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An IoT-based Emergency Evacuation System

Imran A. Zualkernan
American University of Sharjah
Sharjah, UAE
izualkernan@aus.edu

Fadi A. Aloul
American University of Sharjah
Sharjah, UAE
faloul@aus.edu

Vikram Sakkia
American University of Sharjah
Sharjah, UAE
b00064566@aus.edu

Hassan Al Noman
American University of Sharjah
Sharjah, UAE
b00059444@aus.edu

Salman Sowdagar
American University of Sharjah
Sharjah, UAE
b00061479@aus.edu

Omar Al Hammadi
American University of Sharjah
Sharjah, UAE
b00062027@aus.edu

***Abstract*— During a fire emergency, most people tend to panic and head towards a known exit that is not necessarily the best option. Therefore, a system that dynamically directs people to the safest exit is needed to reduce congestion, speed up the evacuation process and to save lives. This paper presents a system that uses IoT technologies to track location of the fire and building occupants, and then directs the occupants smartly towards a safe exit. The system uses Bluetooth Low Energy (BLE) beacons for indoor localization using the occupant's mobile phones. The system also tracks areas of danger using smoke and temperature sensors. For resiliency in face of a fire, the system uses multiple networks including WiFi and the DigiMesh. A publish/subscribe architecture using an MQTT broker was implemented. In case of a fire, occupants can use a smart mobile application that provides the occupants with a live map of the current danger levels within the building. In addition, smart exit signs are deployed throughout the building that dynamically change their state based on location of the fire to guide the occupants to safety. Real-time information gathered from sensors and occupants is also provided to emergency response services. The proposed system can be scaled to a city-wide emergency network.**

Keywords*— BLE, MQTT, iBeacon, evacuation, emergency, robust, DigiMesh, fire, safety, ad-hoc networks, smoke, localization, indoor navigation, mobile phones.

I. Introduction

Fire is a major emergency threat to citizens, especially in large public buildings. Consequently, most countries enforce fire safety by enacting laws and regulations on buildings to minimize the fire threat. According to the World Fire Statistics [1], 28 countries had at least 1000 deaths in each country due to fire related incidents in 2017. Loss of life was not only limited to civilians but in 2017, over 10,000 firefighters worldwide also perished while carrying out rescue operations.

From a building resident's perspective, the process of fire evacuation comprises of three main phases: awareness, response, and movement. Fire alarms are typically used to raise *awareness* that there is a fire. A recent study showed that standard fire alarms are not sufficient to trigger the evacuation of people during actual emergencies [2]. This is due to the numerous false alarms and evacuation drills that occupants participate in. In addition, in a number of cases the alarms within the building failed or were not able to alert all the occupants within the building. The next phase in emergency evacuation is *response*, which requires people to assess the situation, and to make a response regarding the situation at hand. In the case of public buildings, occupants and visitors of the building rarely have prior information of the layout or the exits within the building. Hence, during the response phase, most occupants were found to head towards the main entrance they came from, which is not always the safest exit [3]. This, in turn, may also cause primary exits to get more congested. Occupants and visitors within the building may also proceed towards dangerous exits since they are unaware of the current fire situation. The final phase in fire evacuation is *movement*. This involves people moving towards exits and towards safe assembly points outside the building. Movement can be hindered due to poor visibility caused by noxious gases and pollutants created by the fire. During the movement phase, people are also prone to panicking resulting in increased chaos that causes people to get injured, and in some cases trapping people within the building [3]. Without information of danger within the building, the occupants have trouble navigating and identifying the optimal exits.

Firefighters face a variety of challenges when trying to tackle a raging fire. A primary issue is lack of awareness of situation within the burning building [4]. Without this internal knowledge, it is difficult for firefighters to safely enter and attend to people appropriately. Even if the building plans are provided, the plans do not reflect the real-time emergency situation inside a building. Another hindrance to effectiveness of fire departments is the proportion of emergency calls that are false alarms. According to the United Kingdom (UK) Home Office [4], only 30% of fire incidents reported were legitimate fires. In 2017 and 2018, the fire departments attended to more false alarms than actual fires. The fire department was often unaware of the status of the buildings within its jurisdiction. They only became aware of the situation once they surveyed the incident manually. This takes away time for the legitimate fires to be attended to.

