An Integrated Assistive System to Support Wayfinding and Situation Awareness for People with Vision Impairment

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Dedication

I dedicate this dissertation to my loving family, especially …

To my wife for her unwavering support, love, understanding, and encouragement over the years;

To my children for their patience and understanding; and

To my loving parents for being understanding and supportive of my decisions in life.

Abstract

People with vision impairment usually use a white cane as their primary tool for wayfinding and obstacle detection. Environmental cues, though not always reliable, are used to support the decision making of the visually impaired at various levels of navigation and situation awareness. Due to differences in spatial perception as compared to sighted people, they often encounter physical as well as information barriers along a trip. In order to improve their mobility, accessibility and level of confidence in using our transportation system, it is important to remove not only the physical barriers but also the information barriers that could potentially impede their mobility and undermine safety.

Many assistive systems have been developed in the past for visually impaired users to navigate and find their way. However, most of these systems were not adopted by users mostly due to the inconvenience of using such systems. In this research, we developed a mobile accessible information system that allows people with vision impairment to receive transportation information at key locations where decision making is necessary.

A smartphone-based personal assistive system, called MAPS (Mobile Accessible Pedestrian System), was developed to provide intersection geometry and signal timing information, not available from other apps in the market for people with vision impairment. In addition, the MAPS incorporates a geospatial database with Bluetooth beacon information that allows the MAPS to provide navigation assistance, situation awareness, and wayfinding to users even when a GPS solution is not available. The

MAPS app communicates with the traffic signal controller through a secured wireless link to obtain real-time Signal Phasing and Timing (SPaT) information, which together then inform visually impaired pedestrians with their current locations and when to cross streets.

A self-monitoring infrastructure using a network of Bluetooth Low Energy (BLE) beacons was developed to ensure the information integrity of the network.

The key contributions of this dissertation include the development of:

- A smartphone-based navigation and decision support system that incorporates intersection geometry and traffic signal information for people with vision impairment,
- A simple user's interface (using a single or double-tap on a smartphone screen) that is easy for the visually impaired to learn and use,
- Standardized message elements for an audible work zone bypass routing information system,
- A self-monitoring infrastructure using a network of commercial off-the-shelf (COTS) low-cost BLE beacons, (including customized firmware allowing BLE beacons to monitor each other),
- A crowdsourcing approach using users' smartphones to monitor the status of BLE beacons and update messages associated with beacons,

- A cloud-based geospatial database to support navigation by incorporating BLE beacon localization information when a GPS solution is not available,
- A Singular Value Decomposition (SVD) based Multivariable Regression (MR) algorithm together with an Extended Kalman Filter (EKF) technique using beacon localization to provide a positioning solution by the smartphone even if a GPS solution is unavailable, and
- Statistical methodologies and wireless signal fingerprinting techniques to monitor BLE beacons in a network in order to determine when a beacon is moved, removed or disappears.

The intent of the MAPS is not to undermine the maintenance of skills and strategies that people with vision impairment have learned for navigation and wayfinding. Instead, the system aims to support their wayfinding capability, extend mobility and accessibility, and improve safety for the blind and visually impaired. This self-monitoring infrastructure ensures that correct information is provided to users at the right location when needed. This thesis also introduces the idea of using the same system to warn sighted pedestrians about approaching an intersection when they are distracted by looking at their smartphone.

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CHAPTER 1 INTRODUCTION

People with vision impairment usually travel on foot or use public transit as their primary mode of transportation to attend to their daily activities. Due to differences in spatial perception as compared to sighted people, they usually encounter physical and information barriers that limit their transportation accessibility and mobility.

Many technological approaches using Inertial Navigation Systems (INS), Global Positioning Systems (GPS), or machine vision sensing for localization of the pedestrian have been studied in the literature. Many prototype systems have been developed for assisting with the navigation of people with vision impairment (more details in the literature review in Chapter 2). However, most of these systems were not adopted by visually impaired users due to the fact that it was often inconvenient to carry or wear such systems while traveling. Today, a white cane is still the primary mobility tool used by most people who are blind or visually impaired to navigate unfamiliar environments.

With the advance of mobile computing, Internet of Things (IoT)[1], Information and Communication Technologies (ICT), and the growing ownership of smartphone devices, many smartphone apps have been developed to improve the quality of our life. Many of these apps integrate GPS, the digital compass, the camera, and other motion sensors already embedded on smartphones to support pedestrian navigation and wayfinding. However, none of these smartphone apps provide traffic signal information, such as

[1] The Internet of Things (IoT) is the network of physical objects—devices, vehicles, buildings and other items embedded with electronics, software, sensors, and network connectivity—that enables these objects to collect and exchange data (from https://en.wikipedia.org/wiki/Internet_of_Things)

signal phasing and timing at intersections or with bypassing information at work zones, for people who are blind or visually impaired while traveling in a transportation network.

The GPS receiver has been broadly used as one of the primary navigation sensors for providing a positioning solution. In general, the positioning accuracy of the GPS receiver on a smartphone ranges from a few meters to several decameters depending on hardware, the environment, the satellite constellation and many other factors. Modern smartphone devices also take advantage of the Assisted-GPS (A-GPS) signal to improve startup positioning performance when the knowledge of location of nearby Wi-Fi stations or nearby cellular towers is available. The accuracy of a GPS based solution can be further improved if it receives Wide Area Augmentation System (WAAS) corrections or uses additional hardware, such as a differential GPS (DGPS) receiver, for acquiring positioning corrections. However, the GPS positioning solution is not reliable in GPS unfriendly environments (for example, subway stations, indoors, or an area with skyscraper canyons) to support pedestrian navigation.

1.1 Motivation

According to an estimate from the World Health Organization (WHO) published in 2014, there are over 285 million people in the world with vision impairment and 39 million of them are blind. Age-related eye diseases affect more than 35 million Americans age 40 and older (Blackwell et al., 2014). There are approximately 2 million adults with reported vision loss in the United States (Bell & Mino, 2013).

Blind people's perception of the environment is different from the spatial cognition of sighted people. With the limited visual feedback available to them, unsighted people primarily rely on auditory, olfactory, or tactile feedback to determine their location with respective to their immediate environment. Due to the lower fidelity of information from their other non-visual sensory systems, updates of location with respect to their immediate environment are less frequent to blind people as compared to sighted individuals. In particular, when blind pedestrians travel in less familiar areas, movement and information barriers create additional challenges for them to find their way and further limit their accessibility and mobility. Therefore, providing information to the blind that make them aware of where they are with respect to the surrounding environment at key decision-making locations becomes essential.

For example, an intersection crossing may be the most dangerous part of wayfinding through unfamiliar environments. The act of crossing the street involves the demanding tasks of iteratively adjusting orientation and timing while using a variable set of stimuli (i.e., moving vehicles), where minor mistakes can lead to fatal consequences (Gaunet & Briffault, 2005). The street crossing tasks for unsighted pedestrians involve; (1) locating the edge of street, (2) locating the crosswalk, (3) aligning toward the crosswalk, (4) locating the pushbutton if there is one, (5) discerning when to cross, and (6) maintaining alignment to the crosswalk while crossing an intersection. Locating the sidewalk and the pushbutton associated with a desired crossing direction, and maintaining alignment during crossing are among the most difficult tasks for blind pedestrians to cross a street (Bentzen et al., 2000). In addition, using the pushbutton, crossing straight across the street, and determining when to begin crossing are the most important causes of difficulties (Bentzen et al., 2000).

Although, there has been much research in wayfinding for the blind using various types of technologies, there is a need to investigate how environmental, directional, traffic signal, and safety information can be reliably provided to pedestrians with vision impairment, and to understand the impact of spatial learning and cognition load that influence their decision-making strategy for navigation and wayfinding.

1.2 Problem Statement

Many cities in the US have installed Audible or Accessible Pedestrian Signals (APS) beacons at selected intersections to make intersection crossing more accessible for the visually impaired. The APS provides signal and street information at an intersection. It was not included in the U.S. standards and regulations (Manual on Uniform Traffic Control Beacons, MUTCD) until 2000.

A blind pedestrian is required to locate and push the walk button by listening to a separate audible cue at the intersection. There is inconsistency in type and placement of pushbuttons at different signalized intersections. The audible messages are often confused with noise in the vicinity and heavy rush hour traffic (Schworn, 2009). The usability of the APS system becomes even more limited when information cannot be heard or is unclear.

Currently, the number of installed APS system is limited to select intersections due to limited resources available to public agencies. The hardware costs about $3,600 per intersection. The estimated life cycle or replacement rate for existing pedestrian signals is 25 years[2]. In northern climates where temperature fluctuations are significant, maintenance costs can be high and often times the APS are not repaired in a timely fashion. There is a need to provide a network-wide solution to improve the mobility and safety for people with vision impairment.

To assist wayfinding for the visually impaired, the satellite based positioning and navigation solution is not always reliable in GPS-denied environments. There is a need to reliably identify a traveler's location when he or she arrives at a decision point, such as an intersection, bus stop, etc. In addition, it is essential to ensure that traffic information provided to the travelers is reliable and accurate.

This dissertation aims to investigate an assistive wayfinding solution that integrates embedded computing technology on modern smartphones and the latest Bluetooth low energy technology to provide reliable traveler information and support situation awareness for people with vision impairment while traveling in a transportation network.

1.3 Objectives

The objectives of this dissertation are to, (1) understand the needs from the visually

[2] The US Access Board (2011), https://www.access-board.gov/guidelines-and-standards/streets-sidewalks/public-rights-of-way/background/regulatory-assessment/accessible-pedestrian-signals-and-pedestrian-pushbuttons

impaired community regarding transportation accessibility and mobility, (2) design and develop a personal assistive system, namely, the Mobile Accessible Pedestrian System (MAPS), to assist blind pedestrians while wayfinding by providing additional traffic and infrastructure information through the integration of embedded sensing, computing and wireless technologies; and (3) develop a positioning and mapping algorithm based on the Received Signal Strength Indication (RSSI) from the BLE beacons to create a self-monitoring infrastructure. The purpose of a self-monitoring infrastructure is to ensure that correct audible information is provided to users at the right location. A geospatial database that contains the location and corresponding message of each BLE beacon is integrated with the smartphone app to provide situation awareness and corresponding navigation information to assist wayfinding for people with vision impairment.

Furthermore, the following research goals are investigated:

1. A “self-aware” BLE network to monitor the location and status of other BLE beacons and alert the system manager when the location of a BLE beacon is changed.
2. A Statistical Process Control (SPC) technique to monitor BLE modules and detect failure or location changes of BLE beacons in a BLE network.

1.4 Significance of Research

The unique contributions of this dissertation include the development of:

- A smartphone-based navigation and decision support system that incorporates intersection geometry and traffic signal information for people with vision impairment,
- A simple user's interface (using a single or double-tap on a smartphone screen) that is easy for the visually impaired to learn and use,
- Development of standardized message elements for an audible work zone bypass routing information system,
- A self-monitoring infrastructure using commercial off-the-shelf (COTS) BLE beacons, (including customized firmware allowing BLE beacons to monitor each other),
- A crowdsourcing approach using users' smartphones to monitor the status of BLE beacons and update messages associated with beacons,
- A cloud-based geospatial database to support navigation by incorporating BLE beacon localization information when a GPS solution is not available,
- A Singular Value Decomposition (SVD) based Multivariable Regression (MR) approach together with an Extended Kalman Filter (EKF) technique to provide a positioning solution,
- Statistical methodologies and wireless signal fingerprinting techniques to monitor BLE beacons in a network when a beacon is moved, removed or disappears, and
- An architecture for distributed low-power low-cost BLE network and database server and crowd-sourcing methodology using users' smartphones.

The Mobile Accessible Pedestrian System (MAPS) was developed to provide navigation and signal information to the visually impaired. The MAPS is a personal system based on a smartphone carried by the user as compared to the existing infrastructure-based APS system installed at an intersection. The MAPS system integrates information from sensors commonly available on a smartphone, and then wirelessly communicates with the traffic signal controller in order to obtain real-time Signal Phasing and Timing (SPaT) information, which together then informs the blind pedestrians where they are and when to cross streets. An automated '*pedestrian call*' request (i.e., a signal sent to the intersection traffic controller when a pedestrian presses a pushbutton) can be sent to a traffic controller wirelessly from a smartphone of registered blind users after confirming the direction and orientation that the pedestrian intends to cross. The MAPS eliminates the need of physically locating and pressing a pushbutton near a crosswalk and provides intersection geometry information, such as street name, number of lanes, signal types, to the blind at intersection crossing. The smartphone app provides an auditory or vibrotactile warning message to pedestrians when the walk sign is ON and when the walking time has about 5 seconds left.

Traffic signal phasing and timing information is specific to the location and orientation of a pedestrian at an intersection. In an urban canyon or a GPS-denied environment, the GPS positioning solution is not sufficiently reliable to identify which side of a street or which corner of an intersection a pedestrian is located. A low-cost positioning and mapping method was developed to complement GPS solution using the Bluetooth technology.

The latest Bluetooth Low Energy (BLE) technology, also known as Bluetooth Smart, was developed as one element of the Internet of Things (IoT) with a very low energy consumption rate (for example, the BLE112[3] module from BlueGiga draws a peak current of 27 mA in transmit mode and consumes only 0.4uA in sleep mode). The Received Signal Strength Indication (RSSI) from a BLE beacon is used to estimate the proximity of the Bluetooth sensor.

For position and mapping, a Multivariable Regression (MR) model was developed to model the range and Bluetooth Received Signal Strength Indication (RSSI) relationships among BLE tags. The objective of the MR model is to model the geometric relationship of a BLE network. A Singular Value Decomposition (SVD) technique was introduced to remove RSSI range noise and estimate ranges among BLE tags. In addition, an Extended Kalman Filter (EKF) was formulated to determine the position of a user's smartphone. The EKF uses the MR and SVD combined model to find the range estimates from a smartphone to BLE beacons. The ranges estimates are then used to determine the location of the smartphone with respect to a local coordinate system of a BLE network.

For self-monitoring, a Statistical Process Control (SPC) technique, called Cumulative Sum (CUSUM), was developed to monitor if the location of one or multiple BLE beacons in a network is changed based on Bluetooth RSSI measurements. In addition, two wireless signal fingerprinting techniques, based on the Jaccard and Normalized Weighted Signal Level Change (NWSLC) indices, are introduced to detect geometry

[3] https://www.bluegiga.com/en-US/products/ble112-bluetooth-smart-module/

changes of a BLE network.

The mapping method and the SPC technique allow us to create a "*condition-aware*" local map of an environment that might be unfamiliar or hazardous to the visually impaired. A geospatial database (as shown on the right of Figure 1-1) that contains the location and corresponding message associated with each BLE beacon was also developed to support the smartphone app (as shown on the left of Figure 1-1) and provide situation awareness and corresponding navigation information to assist wayfinding for the visually impaired. The computation associated with the self-monitoring infrastructure takes place on the database server when new Bluetooth signal updates become available. The MAPS app integrates the street crossing and work zone bypassing information. The positioning solution using MR+SVD and EKF methods is computed on the Smartphone as illustrated in Figure 1-1.

