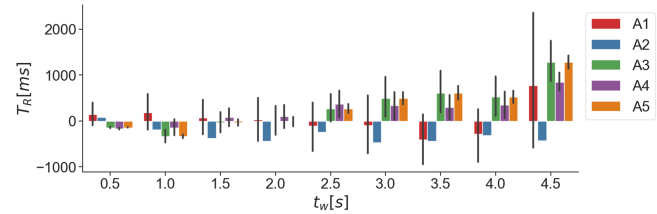


Fig. 12. Average value of time of reaction, T_R by varying time window t_w. Vertical black bars show how the time of reaction varies for a specific algorithm.

from the tags positioned according to Fig. 9. Data collected with the smartphone are used to execute the five handoff algorithms. For the purpose of this work, we evaluate the following metrics: Accuracy, F_1, p_{eh}, and T_R, as reported in Section V. We then analyze how p_{eh}, T_R are influenced by two crucial algorithm's settings, as reported in Section III.

B. Results

We first analyze how RSS values estimated by the receiving device fluctuate while the user approaches to the transition area between two ILSs (see the dotted red-line in Fig. 9). We show in Fig. 10 the RSS variation of two tags: the orange line shows the raw RSS values of the tag advertising ILS_1, while the second tag, depicted in blue color, advertises ILS_2. In the figure, it is evident that the RSS values linked to ILS_1 exhibit a decreasing trend over time, whereas the RSS values corresponding to ILS_2 beacons tend to increase. To smooth spiky noise and mitigate fluctuations in RSS, we applied a median filter during the preprocessing stage. More specifically, the receiving device collects data during the time window t_w and then it runs a median filter with the beacon messages received during the time window. The wider the sampling time window, the higher the number of expected beacon messages. The filtered RSS values serve as the input for the proposed handoff algorithms, designed to manage the inherent variability in RSS and trigger the handoff procedure. Experimental results are obtained by executing A1-A5 algorithms with data obtained from the 64 ILS's transitions. Each of the algorithms analyzes the beacon values in a time window of t_w seconds, after which the algorithm outputs the corresponding result. The time window ranges in the interval 0.5–4.5 s with a step of 0.5 s. Please note that when using short time windows, e.g., 1 or 0.5 s, then the number of beacon messages elaborated might be very limited. More specifically, given a tag's advertising frequency of 2 Hz and a time window $t_w = 1$ s, then two only beacon messages are expected from a tag. As a result, the median filter that we run to smooth the RSS values of beacon messages results in the mean RSS values of the two beacon messages. From our experiments we obtain perfect accuracy and F_1 metrics ($A = 1, F_1 = 1$). Given such results, we observe that the proposed algorithms correctly trigger the handoff procedure when moving from an ILS to the next one. Nevertheless, such metrics (accuracy and F_1) do not provide insights about the time required to trigger the handoff. Concerning metrics p_{eh} and T_R, results are reported in Figs. 11 and 12, respectively.

The probability of an early handoff is defined as the probability that the algorithm returns an earlier ILS transition, with respect to the transition point. Therefore, it measures the probability of anticipating the transition. From Fig. 11, we observe that t_w significantly impacts the performance of the five algorithms (A1–A5). More specifically, and as a general trend, by increasing the time window t_w, the algorithms tend to lower the probability p_{eh} from $p_{\text{eh}} \approx 1$ with $t_w = 0.5$ s to $p_{\text{eh}} \approx 0.7$ with $t_w = 4.5$ s. In particular, for certain values of the time window t_w such a trend is more evident, as for $t_w = 2.5$ s and $t_w = 3$ s, while for other values, the trend is different. This is the case of $t_w = 0.5$ s, 1 s, 1.5 s where p_{eh} remains stable.

The time of reaction T_R is defined as the time required by an algorithm to return the correct ILS to which connect to, after the user crosses the transition line. In particular, when $T_R \leq 0$, then an algorithm is proactive, while $T_R > 0$ implies an algorithm is reactive. From Fig. 12, we observe that t_w impacts the overall performance. The A2 algorithm is proactive and it always anticipates the correct ILS to which it connects, the wider the t_w, the earlier A2 anticipates the transition. Similar considerations also apply for A1 algorithm. A different pattern is implemented with algorithm A3. In this case, the algorithm behaves in a reactive way also when t_w significantly varies.