This paper proposes an IoT-based system that improves the fire evacuation process in buildings in addition to better supporting the fire departments and other emergency response services. The system utilizes BLE beacons, mobile application, and smart exit signs to create a context aware system that dynamically routes occupants to the safest exit. The proposed system is described in Section II. Section III provides the system evaluation and the paper concludes in Section IV.

II. Proposed System

Fig. 1 shows the primary use cases for the proposed system. As the Figure shows, an occupant of a building under fire should be able to receive an emergency response in case of a fire on their mobile phone. In addition, an occupant should be able to see a danger map on the mobile phone that shows them where the fire is in the building and where the safest exits are. If the occupant does not have a mobile phone then they should be able to use smart exit signs that dynamically change state based on the fire to guide the occupants to safety. Finally, the occupant should be able to send their location to concerned individuals to indicate where they are and if they are safe. This information can be used by family members and emergency respondents. As Fig. 1 shows, various emergency response services like the fire department should also be able to see where the various occupants are within a building, receive emergency alerts and should be able to see a danger map showing where the fire is raging the most. In addition, they should be able to and view smoke levels within various parts of the building. When firefighters enter the building, their locations should also immediately become available to emergency services using their mobile phones.

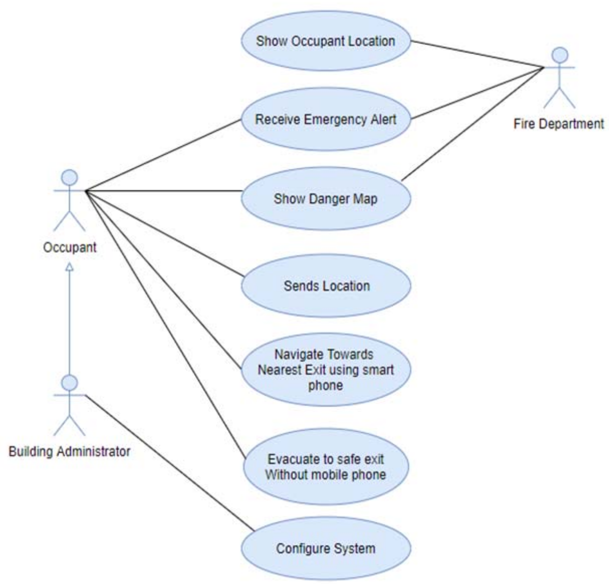

Fig. 1. Use case diagram.

Fig. 2 shows the overall architecture of the proposed system. The system was designed using an IoT paradigm and the various IoT layers are described next.

A. Sensing Layer

As Fig. 2 shows, the sensing layer has two types of edge nodes: Bluetooth Low Energy Beacons (BLE) and the ESP32 microcontrollers. The BLE beacon has a built-in *temperature* sensor while the ESP32 microcontroller is interfaced with an MQ-2 *gas* sensor. The MQ-2 gas sensor can detect 300～10000 ppm of flammable gases including smoke. As opposed to previous approaches such as [5] that have proposed that fire fighters carry a device embedded with sensors, the solution proposed here relies on a static infrastructure of sensors to localize both occupants and firefighters based on their mobile phone locations. Most people are willing to allow access to their mobile phones if they feel that useful services are being provided. For example, a recent survey shows that over 80% of participants mentioned that they would be willing to share the location of their mobile phone if required [6].

