Bluetooth portal-based system to measure the performance of building emergency evacuation plans and drills

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Abstract: The safety of a building can be explicated in two different ways: the ability to withstand a critical event that affects the structure and the ability to safely allow people to leave the building. This article presents a new methodology that can allow engineers to detect people trajectories in evacuation drills and provide a measure of effectiveness for buildings evacuation plans. In the proposed system Bluetooth beacon passive emitters are positioned as reference points and the sensing device is capable of emitting a radio signal. The radio signal can be picked up by the sensors present in smartphones. The signal is then processed by a dedicated application on the device. Information is transferred to a computer and elaborated obtaining a measure of people positions. In the system people movements in emergency evacuation drills can practically be traced with very simple and affordable equipment. Once all data from mobile phones are gathered the system is able to reconstruct the trajectories of smartphones, in indoor (or outdoor) environments, and therefore to assess the overall performance of the building evacuation plan.

1 Introduction and background

The issue of emergency evacuation dates back to 480 B.C. when Themistocles ordered the evacuation of the capital Athens. He was able to save citizen from the Persian army invasion. The volcanic eruption of Mount Vesuvius, that in 79 forced the evacuation of Pompeii and neighboring areas, was the first well-known evacuation event caused by a natural disaster. At the beginning of 1900, the use of concrete and the completion of high rise buildings determined the need for evacuation measures included in the building design. Since then the issue of building safety became an important and delicate issue for tall and crowded buildings. An important special problem, that is always very important, is also the specific planning of the evacuation of crowded areas or public and office buildings due to fires, earthquakes, floods, terrorist attacks etc.

According to the US National Fire Protection Association [1], high-rise buildings are defined as ‘buildings taller than 75 feet (~23 m) in height from the lowest level of fire department vehicle access to the floor of the highest occupiable story’.

Recent research activities have been dedicated to: specific building design for emergencies, evacuation and emergency simulations methods and techniques, performance and accomplishment of successful and meaningful evacuation drills and more recently also the use of new technologies in evacuation drills and emergencies.

Studies on the evacuation of buildings began already at the beginning of the 20th century with many patents requests for fire-escape devices. In 1969, Galbreath [2] published a paper in which the number of people in the stairs of large buildings was linked to the number of those who could reach the outputs.

In the following years, other researches [3–5] led to formulas for calculating the speed of movement of people in an emergency condition, depending on the density, and consequently the estimation of evacuation times. In particular, these studies describe and quantify the space each individual needs to walk to one exit. As a result, some environments such as staircases, access ramps, corridors, doors, turnstiles etc. that present a limited capacity have been given a more specific attention in planning the architectural layout of structures. Others [6] extended this research specifically to tall buildings such as skyscrapers and evaluated the limits of the formulations proposed in the past. Useful papers have been the works of Fruin that establish values that are useful in the definition of a fundamental pedestrian flow function for indoor and outdoor stairways, and the works of Pauls [7, 8].

Based on the fundamental diagram for pedestrian flow in emergencies many simulation models have been proposed and applied to evaluate building performances in case of emergency evacuation. Among them one of the first was EVACNET4 [9] followed by many other developments such as SIMULE [10], EXODUS [11] and many other that are discussed in [12].

Another state of the art on crowd motion simulation model was published by Duives et al. [13].

Simulation models that have been developed can be continuum flow-based models, microscopic models, macroscopic models, genetic algorithms [14], cellular automata [15] and velocity-based models [16].

Such techniques gave a start to the planning of buildings in emergency situations based on specific software simulations. The study [17] showed that, in some cases, choosing the shortest route is not always the best choice. It was also found out that if the distribution of occupants of a building is not homogeneous in every part of it, the efficiency of each emergency exit could not be guaranteed. This is very important in buildings that are open to the public or that are used in a different way than it was originally planned.