We further investigate the performance of the handoff algorithms taking into account two settings: the threshold value τ

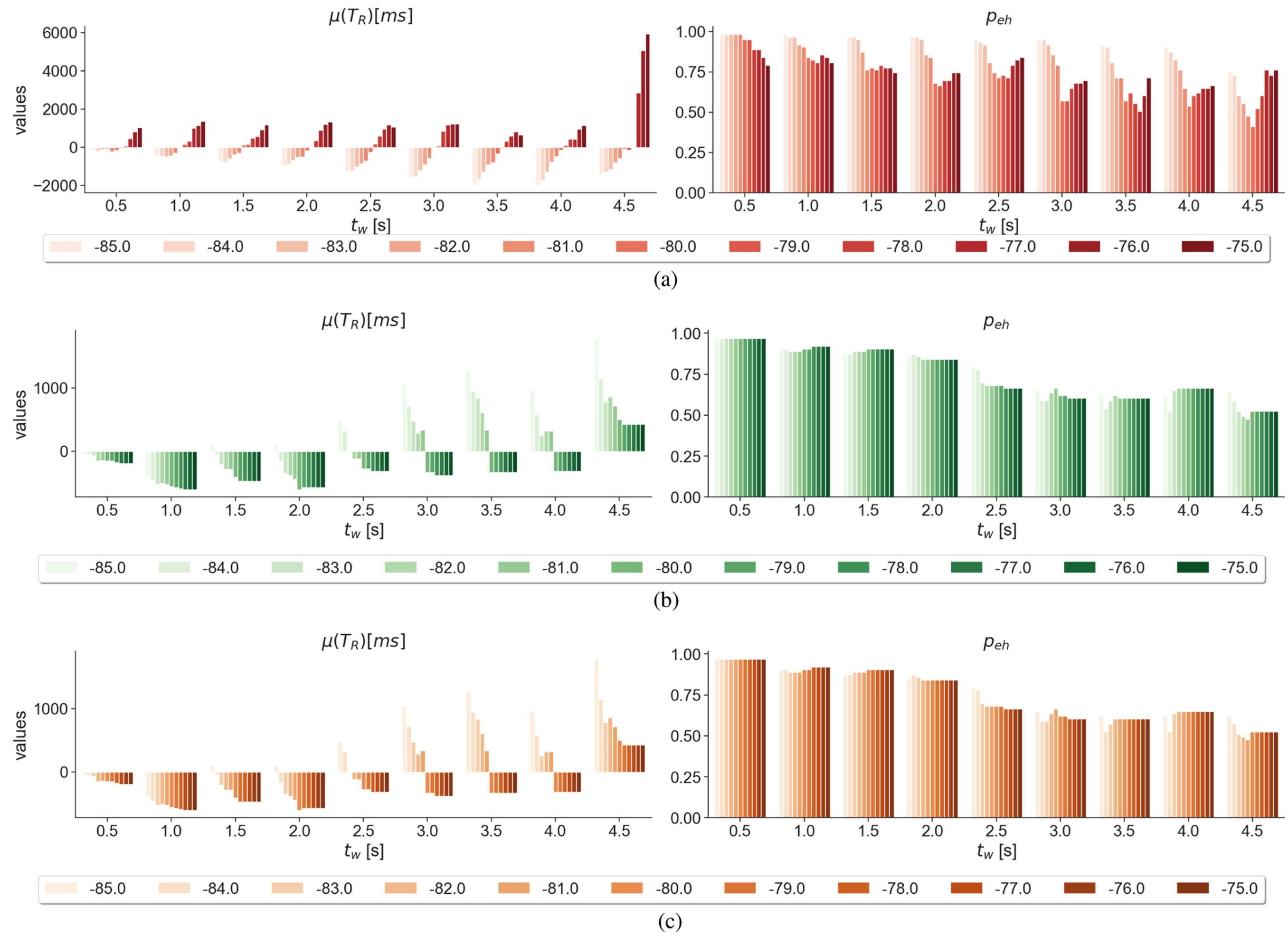


Fig. 13. Impact on the threshold values (τ from -85 to -75 dBm) to T_R and p_{eh} metrics. (a) Algorithm A1. (b) Algorithm A3. (c) Algorithm A5.

