Versatile, Low-cost Indoor Positioning Combining Bluetooth and Ultra Wideband Technologies

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Abstract

In this paper we present XtremeLoc, a low-cost indoor positioning system designed to work in situations where GPS is not a valid alternative. XtremeLoc relies on the use of portable, low-cost, Bluetooth Low Energy beacons using the iBeacon protocol. Instead of setting these beacons in fixed positions, they are carried by the persons or goods to be tracked. The beacons broadcast a signal that is received by a set of fixed, low-cost antennas. These antennas estimate the distance to the emitter using the perceived intensity of the signal, and transfer this information to a cloud-based server that calculates the position of the emitter, storing it and displaying it through a web-based interface. The use of this technology allows a precision of around two to three meters. To track elements with a higher precision, XtremeLoc allows the concurrent use of custom Ultra Wideband devices, that allow a precision of around 10 cm while using the same interface. In this paper we describe XtremeLoc architecture and main features, how to use it to find persons and goods with the help of Augmented Reality applications, and an example of use of this technology to record the behavior of individual persons during evacuation drills.

Keywords

Indoor positioning, Bluetooth Low Energy, BLE, GPS, Ultra Wideband, UWB, risk prevention

1. Introduction

In this paper we present XtremeLoc, a low-cost indoor localization system that allows persons and goods to be tracked in situations where GPS is not a cost-effective or feasible solution. The solution consists of the use of Bluetooth Low Energy (BLE) emitters, called beacons, that are carried by the persons or goods that should be tracked. A set of low-cost, fixed receiving antennas collect the signals emitted by the beacons, calculate the distance to each beacon using the perceived intensity of the signal, and send these distances to a cloud-based server. This server uses a trilateration algorithm to determine the exact position of the elements to be tracked, and draws the position in real time in a web browser. Users can either carry a beacon or install a small APP in their smartphones that sends BLE packets, allowing the system to record their movements inside the facility with a precision between two and three meters, in line with the precision reported by other studies using this technology (e.g. [1, 2]).

For applications where a higher precision is needed, XtremeLoc offers the possibility of

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integrating Ultra Wideband (UWB) technology. Instead of carrying a beacon, the element to be tracked carries a UWB tag. A set of UWB anchors determine the distance to these tags by measuring the time required to the signal to travel between tags and anchors. This technology allows a higher precision, of around 10 cm, that is also in line with results reported by other studies, such as [3]. All distances collected by UWB anchors are sent to an intermediate server, that injects them to the main XtremeLoc server.

XtremeLoc is complemented with an augmented reality APP, called Skywalker. This APP superimposes localization information on the real-time images collected by the camera, indicating how to find a person or good selected by the user, by showing the distance and the direction to him/her. Using Skywalker, a user that does not know the building can find a particular person just by walking in the direction indicated by the application, without the need of knowing the layout of the building.

XtremeLoc can be used for different purposes, including low-cost tracking of persons or goods using BLE, to flying drones in indoor environments using UWB. One application we are particularly interested is its use to analyze what happens during evacuation drills of large facilities. As long as XtremeLoc allows the individual behavior of the building's occupants to be known, it allows to detect bottlenecks, to know the preferred routes, and to record the position of persons that were not able to evacuate the building, in order to rescue them.

This paper discusses in detail the related technologies, XtremeLoc architecture, and main features. We also briefly discuss the use of XtremeLoc in the context of evacuation drills as an use case. This paper is organized as follows. Section 2 discusses the fundamentals of Bluetooth and Ultra Wideband technologies. Section 3 shows the architecture of the base XtremeLoc system, that uses Bluetooth beacons and offers a moderate precision at a low cost. Section 4 describes the Ultra Wideband devices we have developed and how they are integrated into XtremeLoc to offer a higher precision. Section 5 introduces Skywalker, a mobile APP that is able to guide the user to a particular target making use of the XtremeLoc infrastructure. Section 6 briefly discusses the application of XtremeLoc to track the movement of persons during evacuation drills. Finally, Sect. 7 concludes our work.