Bellomo et al. [18] affirm that the best way to simulate pedestrian evacuating a building is to use microscopic models that are able to reproduce microscopic one-to-one interactions between people exiting a building. Sophisticated simulation models as microscopic models require a great deal of information and work for a good calibration. For this reason currently, the investigation of real-time evacuation path information is mostly based on the use of video footage or accelerometer sensors [19]. System based on cameras both normal [20] and infrared [21] can be used to detect and track pedestrians in movement.

Very recent studies [22–24] seek to investigate the implementation of new technologies in the building evacuation scenarios to offer guidance to people that are involved in an emergency. The idea to offer a detailed guidance through the use of smartphones or other dedicated smart guiding objects is promising since new technologies such as smartphones, specific sensors and
2 Indoor localisation issues and Bluetooth

Mobile phones can be geo-localised by GPS and other satellite localisation systems such as Glonass and Galileo with global coordinates. Unfortunately satellite systems practically do not work indoors since the satellite signals are shielded by walls. The need for indoor localisation arises in many situations and while global localisation coordinates cannot be obtained directly many wireless systems can be used to obtain a ‘relative’ localisation. Existing systems use radio-frequency identification, infra-red transmission, short wave radio communication (Bluetooth, WIFI) and other systems [30–33].

The performance of every different system can be evaluated according to the following features:

(i) **Accuracy**: accuracy is the most important feature for indoor positioning. It can be evaluated by the difference in distance between the real position and the estimated position. Systems that perform a better accuracy often do so at the cost of reducing performances regarding the other features.

(ii) **Complexity of the system**.

(iii) **Robustness and reliability**: the ability to perform good localisation in the presence of failed element in the system and the rate of system failings.

(iv) **Scalability**: the ability to deploy the system in different contexts.

(v) **Cost**: in practical applications cost may become the most important feature.

For the evaluation of the performance of emergency evacuation plans the following considerations can be expressed:

(i) **Accuracy** is not the main priority since, while tracking people exiting a building, it is important to know just the path and the time of exit (and eventually the time of passage at intermediate checking points).

(ii) **Complexity of the system** is important since the system must be portable and ready to be deployed in every building where there is no localisation system.

(iii) **Robustness and reliability** is important to obtain measures that are also reliable.

(iv) **Scalability** is obviously a fundamental issue.

(v) **Cost** is also an issue since the funding for emergency prevention is always less than ideal in many countries.

The simplicity, scalability and extremely reduced cost of deploying Bluetooth Beacon devices along the evacuation paths of a building make the proposed system a perfect candidate for the proposed task of measuring performances of evacuation drills.

Bluetooth Beacon devices are built upon Bluetooth low-energy wireless technology, this new technology has been introduced to the consumer market in 2013 by Apple with the iBeacon technology. Apple has developed the iBeacon standard while other standards such as Eddystone by Google have also been developed.

Bluetooth Beacon emitters are very simple devices, with reduced cost, that emit a local radio wave signal that can be picked up by every smartphone coming within range. The signal carries information allowing Smartphones to identify the specific emitter. Bluetooth Beacon devices are considered to be a core technology for the internet of things [34].

Bluetooth technology for indoor localisation has been extensively studied in literature. Different localisation methodologies emerged that are: proximity [35], based on the repartition of the indoor space in cells that have non-null intersection; trilateration [36], based on combining the signal values of different Beacons in sight; based on specific map pre-calculations and stigmergic approach [28]. The methods above listed are applicable for people standing or for people walking at normal speed in a well-established indoor environment, and in some cases require too costly and complicated preliminary operations for the simple indoor localisation of people evacuating a building. For this reason in this paper, it is proposed to use a simple and effective method based on portals. The proposed methodology is presented and experimentally tested in this paper.