TABLE I
RELEVANT PARAMETERS FOR THE TESTED ALGORITHMS (SEE SECTION III)

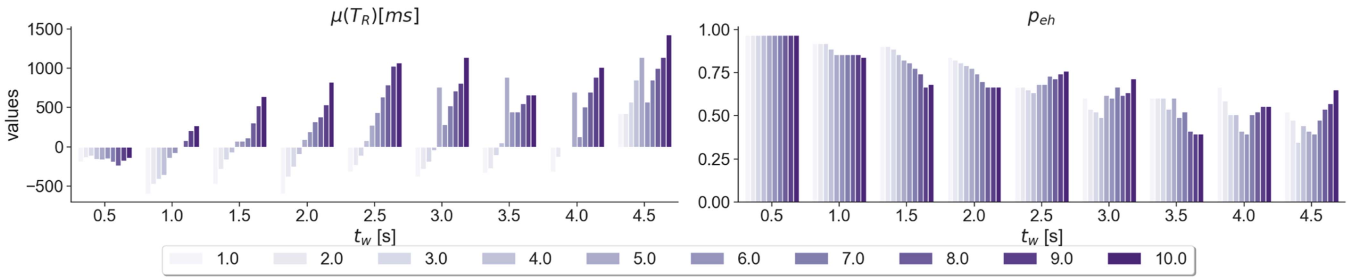
Algorithm	Threshold τ	Hysteresis h	No params
A1	✓(arrival ILS)		
A2			✓
A3	✓(departure ILS)		
A4		✓	
A5	✓(departure ILS)	✓	

and the hysteresis value h. We report in Table I which setting affects the implemented algorithms.

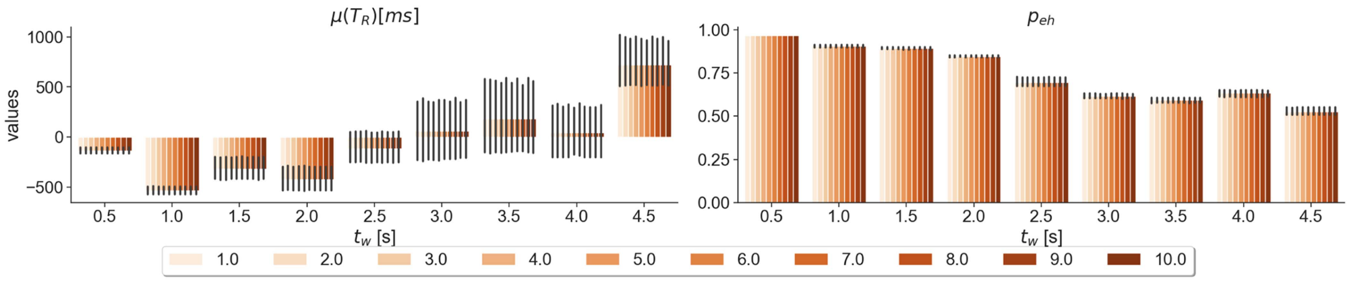
Concerning τ, we show in Fig. 13 the mean value of T_R, $\mu(T_R)$, and of p_{eh} for algorithms A1, A2, and A3 by varying two settings: 1) t_w in the range 0.5 to 4.5 s; and 2) the threshold in the range -75 to $-85\,\mathrm{dBm}$. For a given value of t_w (0.5–4.5 s), the increase in τ remarkably affects the two considered metrics. More specifically, concerning the A1 algorithm reported in Fig. 13(a), we observe that increasing values of τ bring $\mu(T_R)$ from negative to positive values. The increase in the time window further amplifies such a trend. Concerning the probability p_{eh} obtained with the A1 algorithm, by increasing τ we observe a decrease of p_{eh}. Such a decrease is altered when we modify the width of the time window. Concerning A3 and A5 algorithms reported in Fig. 13(b) and (c), respectively, such patterns are slightly modified. In particular, increasing values of τ tend to decrease $\mu(T_R)$ up $t_w \leq 3\,\mathrm{s}$ after which the pattern varies and values of $\mu(T_R)$ range from positive to negative values. The p_{eh} pattern clearly shows a decreasing value of p_{eh} by increasing both τ and t_w.