2. Related technologies

Several technologies for Indoor Positioning Systems (IPS) has been proposed so far. However, as Huang *et al.* pointed out [4], there is no single indoor positioning technology that is able to balance cost, accuracy, performance, robustness, complexity, and limitations. Examples for these techniques can be Zigbee, Long Range (LoRa), Radio Frequency Identification (RFID), Ultra-Wide Band (UWB), Wi-Fi, and Bluetooth Low Energy. Each of these techniques has its own characteristics and limitations. We primarly focus on Bluetooth Low Energy (BLE) technology because it has several advantages, including low energy consumption, good positioning accuracy, and BLE devices are easily deployable [5]. The work by de Blasio *et al.* [6] is a good survey about the use of BLE technology for IPS.

The use of BLE technology for IPS is based on the use of the Received Signal Strength Indicator (RSSI), that allows the distance between a BLE emitter and a receiving antenna to be estimated. RSSI indicates the difference between the transmitted and received signal strengths, and distance can be calculated in terms of the perceived attenuation. However, the received signal can also be attenuated by several factors other than distance, including reflection and diffraction around objects, causing multipath and fading effects respectively;

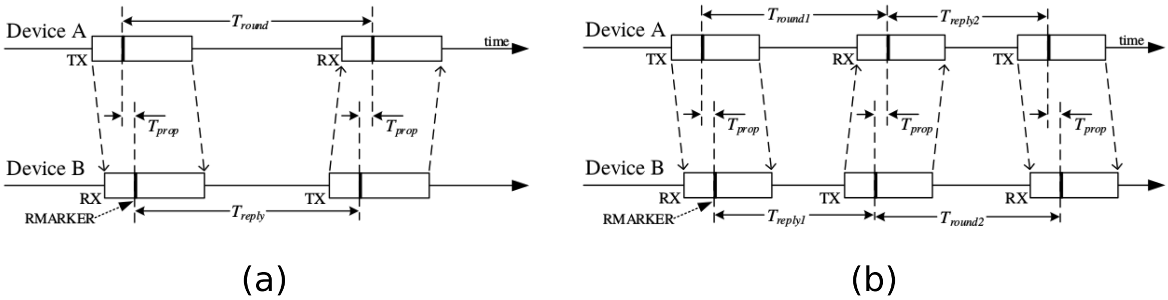

Figure 1: (a) Single-sided TWR protocol, and (b) double-sided TWR protocol using three messages.

transmission loss through walls, floors and other obstacles; channelling of energy, especially in corridors at high frequencies; and motion of persons and objects in the room. In order to mitigate these problems, the RSSI analysis can be enhanced by mapping the radio propagation losses to distance according to a propagation model, and be complemented with the use of a Kalman Filter (KF) in order to improve the accuracy of the calculated position [7].

The use of BLE technology is a cost-effective way to estimate the position of persons or goods to be tracked, with a precision of around two to three meters. Some applications require a higher precision, such as automatic drone flight inside facilities. For these kind of purposes, XtremeLoc offers the possibility of using Ultra Wideband technology. This technology allows the transmission of information at high speed with a low power consumption, and can coexist with other technologies. Instead of simply measuring the perceived intensity of a given signal, UWB devices rely on the Two-Way Ranging (TWR) protocol. In this protocol, two UWB devices exchange messages, storing the exact times when messages are sent and received, in order to calculate the round trip time. The simplest TWR protocol, called single-sided TWR, includes the exchange of just two messages (see Fig. 1a). Device A starts the data exchange and device B replies to complete it. Both devices store the exact times where transmissions and receptions take place, in order to calculate the flight time using T_{round} and T_{reply}. To enhance precision, a double-sided TWR can be used, where error is reduced by exchanging two pairs of messages and averaging the times recorded. Double-sided TWR can be either implemented using four messages, or reusing the second message to start the second message exchange (see Fig. 1b). XtremeLoc Ultra Wideband devices use this three-messages version of the double-sided TWR protocol.

3. XtremeLoc BLE architecture

XtremeLoc BLE architecture is composed of the following components: Bluetooth Low Energy emitters, receiving antennas, and a cloud-based service that performs the calculations and stores and shows the information in a web-based representation. Figure 2 shows the system architecture. We will examine these components in detail.