### 3 Proposed methodology: Bluetooth portal localisation and the proposed algorithm

The proposed methodology allows engineers and practitioners to estimate the evacuation times of each individual person in a staged building evacuation. An ad hoc application for smartphone allows to detect the Beacon radio signals, and thus estimate the distance. The technique is to place a Beacon set in a building in some key points. These points are identified such as special nodes in a sequence of links of an evacuation path such as stair nodes or the beginning, centre and end of the corridors. When someone walks within the radius of a Beacon radio emitter (Fig. 1), the estimated distance between the Beacon and the smartphone is read by the application on the smartphone. Readings from every smartphone can be transferred to an elaboration unit. The single positions and trajectories of people in the building can be obtained by a post elaboration on the elaboration unit.

The general evacuation of a building to be evaluated is planned and executed by giving to all people involved and moving out of the building the mobile phone application that must be installed and run on smartphones during the evacuation. During the evacuation, since the Beacon is positioned in known point it is possible to reconstruct the trajectories of all people exiting the building and the time used by each person to leave the building.

For the evacuation test we conducted, Beacon devices have been installed in special nodes inside the buildings, at critical points to form Bluetooth portals (Fig. 2) along the escape routes. The dedicated mobile phone application is capable of receiving the signal emitted by the Beacons, processing it and storing it and eventually the time of passage at intermediate checking points. This information is then sent to a dedicated elaboration unit for further processing.
In our proposed methodology (based on portals), the issue of accuracy in the localisation of people evacuating a building becomes the issue to establish the moment of passage under the portal and there is no need for any complicated site investigation and fingerprinting nor there is the need for triangulation between different Beacons to ensure a continuous localisation of all users.

The proposed algorithm to establish the moment of passage under the portal is applied and presented in the following sections. A suitable algorithm has to be able to give an estimate of the passage time under the portal, receiving as input the distance from a given Bluetooth portal read by a given smartphone. All data can be read from smartphones after the evacuation drills have been completed. The problem is a maximum signal problem (minimum distance problem) in one single dimension. The simplicity of the problem turns into a simple algorithms since the Bluetooth portals would not clearly be suitable for evacuation drills.

The proposed system is composed of Beacon transmitters that work with Bluetooth low-energy radio waves and a dedicated smartphone for data collection. In this paper to carry on the experimental survey, we used standard Beacon transmitters that work with Bluetooth low-energy radio waves and different commercial models of smartphones for data collection.

The Beacons devices emit a signal that can be related to a radial distance. Theoretically, the maximum radius of radio signal (RSSI) is about 70 m. As from literature [25], the signal power emitted by the Beacon can be explicated by the RSSI formula:

\[
\text{RSSI} = - (10 \log_{10} d + A)
\]

where \(n\) represents the propagation constant of the signal, \(d\) is the distance between transmitter and receiver and \(A\) is the signal power received at 1 m distance. From this formulation, it is thus possible to reverse estimate the distance between the transmitter device and the receiver. Since there is no literature on Beacon signal characteristics in an actual building evacuation some preliminary tests were made with smartphones carried on by walking at a constant speed.

Tests showed an increase in signal latency as the walking speed increases (Fig. 4).

In other words what Fig. 1 presents is the fact that generally there is a delay in the estimation of the moment that each smartphone passes near a Beacon. This preliminary study was obtained by measuring data for a single Smartphone and Beacon and has allowed to obtain some first results that can be useful for a meaningful detection of trajectories applying smartphones in the proposed system.

The following tables (also relative to a single Smartphone and Beacon) show the error and variance (standard deviation) in the error between real and estimated passage time under an isolated portal.

The measurement procedure was improved by using three Beacons instead of a single Beacon in the Bluetooth portal. The intention was to reduce errors and improve accuracy. Results show, in fact, a reduced mean error and a reduced variance by using three Beacons instead of a single one.

**4 First preliminary experimental results on Bluetooth Beacon signal features in walking detection under Bluetooth portals**

Results show, in fact, a reduced mean error and a reduced variance.
The first experimentation carried on with just a single Smartphone and a single Beacon was very positive: there was no occurrence of cases where the passage under the portal was not detected. A real evacuation scenario would pose different problems. There is no theoretical limit to the number of devices and the crowd density that can be detected since each person has a single radio receiver and the Bluetooth Portals just act as radio transmitters. Problems can arise though when a big crowd is moving together and possibly queuing creating physical shields to radio wave transmission. More problems can arise due to differences in signal detection capacities of different mobile phones.