The pattern we explained is particularly noticeable in Fig. 13(a) for the A1 algorithm. Given the time window $t_w = 4.5\,\mathrm{s}$, the A1 algorithm reports T_R up to 6 s and $0.45 \leq p_{\mathrm{eh}} \leq 0.75$. This situation describes a case in which A1 behaves proactively in high probability, but when A1 is reactive it introduces a high delay to trigger the handoff (T_R up to 6 s). Please notice that in Fig. 13 we always report the mean value of T_R which is influenced also by outliers values. In other words, A1 is generally proactive, but when such an algorithm behaves reactively the time required to trigger the handoff (T_R) is very high.

Concerning the hysteresis value, we show in Fig. 14 the results of T_R and p_{eh} by varying: t_w in the range 0.5 to 4.5 s and the hysteresis in the range 1–10 dBm. In Fig. 14(a), the A4 algorithm demonstrates that as t_w increases, p_{eh} decreases. Simultaneously, an increase in h steers the algorithm toward a more reactive characteristic.



(a)



(b)

Fig. 14. Impact of the hysteresis values (h from 1 to 10 dBm) to T_R and p_{eh} metrics. Vertical black bars show how the two metrics vary with a specific value of t_w and h. (a) Algorithm A4. (b) Algorithm A5.

In the case of the A5 algorithm, its behavior depends on both h and τ values. However, as illustrated in Fig. 14(b), the algorithm proves to be independent of the hysteresis value h. The performance, in terms of t_w and p_{eh}, remains unaffected by changes in h. The only variation observed is due to the threshold τ [depicted by the black bar in Fig. 14(b)].

C. Determining Threshold and Hysteresis Ranges

The effect of threshold and hysteresis settings on the evaluation metrics is remarkable for A1, A3, A4, and A5 algorithms. We discuss in this section an empirical approach to determine the threshold and hysteresis in a realistic environment. The approach we follow consists of collecting beacon messages in the transition line.

More specifically, we collect data on the transition line for about 30 s by varying the user's orientation (east and west). Given the collected data, we can define τ as the average of the RSS measurements of the target ILS. Concerning the hysteresis h, it can be obtained as the standard deviation of the collected RSS measurements. From the conducted tests, we measured $\tau = -78$ and $h = 3\,\text{dBm}$.

D. Discussion

In the use case we analyzed in this article, specifically focusing on the near ILS topology, algorithms that perform better are A3 and A5. As illustrated in Table II, which reports the results averaging over 64 transitions, setting $\tau = -78\,\text{dBm}$ and the hysteresis $h = 3\,\text{dBm}$ as described in Section VI-C, the algorithms exhibit variable performance. In particular, choosing a time window $t_w = 1\,\text{s}$ (i.e., the handoff decision algorithm assesses whether to trigger the handoff procedure every second), the A1 algorithm exhibits $T_R = 0.33$ s and $p_{\text{eh}} = 0.8$, A2 algorithm $T_R = -0.2$ s and $p_{\text{eh}} = 0.88$, A3 algorithm $T_R = -0.6$ s and $p_{\text{eh}} = 0.92$, for A4 algorithm $T_R = -0.4$ s and $p_{\text{eh}} = 0.92$, and for A5 algorithm, $T_R = -0.6$ s and $p_{\text{eh}} = 0.92$.

TABLE II
RESULTS OF ALGORITHMS A1–A5 WITH OPTIMAL SETTINGS: THRESHOLD $\tau = -78\,\text{dBm}$, HYSTERESIS $h = 3\,\text{dBm}$, AND TIME WINDOW $t_w = 1\,\text{s}$

Algorithm	Acc.	F_1	p_{eh}	T_R[s]
A1	1	1	0.8	0.3
A2	1	1	0.88	–0.2
A3	1	1	0.92	–0.6
A4	1	1	0.92	–0.4
A5	1	1	0.92	–0.6

The optimal algorithm is the one that achieves the highest possible value for p_{eh}, indicating a high probability of proactively triggering the handoff procedure, and simultaneously, a lower value for T_R, indicating the algorithm's ability to anticipate the triggering event in a proactive manner as early as possible. In this context, the algorithms A3 and A5 both demonstrate optimal performance, exhibiting identical results. This is attributed to the fact that the A5 algorithm is independent of the hysteresis parameter. This independence is evident in Fig. 14(b), where varying h values do not modify the algorithm's performance. Given that the A3 and A5 algorithms are essentially equivalent (except for the hysteresis margin, which is set to zero in the A3 algorithm), and considering that the A5 performance is independent of hysteresis value, the performance of A3 and A5 is identical.