3.1. Bluetooth emitters

The key characteristic of XtremeLoc is the use of low-cost Bluetooth Low Energy (BLE) emitters as mobile devices. Any BLE emitter capable of broadcasting data packets using the iBeacon protocol can be use for this purpose, such as the iBKS 105 BLE beacon made by Accent

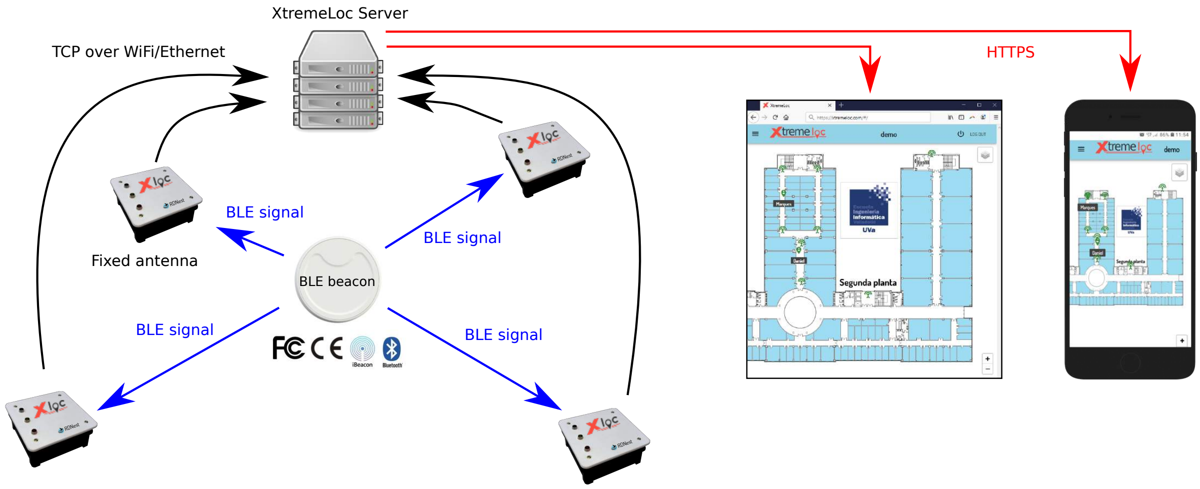

Figure 2: Xtremeloc Bluetooth architecture.

Systems[1]. We have found that these emitters represent a good balance between cost (around 15 €) and features. These devices, also called "beacons", are battery-powered devices, with cell batteries that last for a couple of years. The beacons broadcast data packets at configurable, regular intervals, between ten per second to one each five seconds. The broadcasted data packet using the iBeacon protocol includes a unique ID for each beacon, and also an estimation of the remaining battery. This feature allows their batteries to be replaced before they run out of energy.

The broadcast packet also includes information about the power used to broadcast the signal. Comparing the declared intensity of the signal with the perceived intensity, a Bluetooth receiver is able to estimate the distance to the beacon. This is not a precise measurement, however: The perceived intensity of Bluetooth signals depends on several factors, including attenuation due to obstacles, position and orientation of both the emitter's and receiver's antennas, etc. Therefore, to use this feature as a way to measure distance, several packets should be received in order to average their perceived intensity. On the one hand, the higher the number of packets emitted per second, the more precise the distance measured, and the more sensitive to sudden changes in such distance, a useful feature when the beacon is traveling fast. On the other hand, the higher the number of packets per second, the higher the power consumption, thus shortening the battery life. The sweet spot depends on the mobility of the target. For example, we have found that emitting three packets per second is a good tradeoff between precision and power consumption to track people carrying this device. Other use cases, for example when tracking a forklift that moves quickly, or an object that is almost always quiet, require a different configuration.

XtremeLoc is based on Bluetooth emissions. These emissions can not only be generated by beacons. Any mobile phone with a Bluetooth interface can do the same task, so a person can be tracked not only by carrying a beacon but also by having a lightweight, background service in his/her mobile phone, that emits XtremeLoc Bluetooth packets regularly. This solution has the advantage of saving costs, using people's phones instead of an external device, although it can be viewed by users as a more intrusive mechanism.

[1] https://accent-systems.com/product/ibks-105/.

3.2. Receiving antennas

The second component of XtremeLoc is a set of receiving stations (called antennas) at fixed, known positions of the infrastructure. These antennas, connected to the Internet using either WiFi or an Ethernet link, scan the Bluetooth signals around, thus detecting packets emitted by the BLE beacons. Each antenna uses the perceived intensity of the signal to estimate the distance to the beacons in range, and sends this information to a cloud-based server. This information is sent to the server once per second using HTTPS.