B. Communication Layer

As Fig. 2 shows, BLE beacons communicate their location and signal strength to an occupant's mobile phone or an intermediary Raspberry Pi server using the Eddystone Beacon protocol over BLE. The ESP32 edge node and the Raspberry PI can communicate either using WiFi or the DigiMesh ad-hoc wireless protocols [7]. Both protocols are supported for redundancy and resilience. During initial stages of the fire WiFi is used to convey the dynamic path information the occupants. However, if WiFi routers are damaged due to the fire, then the system automatically switches to the DigiMesh network which is entirely peer-to-peer and does not require a centralized coordinator. This degrades the location services being provided but keeps various components of the system like the smart signs alive. At the application level, the ESP32, Raspberry PI, and the occupant's mobile App rely on the Message Queuing Telemetry Transport (MQTT) protocol when WiFi is available and native protocol otherwise. Similar ideas of implementing network resilience for emergency evacuation have been proposed in [8].

C. Middleware

Middleware for the proposed system has an application server, an MQTT broker and two back-end databases. MQTT broker supports the publish/subscribe architecture used by the mobile application, ESP32's and Raspberry Pi's. This allows queuing and various quality of service levels for the messages being exchanged. A Golang based server was used as an application server. Finally, CouchDB, which is an NSQL database, was used for normal non-real time processing tasks like user registration and map configuration. Remote Dictionary Server (Redis) database was used for dynamic exit path calculations to provide a real-time response to a large number of occupants. In addition to these generic services, the middleware provided two key services; localization and safe path finding. Each is described below.

1) Localization Service: The purpose of the localization service is to determine an approximate indoor position of each occupant in the building. The most commonly used indoor localization techniques typically measure the received strength signal indicator (RSSI) and calculate the distance of each BLE beacon from each occupant. Multiple readings from BLE beacons can then be used to determine indoor location using some variant of triangulation [9]. An alternative technique called the fingerprinting technique uses known signal strengths for all points within the building to determine where an occupant is at any point in time [10]. Fingerprinting using traditional learning algorithms that use large amounts of signal strength data showed high accuracy in localization [11]. Recently, deep reinforcement learning [12] has been used to further improve the precision of localization. One problem with most current approaches is that they require extensive data collection that is specific to a particular placement of beacons within a building. As opposed to previous approaches, this paper used a probabilistic approach that does not require extensive data collection but uses only the RSSI strengths of the various BLE beacons to find an approximate location of each occupant. This approach provides a good enough position for each occupant's position within the building but obviates the need for extensive data collection and model training.