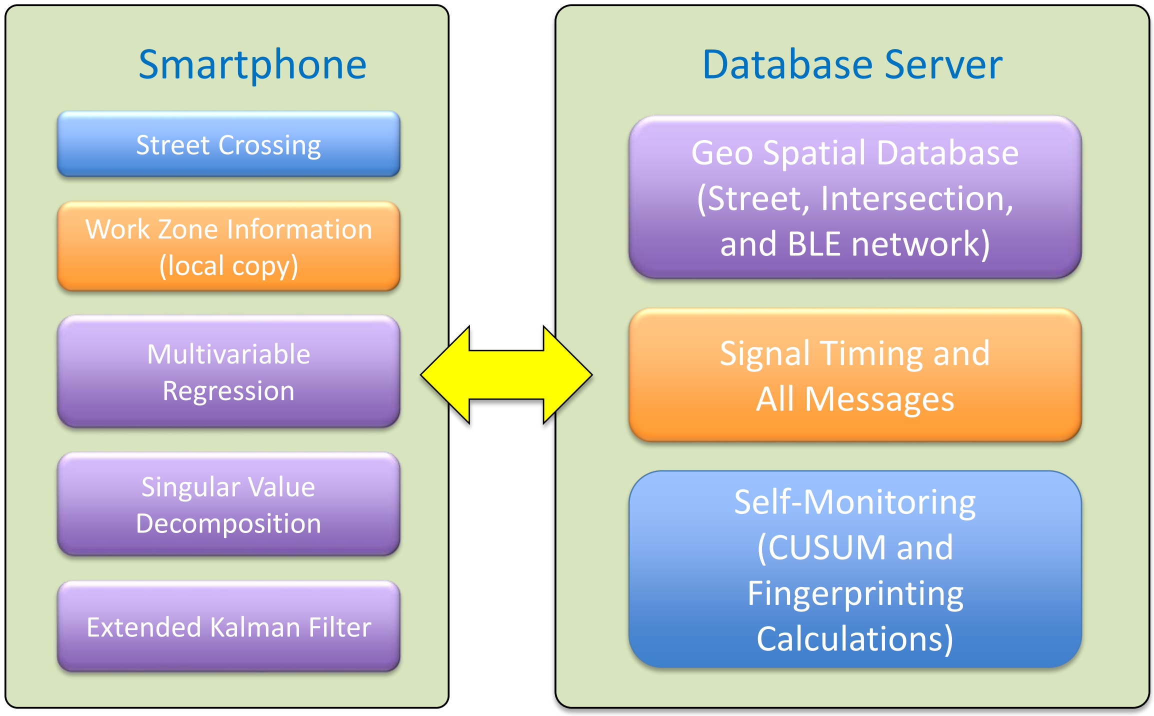

Figure 1-1 Components of the MAPS App and the Geo Spatial Database

1.5 Dissertation Overview

In Chapter 2, we review the literature in various areas related to navigation technologies, local based services, and spatial cognition and mapping for people who are blind or visually impaired. Chapter 3 describes a smartphone based decision support system, namely the Mobile Accessible Pedestrian System (MAPS), which was developed to provide street and traffic signal information to people with vision impairment. In Chapter 4, we describes field experiments with 18 visually impaired participants conducted at two signalized intersections. Subjective and objective performance measures were developed to validate the system performance and usefulness of the MAPS. In addition to the intersection crossing experiments in Chapter 4, we also describe the experiments conducted in a work zone by incorporating the Bluetooth technology on a smartphone to validate the system performance of the MAPS app when a GPS solution is not reliable.

Chapter 5 presents positioning and mapping algorithms, and statistical methodologies for a self-monitoring infrastructure to ensure that information provided to the visually impaired is at the right location. Analysis results using the Received Signal Strength Indication (RSSI) measurements from Bluetooth Low Energy (BLE) beacons are also discussed. Finally, we conclude with a discussion, include steps for system implementation, list known limitations of the system, and present future opportunities of this research in Chapter 6.

CHAPTER 2 LITERATURE REVIEW

An extensive literature review on topics related to navigation and wayfinding technologies, intersection crossing support, work zone mobility, non-visual user's interfaces, and spatial learning and cognition for the visually impaired, are included in this chapter.

2.1 Personal Navigation Systems

The advance of wireless communications and mobile devices equipped with global positioning system (GPS) enables the deployment of personal navigation systems (PNS). The PNS includes positioning and navigation capabilities that provide location information for individuals using a portable device.

2.1.1 Inertial Measurement and Satellite Based Navigation Systems

Inertial Navigation Systems (INS) are autonomous and self-contained systems that include multiple sensors, such as accelerometers, magnetometers and gyroscopes, for determining the position, orientation, velocity and attitude of an object. They often are integrated as part of a Dead Reckoning (DR) system. INS can provide continuous position, velocity, and orientation estimates, which are relatively accurate for a short period of time, but are subject to error growth over time due to sensor drift. Therefore, they require frequent correction or updates to minimize the growing sensor error in order to provide accurate and reliable navigation solutions. For pedestrian navigation, foot-mounted inertial sensors are often used for step detection and precise localization in GPS denied environments (Ruppelt et al., 2016, Le & Gebre-Egziabher, 2016).

Global Navigation Satellite Systems (GNSS) or the United States' Global Positioning System (GPS) offer world-wide coverage through various satellite constellations (GPS/GLONASS/Galileo/BeiDou) and provide a positioning solution with relatively high accuracy for vehicle navigation. GNSS has been widely used to provide accurate solutions for various positioning and navigation applications such as surveying, aviation, aircraft automatic approach and landing, land vehicle navigation and tracking, etc. (Misra and Enge, 2006). With recent technological advances, a commercial grade GPS receiver can provide instantaneous position updates at 5 Hz rate or higher. Commercially available GPS receivers using code phase techniques with corrections can provide a relative high accuracy (1~5 meters) position solution that does not drift over time. Additional enhancement using carrier phase techniques with differential correction can achieve even better positioning accuracy (sub-meter) under controlled conditions. However, a standalone GNSS navigation system is subject to intentional or unintentional signal blockage, such as an urban canyon environment with insufficient number of visible satellites (Godha et al., 2006), low signal to noise ratio, and multipath issues that can limit GNSS from providing reliable positioning information continuously.

The complementary characteristics of GNSS and INS make them a great companion for providing a continuous and reliable navigation solution. This has led to extensive theoretical and practical research activities focusing on the fusion of INS and GNSS to improve the accuracy and reduce the cost of navigation systems as presented in the literature. For example, attributes and shortcomings of GNSS and INS systems were discussed by Phillips and Schmidt (1996). Extensive studies of GNSS and INS integration using different techniques have been long discussed in the research literature (Phillips and Schmidt, 1996; Gabaglio, 2001; Alban et al., 2003; Samuel, 2003; Titterton and Weston, 2004; Wagner, 2005; Groves and Long, 2005; Gebre-Egziabher, 2007; Hasan et al., 2009). One trend is to incorporate a strapdown (lower cost) inertial sensor with a higher performance GNSS sensor using tightly or deeply-coupled integration structures to provide robust navigation solution (Gebre-Egziabher, 2007; Phillips and Schmidt, 1996).

In general, an INS provides a primary navigation solution and GNSS measurements are used to correct and calibrate the INS though an integration algorithm using optimal filtering and estimation methodologies. The integration of GNSS and INS eliminates the shortcomings of each individual system (e.g., the typical low rate of GNSS measurements as well as the long term drift characteristics of INS). Integration can also take advantage of the uniform high accuracy trajectory information of GNSS and the short term stability of INS. However, the main drawback in a cost-effective GNSS/INS system is that the integrated system becomes more dependent on the availability and quality of GNSS solution. The GNSS solution that relies on external satellite signals can be easily blocked or jammed by external interference. Even a short duration satellite signal blockage can cause significant deviation in the navigation solution (Phillips and Schmidt, 1996).

2.1.2 Personal Navigation in Unstructured Environments

In 2012, the Accessible Transportation Technologies Research Initiative (ATTRI), a joint federal initiative led by the Federal Highway Administration (FHWA) and the Federal Transit Administration (FTA), sponsored three research studies to develop situational awareness and guidance solutions for people with vision impairment and other disabilities. The first study sponsored by the Exploratory Advanced Research (EAR) program focuses on navigation and wayfinding for the visually impaired in unstructured environments. Rose et al. (2016) developed a prototype system that incorporates wearable components such as GPS, Inertial Measurement Unit (IMU), stereo camera, pedometry IMU, tactile belt, smartphone, and a wireless radio to provide navigation solutions to the visually impaired.

Another approach for indoor navigation was developed by TRX[4] systems using sensor fusion techniques and a proprietary mapping software for cloud based indoor navigation. The system uses a wearable beacon, an Inertial Navigation Unit (INU), paired with a smartphone. The INU includes a 3-axis gyroscope, a 3-axis accelerometer, a 3-axis magnetic field sensor, a barometric pressure sensor, and both Bluetooth low energy and Ultra-wideband (UWB) transceivers. The UWB transceiver provides a time of flight ranging corrections from UWB beacons installed in indoor environments.

The third study uses computer vision on a smartphone to provide situation awareness and simultaneous location and mapping (SLAM)-based navigation assistance (Tian, 2014; Yi et al., 2014; Tian et al., 2015) based on the Google Project Tango[5] technology. They used a fish-eye camera to detect sparse features from an environment and stored the detected

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[4] http://www.trxsystems.com/

[5] Google Project Tango, https://www.google.com/atap/project-tango/

features in a database. A user's position is then determined when the same set of image features are detected and matched with stored features during navigation. Image processing techniques are also implemented for signage detection and recognition. The Google Project Tango system integrates a motion tracking camera and depth sensing for navigation without using GPS or other external signals. It incorporates advanced computer vision, image processing, and special vision sensors for spatial perception. The Google Tango technology is only available on limited number of Android smartphone and tablet with a fisheye-lens camera for motion tracking.

In 2013, a haptic shoe[6] was developed to receive signals from a GPS-enabled smartphone and provide navigation information for the blind and visually impaired. Commercially available smart shoes, developed by Lechal[7], use vibrations and GPS from a smartphone to point people in the right direction. In 2016, Sneakairs[8] developed a system by integrating a vibration module, battery and a miniature Bluetooth Low Energy sensor that fits into the sole of each shoe. The smart shoes can direct people to their destination by triggering different vibrations that indicate when to turn. However, the vibration or haptic feedback could potential require additional cognitive load for the users to remember and interpret the meaning of each vibration pattern.

2.2 Mobile Navigation Technologies

Mobile computing technology has led to the development of smaller and cheaper

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[6] Anthony Vipin Das, http://blog.ted.com/soul-to-sole-eye-surgeon-anthony-vipin-das-has-developed-shoes-that-see-for-the-blind/

[7] http://lechal.com/

[8] The Barcelona Street Project, http://www.barcelonastreetproject.com/

electronic components for pedestrian navigation services. Micro-Electro-Mechanical Systems (MEMS) based inertial sensors have been widely used for applications such as digital camera, smartphone, videogame controller, autonomous vehicle control and pedestrian navigation. Because of the significant advantage on cost, size and weight (De Agostino et al., 2010; Lachapelle, 2007; Kubrak et al., 2005; Kasameyer, et al., 2005), MEM sensors become common in consumer electronic products. However, pedestrian navigation using MEMS sensors requires advanced algorithms due to the relatively low travel speed of pedestrians as compared to sensor errors (Godha et al., 2006; Kappi et al., 2001).

Several Pedestrian Dead Reckoning (PDR) algorithms that integrate multiple sensors, such as the digital compass, rate gyro, and accelerometer, have been studied to provide reliable positioning solutions. These approaches include step detection, step length estimation and heading determination (Kappi et al., 2001; Moafipoor et al., 2007; Shin et al., 2010), zero-velocity update (Groves, 2008), body-mount inertial navigation system (Soehren & Hawkinson, 2006; Kourogi et al., 2010), and using the kinetic model of human gait (Matthews et al., 2010).

For example, Bebek et al. (2010) developed a navigation system to provide a long-term precise solution using secondary inertial variables from high-resolution gait-corrected Inertial Measurements Units (IMU). Frank et al. (2009) developed an indoor positioning system for pedestrian navigation by combining Wireless LAN (WLAN) fingerprinting with foot mounted inertial and magnetometer sensors. The WLAN fingerprinting method is based on Received Signal Strength Indicators (RSSI) and a calibrated Radio Frequency (RF) map of an environment in order for location determination. Seitz et al. (2007) described that WLAN fingerprinting can be simplified by using an INS during calibration to enhance positioning performance.

Step length and heading are two key parameters in PDR. Step length estimation can be made through acceleration measurements (Kappi et al., 2001). Sabatini (2008) developed an adaptive Extended Kalman Filter (EKF) algorithm based on unaided inertial and magnetic sensing to accurately determine pedestrian location and orientation. Accuracy of step length estimation is affected by the walking frequency and acceleration variance (Shin et al., 2010). Chen et al. (2010) developed a unified heading error model through an EKF to compensate heading estimation. Zhao et al. (2010) classified six common placements of smart mobile beacons to adapt a proper PDR algorithm for pedestrian navigation.

2.2.1 Assisted GPS

A typical GPS receiver searches for satellite signals and decodes the satellite ranging signals to compute a position fix. It requires a sufficient number of satellite signals and additional processing power. The latest generation of smartphones integrates Assisted GPS (A-GPS) which uses wireless network resources, such as an assistance server and reference network, to quickly determine a user's location in GPS unfriendly environments (Karunanayake et al., 2004). A-GPS has significant performance advantages over autonomous GPS, particularly in urban areas and indoor environments where signals are weak and RF reflections are significant (A-GPS/A-GLONASS).

Usually, the assistance server for an A-GPS approach can provide precise GPS satellite orbit and clock information; initial position and time estimate; and satellite selection, range, and range-rate information. Furthermore, the powerful assistance server can even compute position solutions and leave the GPS receiver with the sole job of collecting range measurements. For example, a cellular network is used to assist a GPS receiver by providing an initial position estimate of the receiver and the decoded satellite ephemeris and clock information. Thus allows the receiver to quickly determine its position even when satellite signals are weak (Jarvinen et al., 2002). However, Mezentsev (2005) argued that the reliability and accuracy of such positioning technique using assistance from external sources is questionable.

2.2.2 Wi-Fi Based Positioning System

Wi-Fi based Positioning Systems (WPS) offer positioning solutions by measuring the intensity of returning signal strength and taking advantage of high density of Wi-Fi access points in urban communities. For example, Ekahau[9] Real-Time Location System (RTLS) implements software-based algorithms for indoor positioning using Wi-Fi network and location beacons. Skyhook[10] utilizes a software-only location system that quickly determines the location of a beacon with 10 to 20 meters accuracy. Skyhook uses proprietary hybrid positioning algorithms to determine the position of a mobile beacon, by integrating raw data from Wi-Fi access points, GPS satellites and cell towers

[9] http://www.ekahau.com
[10] http://www.skyhookwireless.com

information. The location estimate of a beacon can be received by wirelessly sending the raw data to a location server in a cloud network. For example, Gartner et al. (2005) use Wi-Fi based mobile positioning approach for pedestrian navigation. Bae et al. (2009) evaluated a location tracking system using an IEEE 802.11b Wi-Fi system to analyze the requirements of location based services in an indoor environment.