To keep the cost of these antennas to a minimum, we use the Raspberry Pi 3b+ platform, an inexpensive system capable of running Linux, using an SD card to store the filesystem. To avoid the degradation of the SD card after intensive use, we have developed a novel solution, with the collaboration of RDNest, a start-up company in the field of IoT in Valladolid, Spain (www.rdnest.com). The solution consists of developing a novel operating system, called RDos, based on Linux source code and with a footprint of less than 100 Mb, which includes some software features that allows the life of SD cards to be greatly extended.

In open spaces, receiving antennas should be installed in the vertices of a grid with sides of around 30 to 40 meters. In the presence of walls, more antennas and/or smaller grids may be needed, depending on the materials used in the building. After installation, their position is recorded in the cloud-based service. To avoid the need of physically accessing each antenna for software maintenance, RDos include an automatic software update service. This service periodically connects to the cloud-based server in order to download and install software updates. Both major and minor updates can be launched. Major updates involve replacing the entire filesystem, while minor updates only changes certain files within, basically those related to the Bluetooth listening service and distance estimation. The updating mechanism for major updates is a rather complex process, that implies, among other steps, downloading the new version, verifyig its integrity, an attempt to boot with it, and a rollback mechanism to a previous version (or even to a factory-default version) if something goes wrong. All this process has been designed with robustness in mind.

3.3. XtremeLoc cloud-based service

As we said above, all receiving antennas scan their Bluetooth interface, capturing the signals emitted by the beacons. Antennas packet this information and send it regularly (once a second) to the XtremeLoc cloud-based service. This service uses a trilateration algorithm, similar to the one used by GPS receivers, to calculate the position of each beacon inside the infrastructure. To calculate the position unambiguously, this algorithm needs at least the distance to three receiving antennas. All the distances sent by antennas and the calculated position are permanently stored in the service.

The cloud-based service offers a REST API that the system to queue for different purposes, from locating a particular beacon in real time to measuring its battery status or checking the health of the receiving antennas. A web-based frontend uses this information, in conjunction to accesses to a cartography service to picture the position of a particular beacon in real time. The interface works in both laptop and mobile devices (see Fig. 3), and not only depicts the position, but also represents graphically the distances as measured by the antennas (Fig. 4).

XtremeLoc does not use any proprietary software: all the software stack is open source, as well as the cartography used for building positioning (OpenStreetMap [8]), and the online generation of the views needed at different scales (using Leaflet [9]). Therefore, XtremeLoc

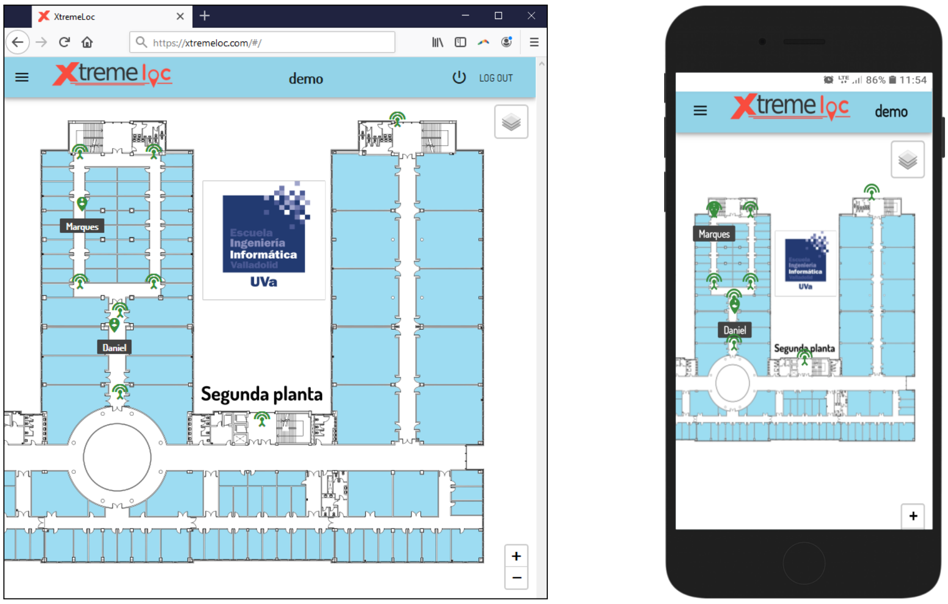

Figure 3: Web-based interface for XtremeLoc, depicting positions in real time.