VII. Conclusion

The increasing adoption of LBSs hinges on the possibility of localizing users, even in indoor environments. In the near future, we anticipate a proliferation of ILSs, each covering a specific area and providing distinct services. As more solutions become available on the market, the interoperability problem will become even more stringent, necessitating handoff procedures. In this work, we have focused on radio-based algorithms among the various solutions and studied the problem in isolation. We argue that the *best* algorithm cannot be identified for any scenario. Rather, the five algorithms can be selectively adopted according to specific requirements. In particular, we identify three key selection criteria.

1) Device heterogeneity: Vendors provide very different wireless chipset equipped with different antennas and sensitivity. As a result, not all the devices estimate RSS values in a similar way. This aspect is also referred to as device heterogeneity (also studied in [21]). Therefore, such algorithms based on a threshold can be modified to adapt the threshold according to a specific device model. Under this respect, we refer to the exposure notification API provided by Google[1] which also deliver a set of attenuation factors.
2) Beacon loss rate: The amount of collected beacon messages is strongly influenced by the OS. From our experience, we observe a strict limitation of the Android OS to the Bluetooth scans executed while the application is running in background mode. Such limitations reduce the number of collected beacons. At the current stage, only countermeasures can be adopted to increase the amount of the collected beacon messages such as to limit the scan's frequency.
3) Proactivity versus reactivity: As reported in Fig. 13, the algorithms exhibit different behaviors. When the goal is to anticipate the handoff procedure, then it is convenient to tune the algorithms with a small value of t_w (time window). Such a tuning has a twofold effect. On the one hand, algorithms tend to anticipate the handoff procedure, but on the other hand, they might be prone to error if users suddenly detour without changing ILS. This is the case of a user approaching ILS_2 from ILS_1 but deviating right before entering ILS_2. In this case, the algorithms already started the handoff procedure even if the user remains in ILS_1. Conversely, when the goal is to reduce errors, then a reactive behavior of the algorithms might be desirable. In this last case, high values of t_w tend to increase the reactive behavior according to which an algorithm triggers the handoff only after changing ILS.

The algorithms proposed in this work are all based on the analysis of RSS values emitted by commercial Bluetooth tags. RSS represents an interesting metric, but it is highly affected by environmental parameters such as obstacles, presence of people, and interference. We plan to extend the proposed algorithms by taking into account other proximity techniques, such as the ToF and AoA [22]. A number of smartphones are already equipped with an UWB chipset. This technology allows a smartphone to estimate the distance from a tag (deployed in the transition area) more accurately than the use of commercial Bluetooth tags.

Another line of investigation is to reduce energy consumption due to the radio listening. Android APIs, for example, limit the number of scans that can be performed, for this reason. In addition to radio-based techniques, we aim to integrate location information, leveraging the position estimation provided by the ILS to trigger the handoff procedure. The position information can be exploited not only to perform a more accurate handoff procedure, but also to activate radio listening only when the user is close to a specific area, e.g., the proximity area.

Finally, a greater number of use cases must be tested, under stress conditions regarding the number of people crowding the spaces, fake transitions, presence of multiple ILS signals coming from different floors.

[1] [Online]. Available: https://developers.google.com/android/exposure-notifications/bleattenuation- overview?hl=en