2.2.3 Machine Vision Based Navigation

Machine-vision based scene analysis and positioning techniques are often used for navigation and guidance in scenarios where dynamic lighting shifts and environment changes are not dramatic. For example, a handheld camera and machine-vision system were developed for blind or visually impaired pedestrians to identify and navigate through unfamiliar indoor environments (Miyazaki & Kamiya, 2006; Tian et al, 2010; Venable et al., 2010; Coughlan & Shen, 2013; Tian et al., 2015). Coughlan and Shen (2013) developed a smartphone application by incorporating augmented computer vision, geographic information systems (GIS), and other sensor data on the smartphone to infer the user's location. They reported that the vision based integrated system provides more precise positioning solution than using GPS alone. However, the vision based solution could presents additional challenges when the street marking is unclear, covered with snow, or when the lighting is dim. In addition, GeoVector[11] developed an application called World SurferTM to allow compass-enabled GPS smart phone users to point their phone in a particular direction and search for information about the desired point of interest. This service allows travelers to utilize their smart phone beacon as a personal

[11] http://www.geovector.com/

travel guide (Markoff and Fackle, 2006).

Google's Project Tango[12] provides a platform using computer vision technologies that combine motion tracking and depth sensing to support navigation and mapping on mobile devices. The Project Tango technology enables real-time 3D map reconstruction on a mobile device. It extracts visual features of the environment, in combination with accelerometer and gyroscope data, to closely track the device's movements in space. The depth perception feature detects distances, sizes, and surfaces in the environment. At the Consumer Electronics Show (CES) 2016, Google announced that more smartphones will be available in the consumer market with Project Tango capability in 2016.

Project Tango is also powered by Apple technology. Alongside two Myriad[13] vision co-processors, Project Tango utilizes a PrimeSense[14] Capri PS1200 3D imaging system-on-a-chip (SoC) technology that Apple acquired when it purchased PrimeSense in 2013. We believe that Apple is also experimenting with the technology. A commercially available product, namely Structure Sensor[15] (an infrared sensor bar built for iPad), incorporates iPad's color camera to offer 3D scanning capabilities. It empowers the iPad to create real-world objects for applications such as mapping, instant measurements, and augmented reality.

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[12] https://www.google.com/atap/project-tango/
[13] http://www.movidius.com/
[14] http://appleinsider.com/articles/14/07/11/apples-secret-plans-for-primesense-3d-tech-hinted-at-by-new-itseez3d-ipad-app
[15] http://structure.io/

2.3 Assistive Technologies and Location Based Services (LBS) for the Blind

A robotic navigation system is a closed-loop system with an onboard computer that functions as the main intelligent unit to process signals from multiple sensors, make decisions and generate motion commands to drive the robot. Unlike the robotic navigation system, an assistive navigation system relies on humans to take full control and make decision for wayfinding tasks. An extensive human-machine interface is required and is critical for providing effective navigational assistance to the users.

Development of navigation aids based on GPS has a long history. The first satellite navigation system, used by the US Navy, was first tested in 1960. Publicly available GPS devices have been around since the early 1980s. Nowadays, portable navigation devices, in-vehicle GPS systems, and GPS-enabled smartphones are commonly used for vehicle and personal navigation. The use of GPS to guide blind, visual impaired or elderly people has also been studied extensively (Gill, 1997; Garaj, 2001; Helal et al., 2001; Tian et al, 2010; Venable et al., 2010; Coughlan & Shen, 2013; Tian et al., 2015). In the past, many navigation and guidance systems have been developed (in the US and other countries) to support navigation and wayfinding for people with vision impairment. However, most of these systems are not adopted by the users due to the fact that it is often inconvenient to wear or carry such systems while traveling.

2.3.1 Use Technology to Assist Navigation

Due to differences in step sizes and direction in which each foot lands, humans tend to veer without receiving feedback (e.g., audible or visual feedback) to walk along a path or without a target to walk toward (Guth, 2007). Blind people tend to veer when crossing quiet streets. And, the spatial characteristics of the veering tendency differ between and within individuals (Guth & LaDuke, 1995). For example, Kallie et al. (2007) conducted a study of the veering of blind and blindfolded sighted participants and a study of the same participants' thresholds for detecting the curvature of paths they were guided along. For intersection crossing, pedestrians typically need to understand the relevance for crossing safely and then select a strategy to cross with lower risk.

Transportation options for people with vision impairment are often limited to walking, taxi, and public transportation. To improve their mobility, accessibility and level of confidence in using the transportation system, it is helpful to remove physical barriers that potentially impede their mobility, but this is not always possible. Many environmental cues are available to support their decision making on various components of a wayfinding task. However, it is important to understand their challenges, identify what information is needed for the blind pedestrian and what is available. For example, Long (2007) suggested that decision making using auditory feedback for the visually impaired usually requires more processing time than that based on visual information received by sighted people.

Many traveling aids (such as electronic, Braille map, etc.) are available in the market to assist with wayfinding. However, blind people often rely on their internal cognitive map and spatial knowledge as primary guidance (Hesch & Roumeliotis, 2010). Golledge & Gärling (2004) reported that people with low vision, when taught to pay more attention to auditory cues for determining when to cross an intersection, often increase their street crossing ability. However, street crossing is an important yet challenging task for many vision impaired individuals. We believe, training and technology can complement each other to improve the blind pedestrians' mobility, safety and accessibility while traveling in a transportation network.

Giudice and Legge (2008) reviewed various technologies developed for blind navigation. To our knowledge, there is no single technology alone that can offer a complete solution to assist people with vision impairment while navigating both indoor and outdoor environments. In addition to providing navigational information, it is critical to gain more insight from the spatial perception of the visually impaired and obtain a clear understanding of the cognitive demand associated with interpreting the information received from a blind people's sensory system.

2.3.2 Navigation and Wayfinding

Navigation and wayfinding involve dynamically monitoring a person's position and orientation with respect to the immediate environment and destination (Klatzky et al., 1998, 1999; Aslan and Krüger, 2004; Rieser, 2007; Dias & Ravishankar, 2015). Navigation usually implies that a user will follow a predetermined route or path between a specific origin and destination. Navigation is often referred to as an optimal path based on a specific goal, such as the shortest time, distance, minimum cost, etc. However, wayfinding refers to the process of finding a path (not necessarily traveled previously) between an origin and a destination. In general, the wayfinding process is more adventurous and exploratory.

People with vision impairment receive training from an orientation and mobility (O&M) specialist to help them develop or relearn the skills and concepts they need to travel safely and independently in the community. The O&M instructors often raise a concern that providing wayfinding technologies to the blind and visually impaired may undermine the maintenance of the skills they already learned. However, the benefits of using technologies to improve safety and mobility for people with vision impairment are likely to outweigh the overall cost (Loomis et al., 2007).

Starting in 1990, the American Disability Act (ADA) requires that a built environment be accessible to people with disabilities (Bentzen, 2007). Blind people are more vulnerable to collision due to insufficient information (such as distant landmarks, heading and self-velocity) and time for planning a detour around an obstacle (Loomis et al., 2001, 2007). People with wayfinding difficulties, such as the visually impaired (Golledge et al., 1996; Helal et al., 2001), elderly people (Rogers et al., 1998; Kirasic, 2002; Hess, 2005), dementia or Alzheimer's diseases (Uc et al., 2004; Rosenbaum et al., 2005; Pai 2006), can benefit from a personal navigation system for navigation and wayfinding assistance.

In addition, there has been significant research investigating Geographic Information System (GIS) and Global Positioning System (GPS) based navigation systems for the visually impaired pedestrian (Golledge, et al., 1991, 1996, 1998, 2004; Helal et al., 2001; Ponchillia et al., 2007, LaPierre, 2007). Several researchers also focused on the development of a user interface with non-visual spatial displays, for example, haptic (Loomis et al., 2005 & 2007; Marston et al., 2007), auditory (Loomis et al., 1998; Kim et al., 2000; Marston et al., 2007), or a virtual acoustic display (Kim and Song, 2007), in order to provide perceptual information about the surrounding environment.

Willis & Helal (2005) used programmed Radio Frequency Identification (RFID) tags to provide location and navigation information for the blind. However, the RFID information grid systems require short range communication (7~15 cm or 2.75~6 in) and a high density of tags (30 cm or 12 in apart) to provide navigational guidance. Hesch and Roumeliotis (2010) developed an indoor navigation aid for the visually impaired using a foot-mounted pedometer, a white cane-mounted 3-axis gyroscope and a 2D laser scanner. Kim et al. (2010) developed an electronic white cane with integrated camera, ZigBee wireless radio and RFID tag reader to provide route guidance information to the blind and visually impaired at transit transfer stations. Grierson et al. (2009) utilized a wearable tactile belt developed by Zelek & Holbein (2008) to assist people with wayfinding difficulties. The wearable belt is integrated with GPS, a compass, inertial sensor, battery and small vibration motors to provide direction relevant cues for wayfinding. The results indicated that older people generate more wayfinding errors than young people. The tactile wayfinding belt can provide an effective navigational aid even for the abled user. Wilson et al. (2007) developed a wearable audio navigation system to assist blind or visually impaired people getting from their origin to their destination. The system uses a GPS, digital compass, cameras, and a light sensor to transmit 3D audio cues to guide the travelers along a path to their destinations.

Tjan et al. (2005) and Legge et al. (2013) designed and implemented a Digital Sign System (DSS) based on low-cost passive retro-reflective tags printed with specially designed patterns for indoor wayfinding. A tag reader was designed and developed to detect a tag when properly oriented. Feedback from a human performance testing raised concerns on the size of the tag reader and the requirement of using two beacons (e.g., tag reader and cellphone) while wayfinding.

2.3.3 Navigation System for the Blind in the U.S.

Bousbia-Salah et al. (2011) developed a navigation aid by integrating ultrasonic sensors on a cane with vibrotactile feedback to inform the visually impaired of the location of obstacles. Al-Fahoum et al. (2013) used infrared sensors to detect and determine the direction and distance of objects around the visually impaired. Kim et al. (2014) developed a stereo camera based system to detect the user's pointing finger in 3D using color and disparity data. An object within the estimated pointing trajectory in space and the distance to the object can be determined. The drawbacks of this system are its computation cost and limited range of detection. Dang et al. (2016) developed a virtual blind cane system for indoor application by integrating a camera, a line laser, and an inertial measurement unit (IMU) for obstacle detection.

Researchers (Ganz et al., 2011) at the University of Massachusetts Amherst developed an app, called PERCEPT, to help visually impaired people navigate unfamiliar environment, such as Massachusetts Bay Transportation Authority (MBTA) stations, on their own. The PERCEPT used RFID technology with a customized handheld device to support navigation for the blind in an unfamiliar indoor environment. The application gives audio directions to guide users to the location of an electronic tag. The tag is similar to what the MBTA fare gates use to read a Charlie Card. Travelers can either place their phone near the tag to receive the next set of directions or instructions. The next set of audio directions will then lead the user to the next tag for further information.

At Carnegie Mellon University, the NavPal[16] project incorporates a smartphone app and accessible online software tools to give navigational assistance to blind and deafblind users as they move around unfamiliar indoor environments. Visually impaired users can use the accessible online tool to pre-plan routes in an unfamiliar indoor environment. The NavPal system integrates GPS, motion sensors on the phone, Wi-Fi and cellular signal strength fingerprinting techniques to determine a user's location (Min et al., 2015).

Barbeau et al. (2010) developed a Travel Assistance Beacon (TAD) using a GPS-enabled smart phone to assist transit riders, especially for those who are cognitively disabled. The TAD prompts the rider in real-time with a recorded audio message, visual images, and vibration alerts when the rider should pull the stop request cord to exit the bus. It is especially helpful for those who are cognitively disabled.

With the advent of smartphone technology, smartphone apps, such as Seeing Eye GPS[17],

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[16] Carnegie Mellon University, http://www.cs.cmu.edu/~navpal/
[17] Sendero Group LLC, https://www.senderogroup.com/products/shopseeingeyegps.htm

BlindSquare[18], and Ariadne GPS[19], can provide and update location information for pedestrians while walking to their destinations. However, none of them provides traffic signal or work zone information.

2.3.4 Navigation System for the Blind in other Countries

Gorges et al., (2010) evaluated APS in Copenhagen and suggested solutions with possible implementation strategies to the Dansk Blindesamfund (Danish Association of the Blind). The report suggested using a knocking sound and standard APS configuration as a short-term solution. For a mid-term solution, tactile arrows to indicate total number of traffic islands and a pedestrian activation system to reduce noise pollution are recommended. A complete system, such as a tactile path, was recommended as a long-term solution to convey all information necessary for the blind at intersection crossings. Feasibility of the complete system involves installation and maintenance cost as well as the effectiveness of the tactile path.

The City of Stockholm together with other stakeholders started an e-Adept project (2009) to make the city the most accessible in the world by 2010. A digital pedestrian network, consisting of pedestrian paths, sidewalks, signs, stairs and many detail features, was developed based on an open platform to integrate pedestrian navigation technology in assisting the visually impaired or disabled. This pedestrian navigation system includes a digital map, GPS receiver, mobile phone, and inertial navigation module. The digital network integrates municipal data such as road geometry, facility, and traffic information,

[18] BlindSquare, http://blindsquare.com/
[19] Ariadne GPS, http://www.ariadnegps.eu/

to provide personal navigation services to the elderly and people with disability in both outdoor and indoor environments (Jonsson et al., 2007; Dawidson, 2009; Johnni, 2009).

The NOPPA (2009) project conducted by VTT Technical Research Centre of Finland is designed to provide public transport passenger information and pedestrian guidance through a speech interface. The NOPPA system uses GPS, mobile phone and an information server to provide door-to-door guidance for visually impaired or sighted users taking public transportation (Virtanen & Koshinen, 2004).

The ASK-IT project (2009), partly funded by the European Commission under the 6th Framework Programme, uses personal profiling and web services to provide the user with navigation, transportation and accessibility information. The ASK-IT architecture is designed to allow mobility impaired people to live more independently. Users have access to relevant and real-time information through a mobile beacon primarily for travelling but also for home, work and leisure services. The emphasis is on a seamless service provision and a beacon that is intelligent enough to address the personal needs and preferences of the user (Bekiaris et al., 2007; Edwards et al., 2007). In France, the Mobiville project (Coldefy, 2009) aims to develop a real-time multimodal transportation information service and provide location based navigation service for pedestrian using a GPS-based mobile phone.