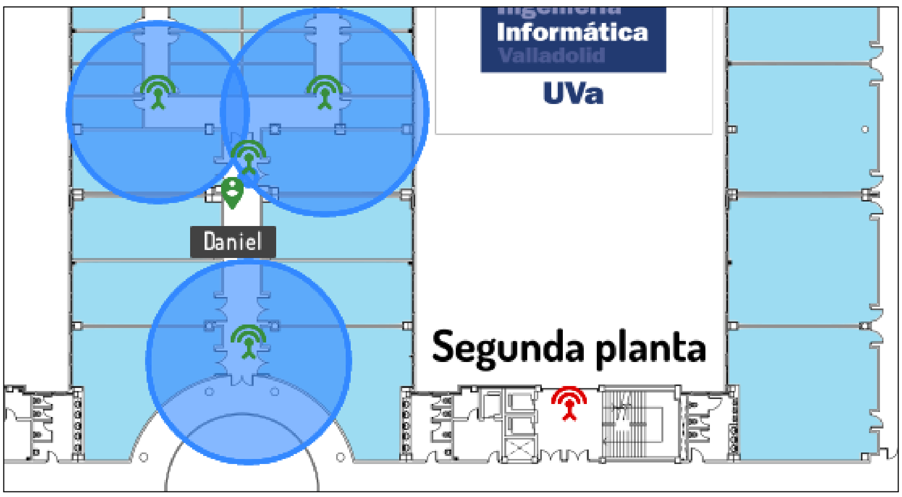

Figure 4: Web-based, real-time representation of distances measured to a beacon (Daniel).

does not have hidden running costs.

4. XtremeLoc UWB extension

The use of Bluetooth technology allows XtremeLoc to obtain a precision of around 2-3 meters, enough for many purposes, including the location and tracking of people and goods. Our research group has also built an extension that uses Ultra Wideband [10] technology. With this technology we have obtained an accuracy of around 10 cm, at the cost of more expensive tracking devices. While Bluetooth technology can be used for applications where a 2-3 meters error margin is acceptable, our Ultra Wideband solution offers the precision required, for

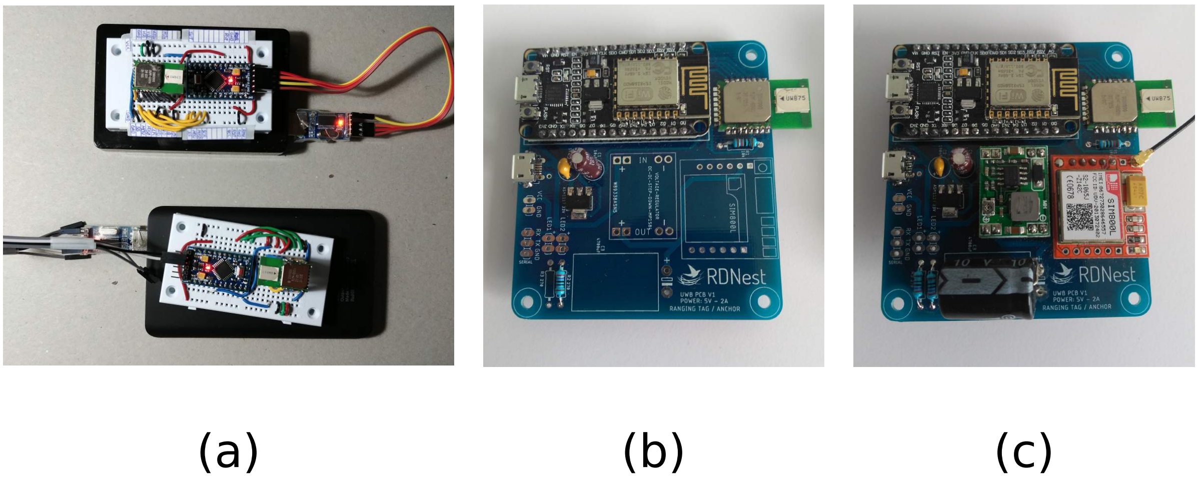

Figure 5: UWB devices developed: (a) First prototype; (b) UWB tag Mk1; (c) UWB anchor with GPRS modem, Mk1.

