Location-Based Services for High-Rise Fire and Rescue Situations

A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at George Mason University

by

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DEDICATION

This is dedicated to my fellow service men and women. These are the people whom provided mental support during difficult times and encouraged me to finish this degree. They recognized the level of difficulties and sacrifices that are required of us to maintain our commitment to our military obligations and still attempt to maintain a normal life back home. Also, to those first responders whom always run toward the sound of trouble and ensured all of us can have nice things and sleep safely in our beds every night.

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LIST OF ABBREVIATIONS

Adaptive Kalman Filter……..AKF
Adaptive Noise Filtering……ANF
Bluetooth Low Energy.....BLE
Butterworth Filter……..BF
Emergency Operation Center.....EOC
Geographic Information System..... GIS
Global Positioning System..... GPS
Global Systems for Mobile Communication .....GSM
Internet of Things.....IoT
Incident Command……IC
Incident Command System…...……...…..……...ICS
industrial, scientific, and medical.....ISM
Location Based Services..... LBS
Location, Unit, Name, Air and Assignment, and Resource…….LUNAR
National Fire Protection Association..... NFPA
National Institute of Standards and Technology……...NIST
National Institute of Occupational Safety and Health……...NOISH
Personnel Accountability Report.....PAR
Personnel Accountability Systems…….PAS
Real Time Location Services……...RTLS
Radio Frequency.....RF
Radio Frequency Identification.....RFID
Selective Availability..... SA
Special Interest Group…….SIG
Support Vector Machine……...SVM
Talk About.....TA
World Geodetic System.....WGS

ABSTRACT

LOCATION-BASED SERVICES FOR HIGH-RISE FIRE AND RESCUE SITUATIONS

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Technology has an important role in emergency response processes in the command center and in the field. Successful operations during emergency rest entirely on the level of success of information relay to allow timely decision-making process from the Incident Command (IC) level to the firefighter. Although it is one of the most important aspect of emergency response, it remains a challenge within the Fire-Rescue community. Communication during high hazard incident, is recognized by the National Institute of Standards and Technology (NIST) during the 2013 research, as one of the interests for future research to improve communication and streamline accountability process; where communication is often profuse, interrupted, misunderstood, garbled, and chaotic.[10]

The most important aspect of communication during fire-rescue operation is to achieve personnel accountability. This is a key component of NFPA 1500: Standard for Fire Department Occupational Safety and Health Program. The main objectives for

enforcing accountability as part of the national standard are to (i) identify individuals on scene, (ii) knowing the physical location of everyone operating on scene, and (iii) to be able to quickly account for the location and safety status for everyone on scene in the event of unexpected change in condition. At any moment during an emergency, firefighter could be injured, lost or killed.

Personnel Accountability Systems (PAS) are vital to all emergency operations and the effectiveness of the systems is the difference between life and death. Based on 2016 FEMA report, fatality could have been reduced or prevented with improved accountability through personnel location identification tools.[11] Technology to improve fireground accountability has been making significant progress. Known for popular use of asset management tracking and healthcare solution, Real Time Location Services (RTLS) will play a major role in fireground accountability process. Multiple types of technology relating to RTLS are available today with the design aiming for specific requirement.

This research will identify technology best suited for high-rise fire and rescue situations. The research will provide baseline understanding of the national standard, published by the NFPA, and current policy and process practice at the City of Miami. Additionally, current technology on RTLS will be discussed with the focus of the requirements determine by the City of Miami Fire and Rescue interviews. Finally, the research will discuss on current technology of RTLS and the usage to enhance accountability technology in high-rise fire and rescue situations.

CHAPTER 1: INTRODUCTION

Keeping up with all assets and people are the most important aspects of running a business, either in the office or operations in the field. Accountability is found everywhere and each of us are very familiar with the concept. In reality, many of us are not very good at keeping up with accountability without technology. Some challenges relate directly to human defects such as lack of compliance or missed opportunities. Other challenges are due to gaps in operation processes or out-of-date technology.

In multiple occasions, during emergency operations, communication and information flow in multiple directions and often slow down with the intensity of the emergency. A study done on Collective Response of Human Populations to Large-Scale Emergencies[12] shown that significant amount of communication increase during different types of emergency. The intensity, shown in Figure 1, conclude that terrorism type of emergency such as bombing, significantly affect communication volume. Although this research is not focusing on emergency during terrorism events, it is important to point out the importance of effective communication, mainly communication traffic, this affect the focus on accountability efforts.

Firefighters fatalities and injuries are of the utmost concern for any fire service organization. In the rush to set-up for battling structure first, it is difficult and imperative, to use a system to manage possible incidents. Generally, fire departments across the

country utilize Incident Command System (ICS). Proper use of the ICS, including the accountability system, will reduce freelancing, thus reducing firefighter injuries and fatalities. Freelancing or performing without specific task assignment, could be an ingredient that undermines the safety aspect of running almost any operation. "There are many trends in the fire service today. Accountability is one of them…Accountability is not just an in-fashion term, it's an essential tool for incident commanders."[13]

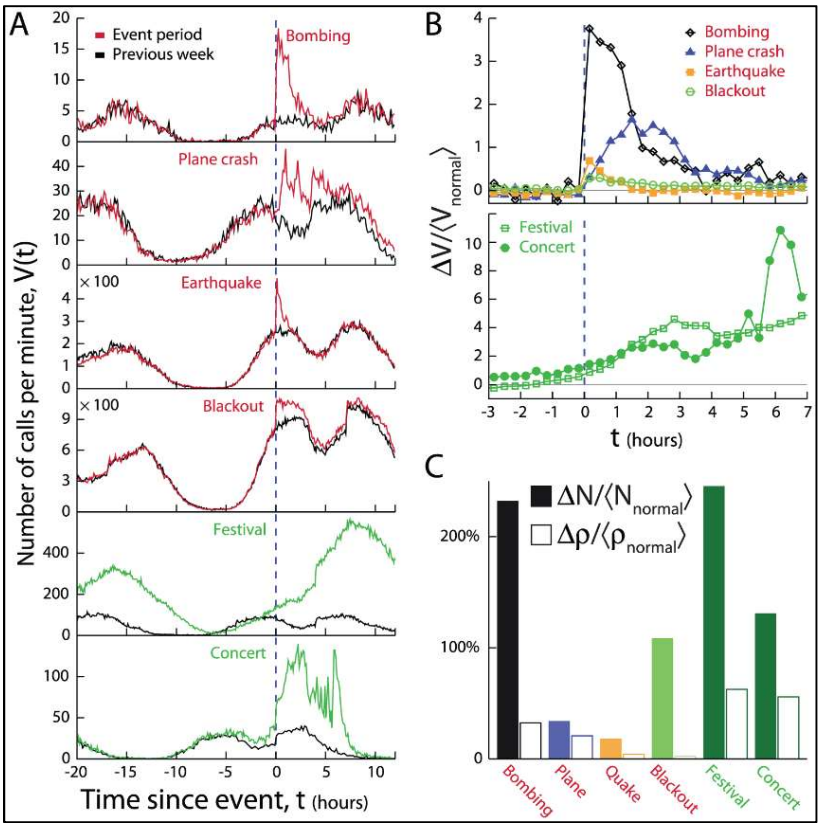


Figure 1: Call anomalies during emergencies[12]

1.1. Background and Significance

Responding to an emergency in urban environment is a unique challenge. The task is not only rest on the danger of the situation reported but the logistics that goes along with getting personnel and equipment to the right places at the right time. High rise firefighting poses unique challenges. Radio Communications are extremely limited due to the density of concrete construction. Evacuations of occupants are extremely difficult and manpower intensive and, in some case, not possible. Finally, the logistics of moving crews and resources up to the fire floor or staging floor can be difficult and be delayed by evacuation efforts.