In 2015, a team from the Royal London Society for Blind People (RLSB) in the UK organized an open standard (called *Wayfindr*) for audio based navigation for people who are blind or visually impaired. Through the RLSB, the *Wayfindr* program was awarded a one million dollars grant by Google Inc. in 2015 as part of the Google Impact Challenge: Disabilities program that seeks to solve problems for people living with disabilities, through technology (Metro Magazine 2015). The *Wayfindr* standard aims to focus on guidelines on (1) integration with digital navigation services and (2) integration into venues or built environments.

2.4 Intersection Crossing Assistance for the Visually Impaired

People who are blind or visually impaired use auditory and limited visual information that they can gather to make safe crossing decisions at signalized intersections. They generally have difficulty crossing intersections due to the lack of information available to them about traffic signal and intersection geometry (Ponchillia et al., 2007). A study of the blind pedestrian's behavior in three cities found that only 49% of the crossings started during the walk interval (Barlow et al., 2005). The study also found that 27% of all crossings (that did not involve outside assistance) ended after the onset of the perpendicular traffic stream.

At street crossings where using a pushbutton is required, Barlow, et al. (2005) found that few (0% - 16%) looked for and found the button; they also began walking only 20% of the time during the walk signal as compared to 72% of the time when the pedestrian phase was requested. The reason may be because searching for the button often requires the pedestrian to move away from their path of travel, which is often used as an alignment cue for crossing. In addition, Barlow et al. (2005) found that although 72% of blind participants started with an appropriate alignment, location, or both, 42% ended their crossing maneuver outside the crosswalk. Guth et al. (2007) found that site-specific characteristics (for example, treatments such as rumble strips or speed countermeasures) appeared to have a greater impact on reducing the number of conflicts between pedestrians and vehicles than did a mobility beacon (e.g., cane or guide dog). Therefore, enhancing the pedestrians' ability to perceive useful cues at an intersection may be an effective method of reducing crash events. There is room for improvement in terms of the design and accessibility of both Accessible Pedestrian Signals (APS) and non-APS crosswalk signals for blind and low-vision pedestrians.

2.4.1 Accessible Pedestrian Signal (APS)

The Accessible Pedestrian Signal (APS), indicating the onset of the pedestrian phase at the signalized intersection, has been deployed in selected intersections to assist blind people at intersection crossings. As of 2015, the City of Minneapolis has installed over 30 APS systems to provide audible indication of the 'WALK' interval to blind pedestrians. They plan to install additional APS systems in the future when funding is available. In the City of Minneapolis, an APS transition plan was drafted under which all traffic signals will be evaluated and prioritized for APS installation over the next 10 years as described in the pedestrian master plan[20].

APS systems installed at the beginning of crosswalks continuously generate beeping cues to help the blind pedestrians locate the pushbutton. After an APS pushbutton is activated,

[20] http://www.minneapolismn.gov/pedestrian/projects/pedestrian_pedestrian-masterplan

the APS system announces an audio message '*Street name, Walk sign is ON*' when the pedestrian signal head is in the 'WALK' phase or '*Wait*' when the '*Don't Walk*' signal is on. Although, the countdown message is not compliant with the Manual on Uniform Traffic Control Devices (MUTCD) published by FHWA, many APS devices can vocally count down the remaining time (in seconds) to finish the crossing task during the walk phase.

There are problems with the traditional APS including the volume of announced message, not knowing which street has the 'WALK' signal on, and confusion of alerting tones with traffic noise (Bentzen et al. 2000). Respondents to a survey (Harkey et al., 2007) indicated that '*direction taking at the starting position*' and '*keeping direction while walking in the crosswalk*' were problems, even with an APS. Other problems are cited in the literature. These include: the acoustic signals from the APS systems are often confusing (Tauchi et al. 1998), the pushbutton location of the current APS system is difficult to locate (Barlow et al., 2005), and the modern roundabout intersection design presents more challenges for pedestrian with vision impairment in maintaining alignment, determining walking direction, and selecting gaps between vehicles (Long, 2007).

Bohonos et al. (2007) used Bluetooth wireless communications to provide signal information to cell phone users. Bohonos et al. (2008) developed a Universal Real-Time Navigational Assistance (URTNA) system using Bluetooth beacons incorporated into the traffic controller to transmit signal information to a user's cell phone. URTNA has proven that appropriate software can be developed, but no further research was found in the recent literature.

Through a Small Business Innovation Research (SBIR) program from the USDOT, Savari Inc. (Puvvala, 2014) developed a Dedicated Short Range Communication (DSRC) enabled pedestrian safety system to deliver traffic Signal Timing and Phasing (SPaT), intersection geometry, and other safety related messages to a smartphone. The DSRC is a short- to- medium-range wireless communications that permits very high data transmission critical in communications-based active safety applications. There are three broad categories of DSRC: Vehicle-to-Vehicle (V2V) communications, Vehicle-to-Infrastructure (V2I) communications, and the Vehicle-to-Everything (V2X) communications.

2.4.1 Computer Vision Based Crosswalk Assistance

Coughlan and Shen (2013) developed a smartphone-based system for providing guidance to blind and visually impaired travelers at traffic intersections. Their system, called *Crosswatch*, aims to provide a much larger range of information about traffic intersections to the pedestrian by using augmented computer vision, geographic information systems (GIS), and sensor data to infer the user's location more precisely than using GPS alone. However, the vision based solution could present additional challenges when the street marking is unclear, covered with snow, or when the lighting is dim.

In addition, Wang et al. (2014) used machine vision processing techniques based on red, green, blue, and depth (RGB-D) images to detect and recognize stairs, pedestrian crosswalks, and traffic signals. They reported an accuracy rate of 91% for detecting stairs and pedestrian crosswalks from scene images, 96% for classification of stairs and pedestrian crosswalks, 90% for classification of upstairs and downstairs, and 95% for "*Don't Walk*" crosswalk sign recognition.

2.5 User Interfaces for People with Vision Impairment

The touch screen interface on a smartphone is not readable by the blind people. Commercial text-to-speech (TTS) applications developed to read messages on a computer or cell phone screen to users have been used to translate information for the blind and visually impaired. For example, A blind scientist and engineer at Google is developing a touch-screen phone for the blind (Helft, 2009). Helft (2009) suggested that such a beacon, in addition to its utility for the blind, could provide eyes-free access for drivers.

Navigation guidance using verbal description and instructions has been studied as an efficient way to communicate to people with visual impairment (Bentzen et al, 1999; Crandall et al., 1999; Gaunet & Briffault, 2005; Giudice & Tietz, 2008; Giudice et al., 2007, 2010). Marin-Lamellet and Aymond (2008) conducted an experiment in an underground transport station with two groups of visually impaired pedestrians using verbal guidance combined with tactile surface system and verbal guidance system alone. They reported that the group using the combined guidance system completes the trip in a shorter time and with less difficulty.

Li (2006) investigated the user information required at the individual level for location based service focusing on the interaction among individuals, environment, and mobile beacons. In wayfinding, user preferences on route and map information vary depending on spatial layout, level of confidence, and surrounding situations. Golledge et al. (2004) conducted a survey of preferences of visually impaired people (30 persons) for a possible personal navigation beacon. They found that the most preferred output beacon was a collar or shoulder mounted speech beacon and the most preferred directional interface was a handheld beacon which users can scan the environment to get directional information.

2.5.1 Audio and Sonic Outputs

Holland et al. (2002) created a prototype of a pedestrian navigation system called AudioGPS that relies on a virtual acoustic display as the user interface. By taking an audio signal and transforming it into a binaural signal that the user listens to through the headphones, the signal appears to emanate from a given environmental location and can assist the user to navigate towards his destination or an intermediate waypoint. AudioGPS provides the user with two essential pieces of navigation information in non-speech audio: the distance and direction to the destination or an intermediate waypoint. Other similar beacons such as gpsTunes (Strachan et al., 2005) and ONTRACK (Jones et al., 2008) embedded spatial cues in the music to guide user to target location. The key drawback is that audio based navigation makes it very challenging to present information about multiple targets in the same time.

Havik et al. (2011) examined the effectiveness of different types of verbal information provided by electronic travel aids from 24 visually impaired users. They concluded that a combination of route and environmental information did not always result in an optimal wayfinding performance, but users preferred it. They suggested that the system include more detailed information and making it easier for blind users to associate the information to their immediate surroundings. Furthermore, a wayfinding aid system could include more beacons along a route to update and assure the visually impaired more frequently that he or she is traveling in the correct direction.

2.5.2 Tactile Icon (Tacton)

Tactile cues can be used for conveying simple navigation information using a mobile phones vibration alert and for example presenting the information through vibrotactile rhythms. For example, Lin et al. (2008) introduce a pedestrian navigation system that uses tactons to provide navigation information to the user. Three different vibrotactile rhythms represent the direction of travel: seven short pulses for 'turn right', four longer pulses for 'turn left' and one short and one very long pulse for 'stop'. Deciphering vibrotactile rhythms becomes more complicated and difficult for users to remember which induces additional cognitive load to interpret and understand information.

People with vision impairment preferred a simple tapping tactile interface to a generated sound feedback (Ross and Blasch, 2000). Johnson & Higgins (2006) use a wearable beacon that converts visual information into a tactile signal for orientation and wayfinding. The wearable beacon with tapping interface helps reduce veering by over

30% (Ross and Blasch, 2000). They concluded that a tapping interface combined with a speech interface may be more usable and flexible for supporting the orientation aids of the majority of the target population.

Velazquez et al. (2005) identified four fundamental shortcomings of electronic travel aids (ETA). One of these is that most ETAs provide an acoustic feedback that interferes with the blind's ability to pick up environmental cues through hearing. Velazquez et al. (2005) developed a prototype system that consists of stereo cameras and a Braille-like tactile display to translate visual data into a tactile representation for the visually impaired. However, the Braille-like tactile display is expensive and displaying a 3D environment in 2D graphical format is quite challenging.

2.5.3 User Input

The *VoiceOver*[21] is a built in feature for Apple's operation system (OS) X. It tells users what's on their screen, and walks them through actions like a sighted person selecting a menu option or activating a button on a screen. The *VoiceOver* feature provides users with complete control of their mobile devices, with no need to see the screen.

Similarly, the Android[22] system also provides accessibility features and services for helping visually impaired users navigate their devices more easily, including text-to-speech, haptic feedback, and gesture navigation. For example, the *TalkBack* on Android OS is a screen reader service that provides spoken feedback to describe the results of

[21] http://www.apple.com/accessibility/osx/voiceover/
[22] http://developer.android.com/design/patterns/accessibility.html

actions. The *Explore by Touch* is another system feature that works with *TalkBack*. It allows people with vision impairment to touch their device's screen and hear what's under their finger via spoken feedback.

Speech recognition or voice recognition uses a computer program to identify words and phrases from a human and converts them into machine readable format. It is a natural way to interact, and it is not necessary to use a keyboard. However, the speech recognition system is sensitive to noise in the environment. It works best if the microphone is close to the user or if the user is wearing a microphone (Beigi, 2011). Gesture inputs such as scrolling, multi-touch, dragging and scaling are commonly available on smartphones.

Other software based inputs, such as BrailleType (Oliveira et al, 2011), BrailleTouch (Romero et al., 2011), or Braille Dict (Chomchalerm et al, 2014), use the touch screen of a smartphone to allow blind and visually impaired users entering text into the smartphone. The software based approach is cost effective to enable Braille-like text input to a mobile device. However, this Braille text input is time consuming and it requires addition text to speech (TTS) interface to read out the input text for accuracy verification (D'Andrea, 2012). Kocielinski and Brzostek-Pawlowska (2013) developed a prototype system that integrates Android-Based Devices and Braille NoteTakers[23] for people who are blind or visually impaired to efficiently input text into a smartphone.

[23] BrailleNote products from HumanWare Group, http://www.humanware.com/en-usa/products/blindness/braillenotes

2.6 Work Zone Accessibility and Mobility

According to statistics from the Federal Highway Administration (FHWA), each year approximately 17% of all work zone fatalities are pedestrians. Since the ADA was enacted in 1990, there has been growing emphasis from both federal and local transportation agencies to provide safe pedestrian access in and around work zones. The ADA requires that pedestrians with disabilities be accommodated in completed facilities as well as during times of construction.

The Manual on Uniform Traffic Control Beacons (MUTCD) published by the FHWA and the Minnesota MUTCD (part 6) provide specific guidelines for Temporary Traffic Control (TTC) in work zones and outline specific requirements to accommodate pedestrians with disabilities (MN MUTCD, 2011). One of the requirements is, for example, to provide audible information for the visually impaired. Ullman & Trout (2009) emphasized the importance of clear audible messages and spatial message elements that are critical in guiding the visually impaired pedestrians along a temporary route and supporting navigation in a less familiar environment.

A few pedestrian audible beacons with pushbutton or motion-activated options are commercially available. For example, Empco-Lite and the ADA SpeakMaster™ from MDI Traffic Control Products use pre-recorded messages at selected locations around a work zone to inform approaching pedestrians about the construction and provide specific routing information. These audible warning beacons are usually placed at a specified distance before the actual sidewalk closure. As the pedestrian approaches, he/she hears a unique locator tone which indicates more information is available. The locator tone can be programmed to play continuously or be activated by an optional motion sensor. After locating the pushbutton, the pedestrian activates the voice module to hear navigation instructions to safely pass through the temporary pedestrian accessible route.

One concern about these audible systems is the consistency of information elements in a pre-recorded message and its clarity in an outdoor environment (Ullman & Trout, 2009). In addition, information overload could be another concern as most people may have difficulties in memorizing long verbal messages accurately. Transportation engineers and practitioners often face the challenges between verbosity and efficiency of auditory messages.

2.7 Spatial Learning and Cognitive Mapping

Individuals generally acquire environmental information gradually. It starts with selective fragmental information that is of interest. Additional information is then added over time gradually (Denis & Loomis, 2007). Spatial knowledge may be acquired from direct experience with the environment or from media such as map or navigation technology (Loomis et al., 1999; Ishikawa & Montello, 2006). Both route-based and landmark-based spatial learning were studied in understanding the spatial knowledge acquisition processes (Lovelace et al, 1999; Montello, 2001).

A cognitive map is a personal mental representation of the spatial environment. It consists of spatial information about the environment, including place and route identity, location, distance and direction (Downs and Stea, 1977). It also includes both person-to-object relationships and object-to-object relationships (Golledge and Stimson, 1997). A cognitive map is primarily developed through personal wayfinding and travel experience (Golledge & Gärling, 2004).