For this reason in the following crowded scenario, experimental tests are presented assessing the limits and merits of the technology.

5 Setting the first experimental experience of a building evacuation

The first experimental experience of a building evacuation was conducted at the Department of Civil Engineering at the University of Calabria using 3 Beacon per floor plan plus 2 for the stairs. Beacons were positioned along the suggested (shorter) escape routes.

The Beacon beam radius was set at 15/30 m to cover a wider area and the totality of every single room in which they were positioned.

The test involved people for each office room who simulated their escape from the door of the office (to reduce uncertainty in the result verifications) to the closest exit of the building. It was asked to participants to maintain as much as possible a constant speed while exiting the building. Evacuation participant's trajectories have been schematised according to the theory of graphs in Fig. 5. Cameras have been used to check the coherence of movements along the path with the given graph. These cameras have also been used to estimate with absolute certainty the real actual times of people passage through the various portals.

The experiment involved two participants for each of the ten rooms for each of the two floors, generating a total of 40 trajectories to the shortest escape exit. The application mounted on the various smartphones recorded the RSSI signal and consequently the distance between the device and the Beacon portals. The following figure (Fig. 6) shows an example of the distance signal detected by a single smartphone for the three Beacons positioned in the first floor depicted in Fig. 5.

In this way, for each Beacon and smartphone, it was possible to identify an estimate of the instants in which participants in the evacuation would walk under the portal. The estimation of times is completed by taking into consideration the time corresponding to the minimum distance read by the smartphone for each Beacon. For the smartphone of Fig. 6, the estimated times of passing through portals passage would be 8, 16 and 17 s, respectively, for portals 1, 2 and 3.

All trajectories obtained with the systems were compared to the real one obtained from the control cameras. Results show that an error is always present in estimating the passing time of participants under the portals. For each Beacon of floor one the resulting distribution of error in the measurements is presented in Table 1. As described in the previous chapter, each device is subject to a delay in the estimated instant due to the latency of the signal. In other words, an advanced reading of the RSSI signal must be taken in consideration when estimating the passing under portals (Table 2 and 3).

The data have been elaborated also on an identical floor of the building, in order to improve and increase the sample of data. Table 2 shows the statistical information for this second group of Beacons.

For the experiment, two different smartphones were assigned to each of the two workers in each of the ten rooms of the building floors.

In Tables 5 and 6, it is possible to see the total travel times from the door to the exit and the relative speeds that each worker experienced during the simulation of the evacuation for floor 1 of the studied office building.

In this first experimental test, there was no density problem and no queuing at the portals since every room was evacuated separately (instead of starting a common alarm and evacuating all people in all of the rooms at the same time), the smartphones used were given with the running application to the people participating in the experiment and the two used models have been previously...
positively experimented in the system. With this simple scenario, there was no occurrence of lost detections under the portals. Results were very good and all participants were detected in all passages under every portal.

Moreover, we had no evidence of interferences or false detections with Beacons between different levels of the building.

### 6 First experimental experience of a crowded area evacuation

In this experimental test, a crowded room with medium people density was evacuated to the outside entrance.

The plan of the single-level building in Fig. 7 shows the three portals. The first portal was composed with three Beacons and the other two with one single Beacon.

There was a dense queue formation at the room entrance and the queue moved without disappearing until the main exit of the building (same floor).