Modern location services, such as GPS navigator, are being utilized everyday by emergency response personnel by finding the shortest route to their destination to help decrease their response time. The technology works great until the scenario involves high-rise facilities which introduces new challenges and considerations to maintain "reasonable" response time. An example of factors that contributed to slowing down response time are inefficient method of primary communication and lack of redundancy; especially during high hazard "roll call" from fireground.

The City of Miami is protected by fourteen fire stations which are strategically placed throughout the city for effective response time. The City of Miami has 789 full time firefighters/EMT personnel[14] serving a population[15] of 443,007 and 134,115 properties, 546 of them are considered "high-rise." In a large city such as the City of Miami, high-rise structures required additional protocol to ensure accountability as a part of safety standards. These standards not only required by the National Fire Protection Association,

but also are in place to help set guidelines with the hope to prevent lives lost, anyway possible. Such a protocol or procedures are in place as part of the Incident Command System that oversees the entire operation during a response to an incident.

The main concern during any operation during an emergency, commonly refers to as an incident, is personnel hazards. To be effective in the business of fire protection and to preserve lives and equipment, the organization identified multiple hazards generally involving high rise fires. Personnel hazards, identified by the City of Miami Emergency Operation Manual, has listed "poor radio communications[17]" as one of the major concerns in the "High-Rise Building Operations Guidelines" section.

During the response in a high-rise situation, radio communication can be negatively affected when operating in high-rise structures. Occasionally, this can overcome by utilizing the Talk About (TA) feature on handheld radios[17]. However, TA communications are strictly "radio-to-radio" and will not be heard by the dispatcher or other divisions monitoring outside the incident area. With the TA process, the Incident Commander (IC) must monitor the Alarm Office (dispatch) communications along with TA and other tactical channels.

The primary problem domain that will be discuss during this research is the accountability process at the City of Miami. Based on the interview with the Fire Station Chief and a Fire Lieutenant at one of the high-rise fire service districts in the City, accountability protocol is available and written in part of the comprehensive Emergency Operation Manual. The protocol written in manuals alone may not be enough. The accountability process, Article 2: Communication and Notification, could be enhanced by

adopting newer technology, available on the market today, to assist with automated accountability that can also provide real time data.

1.2. Objectives of the thesis

Fire and rescue operations rely on the physical and mental readiness of the fire fighters as well as reliable support equipment. The fire-rescue vehicles and other life support tools used by the fire fighters are essential but we cannot deny that without proper communication tools and accountability system redundancy. The operations can fail when people's lives are at risk due to with poor or communication delay.

The objective of this research is to find existing location-based technology solution for indoor use that will meet the required needs defined by the City of Miami Fire Department and can support high-rise environment.

Hypothesis statement: Indoor location-based services can be achieved by using smartphones to detect and relay location data without the expenses of installing fixed infrastructure.

To assist with this research, the following questions were developed.

Research Questions

1. What is the accountability standard and associated technology requirement for fire-rescue at the national level?
2. What is the current process of accountability and technology used for fire-rescue emergencies at the City of Miami?
3. What are the requirements for indoor positioning based on City of Miami Fire Department feedback?

4. What is the existing technology that can meet the City's requirement and can be used for accountability tracking for indoors and high-rise facilities?

1.3. Key Terms

1.3.1. Accountability: A system or process to track personnel specific location and status at an incident scene[22].

1.3.2. High-Rise Facilities: According to NFPA Life Safety Code, high-rise building is defined as a building where the floor of an occupiable story is greater than 75 feet above the lowest level of fire department vehicle access.[3] These structures are generally a minimum of seven stories tall and are usually equipped with multiple fire protection and detection systems. High-rise can be classified as residential, commercial, or mixed-use occupancies. Working fires in these structures often present significant life safety hazards and logistical challenges as the need for resources can rapidly escalate. This is further complicated by the potential for multiple victim/occupant removal.

1.3.3. Location Based Services: This is the terminology commonly used to describe Global Systems for Mobile Communication (GSM). It offers value-added "services" and uses location to provide end users with ability to identify and communicate messages along with associated spatial data[4].

1.3.4. Real Time Location Service: A service, often refer to indoor application, that uses electronic systems to pinpoint a location of the people or things by using small electronic devices installed, implanted, or

carried by people or objects. This is done in attempt to determine the real-time identity and/or location of a person or object, either continually or when the tracking device is interrogated.

1.3.5. Bluetooth: A wireless technology that uses short-range radio frequency (RF) to connect between mobile electronic devices. This term is also referred to as Bluetooth Basic Rate/Enhanced Data Rate (BR/EDR). The operating in the unlicensed industrial, scientific, and medical (ISM) band at 2.4GHz; transmitting with frequency hopping approach over 79 channels. This technology is intended to replace cable connections and synchronized data between devices as a point-to-point network topology[19] for streaming optimization.

1.3.6. Bluetooth Low Energy (BLE): A wireless technology that is similar to traditional Bluetooth with additional enhancement on power consumption and security options. This technology uses the same 2.4GHz ISM frequency band and use less channel hopping, at 40 channels[19]. Power consumption, depending on the use case, is between 10%-50% of the Bluetooth BR/EDR. Another enhancement for BLE it can operate in multiple network topologies such as point-to-point, mesh, and broadcast[19].

1.3.7. Beacons: Electronic devices that uses BLE or RFID signal to exchange data and provide location information[20].

1.3.8. Radio-frequency identification (RFID): A technology that utilize radio wave to automatically identify objects, collect data about the said

objects, and input those data directly into the computer systems with little or no human intervention[21]. RFID can be passive or active, depending on the use and the device. Active RFID has its own power source and transmitter. Common active RFID are beacons that emits signals at pre-set interval to provide RTLS solution. Passive RFID uses backscatter technique to reflect energy and communicate with the system. Examples of passive RFID are the race timing chip and access control badge.

CHAPTER 2: LITERATURE REVIEW

2.1. Death in the Line of Duty

Firefighters faces life threatening danger each time the alarm goes off at the station. They know that a split second in change of environment can be their last alarm. There are numerous causes for fatality in the firefighting community. Some are pure accidents and events out of their control and some causes are preventable. One preventable cause of death surfaced during the research is accountability.

The May 2018 investigation, performed by the National Institute for Occupational Safety and Health (NOISH), an arson fire killed three firefighters and injured four fire fighters in Delaware. The incident occurred in a multiple stories homes which the first floor collapsed into the basement structure. The investigation listed the contributing factors[27] as "lack of personnel accountability system" and "Ineffective fireground communications" amongst other factors.

Another incident happened in Michigan, where a firefighter ran out of oxygen and died in a commercial mall fire. Lack of communication[28] was also listed as contributing factors in a report done by NIOSH. Another report from 2016, a volunteer fire fighter dies at residential structure fire[29]. The major contributing factors of this fatality were lack of communication and ineffective personnel accountability system.