Cognitive mapping allows an individual to create mental images and a model of the spatial environment he or she interacts every day. It manipulates the spatial knowledge to know where people and things are and how to get there. As defined by Downs & Stea (1973), cognitive mapping is "*a construct which encompasses those cognitive processes which enable people to acquire code, store, recall, and manipulate information about the nature of their spatial environment. This information refers to the attributes and relative locations of people and objects in the environment, and is an essential component in the adaptive process of spatial decision making.*"

The incomplete and error-prone nature of cognitive mapping causes variability between the cognitive maps of individuals (Golledge and Stimson, 1997). Individuals can develop different levels of a cognitive map regardless of their wayfinding experience (Allen, 1999). Sometimes, individuals may choose seemingly irrational routes or destinations that, within the framework of their cognitive maps, which are completely logical. Error and incompleteness are not completely random in individuals' cognitive maps. Rather, variations across individuals are due to experience, social processes, demographic differences and other factors (Kitchin and Blades, 2002). Kitchin and Blades (2002) found that social and economic differences, such as social and cultural characteristics, education and income, are potential causes of cognitive map variations across groups and individuals.

Elderly people usually perform more poorly in recalling landmarks and recognizing environmental scenes during wayfinding than younger adults. Older people usually take a longer time to form and use a cognitive map of the environment. Studies have shown an age-related decline in navigational ability (Iaria et al., 2009). In route learning experiments, older adults also experienced difficulties with location, temporal order and directional information of landmarks (Head & Isom, 2010). The spatial capability of forming a cognitive map differs among individuals. Information provided to assist younger people with navigation tasks may not be optimal for older adults. Older people benefit from auditory navigational aids but have greater reliance on map and heading information as compared to younger adults (Baldwin, 2009). The cognitive map and spatial knowledge learned by each individual varies with their previous experience with different travel modes (Mondschein et al., 2010). Mondschein et al. (2006) indicates that path based spatial learning affects accessibility by whether and how destinations are encoded into a person's cognitive map. They suggested that variations in spatial knowledge can result in different levels of transportation accessibility disregarding other factors influencing travel behavior.

Giudice et al. (2007) suggested that dynamically updated verbal descriptions are sufficient to describe local geometric details for blindfolded-sighted participants in an indoor environment. Giudice et al. (2010) developed a non-visual interface, called Virtual

Verbal Display (VVD), to provide a first-person verbal description about a user's location and orientation in the environment and its corresponding geometry layout. The VVD can support spatial learning and navigation of non-visual learners in virtual environments (Giudice et al., 2010). Klatzky et al. (2006) found that virtual sound, and perceived azimuth of sound indicating target direction, presented better performance than spatial language in guiding blind people under cognitive load.

2.8 Mapping and Positioning Using Wireless Signal Strength

In general, GPS has been broadly used for mapping, positioning, and navigation applications. However, due to the significant loss and multipath of satellite signals in urban canyon or indoors, it is difficult to acquire reliable positioning solutions using the GPS technology in GPS-unfriendly environments. Other approaches, such as using Wi-Fi (Navarro, et al., 2011), infrared light (Gorostiza et al., 2011), ultrasound (Hazas & Hopper, 2006), Bluetooth (Kotanen et al, 2003; Sheng & Pollard, 2006; Hossain & Soh, 2007; Pei et al., 2010; Raghavan et al., 2010; Wang et al., 2010; Subhan et al., 2013; Zhang et al., 2013; Zhu et al., 2014), etc., are used for positioning and location sensing.

Wi-Fi beacons usually consume more power than Bluetooth beacons. In recent years, the Bluetooth technology has increasingly been used for communication among consumer electronics, particularly mobile beacons such as smartphone/tablet devices, due to its low cost, low power consumption, and ease of integration characteristics. Bluetooth wireless technology is often used to transfer information between two or more beacons that are close to each other in relatively low-bandwidth situations. It operates in the range of 2400 to 2483.5 MHz under the Industrial, Scientific and Medical (ISM) 2.4 GHz short-range radio frequency band. Bluetooth also uses frequency-hopping technology in which transmitted data are divided into packets and each packet is transmitted on one of the 79 designated Bluetooth channels (Bluetooth SIG).

Many studies in the literature investigated the functional capability and signal characteristics of earlier version of Bluetooth beacons for positioning (Bandara et al., 2004; Almaula & Cheng, 2007; Altini et al., 2010; Diaz et al., 2010, Pei et al., 2010; Oliveira et al., 2012; Wang et al., 2013; Oguejiofor et al., 2013). Hossain & Soh (2007) investigated four Bluetooth signal parameters (connection-based RSSI, link quality, transmit power level, and inquiry-based RSSI) for Bluetooth localization and positioning. The inquiry-based RSSI does not require active connection between Bluetooth beacons. It monitors the received power level of inquiry responses from a nearby Bluetooth beacon and infers the corresponding RSSI value. Hossain & Soh (2007) confirmed that inquiry-based RSSI provide better measurements than the connection-based RSSI and other parameters.

2.8.1 Received Signal Strength Indication (RSSI)

The latest Bluetooth technology (version 4.0 or higher), namely Bluetooth Low Energy (BLE) or Bluetooth Smart, has considerably reduced power consumption as compared to earlier versions. The low-cost BLE beacons have enabled many applications using BLE tags together with smartphone devices to locate or identify personal items, or alert owners when personal belongings are left behind. All modern smartphones also have BLE technology. When the smartphone app scans and receives a wireless signal from a BLE tag, it also receives a unique address of the BLE tag and its corresponding Received Signal Strength Indication (RSSI) from the specific broadcasted message. The RSSI is used to evaluate the distance from the tag. Some applications use crowd-sourcing to help retrieve lost items when the items are out of the Bluetooth communication range (typically, 50-70 meters based on line of sight). BlueGiga[24] recently released a long-range BLE module which, according to the manufacturer, has a communication range up to 450 meters. Our experiment results indicate that while travelling at 70 MPH, a smartphone app is able to successfully detect the long-range BLE beacon placed 125 m away on a traffic barrel on a roadway shoulder.

Kikawa et al. (2010) developed a presence detection method using the received signal strength indication (RSSI) of a Bluetooth beacon and a judgment time threshold. Liao (2013 & 2014) developed a smartphone app, in connection with Bluetooth beacons, version 2.1 with Extended Data Rate (EDR), placed at key decision points near a work zone, to provide situation awareness along with routing or bypassing information to people with vision impairment. A geospatial database of the locations of the Bluetooth beacons was developed to allow the smartphone app to query audible messages associated with discovered Bluetooth beacons.

Due to the reflections of the radio signal and obstructions that attenuate the radio signal, Bluetooth range estimates based on RSSI has a significant degree of uncertainty. Faheem

[24] https://www.bluegiga.com

et al. (2010) developed a RSSI based distance estimation technique by optimizing the standard deviation (SD) of the RSSI and the packet of loss information along with the curve parameters for minimal distance error.

2.8.2 Use Bluetooth Signal for Positioning

Bandara et al. (2004) evaluated the Bluetooth positioning model using RSSI and proposed a multi-antenna Bluetooth access point that supports variable attenuators to reduce error rate. The test obtained 2 meters of error in a 4.5 m by 5.5 m area with 4 antennas. Sheng & Pollard (2006) used RSSI and a radio signal propagation model to estimate the distance between a pair of Bluetooth transmitter and receiver. However, a high density of Bluetooth infrastructure is required to achieve accurate positioning.

Triangulation methodologies and signal propagation modeling were studied for indoor and outdoor positioning and sensing applications (Almaula & Cheng, 2006; Oguejiofor et al., 2010; and Wang et al., 2013). For example, Raghavan et al. (2010) reported a positioning error less than 1 meter using class 2 Bluetooth beacons. Subhan et al. (2011 & 2013) used fingerprinting, trilateration, and Kalman filter based approaches to estimate an indoor location of a Bluetooth network. Their results indicated that the average indoor position error ranges from 1 to 2 meters.

Zhang et al. (2013) studies three fingerprinting-based Bluetooth positioning algorithms, k nearest neighbor (kNN), support vector machine (SVM), and neural networks. They evaluated the accuracy and precision of Bluetooth positioning using an Android mobile phone and five other Bluetooth beacons in a lab office. They concluded that the kNN regression method outperformed the other two algorithms studied.

Wireless signal fingerprinting is a common technique for indoor positioning. The fingerprinting technique usually includes two phases: data training and real-time location determination. Pei et al. (2010) approximated the Bluetooth signal strength distribution using the Weibull probability distribution function (Sagias and Karagiannidis, 2005) with limited RSSI samples in a training phase. A histogram maximization likelihood position estimation based on Bayesian theory (Youssef et al., 2003; Roos et al., 2002) was then used in positioning phase. The results indicated that the fingerprinting solution using the Weibull probability distribution performs better than the occurrence-based approach.

Wang et al. (2010 & 2013) explored the relations between distance and signal strength of Bluetooth beacons using least square estimation (LSE) and trilateration. The results indicated that the LSE method can closely estimate the distance between Bluetooth beacons based on the received signal strength indication (RSSI) in an open space. However, RSSI is dependent on local terrain and transmission obstacles in an environment.

2.8.3 Reliability of RSSI

The received signal strength indication (RSSI) and distance mapping relationship of a Bluetooth beacon is nonlinear. The received signal strength measurements vary by beacon class, implementation, environmental conditions and physical object. Distance accuracy of RSSI measurement is determined by the scanning frequency and overhead. This will impact how well the system handles moving mobile beacons. Scalability is another issue as environments with large number of Bluetooth beacons will require fast RSSI inquiry to avoid connection overhead. Dong & Dargie (2012) suggested that the Bluetooth RSSI is not reliable for precise indoor localization application. Subhan et al. (2011, 2013 & 2015) investigated multiple data filtering approaches to predict reliable RSSI values for indoor positioning applications.

CHAPTER 3 A SMARTPHONE BASED ASSISTIVE SYSTEM

Prior to designing a decision support system to help the visually impaired navigate streets, it is important to gain more insight on their perception and obtain a clear understanding of the cognitive demand associated with interpreting information. One objective of this work is to determine whether blind people's mobility and accessibility can be improved through a better understanding of spatial representation around them while navigating through a less familiar or unfamiliar transportation network.

3.1 Introduction

According to a poll conducted by the Marist Institute in 2009, 87% of the US residents reported that they own a cell phone (Marist Poll, 2009). The latest report on smartphone use in the US conducted the Pew Research Center indicates that 64% of American adults now own a smartphone, up from 35% in the spring of 2011 (Smith, 2015). Smartphone ownership is especially high among younger Americans. Nowadays, all smartphones have embedded sensors, such as accelerometers, gyroscopes, magnetometers, digital compass, GPS, vision, touch screen, and many others, that are intended to support a plethora of applications to improve quality of lives.

We believe, that by understanding the user's needs and by properly designing a simple user's interface, a smartphone based system, what we call the Mobile Accessible Pedestrian System (MAPS), can be developed to support decision making, navigational guidance, and conflict avoidance in a transportation network (e.g., at signal crossings or work zones). The objective of the user interface design is to provide appropriate information at different levels that will not overwhelm the visually impaired user with unnecessary cognitive load while interpreting information.

Many assistive systems have been developed in the past for visually impaired users to navigate and find their way. However, most of these systems were not adopted by users mostly due to the inconvenience of using such systems. The MAPS provides street geometry information and signal timing information. The traffic signal and timing information are not available from other apps in the market. In addition, the MAPS incorporates a geospatial database with Bluetooth beacon information that allows the MAPS to provide navigation to users when GPS solution is not available.

The MAPS system integrates GPS, a digital compass and a Text-To-Speech (TTS) interface on a smartphone together with a digital map to determine a user's location and orientation. A smartphone app was developed to provide the most recent needed information at a decision point (e.g., an intersection crossing or a work zone) by communicating with a cloud server wirelessly.

For intersection crossing assistance, a '*sniffer*' data acquisition system was instrumented inside a traffic signal controller cabinet at a test site to provide real-time signal timing and phasing information. This roadside unit eliminates the need for pressing a pushbutton at the beginning of a crosswalk. This feature automatically handles the '*pedestrian call*' request (i.e., a signal sent to traffic signal controller when a pushbutton is activated) from a smartphone when a registered and authenticated blind or visually impaired person confirms the desired direction of crossing.

For work zone routing or bypassing assistance, a Bluetooth beacon was installed at a construction sign or nearby lamp post to reliably identify a user's location in addition to GPS. When detected by the smartphone app, the Bluetooth beacon serves as a geo-reference to provide a work zone navigation message associated with each beacon to inform a user about the work zone and bypassing instructions.

3.2 Understand User's Needs

Prior to designing a technology solution for people with vision impairment, we first wished to understand their needs and what type of information could be helpful to assist navigate and wayfinding. A supportive system should not interfere or should at least minimize the disruption with the techniques, skills, and tools currently used by people with vision impairment for wayfinding and navigation in a transportation network. A survey protocol was designed and reviewed by the University of Minnesota (UMN) Institutional Review Board (IRB) to solicit user's feedback on traffic information and understanding of navigation guidance using auditory messages. Please refer to Appendix A and B for further discussions.

We also worked closely with local blind communities, including the Vision Loss Resources, Inc. (VLR) in Minneapolis, a UMN disability student group, and the Vision Impairment Service (VIS) group at the Minneapolis VA Health Care System (previously called VA hospital). The recruiting ad for our survey was announced in VLR's monthly newsletter and also distributed through email to visually disabled students though the Disabled Student Cultural Center (DSCC) at UMN. The consent form, approved by UMN IRB, was used to ensure that participants understand the objectives of this research and the purposes of the survey prior to their participations in a survey discussion. Interview protocol and survey questionnaires were used to collect navigational information and comments from the pedestrians who were visually impaired while finding their pathway around work zones. Two separate surveys were conducted to assess the needs of visually impaired pedestrians approaching an intersection crossing and a work zone.

3.2.1 Intersection Crossing Challenges and Information Needs

The first survey was conducted to better understand the challenges experienced by the visually impaired pedestrians and the types of information they use at intersection crossings (Liao et al., 2011). Various information modalities that can assist them were also identified. Ten pedestrians who are blind or have low-vision were interviewed with several questions regarding their vision, navigation, and orientation experience, and their use of assistive technologies in wayfinding.

Key recommendations for a mobile decision support system from the user survey are listed as follows.

- Need additional information about the intersection and signal timing
- Auditory message should be brief and clear
- Use tactile feedback for warning
- Activate pushbutton automatically or from a mobile/smartphone beacon

- Decision support system should not interfere with user's wayfinding ability (e.g., using white cane, listening to traffic)

3.2.2 Information Elements for Auditory Messages

The purpose of the second survey was to understand what message elements are important and useful for the visually impaired while navigating around work zones. We also interviewed 10 visually impaired pedestrians (in-person) to understand what type of information is helpful in providing work zone routing information to them. In addition to demographic information, four different messages with various levels of information content were programmed and announced using synthetic speech voice, i.e., text to speech (TTS), to each participant during the survey.

- Message #1

  "Attention eastbound Dolphin Street pedestrians. Construction ahead on sidewalk between 2nd and 6th Avenue. Use alternate route."

- Message #2

  "Attention southbound Lyndale Avenue pedestrians. East sidewalk closed from 22nd to 26th street. Cross Lyndale. Use sidewalk on the other side."

