PMD-Track: Portable Medical Devices' Real-time Inventory and Tracking

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***Abstract*—The recent COVID pandemic challenged healthcare systems worldwide and highlighted not only a lack of sufficient resources in some cases, but also an overall inefficiency in managing available PMDs (Portable Medical Devices). Hospitals typically provide their staff with smartphones to facilitate internal communication and access to hospital services. The key contribution of PMD-Track lies in the use of smartphones replacing expensive stationary gateways scattered across a hospital, acting as mobile gateways associated with a front-end that allows staff to quickly find PMDs. Thus, employees walking nearby tagged PMDs — as they perform daily activities — constantly help to automatically update these PMDs' locations in a live inventory tracker allowing to retrieve up-to-date information.**

PMDs equipped with traditional Bluetooth Low Energy (BLE) tags will update a backend service with the location of recently spotted tags and display information concerning their position in real-time. Different PMD types can issue alerts according to the type of their mobility (*i.e.*, considering that portable devices can be more or less "dynamic"). Thus, it is expected that PMD-Track will enable hospitals to make efficient use of their PMDs in emergency situations, such as a pandemic or eventual natural disasters, where a sudden increase in demand can now be foreseen.

***Index Terms*—Indoor Tracking, Inventory, Bluetooth Low Energy (BLE), COVID-19, Healthcare**

I. Introduction

The occurrence of a pandemic, such as the COVID-19 one, put immense strain on the availability of intensive care unit facilities, doctors, and nurses, hindering the efficiency of healthcare systems across the world. It exposed several weaknesses in healthcare systems worldwide due to the sudden increase in patient volume [4], with authors [4], [13] analyzing inefficiencies to respond efficiently in periods of crisis. Among such weaknesses, it was identified that, in most cases, hospitals were short-staffed and that critical (and mobile) resources, such as mechanical ventilators and supervisory tools (*e.g.*, electrocardiogram, capnography monitors, infusion pumps, or pulse oximeters), were not efficiently handled within hospital premises [13].

Traditional inventory management systems do not present a practical solution under scaling demands to manage the location and use of these portable resources — termed Portable Medical Devices (PMD) — in real-time [14], [6]. Including solutions for real-time tracking, which are typically cost-prohibitive for monitoring PMDs once gateways are often required [5], [12], [1], [9] to be scattered throughout the hospital's infrastructure to receive localization data, and often not being integrated with existing inventory management systems.

PMD-Track, as proposed here, improves existing solutions in situations of sudden scaling demands revealed during the pandemic and by removing stationary gateways, while ensuring real-time location. A gateway-less tracking solution provides considerable cost-advantages in terms of hardware requirements compared to existing solutions. Healthcare institutions (mainly hospitals) typically equip their staff with smartphones to facilitate internal communication and to access internal hospital services [10]. This is the key novelty as proposed in the PMD-Track's, is to replace expensive, stationary gateways or base stations by smartphones. Therefore, medical staff passing by tagged PMDs constantly would update their location automatically in the inventory as they perform their daily activities.

PMD-Track's solution foresees a mobile application (initially based on Android) that updates a backend service with the location of recently spotted tags (*i.e.*, PMD tracked devices) and displays information (quick visualization in the smartphone's front-end and detailed analytics in a Web front-end) concerning their position in real-time. Furthermore, different PMD types can raise different alerts according to their type of mobility, considering that portable devices can be more or less dynamic. For example, PMDs attached to patients can be constantly moved, but hold an "in use" status. In contrast, PMDs (*e.g.*, electrocardiogram and ventilators) typically allocated to a specific room may trigger alerts, when they are being moved.

In this regard, PMD-Track enables hospitals to make efficient use of their PMDs in emergencies, such as a pandemic or eventual natural disasters, where a sudden increase in demand can be experienced. Thus, the PMD-Track design will result in a higher chance of saving lives in such situations by allowing the efficient usage of critical PMDs. Henceforth, a significant opportunity for a cost-effective operation of the proposed solution is that hospitals' smartphones in use by their employees will function as mobile gateways.

The remainder of this short paper is organized as follows. Section II overviews fundamentals. While Section III describes the design and analytics, Section IV details the use case. Section V summarizes the paper.