Preventable fatalities such as those cause by lacking policy or supporting tools are being closely monitored by organizations at the national level. Organization such as NOISH is a subdivision of the Center for Disease Control and Prevention. They contribute to reduce preventable deaths through investigations and research as well as educate their findings to the workers and other organizations. NOISH works closely with The National Fire Protection Association (NFPA) to expand their resources and collaborate on addressing issues surrounding fire fighter health and safety.

2.2. National Standards

Emergency Services Organizations around the country, such as the City of Miami Fire Department, are required to follow the safety guidelines written in the NFPA 1500 that contains: Fire Department Occupational Safety, Health, and Wellness Programs. Additionally, they must adhere to Incident Command System guidelines written in the NFPA 1561 covering: Standard on Emergency Services Incident Management System and Command Safety. These standards are written to ensure operational conditions and effectiveness of the systems that are in place. They are also serving as the baseline for nationwide emergency services organizations' operational rules and regulations that are interoperable with other government entities (see Figure 2); integrating risk management into regular functions of incident command.

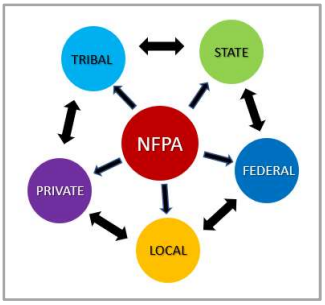


Figure 2: Incident Command System (ICS) inter-organization network

The Incident Command System (ICS) is a management process that enables a fire department to effectively and efficiently control resources at incidents. It is designed to empower a domestic incident management by integrating a combination of facilities, equipment, personnel, procedures, and communications operating within a common organizational structure[17] (see Figure 3). The structure of ICS should be similar across agencies to support the interoperability concepts during larger incident that requires additional help from neighboring agencies, as unified command.

Each level of command structure require involvement with accountability and reporting process. Depending on the level, certain role on the command structure may have more responsibility in the accountability process but it is everyone's job on-site to ensure, at the minimum, report their location and status at regular interval. Figure 4 depicts general understanding of the accountability information flow at each level of fire emergency ICS during high-rise situation.

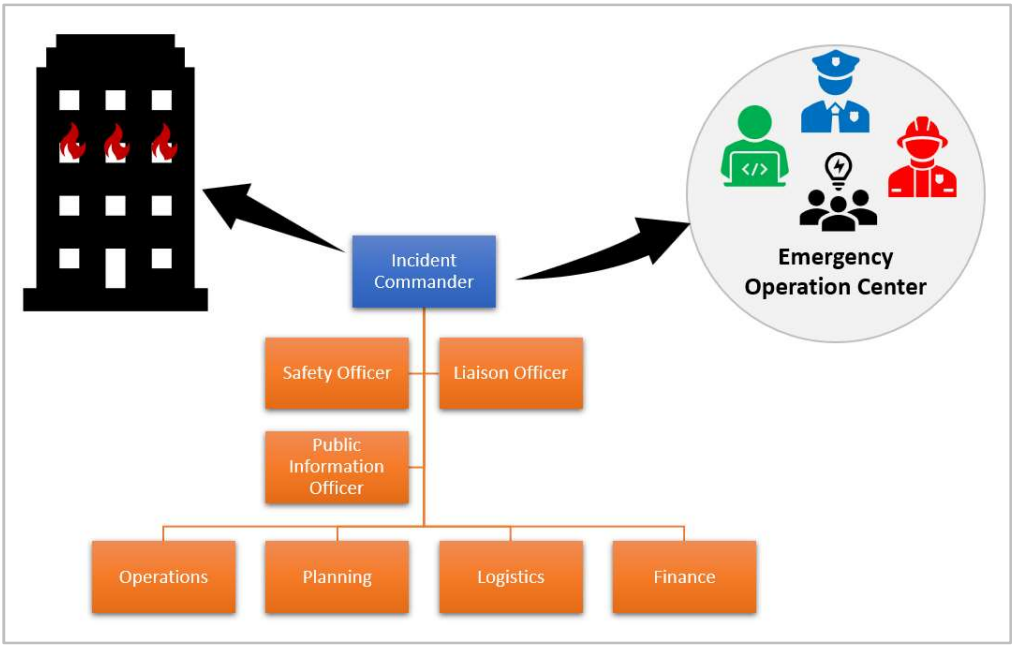


Figure 3: Incident Command System generic structure based on NFPA description

2.2.1. National standards on accountability

This is the general guideline that only the covers the bare "minimum" for individual organization. Generally, the standards call for accountability process that will work for all multiple magnitude of emergency. This means that manual process of using regular whiteboard and post-it notes, to keep track of personnel entering and exiting the incident ground, will meet the minimum requirement of the national standards in the NFPA 1500 and 1561.

The standards, per the NFPA 1561 Section 8.5: Accountability Systems states:

"The incident commander shall initiate an accountability system that includes functional and geographical assignments

at the beginning of operations and that system shall be maintained throughout operations."

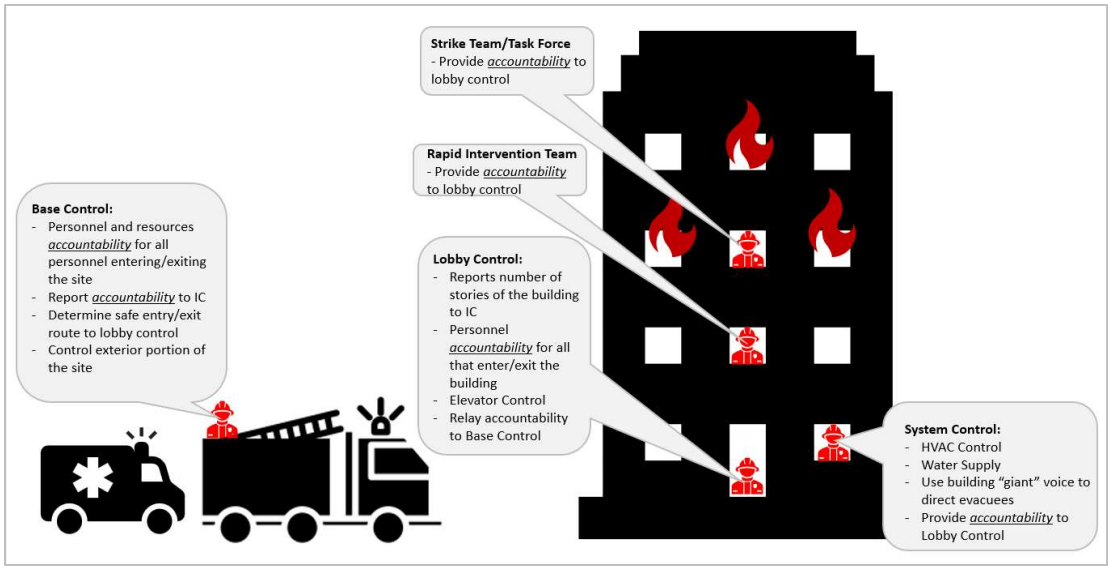


Figure 4: Displaying functional assignment for high-rise building incident and level of accountability.