- Message #3

  "Attention southbound Snelling Ave pedestrians. Sidewalk closed from Marshall Ave for 6 blocks. Cross Snelling at Marshall. Use sidewalk on the other side. Return to original side of street if desired"

- Message #4

Part 1 - *"Attention southbound Lyndale Avenue pedestrians. You are at southwest corner of Lyndale and Franklin. West sidewalk closed from 22nd to 26th street. Cross Lyndale for more bypassing message."*

Part 2 - *"Attention southbound Lyndale Avenue pedestrians. You are at southeast corner of Lyndale and Franklin. West sidewalk closed from 22nd to 26th street. Use sidewalk on this side."*

Survey results were analyzed to develop guidelines in determining various message elements that are essential and useful for providing routing or work zone bypassing instructions to the visually impaired. Recommended audible message elements are listed as follows.

- Brief announcement to get pedestrian's attention
- Current location of a pedestrian
- What
- Where, (accessible path availability and event duration)
- Advisory action

Our system includes the following 2 messages type for providing work zone bypassing information to the visually impaired.

Sample message #1

Attention southbound Lyndale Avenue pedestrians.

You are at southwest corner of Lyndale and Franklin.

West sidewalk closed from 22nd to 26th street for 4 blocks.

Cross Lyndale for more bypassing message.

Sample message #2

Attention eastbound Washington Avenue pedestrians.

You are at southeast corner of Washington and Church.

Road construction on Washington from Church St to Huron for 7 blocks

Protected pedestrian path open on this side.

3.3 Design Objectives

3.3.1 Intersection Crossing

Prior to providing navigational information to a visually impaired pedestrian, we need to know the location and orientation (for example, location with respect to an intersection) of the traveler in a transportation network. The interaction between the user and the smartphone app should be simple for people with vision impairment. Therefore, a 'single-tap' and a 'double-tap' interface were developed in the smartphone app to take inputs from the user. The Text-to-Speech (TTS) output and vibrating alert on smartphones allow the smartphone app to provide audible and tactile feedback to the users.

The first objective is to provide intersection geometry, traffic signal information and automatically submit pedestrian crossing request through a smartphone beacon. A smartphone app was developed to integrate available sensors on the phone to determine a user location and orientation with respect to an intersection. The smartphone app then wirelessly communicates with a traffic controller and receives near real-time signal timing and phasing updates. Corresponding signal phasing information (see Appendix C for details) is sent to the smartphone according to the desired direction of crossing as confirmed by the user. After receiving confirmation from users, the system provides timing information of the corresponding pedestrian phase to users. Warning signals such as 'Do not walk' or 'Walk phase is on, # sec left' is broadcasted through the TTS interface to support decision making at crossing. Automatic pedestrian pushbutton request is sent to the signal controller for registered blind, visually impaired, elderly or disabled pedestrians when they confirm the desired direction of crossing.

The second objective is to evaluate the usability of the system and the users' trust while using this system at a signalized intersection. Both subjective and objective measures are developed to evaluate the performances such as speed on the crosswalk versus the sidewalk, in-position time and time to step into the crosswalk. The in-position time is defined as the time duration from the participant arriving at an intersection to the beginning of waiting to cross. The time to step into the crosswalk is defined as the time duration from when the walk sign is turned on to the participant actually steps onto crosswalk.

3.3.2 Work Zone Navigation

A Bluetooth beacon is introduced for work zone navigation and bypassing. The Bluetooth beacon is attached to barricades or traffic cones at decision points near a work zone to help determine the location of a user. In addition to providing signal information to the visually impaired, we also integrated the MAPS to provide work zone information. The

MAPS incorporates the suggested message elements from the survey results. The smartphone app, after detecting a Bluetooth beacon in discovery mode, provides associated navigation messages to travelers. The navigation program runs continuously in the background as a service on the smartphone. It continuously scans for Bluetooth beacons in the vicinity and identifies available information related to work zone and signalized intersection by comparing the scanned ID of detected Bluetooth beacons with a cloud-based spatial database.

3.4 System Architecture

3.4.1 Intersection Crossing

A smartphone app was developed using the Android SDK. It was also tested on HTC[25] and Samsung[26] Google phones running Android OS 5.x. The MAPS application integrates a digital compass, GPS, Wi-Fi, and a Text to Speech (TTS) interface to identify user location and obtain signal information.

The system diagram of the MAPS data communication is illustrated in Figure 3-1. For the field experiment, a Smart-Signal system, or traffic Data Collection Unit (DCU), was installed in a TS2 traffic signal controller cabinet to obtain signal timing and phasing information through the Synchronous Data Link Control (SDLC) interface, i.e., Bus Interface Unit (BIU). Real-time traffic phasing and timing information is wirelessly transmitted to a signal database server located in the Minnesota Traffic Observatory (MTO) in the Department of Civil, Environmental, and Geo Engineering (CEGE) at

[25] http://www.htc.com/us/
[26] http://www.samsung.com/us/

University of Minnesota.

When users perform a single-tap on the smartphone screen while pointing to a desired direction, the smartphone app interacts with a local copy of the regional map database previously downloaded on the smartphone to obtain geometry information. After determining which direction to cross, the visually impaired pedestrians perform a double-tap on the smartphone screen to submit pedestrian crossing request. The double-tap command wirelessly transmits the request to the traffic controller cabinet through a Wi-Fi or cellular network. The pedestrian call interface, residing in a Virtual Private Network (VPN), handles the request from the smartphone to activate the pushbutton inputs in the controller cabinet. The objective of using VPN is to ensure system security so that no unauthorized users or systems can trigger the pushbutton request remotely. Ideally, the wireless router/modem will not be necessary when the signal data can be accessed through a central traffic controller in a Transportation Management Center (TMC).

A digital map, containing intersection geometry, street name, number of lanes, and direction information is stored in a spatial database on the smartphone as a navigational reference. The geospatial database is structured to identify each corner of an intersection and its neighboring nodes (intersection corners) in the vicinity. In order to handle the GPS positioning uncertainty and unreliability, a Bluetooth beacon is mounted on a lamp post to help identify the location of a pedestrian. As shown in Figure 3-1, the MAPS DB server, residing in the MTO lab, contains the digital map and real-time signal timing information.

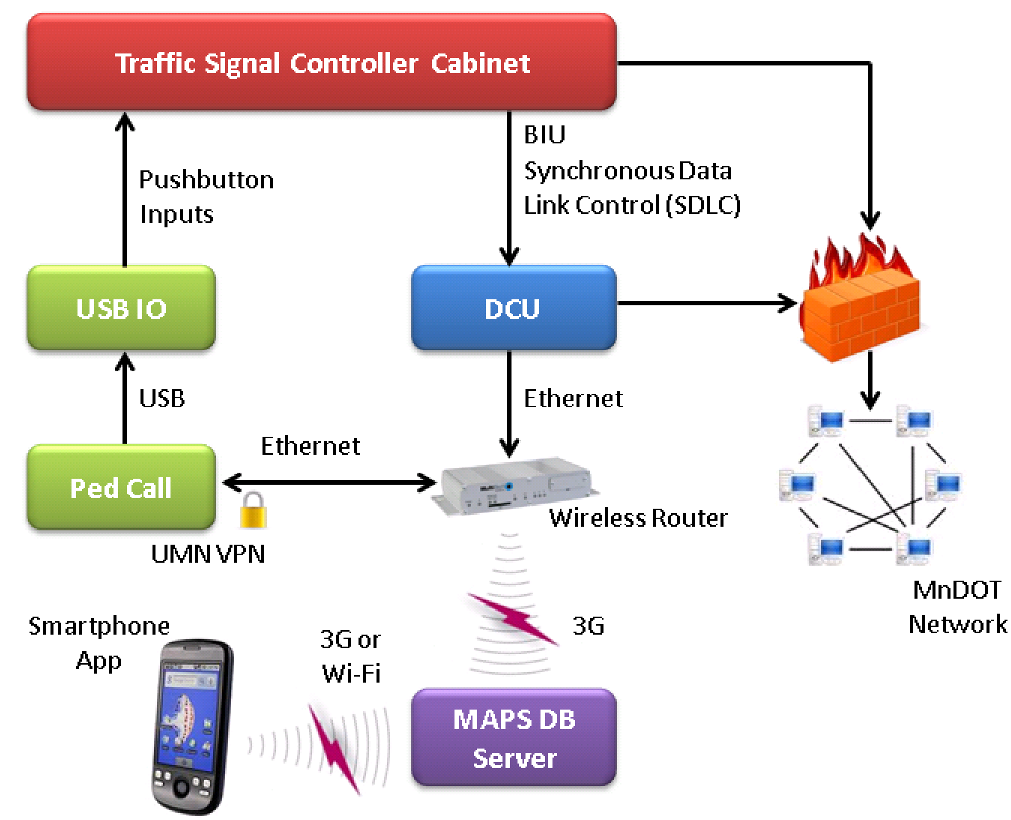

Figure 3-1 MAPS System Diagram

Signal Data Collection System

A Smart-Signal data collection unit (DCU) was developed by Liu et al. (2009). The Smart-Signal systems (Liu & Mar, ,2009; Liu et al., 2009) were deployed at over a dozen actuated intersections in the Twin Cities area to collect traffic data triggered by inductive loop detector, pedestrian calls and phasing changes. The DCU was chosen to leverage previous research effort sponsored by the MnDOT and the Intelligent Transportation Systems (ITS) Institute. The DCU may be eliminated when future Advanced Traffic Controllers (ATC) have the capability of broadcasting signal timing and phasing information wirelessly.

In order to provide real-time signal and timing data, the DCU continuously monitors the states of signal phases, pedestrian walk sign, and loop detectors. When there is a signal phase or a detector state change, the DCU transmits a text string to a server residing in the MTO lab.

For example, a detector state changes from on (high) to off (low) will generate the following output string.

$D010408122300031478114000000328!

Where,

$: Leading character

Intersection ID: 0104

Date: 08-12-23 (yy-mm-dd)

Time: 00:03:14.781

Detector ID: 14

Detector occupied duration: 328 ms

!: End of data string

No data will be sent to the server when the detector status changes from off to on (i.e., rising edge).

As another example, a signal state change generates the following string output string.

$S010112030214154070004G00015000!

Where,

$: Leading character

Intersection ID: 0101

Date: 12-03-02 (yy-mm-dd)

Time: 14:15:40.700

Phase: 04

Status: G (i.e., green)

Duration: 15000 ms

!: End of data string

When the data is sent, the status changes from green to red/yellow. The signal string sent is the information about the previous signal state and not the current one. For example, the above string indicates that G was the previous signal state that lasted for 15000 milliseconds. The phase numbers are 1 to 8 for the normal signal phases and 9-12 for the pedestrian phases.

The various signal statuses sent by the DCU are

- R => Previous signal was R and current signal is G
- G => Previous signal was G and current signal is Y
- Y => Previous signal was Y and current signal is R
- F => Previous signal was a flashing state.

Database Server

A database server contains the following tables that store intersection spatial information, signal timing and pushbutton requests. The database server allows data communications between the smartphone client application and a traffic signal controller.

- The 'intx_geo' table stores the intersection geometry information such as street name and number lanes. It contains the 'Intx_ID', 'Walk_Phase', 'Walk_Time', 'Cross_Street', and 'Num_Lane' data fields. A sample of the intersection geometry table is listed in Table 3-1. The walk_phase is the phase number for pedestrian crossing in a direction.

Table 3-1 Sample List of Intersection Geometry Table

Intx_ID	Walk_Phase	Walk_Time	Cross_Street	Num_Lane
101	2	24	Rhode Island Avenue	4
101	4	15	Highway 55	7
101	6	24	Rhode Island Avenue	4
101	8	15	Highway 55	7

- The 'intx_xing_phase' table defines the crosswalk direction and its associated signal phase. It contains the 'Intx_ID', 'Bluetooth_ID', 'Dir', and 'Phase' data fields. A sample of the intersection crossing phase table is listed in Table 3-2. When there is no crosswalk in a direction, the phase number is assigned to -1.

Table 3-2 Sample List of Intersection Crossing Phase

Intx_ID	Bluetooth_ID	Dir	Phase
101	00:12:F3:0B:49:4C	East	-1
101	00:12:F3:0B:49:4C	North	8
101	00:12:F3:0B:49:4C	South	-1
101	00:12:F3:0B:49:4C	West	2
101	00:12:F3:0B:49:A6	East	2
101	00:12:F3:0B:49:A6	North	4
101	00:12:F3:0B:49:A6	South	-1
101	00:12:F3:0B:49:A6	West	-1
101	00:12:F3:0B:4A:11	East	-1
101	00:12:F3:0B:4A:11	North	-1
101	00:12:F3:0B:4A:11	South	8
101	00:12:F3:0B:4A:11	West	6
101	00:12:F3:0B:4A:27	East	6
101	00:12:F3:0B:4A:27	North	-1
101	00:12:F3:0B:4A:27	South	4
101	00:12:F3:0B:4A:27	West	-1

- The 'pushbutton_request' table stores the pushbutton request from smartphone client when double-tap is performed. It contains the 'Intx_ID', 'Phase', and 'PB_State' data fields. A sample of the pushbutton request table is listed in Table 3-3. When a user submits a request to cross, the PB_state will be set to 1.

Table 3-3 Sample List of Pushbutton State

Intx_ID	Phase	PB_State
101	2	0
101	4	0
101	6	0
101	8	0

- The 'signal_state' table stores the real-time signal data from DCU. It contains the 'data_ID', 'Date', 'TimeStamp', 'Signal_State', 'Time_Left', and 'Intx_ID' data fields.

Table 3-4 Sample List of Signal State

ID	Date	TimeStamp	Signal_State	Time_Left	Intx_ID
377309	2/1/2016	20160201142760.000	72	359.185	101
395613	2/3/2016	20160203135940.075	136	42.031	101
395614	2/3/2016	20160203140029.981	0	49.907	101
395615	2/3/2016	20160203140035.966	34	59.391	101
395616	2/3/2016	20160203140100.606	0	24.641	101
395617	2/3/2016	20160203140108.137	72	145.063	101
395618	2/3/2016	20160203140118.091	0	9.953	101
395619	2/3/2016	20160203140124.106	33	19.453	101
395620	2/3/2016	20160203140131.184	32	7.078	101
395621	2/3/2016	20160203140136.216	34	31.562	101
395622	2/3/2016	20160203140156.278	0	32.172	101

Relay Output and Wireless Communications

A USB IO module, as illustrated in Figure 3-1, is a relay digital output device manufactured by ACCES I/O Products, Inc. (http://www.accesio.com/). When a double-tap is performed on the smartphone and detected by the *'Ped Call'* program, the relay output is then closed from a ‘normally open’ state to request a walk signal from the controller cabinet. This interface replaces the pushbutton functionality as a person is actually pressing down a mechanical pushbutton at an intersection.

For additional system security, data communication between the smartphone, app and signal database uses cellular or Wi-Fi network. User authentication can be implemented using the smartphone International Mobile Equipment Identity (IMEI) number with password protection. For system security purposes, communication between the signal database and the controller cabinet resides inside a private network, for example, the UMN Virtual Private Network (VPN). An additional authentication layer is added to prevent unauthorized access remotely.