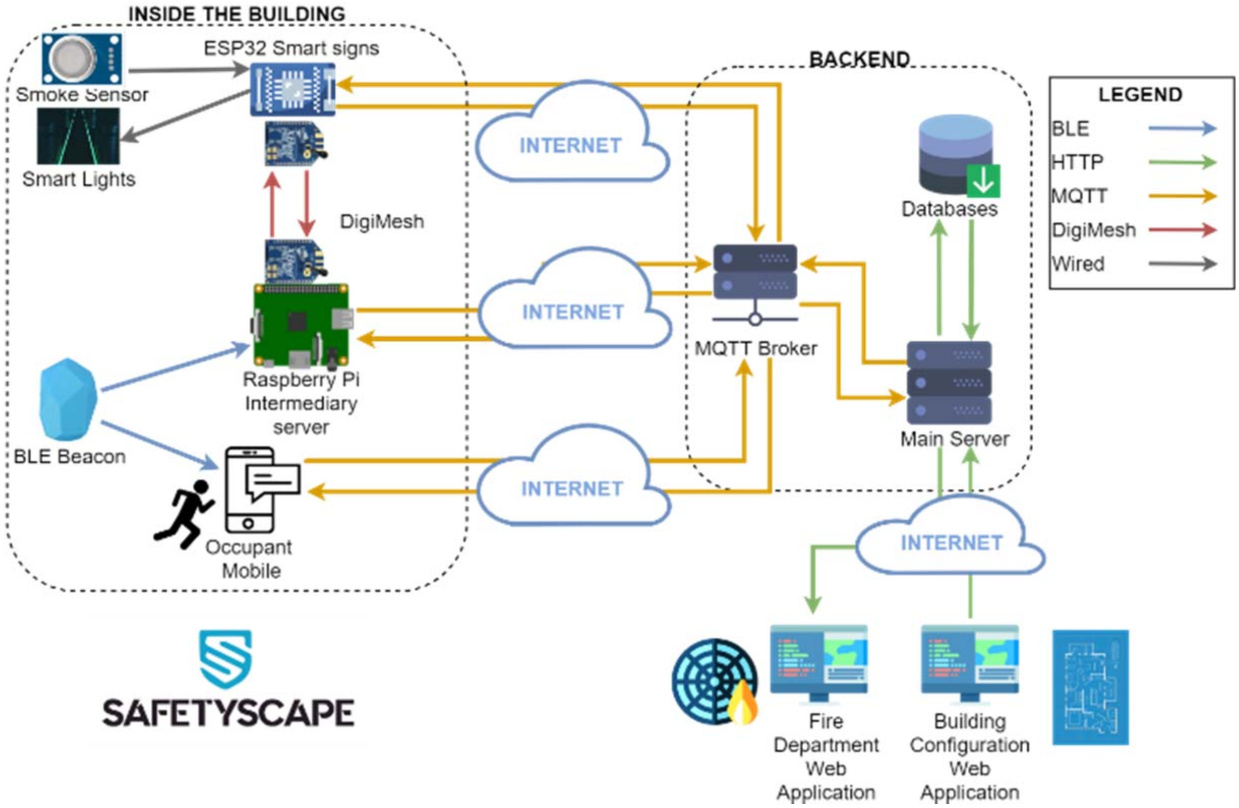

Fig. 2. System architecture for an IoT-based fire evacuation system.

2) Evacuation Pathfinding Service: Calculating an effective evacuation path for each individual occupant in real-time in an emergency is essential towards saving the greatest number of lives. A good evacuation path directs people to the least congested and the safest exits that are nearest to them so that it takes them the shortest possible time to leave the building. Multiple algorithms that considered door sizes, and number of occupants within the vicinity of the specific exit have been previously proposed [13]. However, in the system proposed here, since real-time data about danger zones including temperature and gas readings throughout the building were available, a dynamic A* algorithm that used critical safety points within the building was used to calculate individual evacuation paths for each occupant in real-time [14]. The cost function for the A* algorithm incorporated exit distances, temperature and smoke within the various parts of the building.

D. Application Layer

As Fig. 2 shows, browser-based interfaces are provided to the fire department and for configuring the system for a particular building. The configuration tool is shown in Fig. 3. Fire department can view the status of fire within the building while the administrator can use a web interface to configure the application. The fire department can view a danger map of the building as proposed in [15]. As Fig. 3 shows, the configuration tool can be used to specify the location of BLE beacons and critical safety points (shown in yellow). Critical path points are used to create potentially safe exit paths for occupants. Placement of these points depends on the geometry of the building and is currently decided upon by the system administrators. For example, complex geometries like corridors with many bends require more critical path points. This process of placement of critical points can be automated in the future based on the geometry of paths within the building.

Fig. 4 shows a specially designed exit sign that hosts the ESP32 microcontrollers and the associated wireless networking technologies including WiFi and DigiMesh. Unlike conventional exit signs that do not convey any dynamic information other than location, the smart sign uses a strip of colored LEDs to show the current safety state to an occupant. For example, green color means that path is safe, yellow means marginally safe, and the red color means unsafe. Unlike traditional exit signs, the smart exit signs will be placed near the floor in a manner similar to exit strip lights used on floors of airplanes to guide evacuation. This is because in case of a fire, the traditional overhead fire signs have low visibility due to smoke and are not clearly visible to occupants attempting to flee a fire.

Fig. 5 shows screenshots from the mobile application used by an occupant. As the Figure shows, the mobile application provides an occupant with a real-time display of a safe exit path from their current location indicated by the red triangle. Since the path finding algorithm is written to utilize multiple CPU cores, the algorithm scales almost linearly with the number of CPU cores in the server. For example, on average, the pathfinding algorithm took 59.95 µs per operation on a single CPU core, and 14.55 µs per operation on four CPU cores showing an almost linear scale up. In addition to displaying the safest path, the mobile application also sends location of the occupant using MQTT to the back-end server that displays this position on the web-based application of the fire department or other associated emergency respondents. In addition, family members subscribed to the occupant's position also receive the updated location of their loved one. It is easy to implement any additional subscription service using the MQTT protocol's hierarchical messaging architecture.