The safety standards, the NFPA 1500 Section 8.5.10 also states:

"The fire department shall develop, implement, and utilize the system components required to make the personnel accountability system effective."

The NFPA 1561, Annex E, describes the process of high-rise response with an intention to assist the incident commander to identify, establish, and assign responsibilities for incidents in high-rise environment (see Figure 4). This Annex is not a requirement but is offered for informational purposes.

2.2.2. National standards on accountability resources or technology

The technology dimension is not covered in detail in the NFPA 1561, 1500, or 1221. This allows each organization to develop and implement technology-based accountability system that meets the minimum requirement stated in section 2.1.

The standards, per the NFPA 1561 Section 4.5.3, Resource Accountability states:

> "The system shall include a specific means to identify and keep track of responders entering and leaving hazardous areas, especially where special protective equipment is required."

Specifically, the communication chapter in the NFPA 1561, Chapter 6, provide descriptions on standards of "minimum" systems requirement for ICS. This chapter covers only voice/handheld radio communication requirement.

2.3. Current Operation at the City of Miami

The City of Miami has a standing Emergency Operation Manuals that are being use, not only to educate new recruits at the Fire Academy, but also serves as instructions to follow during an emergency response. The manuals cover many aspects of emergency operations and the information derived from national standards such as NFPA, FEMA, as well as best practices at the organization level. The manuals are organized by article where each article covers one aspect of the operation. Notable standards applicable for this research are Personnel Accountability Report (PAR) and PASSPORT Accountability Policy. These standards are being use and enforce during high-rise fire and rescue situations.

2.3.1. Personnel Accountability Report (PAR)

The emergency operation manual provides description and direction on accountability tools used to assist with completing the Personnel Accountability Report (PAR). This report is the process that assist the IC with personnel location identification and status of the strike team, task force, or company[14]. The IC initiates the PAR by doing "roll call" at a predetermine time or event. The IC establishes the interval of roll call and initiates the PAR as significant event occurs, also refers to as "Tactical Benchmark," by initiating radio communication. Each strike team or task force team leader are responsible to communicate over the handheld radio with the IC. The information transmits over the radio includes current location, and the status of all assigned members or a Location, Unit, Name, Air and Assignment, and Resource (LUNAR).

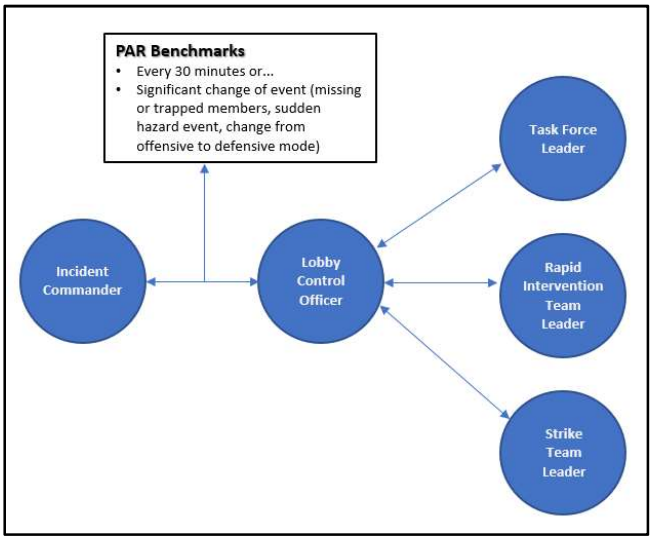


Figure 5: Communication flow during Personnel Accountability Report (PAR)

2.3.2. PASSPORT Accountability Policy

This policy is mandatory and uses to enforce the process to account for the location and safety of all personnel within a "hazard or hot zone" at emergency incidents. The system under this policy is describe as a procedure that utilizes passports and control boards to track the assignment of Sections, Branches, Divisions, Groups, Strike Teams, Task Forces, Companies, and individuals at an emergency incident[17].

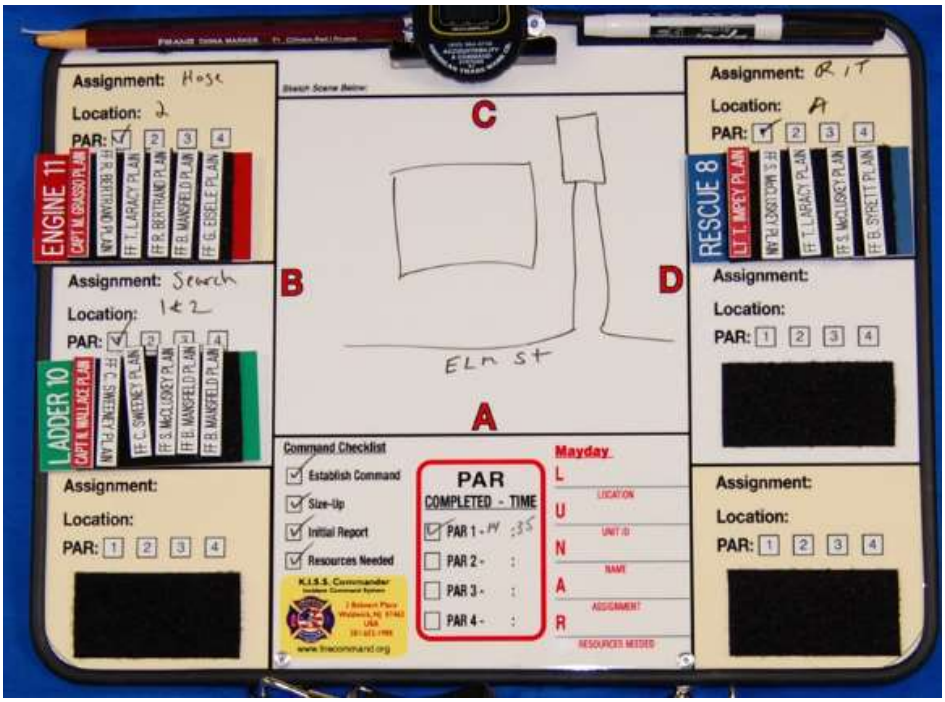


Figure 6: An example of PASSPORT system as part of the Incident Management System.

The PASSPORT system is used along with the PAR process under the Incident Management System to assist the IC with assignments and accountability at an emergency incident. In the high-rise situation, the lobby control officer will establish the PASSPORT system for the IC. The equipment to execute the PASSPORT system includes a 2" x 4" plastic card that contains identification of members and/or teams. An example of the PASSPORT system is shown in Figure 6.

2.4. Current City's Accountability Technology and Workarounds

The only "technology" being used during the accountability processes mention in previous sections is the digital portable radio, Motorola Astro XTS 5000 (see Figure 7). This radio's factory specifications include encryption capability and GPS enabled speaker microphones accessories. The City's radios do not come with GPS enabled speaker microphone. This is the same type of radio commonly used for law enforcement and military because of the ability to withstand extreme environment, encryption capability, and other advance performance specifications.

2.4.1. High-Rise structure communication workaround

Based on the feedback from firefighters from Fire Station 4, in the heart of the high-rise district, radio communications can be negatively affected when operating inside high-rise structures. A few alternatives had been used in the field to assist firefighters in situations where radio communication had failed.