II. Background and Related Work

PMD-Track combines *(i)* indoor tracking based on Bluetooth Low Energy (BLE) with *(ii)* visualization and analytics. Thus, the differential of the approach lies in the use of smartphones as mobile reference points (*i.e.*, replacing gateways) to update the real-time location of PMDs in the inventory. As indoor location services gain popularity due to the absence of a Global Positioning System (GPS) signal, indoor, BLE, and RFID (Radio Frequency Identification) technologies emerge as alternatives (such as WiFi, Ultra-WideBand - UWB, or Visible Light Communication – VLC) [11].

A. Indoor Tracking

[9] employs a trilateration algorithm using Bluetooth RSSI (Received Signal Strength Indicator) values and device's sensors data (*e.g.*, accelerator and gyroscope) to improve the accuracy of the position of devices using the iBeacon protocol. [9] applies a Kalman Filter (KF) to estimate the real-time trajectory of the device. Although the accuracy of the iBeacon positioning was improved, the approach cannot be directly employed in PMD-Track as it relies on several (*i.e.*, 10) iBeacons for a 44 m x 17 m area, fixed stations to sample RSSI values, and smartphone sensors. In contrast, PMD-Track reduces the number of fixed BLE tags and relies solely on RSSI values measured from devices' encounters.

[1] proposed a real-time tracking solution based on Arduino to track Bluetooth devices at a maximum range of 10 m. The Arduino board also contains a GSM (Global System for Mobile Communications) antenna that periodically transmits data collected to a user's smartphone. [1] raises two concerns that PMD-Track solve: the use of several static sinks to collect data from BLE tags and the limited mobility, which, combined with the short-range, makes the solution ineffective to track PMD objects.

[5] proposes an accurate Indoor Positioning System based on BLE using frequency diversity, trilateration, and KF. In the approach, the tag position is calculated based on the trilateration of 3 RSSI sniffer devices and the tag sending RSSI values. One shortcoming is that it relies on four beacons per room, and each receiver gateway costs around 120 Euros (*i.e.*, 500 Euros per room).

[6] covers a wide range of theories, methods, and technologies. It also provides mathematical foundation given the use of different tracking methods and technology, *e.g.*, which path-loss models can be used in geometric-related measurements. Thus, [6] is essential to provide a theoretical basis for tag localization based on reference beacons and smartphones.

B. Indoor Visualization and Analytics

As important as the acquisition of location data is *(i)* the visualization of this data in an easy to access and intuitive way on the smartphone (providing agility in location) and *(ii)* detailed information of usage statistics via a Web interface. Selected approaches determined present recommendations for the development of such interfaces.

[7] surveys of large numbers of users to delineate critical aspects of UX (User Interfaces), which is helpful for Web interface analytics in PMD-Track. It highlights significant characteristics that impact users positively (*e.g.*, clear, concise, comprehensive, and straightforward UX) and negatively (*e.g.*, ambiguous, circular, too academic, too detailed). Although not being specific on UX insights for mobile devices, the work highlights major characteristics in general.

[3] presents an approach using wireless sensor nodes (TelosB motes based on the ZigBee protocol), focusing on visualization. The visualization is based on VRML (Virtual Reality Modeling Language) for real-time monitoring, control, and arrangement of sensor nodes, supporting real-world applications.

[8] describes an indoor navigation system based on the accelerometer and the compass (typically present in modern smartphones) integrated in OpenStreetMap (a collaborative geographical database). The use of OpenStreetMap for internal building mapping is a viable alternative to be used in PMD-Track, *i.e.*, relatively straightforward and more efficient than, for instance, a 3D visualization as of [3].

C. Discussion

PMD-Track's major contribution lies in the combination of real-time tracking approaches of BLE tags, with a front-end interface that allows medical staff to locate quickly, utilizing a smartphone, needed PMDs, and in a web front-end, detailed information and statistics about the use of these devices [7]. Traditional inventory management approaches rely on manual input and update of data, *e.g.*, scanning a QR code on a smartphone to register objects. In addition, the use of portable medical devices requires a constant update of their position, which is typically prone to errors in manual input. Further, there exist real-time inventory tracking proposals [1], [5] that make use of expensive Bluetooth gateways scattered across a hospital's infrastructure. In contrast, PMD-Track eliminates the need for such gateways by relying only on mobile devices, tags, and anchor tags at known positions.

III. PMD-Track Design

PMD-Track does explore two fundamental pillars: *(i)* tracking operation based on smartphones and static BLE tags components that simplify the operation in contrast to existing indoor tracking solutions, combined with a *(ii)* visualization and detailed analytics on the usage of PMDs. Replacing gateways or base stations, typically used in real-time tracking solutions by smartphones, represents a considerable reduction of costs while adopting the solution proposed. Furthermore, critical security, safety, and privacy aspects involved in this approach are considered.