The participants in this test were instructed to leave right away all together from a common room in which they were seated. All participants were preliminary asked to load the application on their Android-based smartphone, to start the application and wait for the alarm. At the alarm, they were instructed to leave the room and follow the main evacuation path. Results showed that not all participants smartphone were able to detect the used Beacon. Out of 32 participants only 28 had phones that were compatible with the experimented system. These 28 participants (the owners of the working Smartphones) were all successfully detected by a 3 Beacon Portal, though in many cases there were missing detections. The percentage of missing detection was: 0% for the three Beacon portal, 14.29% for single Beacon portals. The three Beacon portal had a total of 20.51% missing detections of the Beacons, this error is higher than the Beacon in single Beacon portals though, since there are three Beacons, the missing detection were zero.

Results show that for the proposed system it is necessary to use more Beacons for each portal to avoid missing detections.

### Table 3 Difference between observed and real time on floor 1

| BEACON | 1 | 2 | 3 |
|--------|---|---|---|
| Average | 2.70 | 1.39 | 2.19 |
| Sta. dev. | 2.66 | 2.15 | 1.43 |
| Median | 2.54 | 1.33 | 2.32 |
| Min | −0.83 | −2.63 | −1.68 |
| Max | 8.47 | 5.49 | 4.88 |

### Table 4 Difference between observed and real time on floor 2

| BEACON | 4 | 5 | 6 |
|--------|---|---|---|
| Average | 3.21 | 1.54 | 1.73 |
| Sta. dev. | 3.87 | 2.27 | 1.25 |
| Median | 3.53 | 1.49 | 2.30 |
| Min | −5.29 | −1.23 | −0.55 |
| Max | 10.11 | 7.46 | 4.75 |

Moreover, results were also a little disappointing with regard to the accuracy of the time of passage under the portal. The average delay was −3.8 s for the portal of the crowded room. This means that participants were detected, as an average, in advance with respect to the real time of passage through the exit of the crowded room. The standard deviation was much higher than the previous experiment: 6.99 s.

The reduction in accuracy and the anticipation in the time measure is due, as disclosed before, by the queue formation that creates physical shields to radio wave transmissions and by differences in signal detection capacities of different mobile phones.

In other words, the results show that with low crowd densities the accuracy is higher than in the case of high densities and queuing. The Beacon portals offer a better measure when the walking flows are low and the estimation of the real passing time in case of a queue is not very accurate for all component of the queue.

These phenomena can be for sure investigated in greater details and it is opinion of the authors that while correction algorithms can possibly be implemented given enough queue experimentations the presented results show that the system gives a better accuracy exactly when it is needed.

In the evaluation of some measure of performance for the building evacuation it is important to know whether the participants are able to choose the right path and it is also important to evaluate with accuracy the time of passage of the slow participants: the ones that are left behind by the main flow.

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time that was 60.2 s. The value of relative percentage error is around 3% in our experiment and longer paths would turn out in a reduced relative error since the absolute error values would be expected to be the same.

Two out of the 28 participants were not detected by the second portal and six out of 28 for the third portal. The last five persons passing through each of the two single Beacon portals were successfully detected confirming the expected result that the system performs better with the tail of a queue.

This experiment has shown a considerable reduced accuracy with regard to the previous experiment. The results though still prove that the system can be successfully used for buildings in the presence of a dense crowd queuing at exits. A dedicated experimentation on the applicability of the system for large areas (such as art, music and sport events) could dissipate any doubt and extend the usefulness of the proposed portal approach. This is beyond the object of this paper (dedicated to building evacuation issues) and it is faithfully left to independent verification.

7 Detection of paths

A specific experiment was carried on to establish the capacity of the system to catch people that miss the right path. To perform such detection portals have to be set on all the possible building paths. The experiment we carried on was with two single Beacon portals positioned at two different exits (Fig. 3).

Eight participants were instructed to exit at portal A and 16 at portal B.

Once participants were inside the corridor between A and B some of them were detected by both portals. In detail one out of eight that exited through portal A was detected also by portal B. Nine out of 16 exiting through portal B were detected also by portal A. By using the minimum distance measured from each portal and the time sequence of detections, it was possible to assign each participant to a 'logical' path.