- **Talk About:** To overcome this situation, they utilize the "Talk About" (TA) feature. The TA communications are strictly "radio to radio" and will not be heard by the dispatcher. The IC must monitor communications

through alarm office along with TA and other tactical channels. This method is time consuming and most inefficient. In the event of a "Mayday", emergency communication of trapped or lost firefighters, all other radio traffic must "step-down" to the next radio channel.

Figure 7: Motorola Model III, XTS 5000

- **In-house communication:** Units may carry a telephone headset to connect to communication ports available next to the elevator, at every floor. The communication ports will connect the fire floor to the lobby control directly. Additionally, some high-rise facilities have extensive building security systems that also have on-site radio signal repeaters for each floor. In-house communications are being considered to help reduce radio traffic on the main frequency but may not be the most suitable on certain extreme hazard situations.

- **Cellular phones:** Individual firefighter cellular phones had been utilized in the past and works well in certain situations. This method provides redundancy of communication when all other methods had failed.

CHAPTER 3: CONCEPTS

3.1. Understanding the requirement

Interviews were conducted to identify the requirements based on candidates' previous experience. Candidates were from the Fire Station in high-rise districts and City's Fire Academy; one Station Chief, two Fire Lieutenants. Fire station territory 1 (Downtown), 2 (Wynwood/Edgewater), 4 (Brickell), and 8 (Coconut Grove), they are all along the coast line and contain most of the high-rise facilities in the territory. In Figure 8, the graphic displays the alarm count for 911 calls from 2017; totaling 101,521 alarms for the entire City. The term "alarm" refers to the activation of the alarms at stations to initiate or activate a team in response to an incident provided by the 911 dispatch. Downtown, Wynwood, and Brickell show the highest alarm count due to the density of the population in the area and due to most structures are classified as high-rise structures.

The interview questions are specific to the type of communication devices use during an incident and the consistency of the PAR process during a response. The questions and answers are as followed:

1. Is PAR process being practiced for all incident response?

   Answer: All candidates agreed on the PAR process being practiced regularly, but the more common practice is 20 minutes interval between the PAR roll call, initiated by the IC.

2. Current device use to communicate between teams and IC?

   Answer: The standard communication device for the fire stations is Motorola XTS5000, ruggedized model.

3. What type of situation do you notice a lag in communication?

   Answer: The Candidates agreed on the difficulties of using the radio in high-rise areas. Although, there are other situations, even outdoors, where radio communication did not work.

4. Do you ever use personal cellular phones during incident response to relay information?

   Answer: All of them used personal device to relay messages when radio communication was reduced or stopped working. Also, most of the time, they used the headset connection to communication ports by the elevators. They have not use personal cellular phones during high heat and high hazard incident.

5. What do you think is the new requirement for improving communication, specifically during accountability process?

   Answer 1: One answer is on redundancy. They need some sort of redundancy system that can assist the IC or other entity to view their location on-the-fly. "The radio will never go away because we still need to communicate information via voice and provide detail information of our status, in addition to our location", said the Lieutenant from Station 4.

   Answer 2: The Station Chief and the Lieutenant from the Fire Academy like the idea of somehow allowing indoor tracking information to show via dashboard, but

there is a concern that the amount of additional equipment will be impractical. The need for the system to be light, easy to use, and if possible, can be switched on automatically would be ideal. Finally, they need to be able to tell the location of personnel between the floors. The desire level of horizontal and vertical accuracy is less than 10 feet; based on average size of a room in an apartment or an office.

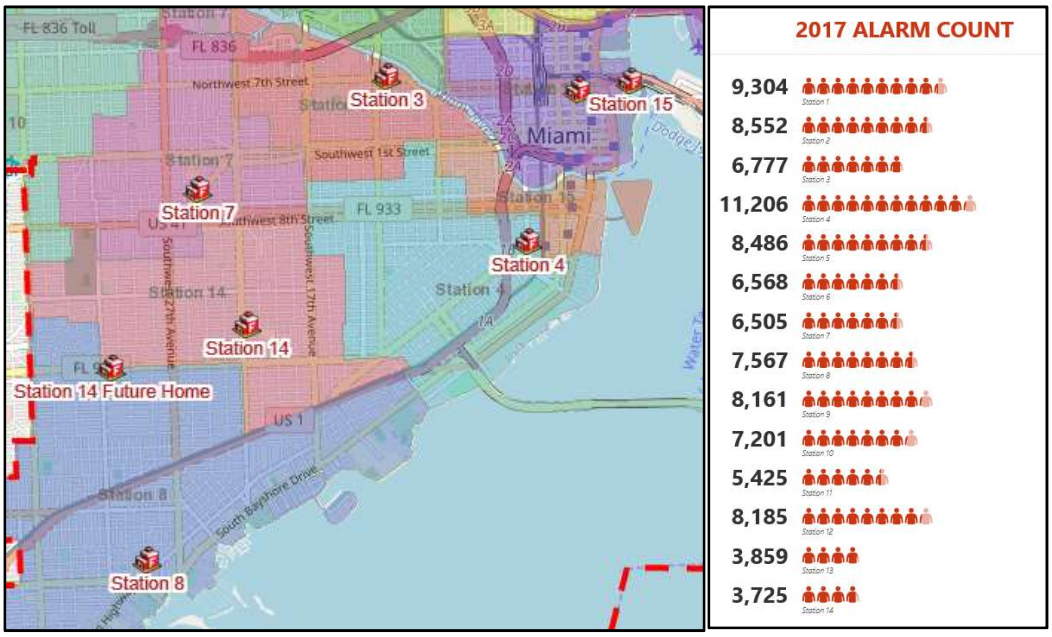


Figure 8: Map of the City of Miami and 2017 Alarm count by station

3.1.1. Summary of the requirement

The interview questions are simple but the answers they provided are crucial to narrow down suitable technology for the requirement. Based on the interviews, it is confirmed that they don't need to replace their current system and process but to

"enhance" with and up-to-date technology. This additional technology needs to include:

1. Redundancy system that pinpoint location indoors
2. Horizontal and vertical accuracy less than 10 feet
3. Lightweight solution
4. Activate automatically or easy to initiate and operate

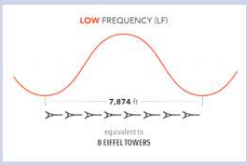
These requirements will be used later in the research to evaluate the suitability of a few types of technology discussed in the next section.

3.2. Understanding of Potential Technology

There are many technologies exist today that claim to provide real-time location services with varying accuracy levels. A few of the technologies have shown capability of higher accuracy with increase range and even required less existing infrastructure to obtain the accuracy. Considering notable capacity for this research are wearable RFID tag tracking and BLE beacons.

3.1.1. Wearable RFID Tag

RFID tag is a memory device that is portable and can be embedded in any object or a protective shell. Each tag contains small circuit chip with antenna enabled it to receive and respond to radio frequency from a reader[23]. The tag can be active or passive tags. The passive type does not require power source and can be powered by the magnetic field originate by the reader device. Passive tags can have unlimited lifetime. It is important to note that RFID ranges depends on the type of frequency and perform differently depending on the range (see Figure 9).