A. Tracking Operation Based on Trilateration

Smartphones would interact — as medical staff performs their daily activities — via BLE tags attached to PMDs,

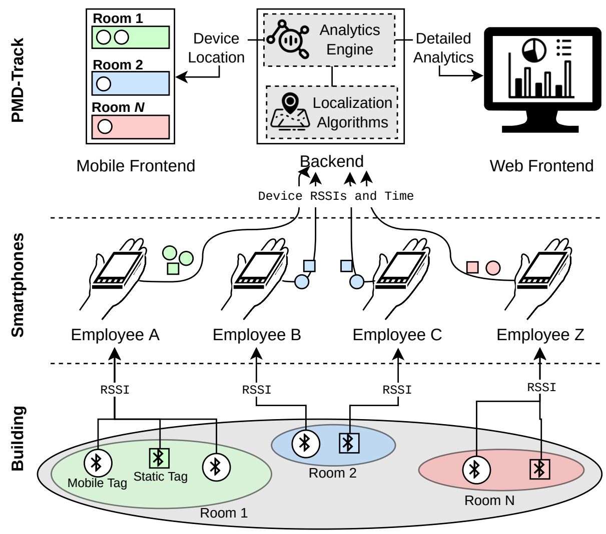

Fig. 1: PMD-Track Architecture

and static BLE tags used as reference points. As soon as smartphones are in range with a BLE tag (static or mobile), it transmits the RSSI information from an active BLE connection with tags to a backend service (*e.g.*, Apache Kafka [2]), which calculates the position of the PMD using a trilateration between BLE signals from smartphones, static tags (used as anchors with known positions), and mobile tags to update in real-time its location in the inventory.

Figure 1 illustrates the architectural design of PMD-Track, including the main backend functions (*i.e.*, localization algorithm and analytics engine). The design comprises of *(i)* a mobile application that records Bluetooth encounters between mobile device and BLE tags placed on objects (depicted by geometric shapes) and *(ii)* a backend that receives information sent by smartphones in the form of message streams to calculates the approximate location (*e.g.*, Room 1, Room 2, Room N) of the object in real-time based on three main reference points: the mobile device, a static tag, and a mobile tag.

Once information concerning static and mobile tags are collected, the smartphone app timestamps their reception and relays to the backend service. At this stage, it will be essential to avoid excessive usage of processing power and data transmission by relaying data in rolling time windows, avoiding draining the smartphone's battery. The backend service, upon receiving data, will *(i)* execute the localization algorithm and updates the PMD's location by triangulating BLE RSSI's values, taking as reference the known position of static (*i.e.*, anchor) BLE tags, and *(ii)* calculate metrics concerning their usage (*e.g.*, heatmap of PMD by type, their time spent in each room, or how many times a PMD has been moved). Finally, the analytics engine provides information for two frontends, a mobile (intuitive and straightforward localization of PMDs) and a Web-based (detailed analytics on PMDs) one.

B. Intuitive Visualization and Detailed Analytics

Visualization has to be intuitive and straightforward by providing only necessary insights on the location and usage status of different PMD types. Detailed analytics (*e.g.*, heatmaps or percentages of usage by PMD type) can be made available in an expert mode in the smartphone or via a Web frontend. While an intuitive visualization enables quick mobility of medical staff to find and collect required PMDs, analytics improves the strategic planning of PMDs by assisting the management staff to make decisions on the acquisition of new or the current location of existing PMDs. The challenge, however, is to strike a balance between an intuitive interface and sufficient information to enable medical staff to find or move PMDs. Thus, interviews and an assessment with medical staff are key to streamlining a minimal and intuitive interface that provides relevant information.

Thus, PMD-Track does enable hospitals and clinics to simplify and optimize their inventory management, asset location, and productivity. It is expected that medical staff can easily verify the location of a PMD in real-time and move to the closest one, improving response time, reducing waiting time of patients, and optimizing productivity. Furthermore, expensive PMDs can be tracked to prevent theft and loss. Thus, avoiding unnecessary purchases of new equipment. Solving the tracking and management of assets using a cost-effective and easy to deploy solution provides an opportunity to create a competitive advantage within the hospital's context and a myriad of other use-cases, *e.g.*, in logistics or manufacturing.