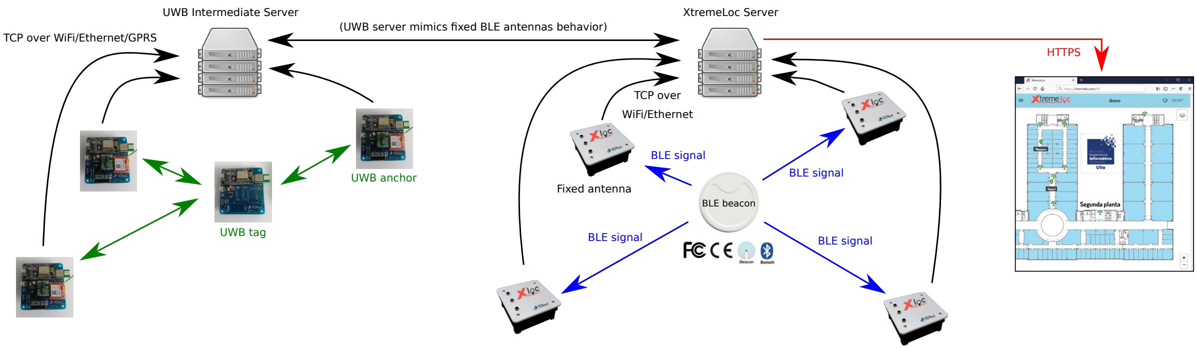

Figure 6: Xtremeloc architecture with UWB extension.

example, to automatically fly a drone inside a factory or a cathedral.

In BLE, beacons broadcast packets that are received by the antennas within range. UWB devices require a bidirectional communication between each pair of tag and anchors (recall Fig. 1). To gain knowledge about this technology, we decided to build UWB devices and their software from scratch. Figure 5 shows the UWB devices developed, from the first prototype to a pair of tag and anchor. From the electronic point of view, both tags and anchors are similar, incorporating an UWB chip and a microcontroller to handle communications and calculate in-flight message times. The difference between them is that the anchors should also transmit the distance to each tag in range to a server. Our first prototypes included an Arduino Pro Mini (see Fig. 5a). To build Mk1 anchors and tags, we used the NodeMCU DEVKIT 1.0, that includes the esp8266 WiFi module (see Fig. 5b and 5c). We also added a GPRS modem to our anchors (see Fig. 5c) for extended connectivity. To keep costs low, we used the same PCB layout for both tags and anchors. The fabrication cost of these UWB devices is around 120€, in part due to the high cost of the UWB chip.

From the architecture point of view, we devised the use of UWB technology as an extension of our XtremeLoc system. Figure 6 shows how we integrate both technologies. Each UWB tag exchanges separate messages with all UWB anchors within range. This is an important

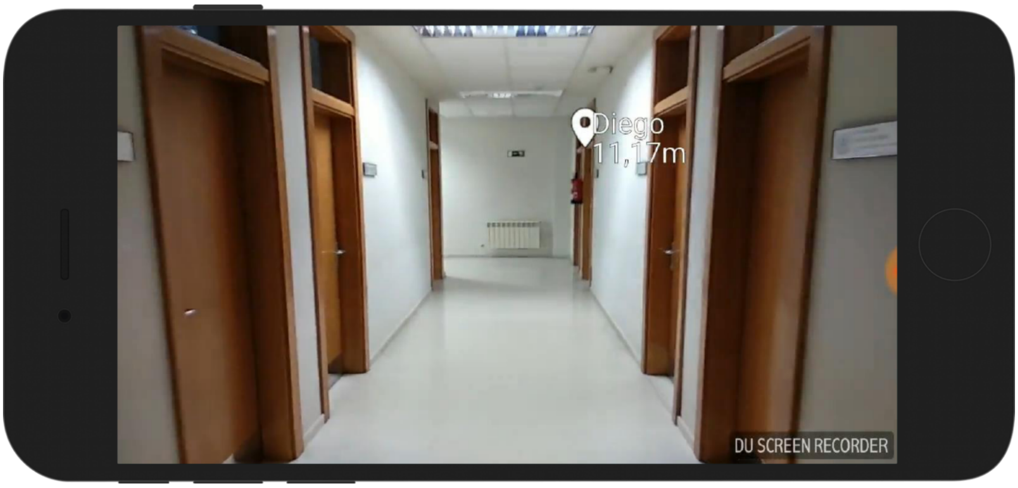

Figure 7: Skywalker APP in use: searching for Diego.