Frequency Type	Frequency Range	Specifications
	30 kHz – 300 kHz	Pet tagging and access control Cost: $0.70 - $20 Read Range: Short (touching)
	3 MHz– 30 MHz	Access control, payment app, ticketing app, passport Cost: $0.35 - $10 Read Range: few centimeters to a meter
	300 MHz – 3 GHz	(Passive UHF RFID) Asset tracking, race timing, Tag Cost: $0.10 - $10 Reader Cost: $450 - $2,500 Read Range: 2-5 meters (Active UHF RFID) Tag Cost: $20+ Read Range: +100 meters

Frequency Image credit: www.atladRFIDstore.com

Figure 9: RFID frequency type and specification. Data derived from Atlas RFID store[24].

To implement, this technology requires a dedicated device to read and transmit the tag data back to the system. Additional equipment will be required to be installed at strategic points throughout the structure or designated "point-of-interest" as fixed infrastructure.

3.1.2. BLE Beacons

This technology is a class of Bluetooth technology that enabled portability and long battery life. As mention in Key Terms section, Bluetooth is a wireless technology that uses short-range radio frequency (RF) to connect between mobile electronic devices. This term is also referred to as Bluetooth Basic Rate/Enhanced

Data Rate (BR/EDR). The signals are operating in the unlicensed industrial, scientific, and medical (ISM) band at 2.4GHz; transmitting with frequency hopping approach over 79 channels. This technology is intended to replace cable connections and synchronized data between devices as a point-to-point network topology[19] for streaming optimization.

BLE was first introduced in 2010 with version 4.0 and has become the most popular technology for low-power and short range wireless[26]. Traditional Bluetooth operate under only point-to-point topology. BLE can operate under different types of topology given the flexibility to expand with other form of technology. Bluetooth Special Interest Group explain the types of topology[30] as followed:

3.1.2.1. Topology types

Point-to-point topology: This type of network has one-to-one (1:1) communication relationship; meaning the data travel between two nodes. This is best use to stream audio or device that requires higher rate of data transfer.

Broadcast topology: This type of network is a one-to-many (1:m) communication relationship. This means data from node-A can communicate with node-B, node-C, node-D, and so on. This type of network is optimized for information sharing and ideal for location services such as wayfinding and indoor navigation.

Mesh topology: This type of network is a many-to-many (m:m) communication relationship. This creates large-scaled network that is

common for monitoring large number of devices in a space and can be linked to multiple spaces to create larger mesh environment.

3.1.2.2. Ranges of BLE Beacon

Maximum range of transmission depends on the location and obstruction in the device's environment[31]. Standard beacons have an approximate range of 70 meters. Long range beacons can transmit up to 300 meters. The power used to transmit signal determines the range of the signal. Different brand of BLE beacons will vary in range due to differences in hardware and power source. Transmission distances directly affect the accuracy of the beacon position. For example, the position categorized as "Intermediate" (a few centimeters apart), the position reading will be more accurate. In contrast, if the position is considered "Far" (15-20 meters), the accuracy of that position will be significantly less. There are two well known beacon protocols: iBeacon and Eddystone.

3.1.2.2.1. iBeacon: This is a beacon protocol developed by Apple and was introduced at the Apple Worldwide Developers Conference in 2013. There are many brands of devices that uses iBeacon protocol. A few known brands are Estimote, RedBear, Sensor Tag, Gilworm, and many more. Ranging from 0.15m to 300m depending on hardware transmission power and obstacles[32].

3.1.2.2.2. Eddystone: This is a beacon protocol developed by Google and it is an open format. Similar to iBeacon, there are numerous hardware manufacturer that supports Eddystone protocol. A few known brands are Estimote, Nordic, Leantegra, and many more. Many hardware manufacturers can support both protocols; hence the signal range are comparable to iBeacon with ranging from 0.15m to 300m.

3.3. Perfect Candidate: BLE Beacon

Based on capabilities of the two potential technology mentioned in this section, broadcasting and mesh topology options are the most correlated to this research objectives. Although RFID tag has potential for indoor tracking and mapping, infrastructure to provide fixed location is required for the location service concept to work. There are multiple research and development concepts of using BLE to communicate with mobile phones for indoor mapping purposes.

3.3.1. Ideal solution

To translate the requirement received from the firefighters, Figure 10 demonstrate the desire communication flow between mobile phone and BLE beacons. The ideal solution is using BLE beacons, not as existing indoors fixed infrastructure, but roaming as a wearable tag that can be attached on equipment or clothing. Typical modern mobile phone is equipped with sensors such as gyroscope that monitors the motion of a device, gravity sensors that measures barometric pressures, and geomagnetic sensors to measure Earth's magnetic field for absolute reference and

heading. Theoretically, these sensors should be able to enable the mobile phone to function as a reference location to BLE beacons as well as broadcast information using cellular services.

Thesis research limitation: The next section, 3.3.2. Research Review, will cover experimental research performed by other institution and researchers. Due to time constraint and limited resources, original research cannot be performed for this thesis. Therefore, the next section serves as additional literature review; not this thesis original work. The purpose is to share the knowledge of their discovery.

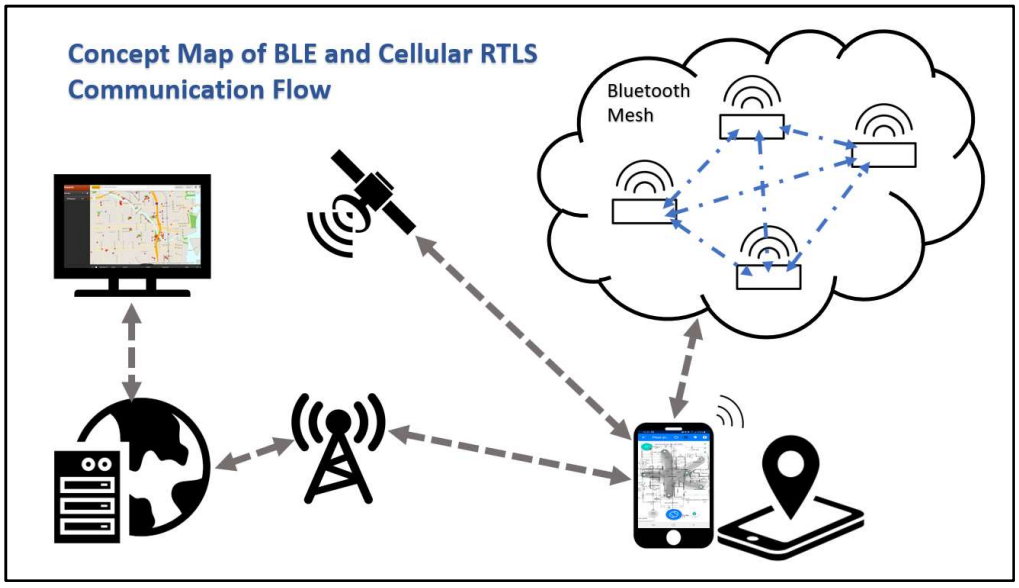


Figure 10: Concept Map of BLE and Cellular RTLS

3.3.2. Research Review

Research completed by Chen et al, covers the development of an application that can collect and calculate location data by using modern smartphone's existing

sensors. This application called LocBLE uses Received Signal Strength (RSS) readings of smartphones and BLE beacons to calculate locations. Limitations are identified by the research with their proposed solutions to help mitigate the challenges based on identified limitation.