3.4.2 Work Zone Navigation

When a work zone Bluetooth beacon is detected, the app alert users with a brief vibration (about 1-sec) and announces corresponding audible messages from our database server through the TTS interface. Users can then perform a single-tap on the screen of a smartphone to repeat the audible message, if desired.

The work zone navigation system consists of three key components, i.e., a digital map database for spatial reference, a smartphone app, and Bluetooth smart beacons. User input is implemented by performing a single-tap on the smartphone screen for repeating audible messages. Vibration and audible feedback are provided to users when a Bluetooth beacon is detected.

The general geometry information of a work zone area, location of Bluetooth beacons, and associated advisory messages can be readily programmed and uploaded to the spatial database through a web interface. The web interface allows engineers to deploy accessible audible messages around a work zone quickly and easily. The smartphone app was developed using the open source Java technology in Eclipse-based integrated development environment (IDE). In the future, the same app can be developed for other smartphones (e.g., iPhone iOS, Windows phone, etc.) running on a mobile operation system (OS) other than Android OS.

3.4.3 Spatial Database System

An open source database server, mySQL, is setup and configured to provide a digital map reference to smartphone clients based on a user’s current location. Using a geo-fencing technique, a location based spatial information, (for example, covering a 5-mile radius around a smartphone user), is periodically updated in an embedded database (SQLite) residing on the smartphone to ensure continuous map coverage. The Media Access Control (MAC) address of individual Bluetooth module, latitude-longitude location, and other spatial information are included in each record of the spatial database. In addition, a Java application was developed on the server side to facilitate the process of creating spatial data records and updating work zone location with corresponding information.

The 3-tier Bluetooth database system design is illustrated in Figure 3-2.The middle tier (*servlet*) application handles the data transaction between the client applications (the PC graphical user interface (GUI) program or the smartphone app) and the SQL database server. The work zone smartphone app downloads spatial data from the Bluetooth database server within +/-7 miles (or +/- 0.1 degree in both latitudinal and longitudinal directions) when the app is started initially. The app continuously monitors the current GPS location and updates the local database on the phone every 15 minutes. The smartphone always has +/- 7 miles of reference data coverage in case the cellular network is temporary out of service. Currently, the smartphone app uses relatively small memory space (in the range of 100 KB to 200 KB) on the smartphone.

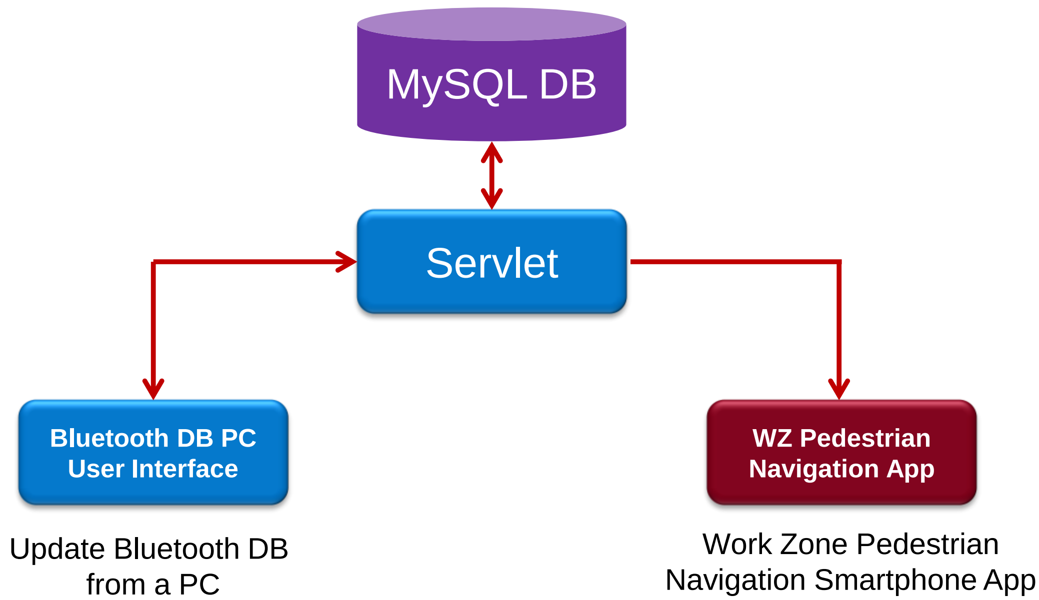

Figure 3-2 Message Database for Bluetooth Beacons

The data scheme implemented in the spatial database, as listed in Table 3-5, is based on the proposed message elements. The *message ID* is the identical MAC address of each Bluetooth module. The *latitude/longitude* data fields store the latitude and longitude location of a Bluetooth beacon. The *message direction* describes which direction of a traveler is affected by the construction. The *Bluetooth ID location* verbally describes the location where the Bluetooth beacon is installed. *Description 1, 2 and 3* inform travelers regarding the nature, location, and the scale of the work zone. The *advisory message* contains the suggested bypassing information for the travelers. The following audible message is used as an example based on the standardized message format described in 3.2.2.

Attention ***southbound Lyndale Avenue*** pedestrians. [***Attention***]

You are at the ***southwest corner of Lyndale and Franklin***. [***User location***]

West sidewalk closed from ***22nd to 26th street*** for ***4 blocks***. [***What & where***]

Cross Lyndale for more bypassing message. [***Advisory action***]

Table 3-5 Data Scheme of Spatial Database for Pedestrian Work Zones

Data Field	**Sample Value**
Message ID	00:12:F3:0B:4A:11
Latitude	44.98339267
Longitude	-93.37697511
Message Direction	Southbound Lyndale Avenue
Bluetooth ID Location	Southwest corner of Lyndale and Franklin
Description 1	West sidewalk closed
Description 2	22nd to 26th street
Description 3	4 blocks
Advisory Message	Cross Lyndale for more bypassing message

3.5 Geospatial Data and Mapping

The MAPS server consists of a SQL-based traffic signal database. A sidewalk GIS network is used for pedestrian navigation. We use the street network as a baseline to build our GIS map for locations without a sidewalk GIS database.

White et al., (2000) discussed several simple map matching algorithms that can be used to reconcile inaccurate locational data with an inaccurate map/network.

Pedestrians are traveling at lower speed as compared to vehicles. The heading measurement from smartphone beacons is not reliable to be used as a parameter for map matching.

As illustrated in Figure 3-3, consider a network representation, S, consisting of a set of polylines (L_i) in $\mathbb{R}^2$, where $L_i \in S$. Each polyline is consist of a finite series of points ($p_1, p_2, \ldots, p_n$). The objective of a map matching problem is to match a known measurement, for example, a GPS location, $\hat{p}(t)$, with a polyline (L_i) in the street network (S) and determine a location on L_i that best corresponds to $\hat{p}(t)$.

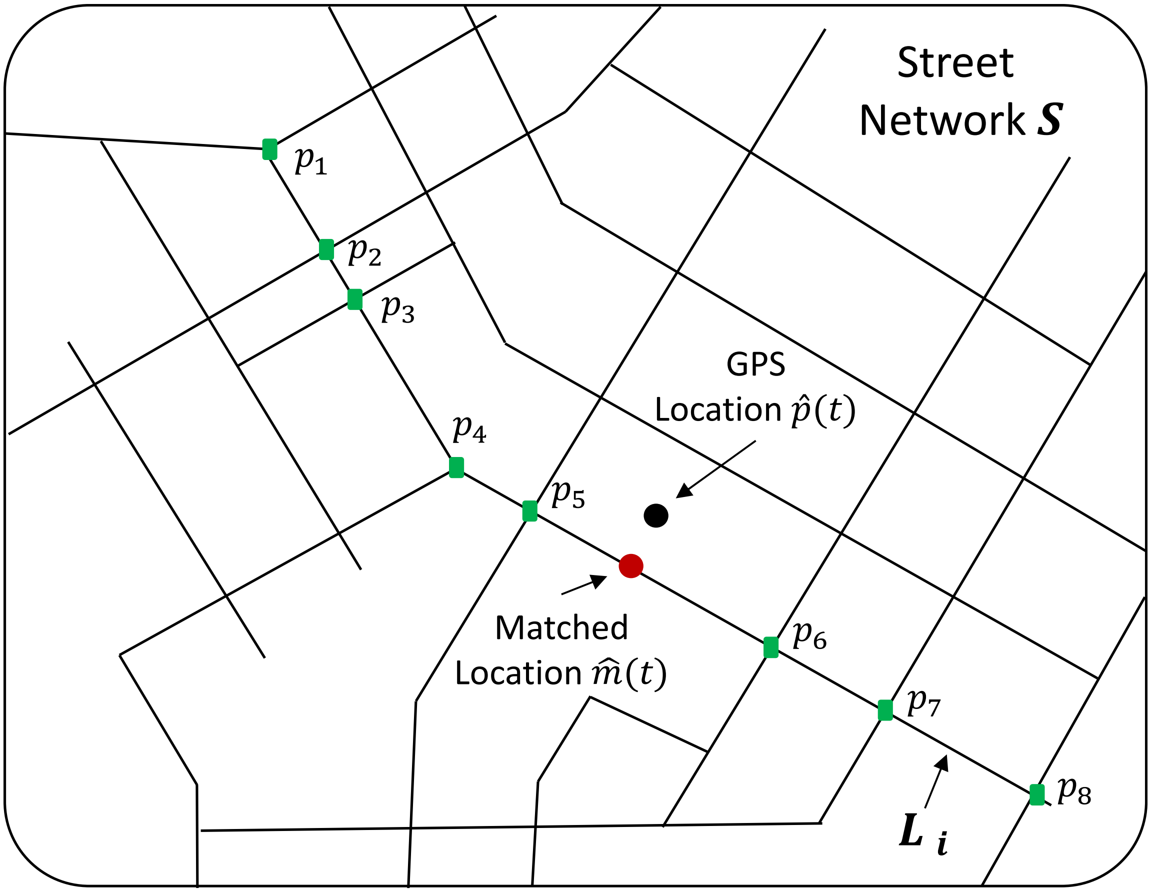

Figure 3-3 Match GPS Locations

3.5.1 Digital Map Data Structure

Computer engineers use hierarchical data structures to implement an Abstract Data Type (ADT) that represents the relationship between parent and child nodes. Bayer & McCreight (1972) invented the B-tree data structure to store data structures on disks. It ensures that few disk reads are needed to navigate to the place where data is stored. R-tree (Manolopoulos et al., 2006) was used to store spatial data objects by grouping nearby objects and representing them with a bounding rectangle in a higher level of the tree. A space-partitioning data structure called the k-dimensional (k-d) tree was used for multi-dimensional search. The k-d tree is a special case of binary space partitioning trees

(Bentley, 1975). The data structure of our digital map is based on a relational tree structure in which each node contains spatial relations and descriptions of its neighboring nodes.

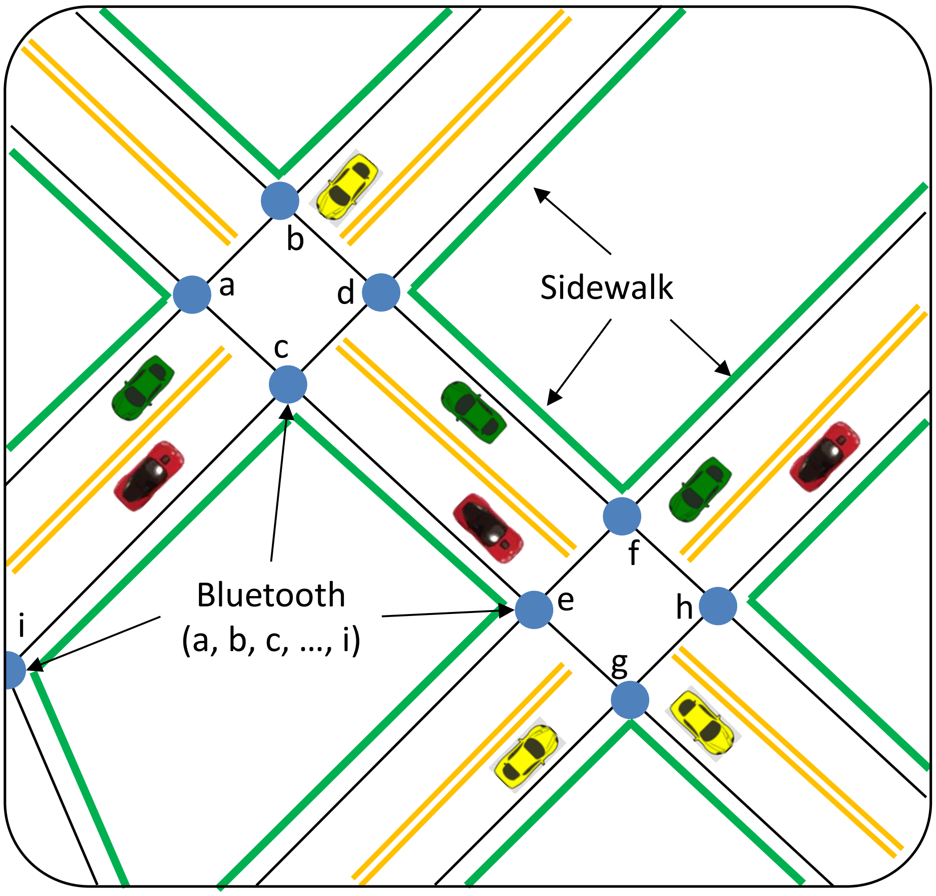

Figure 3-4 A Sidewalk Network and Placement of Bluetooth Modules

Figure 3-4 depicts a simple street network with Bluetooth identifiers placed at corners of intersections. For example, node *c* is connected to 4 other nodes (*a*, *i*, *e* & *d*) in the network. The relationship is described as follows.

- Parent node (*c*): Node ID, Latitude, Longitude, Node Description.
- Child nodes (*a*, *i*, *e* & *d*): Node ID, Direction, Compass, Crosswalk Flag and Street Info.