References

[1] G. Kia, D. Plets, B. Van Herbruggen, E. De Poorter, and J. Talvitie, "Toward seamless localization: Situational awareness using UWB wearable systems and convolutional neural networks," *IEEE J. Indoor Seamless Positioning Navigat.*, vol. 1, pp. 12–25, 2023.
[2] R. F. Brena, J. P. García-Vázquez, C. E. Galván-Tejada, D. Muñoz-Rodriguez, C. Vargas-Rosales, and J. Fangmeyer, "Evolution of indoor positioning technologies: A survey," *J. Sensors*, vol. 2017, 2017. [Online]. Available: https://www.hindawi.com/journals/js/2017/2630413/
[3] F. Zafari, A. Gkelias, and K. K. Leung, "A survey of indoor localization systems and technologies," *IEEE Commun. Surv. Tut.*, vol. 21, no. 3, pp. 2568–2599, Thirdquarter 2019.
[4] C. Laoudias, A. Moreira, S. Kim, S. Lee, L. Wirola, and C. Fischione, "A survey of enabling technologies for network localization, tracking, and navigation," *IEEE Commun. Surv. Tut.*, vol. 20, no. 4, pp. 3607–3644, Fourthquarter 2018.
[5] J. Torres-Sospedra et al., "UJIIndoorLoc: A new multi-building and multi-floor database for WLAN fingerprint-based indoor localization problems," in *Proc. Int. Conf. Indoor Positioning Indoor Navigation*, 2014, pp. 261–270.
[6] D. Zou, W. Meng, S. Han, K. He, and Z. Zhang, "Toward ubiquitous LBS: Multi-radio localization and seamless positioning," *IEEE Wireless Commun.*, vol. 23, no. 6, pp. 107–113, Dec. 2016.
[7] F. Furfari, A. Crivello, P. Barsocchi, F. Palumbo, and F. Potort, "What is next for indoor localisation? Taxonomy, protocols, and patterns for advanced location based services," in *Proc. IEEE Int. Conf. Indoor Positioning Indoor Navigation*, 2019, pp. 1–8.
[8] F. Furfari et al., "Discovering location based services: A unified approach for heterogeneous indoor localization systems," *Internet Things*, vol. 13, 2021, Art. no. 100334.
[9] F. Furfari, M. Girolami, and P. Barsocchi, "Radio-frequency handoff strategies to seamlessly integrate indoor localization systems," in *Proc. IEEE 13th Int. Conf. Indoor Positioning Indoor Navigation*, 2023, pp. 1–6.
[10] G. P. Pollini, "Trends in handover design," *IEEE Commun. Mag.*, vol. 34, no. 3, pp. 82–90, Mar. 1996.
[11] V. Kapor, G. Edwards, and R. Sankar, "Handoff criteria for personal communication networks," in *Proc. IEEE ICC/SUPERCOMM*, 1994, pp. 1297–1301.
[12] M. E. Anagnostou and G. C. Manos, "Handover related performance of mobile communication networks," in *Proc. IEEE Veh. Technol. Conf.*, 1994, pp. 111–114.
[13] M. Gudmundson, "Analysis of handover algorithms (microcellular radio)," in *Proc. IEEE 41st Veh. Technol. Conf.*, 1991, pp. 537–542.
[14] A. Zaidi and M. Suddle, "Global navigation satellite systems: A survey," in *Proc. Int. Conf. Adv. Space Technol.*, 2006, pp. 84–87.
[15] S. Kaiser, Y. Wei, and V. Renaudin, "Analysis of IMU and GNSS data provided by Xiaomi 8 smartphone," in *Proc. Int. Conf. Indoor Positioning Indoor Navigation*, 2021, pp. 1–8.

[16] L. David, A. Hassidim, Y. Matias, M. Yung, and A. Ziv, "Eddystone-EID: Secure and private infrastructural protocol for BLE beacons," *IEEE Trans. Inf. Forensics Secur.*, vol. 17, pp. 3877–3889, 2022.

[17] P. Barsocchi et al., "A privacy-by-design architecture for indoor localization systems," in *Proc. Int. Conf. Qual. Inf. Commun. Technol.*, 2020, pp. 358–366.

[18] T. Inzerilli, A. M. Vegni, A. Neri, and R. Cusani, "A location-based vertical handover algorithm for limitation of the ping-pong effect," in *Proc. IEEE Int. Conf. Wireless Mobile Comput., Netw. Commun.*, 2008, pp. 385–389.

[19] F. Furfari, A. Crivello, P. Baronti, M. Girolami, and P. Barsocchi, "Best practices for model calibration in smartphone-based indoor positioning systems," in *Proc. 18th Int. Conf. Wireless Mobile Comput., Netw. Commun.*, 2022, pp. 443–448.

[20] F. Potortì et al., "The IPIN 2019 indoor localisation competition—description and results," *IEEE Access*, vol. 8, pp. 206674–206718, 2020.

[21] M. Girolami, D. La Rosa, and P. Barsocchi, "A crowdsensing-based approach for proximity detection in indoor museums with bluetooth tags," *Ad Hoc Netw.*, vol. 154, 2024, Art. no. 103367. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1570870523002871

[22] M. Girolami, F. Furfari, P. Barsocchi, and F. Mavilia, "A bluetooth 5.1 dataset based on angle of arrival and RSS for indoor localization," *IEEE Access*, vol. 11, pp. 81763–81776, 2023.

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