3.3.2.1. Current Technology Limitations

Smartphones and BLE beacons are the best candidate to meet the requirement stated in the previous section. There are known limitation from off-the-shelve devices that has beacon protocol such as iBeacon and Eddystone. The research for LocBLE identified BLE beacon's limitation as well as signal reliability suffered from both smartphone and BLE beacon[25].

3.3.2.1.1. Limited transmission power of BLE beacons: Previous versions of v4.0, v4.1, and v4.2 are strong limitation due to level of power able to transmit over long distance. With the new release of v5.1 in January, this limitation should decrease significantly; hence the release of enhancement news by Bluetooth SIG of "Enhancing Bluetooth Location Services with Direction Finding."

3.3.2.1.2. Narrow bandwidth and frequency hopping of BLE beacons: This limitation is due to frequency band sharing of Wi-Fi and other RF signals at 2.4GHz. This sharing of bandwidth may cause the signal more vulnerable to signal fading[33].

3.3.2.1.3. Connectivity of BLE beacons: Connectable and non-connectable are types of BLE beacons which dictates the amount of power consume during

advertisement or discovery. Connectable BLE beacons can receive pairing requests which required more energy. Non-connectable BLE beacons are in broadcasting mode and uses less energy.

3.3.2.1.4. RF signal fading: Radio Frequency signals is known to be problematic in closed space such as interior of the building due to an effect called multipath. This effect causes the signal to bounce off other objects and delay transmission or eventually lost or fade.

3.3.2.1.5. RSS noise: This refers to some hardware configurations and existing RSS fluctuations of the smartphone Bluetooth receiver. This is predictable due to the type of hardware performance and can be corrected if the baseline of the error is known for that smartphone model.

3.3.2.2. Overview LocBLE application and solutions to limitations

This application was presented by Chen et al. at the CoNEXT event in 2017. The application is designed to improve beacon-based proximity from coarse-grained distance estimation to fined-grained by formulate algorithms to solve some of the challenges surrounding the technology. The featured uses-cases for this application is finding lost item such as a wallet, as they mentioned in the example.

The findings in this application is of interest to this research because of the possibility of using this enhancement as the proof of concept to the identify the location of lost or unconscious firefighter. With an understanding that people are

highly mobile and not static like the missing wallet but the same concept applies to unconscious personnel.

The application is a three-layer system architecture consist of Data Collection Layer, Location Estimation Layer, and Calibration Layer. Each layer and associated calculations are explained in detail in their research[25]. The architecture for the three layers is depicted in Figure 11.

3.3.2.2.1. Data Collection Layer

The first step of any data analysis is data collection. This layer focus on sensory data of motion sensor, magnetometer, and BLE scanner. Collected information will be used in the layer to calculate and correct any signal noise or any signal fluctuations.

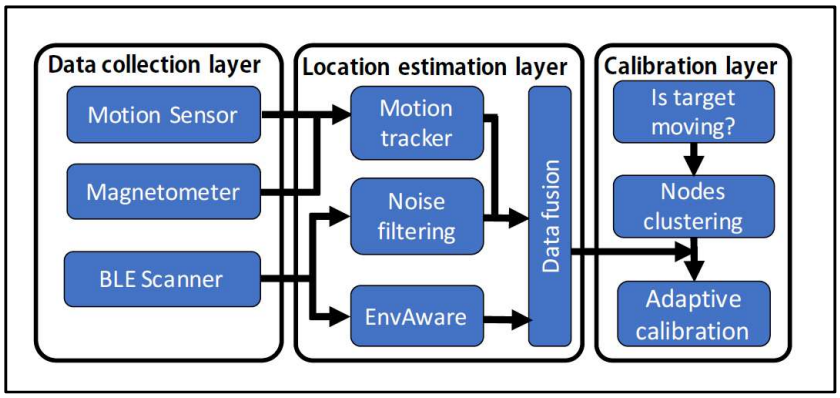


Figure 11: System architecture of LocBLE[25]

3.3.2.2.2. Location Estimation Layer

There are three major goals for this layer. The first goal is to reduce the distortion of the RSS readings for accurate location calculation. To achieve

this, they used environmental estimation model called EnvAware, using Support Vector Machine (SVM) algorithm, specifically SVM with linear kernel as classifier[25], to calculate and recognize environmental changes. This algorithm is a supervised machine learning which can be used for both classification or regression challenges[34]. The EnvAware process will ensure the application will use the correct regression model for estimation calculation.

The second goal is to prepare the data for the next calculation by filtering out RSS noise that occurred during data collection from BLE scanner. The filtering process is called Adaptive Noise Filtering (ANF) which the raw RSS data goes through ANF for smoother readings. They used two noise filtering techniques called fine-tuned Butterworth filter (BF) and Adaptive Kalman filter (AKF). The Butterworth filter is used to remove the effect of rapid fading caused by environmental changes with rapid device movements. The Adaptive Kalman filter is used to smooth fluctuating RSS data. Figure 12 illustrate the performance of Butterworth and Adaptive Kalman filters.

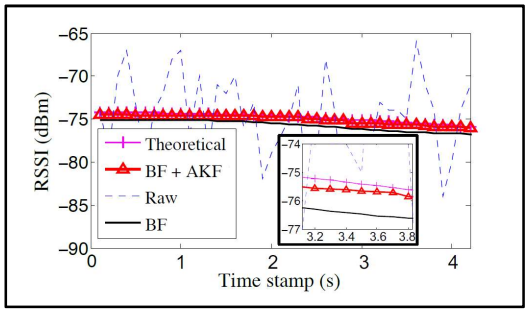


Figure 12: Performance of BF and AKF[25]

Third goal is to perform location estimation by using regression-based data fusion of RSS data and motion sensor data. This section determines the step and direction of the observers (smartphones) and the targets (BLE beacons) then matches the movement with RSS data based on timestamp of result dataset from EnvAware and ANF process. The application, LocBLE, uses the regression calculation to append another EnvAware and ANF dataset if the environment remains unchanged or start new regression with the data if environment changes.

3.3.2.2.3. Calibration Layer

This layer will determine if the neighboring beacons are close enough to form a cluster to improve overall accuracy. If the cluster can be formed, clustering correction techniques is used to calibrate target (BLE beacon) positioning.

3.3.2.3. Performance and results

Focusing on the last layer of LocBLE, an experiment was performed in two environments, a lab (open space) and a hallway (higher multipath). The results from Figure 13, showed clustering calibration had reduce estimation error with higher number of beacons. This is a promising find for this research as the personnel are expected to cluster as team configuration.

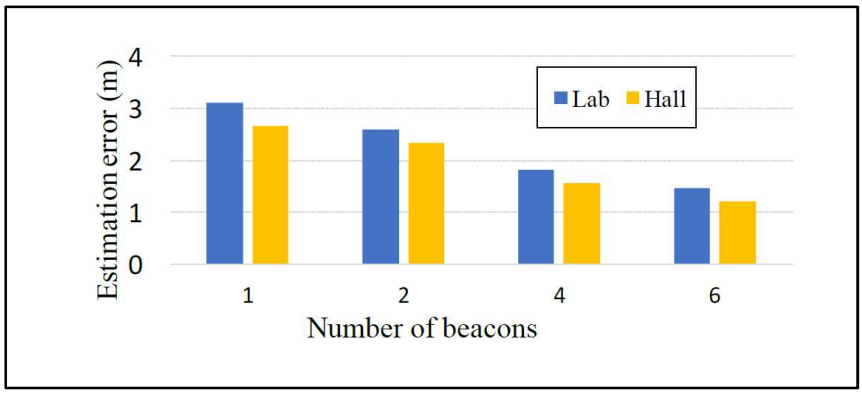


Figure 13: Calibration performance in two environments[25]

The accuracy of LocBLE with clustering calibration can achieve location accuracy of 1.8m for indoor and 1.2m for outdoors. There are some pros and cons with this application, relating to the objective of this thesis.