difference with BLE, because in the latter Bluetooth packets are broadcasted, and all antennas receive the same packet. Therefore, if we have B beacons and A antennas, only B packets are required to determine the positions of the beacons. On the contrary, if we have T UWB tags and N UWB anchors, the number of messages exchanged is $T \times N \times 3$, because we use a double-sided TWR protocol with three messages (recall Fig. 1b). This behavior imposes a limitation in the number of tags and anchors that can interact within range.

All tags report the calculated distances to a dedicated UWB server using a lightweight TCP protocol. The UWB server stores this information and injects it to XtremeLoc as if it came from a set of regular Bluetooth antennas. In this way, XtremeLoc is not aware of the technology used to measure distances, and we can also use the UWB anchors, tags and server in stand-alone mode for other purposes.

5. Augmented reality: Skywalker

XtremeLoc allows the position of persons and goods inside a facility to be determined. A need that naturally arises from it is how to guide us to a particular target. There are many algorithms in the literature that solve the shortest-path problem [11]. However, it is not always easy to get oriented in a map, especially in an emergency situation and/or when the user does not know the premises.

We have developed an augmented reality system, called Skywalker, to help to find persons and goods without the need to follow directions on a map. Skywalker is a mobile application that also acts as a Bluetooth emitter, allowing the cloud-based service to know where the Skywalker user is and where the remaining objects of persons tracked are. Tracked objects can be either BLE beacons or UWB tags. Skywalker uses the main camera of the mobile to get the landscape, and the mobile compass and gyroscopes to correctly augment the image with the information needed to find the target (distance to the target and orientation, as provided by the cloud-based service). All this information is updated in real time to reflect the changes in position and speed of both the target and the Skywalker user (see Fig. 7).

6. Use case: XtremeLoc and Building Evacuation

A low-cost, low-energy indoor positioning system has a myriad of applications, ranging from tracking for logistic purposes to avoid goods being stolen to tracking patients and workers in all kinds of facilities. When it comes to locating people, it is necessary to have their consent, with the aim of improving procedures or facilitating evacuation in case of disaster. The ability of the cloud-based service to store both the position and the list of distances to each beacon in real time allows this information to be retrieved when needed. This is particularly useful in case of an evacuation due to an accident that affects the entire building. Even if the antennas stop working (due to lack of power, to a failure of the interconnection network, or a fire event), the cloud-based service (if running in an external premise) is still able to indicate the last known position of all the beacons inside the building. This information is very useful for guiding emergency services to rescue a particular person.

Another interesting application of XtremeLoc is to monitor the individual behavior of people with respect to an evacuation drill. This information allows to improve both emergency procedures and pre-event emergency training. The evacuation movement of people inside a particular building is usually studied by recording human behavior at strategic points, either in evacuation drills or in controlled experimental environments, and collecting testimonies of people involved, generally at a later time [12]. By their nature, these records are inexact and incomplete, and only show the aggregated behavior of the participants. As long as XtremeLoc is able to record each individual path, the analysis of the data allows interesting individual behavior patterns to be detected, that remain unnoticed when data is aggregated, such as people that does not find the exit within time; people that follow a sub-optimal path to leave the building, or if there was an unexpected bottleneck not related to the architecture, but to a dangerous situation that was not imagined when the emergency procedures were set up.

7. Conclusions

In this paper we present XtremeLoc, an indoor positioning system that is both affordable and effective. XtremeLoc uses low-cost, Bluetooth Low Energy devices to broadcast a signal that is received by a set of fixed antennas. This information is sent to a server that uses a trilateration algorithm to locate the emitter with a precision of around 2-3 meters, enough for a myriad of purposes. We have also developed a more precise yet somewhat more expensive solution, that offers a precision of around 10 cm, using Ultra Wideband technology. The XtremeLoc solution has a wide range of applications, from tracking persons, vehicles and goods in any situation where GPS is not a viable solution, to tracking individual behaviors in the context of an evacuation drill. We will be happy of studying new applications of our technology, from a scientifical and/or commercial point of view.

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