The results of this procedure were able to assign 18 participants out of 24 to a path. Six participants were not detected at all by the exit portals A and B.

The participants that were successfully assigned to Portals A and B were all assigned to the right path: error rate in the estimation of paths was zero per cent.

The results of this experiment confirm previous results that it is more accurate to use portals with at least three Beacons and show that even with single Beacon portals the path identification obtained with the proposed methodology is very accurate.

In other words the experiment shows that the proposed system is successfully able to establish when someone exiting a building takes a wrong path and also to identify the person who has made the mistake. This would allow to give targeted information to assure that in a real emergency no mistakes are made.

8 Discussion of results

The proposed methodology is simple and free from triangulation problems, as Beacon portals are used almost exclusively to determine the pass-through times under the portals and not all the trajectories of the smartphones. In this methodology, therefore, only the instant of passing under the portals created by the Beacon are used to approximate trajectories.

In the first experimental experience of a building evacuation it is possible to notice how, in fact, every smartphone suffers from a latency in receiving the RSSI signal. This results in errors that can be considered distributed with a Gaussian distribution. The error distribution in receiving the signal is not constant because it depends on the location of the Beacons themselves as a function of local characteristics of the room.

From results it is possible to notice that the error is greater in receiving the signal from Beacons positioned in an open area (Beacons 1 and 4). While it is lower with Beacons that are positioned in small rooms since the signal is more concentrated under the portal (as it would be in the case of photoelectric cells).

Moreover, the formation of queues at portals and the consequent higher crowd density has shown to contribute to considerable more error in the estimation of time passages. The errors seem to be caused by shielding of the radio emitting Beacon and by interactions between the different smart phones in a reduced space.

Errors can be reduced by using more Beacons for each portal and more portals. Results have shown that the methodology can be useful for practical purposes.

It is beyond the scope of this paper to develop the best settings in terms of Beacon disposition and practical deployment of the system. This paper has shown that better results can be obtained by using more portals and more Beacons for each portal.

The scope of this paper, in fact, is to give a new insight into the important issue of building evacuation. This paper presents for the first time the Bluetooth portal concept in a reproducible methodology assessing limitations and merits. The methodology can be useful to people that make decisions in organising better emergency building plans that can save lives.

From the above reasons, it was deliberately chosen to implement the system in the most easy and reproducible way to obtain the following results:

(i) The system gives enough satisfactory results for practical applications even with the simplest settings.
(ii) It is possible, in every building evacuation, to implement the system and obtain with little effort and costs a great amount of meaningful data.
(iii) The methodology, that was experimented mainly with single Beacon portals showing a sufficient accuracy, can be improved by using more Beacons for each portal.

Possibly when new accurate Beacons will be on the market it will give an almost perfect evaluation of passing times through portals.

The use of portals is much simpler and cheaper than classic triangulation since less Beacons are necessary to study an entire building. The sensors, in fact, are arranged only along specific portals with a set up that can be easily decided on the spot by the person responsible of performing the measures.

The proposed system is oriented to estimate ‘real’ evacuation times in buildings. In itself it is not a system suitable to modify escape routes in building or architectural design procedures. Further research can also be devoted to the use of collected data in escape route simulation models and in obtaining sufficient knowledge to affect building design procedures.

Fig. 7 Trajectories and layout of the portals in experiment
9 Security index

On the basis of data obtained applying the proposed methodology, it is possible to create a security index for sorting generic buildings from the point of view of emergency evacuations. Moreover, it allows planners to take into consideration specific abilities (or lack of) relative to the actual occupants of the building to improve the index.

10 Conclusion

The final aim of this study is to present a new methodology to estimate evacuation times from buildings in case of danger. Such a methodology could allow to reorganise the evacuation plan of a building by realocating paths and/or people. The workers with walking disabilities could benefit of rooms that are closest to the escape routes. Paths could be reorganised according to the real experimented evacuation times.

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