Pros:

- Corrected location accuracy meets the expected accuracy listed in the requirement. Usable accuracy provided by the Fire Department is less than 10 feet/3.048m. The corrected accuracy of LocBLE is 1.8m for indoors, exceeding the expectation.
- The application does not require pre-installation of the system inside the building structure to work.
- The application does not require any off-the-shelf market BLE beacon hardware modification or smartphone operating system modification.

- This application can be used as a baseline knowledge for future project requirement development with other location service firm whom can provide their own proprietary application.

Cons:

- The application only demonstrated 2-D capability. Real world high-rise environment will require 3-D data collection and calibration. Although, 3-D localization is listed as future work.
- The application is lack of mapping interface and not intuitive.
- The application is not an off-the-shelf application which will require customized work to create proper user interface.

CHAPTER 4: SUMMARY AND CONCLUSION

4.1. Answering the Research Questions

In Section 1.2, there are four questions to guide the focus of this research.

4.1.1. What is the accountability standard and associated technology requirement for fire-rescue at the national level?

This question aims to guide the identification process of current accountability standard and associated technology requirement for fire and rescue at the national level. The details to the answer of this question can be found in Section 2.1. In summary, there are two main national standard literature that defines the "minimum" requirement for safety and incident management system; the NFPA 1500 and 1561. The national standards do not provide specifics on the required technology for accountability other than radio communication; no brand specific or direction on specifications. The national standard sets the baseline for establishment of Incident Command System which include guidelines and recommendation on accountability process. Additionally, the national standards provide supplementary guidelines, the NFPA 1561 Annex E, for high-rise situations. This Annex is not part of the requirement, but it is provided as informational purposes to help define additional roles and responsivity required to operate in high-rise situations[22].

4.1.2. What is the current process of accountability and technology used for fire-rescue emergencies at the City of Miami?

This question is to help guide the identification process of current accountability process and recommend any technology used to support accountability process by fire and rescue units. In summary, the City of Miami has operating manual called Emergency Operations Manual. It serves as a policy and detailed process on Incident Command System as well as other process related to firefighting operations. The City does have an accountability process in place called PAR. Related to PAR is the accountability tool identified as the PASSPORT accountability system. This tool meets the NFPA minimum requirement. It is the most basic form of accountability process. The PASSPORT accountability system mentions in the manual consist of a mobile kit of annotated dry-erased board and Velcro name tags.

4.1.3. What are the requirements for indoor positioning based on the City of Miami Fire Department's feedback?

This question is to help guide the identification process of technology requirements or parameters and minimum accuracy, by using human-centered approach through interviews. In summary, three candidates provided in-person interview based on pre-determine set of questions. Questions and answers from the interviews are listed in Section 3.1. Consensus were made on requirements of desire technology for accountability; serves as redundancy system, provide

accuracy of 10 feet or better for indoor settings, lightweight, and easy to initiate or operate.

4.1.4. What is the existing technology that can meet the City's requirement and can be used for accountability tracking for indoors and high-rise facilities?

This question is to obtain identification process of suitable RTLS technology that can improve accountability process in high-rise situations. In summary, there are multiple location services technology that offer real-time tracking for indoors. Unfortunately, most of the technology available on the market required staging of beacons or other RF devices such as Wi-Fi, BLE, or Z-Wave, or Zigbee to provide fixed position location for higher accuracy. One particular research by Chen et al, presented at a Conference on Emerging Networking Experiments and Technology in 2017, can provide the fundamental needs of using mobile devices such as smartphone to track and transmit data to other less expensive beacon devices such as BLE beacon.

The application presented in this research does not meet some of the requirement needed for this thesis. The application didn't provide information on 3-D localization, only tested for 2-D datasets. The elevation data is vital for the purpose of this research due to the challenges in keeping accountability in high-rise environment.

4.2. Conclusion

The objective of this research is to find existing location-based technology solution for indoor use that will meet the required needs defined by the City of Miami Fire Department and can support high-rise environment. Three out of four research questions received answers favorable to meeting the thesis objectives. The final research question aimed to find suitable technology for the requirements provided by the Fire Department and prove the hypothesis statement.

The technology found during this research has proven that the hypothesis statement is partially true. The application, LocBLE, developed by Chen et al, provide tested solution that the indoor location-based services can be achieved by using smartphones to detect location data without the expenses of installing fixed infrastructure. However, relaying of information between observing devices (smartphones) and target devices (BLE beacons) to other observing devices (internet) as a network still need additional research.

Due to time constraint, this portion of the hypothesis does not have enough information to provide solution with high confidence that such application or system is available. At this time, there is not enough evidence that the off-the-shelve solutions available. Enhancements on smartphone sensors technology will need to be integrated with the BLE beacon to meet the ideal solution. Going forward, a follow-on effort of research is required to continue to find solution for 3-D location finding and reporting technology without existing fixed infrastructure.

4.3.2. Future research considerations

Some considerations and understanding of additional terminology and concepts are required before moving on to the next phase of the research. This will help determine the relevance of research direction.

4.3.2.1. Absolute and Relative Location

An absolute location is a fixed point on the earth's surface. It is described by location identification value of Latitude and Longitude in World Geodetic System (WGS). Whereas, a relative location refers to a location that uses another location as a reference[35]. Relative location is common in land navigation by using a landmark as a control starting point to traverse to another point using distance and angles. Going forward, this research will need to consider the importance of relative and absolute location based on overall requirement. An absolute location may not be relevant to this research if relative location can provide the needed solution.

4.3.2.2. Location vs. Communication Problems

During the process of completing research, additional discussion point arises and must be focus on in the future research. Is this thesis a location problem or is it a communication problem? Will an integration of location finding solve the communication problem too? Is there something that can be integrated to existing communication system, if it is a communication problem? Do they want lost communication problem solved or do they want

to know where they are? These are logical questions that will need to be revisit during future research.

4.3.2.3. Security vs. Privacy

As the technology improves and becomes more transparent, cyber security becomes a major concern. The security aspect will need to be incorporated into the solution to ensured data is only available to the need-to-know party. With the release of Bluetooth 5.1, future generations of the Bluetooth enabled devices with this version will be able to pinpoint your location by the radius distance but not direction. Should this raise additional concerns? More search will be required to improve understanding on the implication of this technological improvement.

4.3.2.4. FirstNet Technology

This technology is intended for first responders' usages during larger scale emergency incidents. The technology will allow first responders to gain priority access to communication channels during major incidents. This is a mission critical capability provided through a partnership with private communication providers such as AT&T and Verizon[36]. This is a useful reference and resources for future research.

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BIOGRAPHY

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