C. Security, Safety, and Privacy

Security. The communication link between the BLE tag and the smartphone can be considered a possible attack vector. An adversary could deploy malicious BLE tags that could intrude or overload the system in the sense of a Denial-of-Service (DoS) attack. The BLE protocol offers various forms of communication schemes between two nodes. Some rely on an established connection allowing for encrypted information exchange, others operate in a broadcast fashion only, thus, not allowing for encrypted payloads. Depending on the chosen communication scheme, it is crucial to address these security considerations specifically.

Safety. The proposed solution has no effect on safety aspects in the hospital. There does not exist any hardware or software integration with existing medical devices. Thus, the physical separation on the hardware level (PMD and BLE tag) enables an entirely independent operation. In case of an outage or attack on PMD-Track, medical devices' operation will not be affected.

Privacy. Knowing the location of medical equipment associated with a patient raise privacy concerns. For instance, tracking the location of an infusion pump attached to a patient also tracks the patient's location. Such concerns need to be analyzed on a legal and ethical basis, and mitigation strategies are being developed, including the anonymization of patient data. Another privacy aspect concerns the smartphone and staff carrying it. Such information can be linked to the employee's location, which is violating the employee's privacy. In this case, a feasible solution to guarantee a privacy-preserving is to anonymize staff identities.

IV. Use case and Discussion

PMD-Track replaces gateways or base stations on the assumption that medical staff is equipped with smartphones. Therefore, medical staff walking nearby a tagged PMD updates their location automatically in the inventory, while staff performs their daily activities as indicated in Figure 2, where the path of a member of the medical staff starts at `T0` and ends at `T3`.

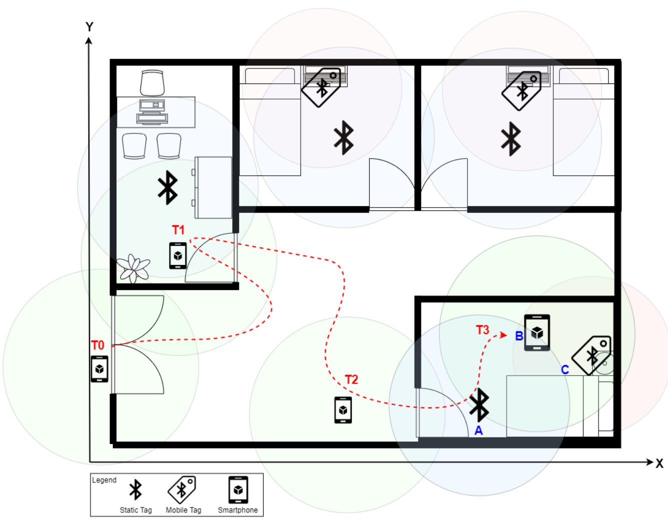

Fig. 2: Localization Scenario

As well, Figure 2 depicts a localization scenario of PMD-Track. The location of an object (*e.g.*, Point C) is approximated by comparing the RSSI value of the object's asset tag (Point C) and the RSSI value of the static reference point (Point A) as well as the surrounding smartphone (Point B). Such an approximation is based on the similarity between the reference points' RSSI values and the object's RSSI value. The static reference point whose RSSI value is most similar to that of the object determines the tag's location (Point C).

The advantages of relying on such anchor tags (*i.e.*, statics tag) over gateway devices are manifold. Firstly, anchor tags are less expensive than gateway devices, thus, reducing CApital EXpenses (CAPEX). Secondly, they are small (size of a Swiss 5 CHF coin) and battery-powered, which allows them to be positioned freely and without a concern of having a power outlet accessible, hence, providing a flexible deployment. Thirdly, the flexibility of mounting anchor tags enables them to be installed at ideal positions in terms of radio-frequency aspects (*e.g.*, on the center of the ceiling), thus, promising more accurate location data.

V. Summary and Next Steps

It is essential to provide useful information in real-time to medical staff about the location of medical devices and their usage to plan medical care efficiently on spot. PMD-Track, as being designed, will accelerate the digitization of hospitals, making them more efficient in dealing with high-demand situations. Aligned with an indoor tracking algorithm, a low cost hardware deployment, and an intuitive interface for end users, staff can easily and precisely handle the hospital's inventory.

Next steps toward the analysis of PMD-Track in different dimensions include *(i)* scalability evaluations, *(ii)* localization accuracy scenarios, and *(iii)* real-world deployment of the solution in two stages: first within the university campus and secondly at hospital premises.

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