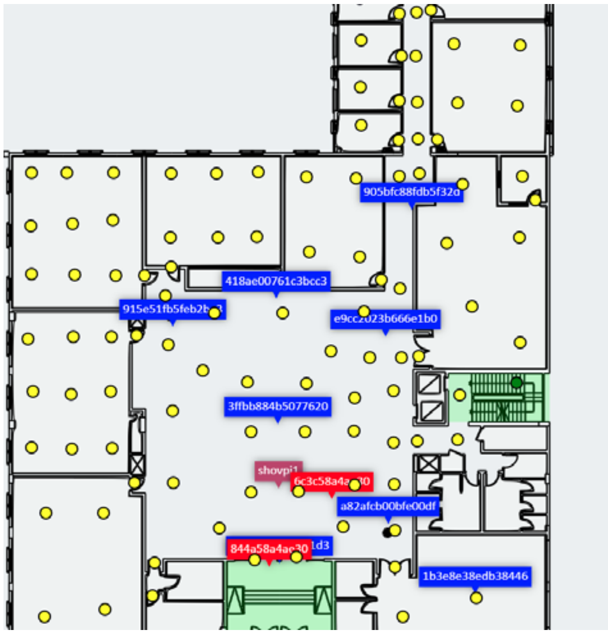

Fig. 3. Building configuration tool showing becaons and safety points.

Fig. 4. Smart exit sign including the ESP32 microncontroller, LED strip, WiFi and DigiMesh network.

Fig. 5. The mobile application interface for occupants showing dynamic exit path.

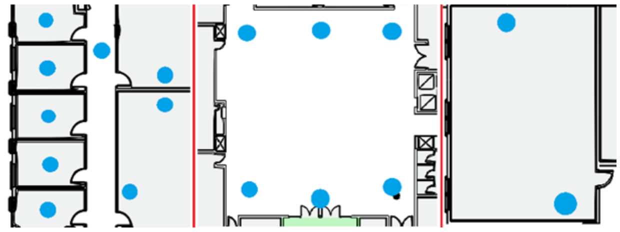

Fig. 6. Example testing scenarios with blue dots representing beacons.

III. Evaluation

The system was tested over an area of 1600m^2 with a variety of indoor spaces including narrow pathways, large wide-open areas, and multiple rooms. Fig. 6 shows three sample configurations. The left configuration consists of a corridor lined with various offices on each side. Only single BLE beacons were required for each office and a few BLE beacons were placed in the corridor. The middle space in Fig. 6 was a large hall which was 30m x 30m with a high vaulted ceiling, but only required six beacons for the technique to be effective. Finally, the large room on the right only required two BLE beacons for effective localization and path finding.

TABLE I. Indoor Localization Results

Technique	Average distance to exact point (m)
UWB [16]	0.5
Fingerprinting [10]	2.48
DRL Supervised [12]	9.4
iBeacon Proximity [5]	10
DRL Unsupervised [12]	12.8
Proposed Algorithm	4

As Table I shows, the proposed localization algorithm was able to estimate the distance of an arbitrary occupant to within about four meters of their actual location. This precision is less than when using digital finger printing or UWB. However, considering that this approach does not require extensive data collection and training, a precision of 4 meter is sufficient for the purpose of fire evacuation.

IV. Conclusion

In this paper, the design of a system utilizing IoT technologies that directs people to the safest exit in an event of an emergency was presented. Multiple edge devices including smart signs based ESP32 microcontroller and supporting WiFi and the DigiMesh network were deployed. BLE beacons incorporating temperature and smoke sensors were used in conjunction with custom middleware services for localization and evacuation path finding to provide safe passage to occupants either through their mobile phones or by following the smart exit signs. The system is robust as the DigiMesh network takes over in case of a failure of the WiFi system.

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