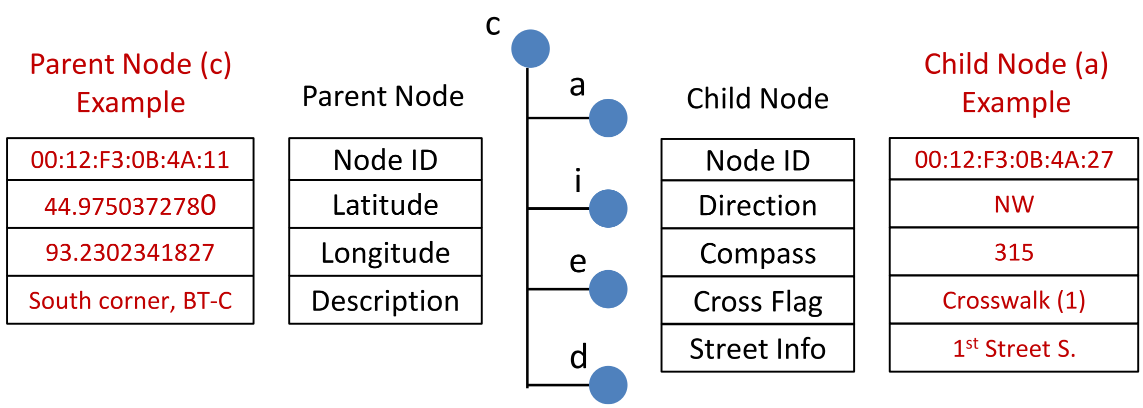

Figure 3-5 Node Data Structure for Pedestrian Navigation

3.5.2 Minimum Norm Distance

The minimum distance between a GPS location, $\hat{p}(t)$, and a polyline (L_i) can be expressed as equation (3-1). However, when GPS positioning inaccuracy is greater than the street network density, the map matching algorithm using the minimum norm distance becomes unreliable. Heading information, $\hat{h}(\widehat{m}(t), \widehat{m}(t-1))$, derived from previous location and previous route information can be incorporated to help determine a user's location in the network.

$$Min\{\, Dist\left[\hat{p}(t), \lambda p_j + (1-\lambda) p_{j+1}\right] \} \quad (3\text{-}1)$$

Where,

$\lambda \in [0, 1],\ \ p_j \in L_i, j = 1\ to\ n$

A sidewalk network equipped with Bluetooth Low Energy (BLE) modules is displayed in Figure 3-4 as an example for pedestrian navigation. Each BLE module has a unique Media Access Control (MAC) address. The unique MAC ID is used as a primary key in the digital map database for determine a user's location when the GPS location is unreliable.

3.5.3 Nearest Neighbor (NN) Search

The near neighbor point search is initially performed by extracting all the point features (as displayed in Figure 3.6) from each roadway polyline in the GIS database. All points in a polyline that are within 50 meters of a GPS point are included and stored for further consideration. As illustrated in Figure 3-6, a bounding box of ± 50 m is used for searching nodes of street polylines in the neighborhood of estimated GPS measurements. Only the roadway segments (polylines) within the 50 meters of a GPS points are considered by the 'select by location (SL)' procedure which was implemented in a script.

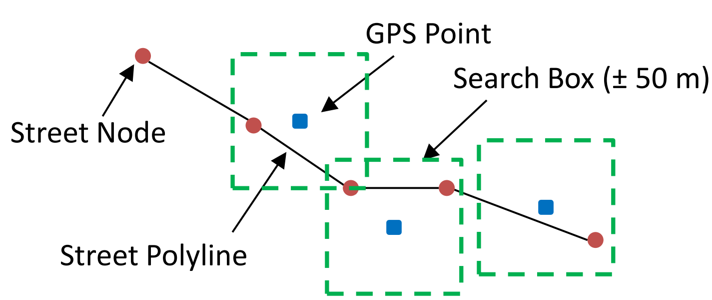

Figure 3-6	Illustration of Searching for Nearby Features

The nearest neighbor algorithm was initially used to find a solution for the traveling salesman problem (TSP). Given a dataset with n points and a query point, **p**, the nearest neighbor (NN) problem is to find the point closest to the query point. The nearest neighbor algorithm is defined as follows.

Given

A dataset **q** with **n** points,

A query point **p**, and

An initial minimum computed distance ($\mathbf{d_m}$) is set to ∞

For each point $\mathbf{q_i}$, where i=1 to n

Compute the distance between point **p** and $\mathbf{q_i}$.

If the computed distance, $\mathbf{d_i}$, is the less than minimum distance ($\mathbf{d_m}$), then set $\mathbf{d_m} = \mathbf{d_i}$

Result is the value of minimum distance, $\mathbf{d_m}$.

Figure 3-7 shows an example of the nearest neighbor problem. It illustrates a dataset (n = 10) in a two-dimensional space with a query point, **p**. The problem solution ($\mathbf{q_i}$) is found with minimum distance to the query point (**p**).

A K^{th} Nearest Neighbors (KNN) technique, supported by an informative and efficient index structure, has been used in spatial database applications to effectively reduce the search space (Belussi et al., 2013; Das, et al., 2004). The KNN query can be applied to find k nearest objects in a two dimensional (latitude, longitude) roadway network. As illustrated in Figure 3-8, evaluation of KNN queries for a large roadway network can be computational expensive, because the distance is a function of the network path connecting the points, shortest distance between 2 points, (Shahabi, 2002).

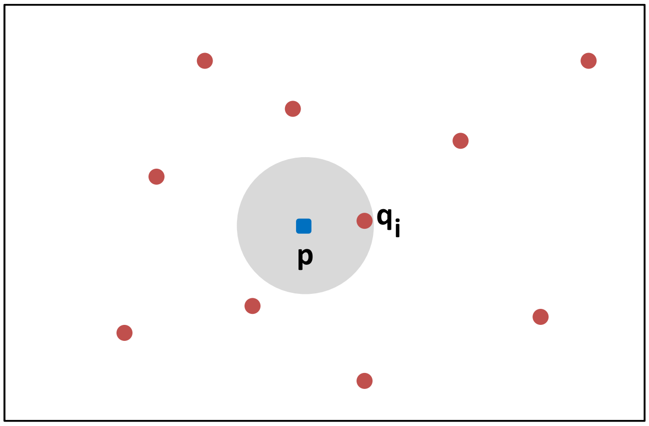

Figure 3-7 Example of a Nearest-Neighbor Search

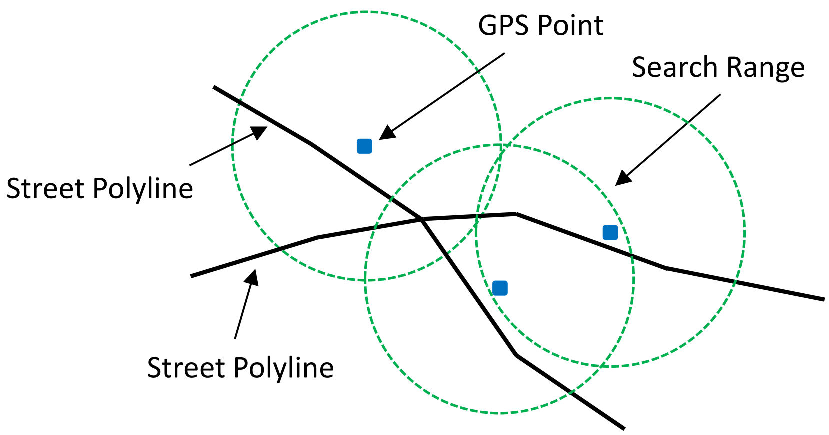

Figure 3-8 An Index-Assisted K nearest Neighbors (KNN) Search

A two-phase query was implemented based on a Generalized Search Tree (GiST) for supporting the KNN search in PostGIS DB server (Mamoulis, 2012). The GiST is a balanced, tree-structured access method that acts as a base template in which to implement arbitrary indexing schemes.

For point data, the bounding boxes are equivalent to the points, so the results are exact. But for any other geometry types (lines, polygons, etc.) the results are approximate. For example, the pseudo script displayed in Figure 3-9 is used to find the 4 closest objects nearby a GPS point (x, y). The indexed query selects the 20 nearest objects by box distance, and the second query pulls the 10 actual closest from that set.

```
with index_query as (
    select st_distance(geom, ST_SetSRID(ST_MakePoint(x, y), 4326) )
    as distance from MAPS_Street_Shapefile
    order by geom <#> ST_SetSRID(ST_MakePoint(x, y), 4326)
    limit 20
) select * from index_query  order by distance limit 4 ;
```

Figure 3-9 Pseudo Code for Index Assisted KNN Search

3.6 Software Design and User's Interface

The MAPS server includes a SQL-based traffic signal database, a network socket listener program that processes signal data from DCU, and a servlet program that handles communications with smartphone clients. As illustrated in Figure 3-10, the socket listener, including socket server, client worker, database connection and signal data classes, is a multi-thread application designed to handle traffic signal data and pedestrian walk phases from multiple intersections. Intersection ID, direction, and pushbutton request are submitted to the Java servlet program when a double-tap is performed on the smartphone. The servlet updates the pushbutton request flag in the database and then returns the corresponding signal phase and state according to the direction and location inputs from the smartphone app.

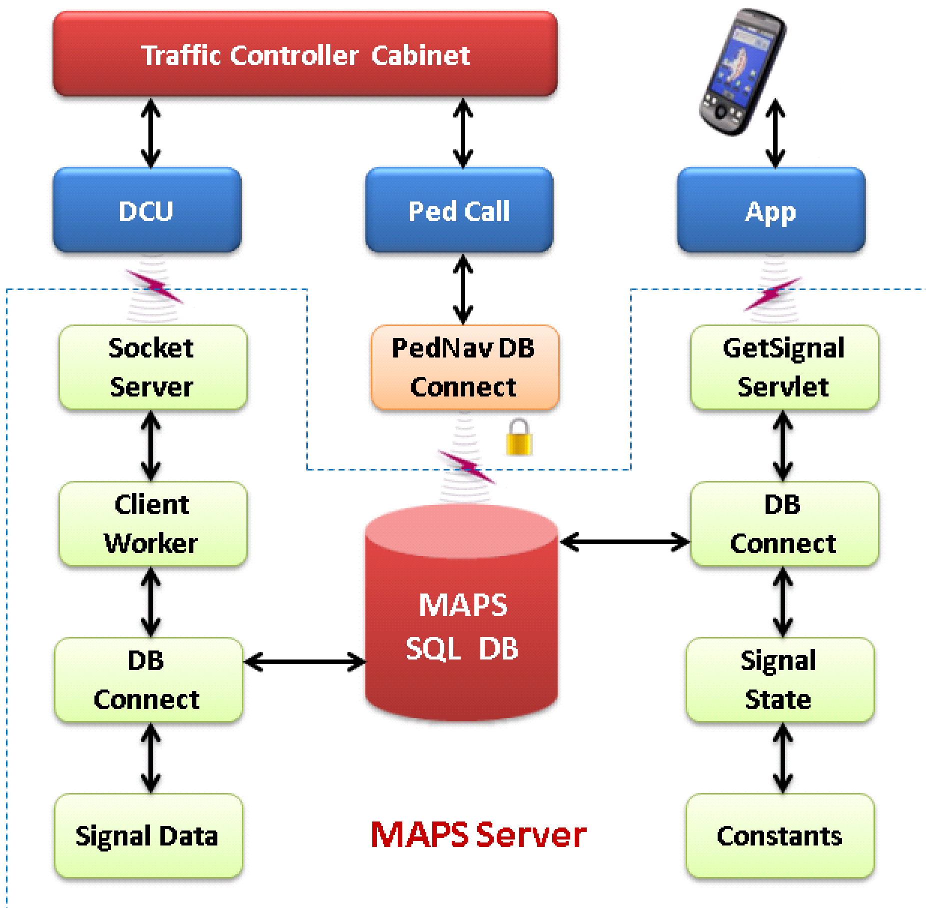

Figure 3-10 Software Architecture of MAPS

The smartphone application consists of a GPS service, the compass service, the digital map database, the Bluetooth communication interface, the wireless client, and the pedestrian navigation classes. The GPS and compass services provide location and orientation updates to a smartphone user. Intersection geometry and available crosswalk and sidewalk directional information are loaded locally to a SQLite database on the smartphone. The Bluetooth interface allows the smartphone app to scan in the nearby vicinity if a Bluetooth ID tag exists. Communication between the smartphone and the MAPS server is handled through the wireless client interface as illustrated in Figure 3-10.

3.6.1 User Interface

Two user inputs were developed for the visually impaired users. The single-tap command on the smartphone screen allows users to request intersection geometry information, such as street name, direction, and number of lanes, at a corner of an intersection, as shown in Figure 3-11. For example, it announces "*You are pointing to east, Harvard street 2-lane*", while pointing the phone in the east direction with a single tap. The MAPS application also provides direction information if there is no crossing information in the direction users pointed to. For example, it announces, "*No information for the north-east. Please turn for data*", while pointing the phone to the middle of an intersection with a single tap.

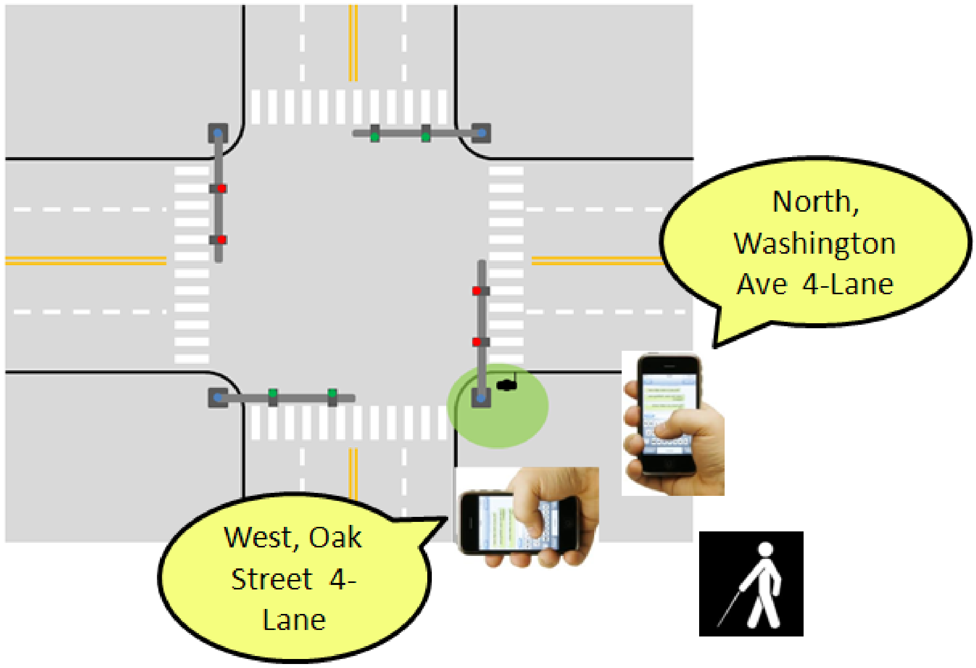

Figure 3-11 Single-Tap to Obtain Intersection Geometry Information

While pointing the phone toward a desired direction of crossing, the double-tap input confirms the crossing direction and submits a request for a pedestrian walk signal. The smartphone application then wirelessly requests signal timing and phasing information from the traffic signal controller. Speech feedback to the blind pedestrians is then announced through the Text-To-Speech (TTS) interface already available on smartphones as illustrated in Figure 3-12. For example, the smartphone announces "*Please wait for walk signal*" every 5 seconds. As soon as the walk sign is on, the smartphone vibrates for 1 second to alert the user and then announces, "*walk sign is on, 20 seconds left*". When it's about 5 seconds before the ending of a walk phase, the smartphone vibrates again then announce "*5 seconds left*" to alert the user to finish the crossing soon. The objective of the vibration alert is to raise the user's awareness of the upcoming audible messages.

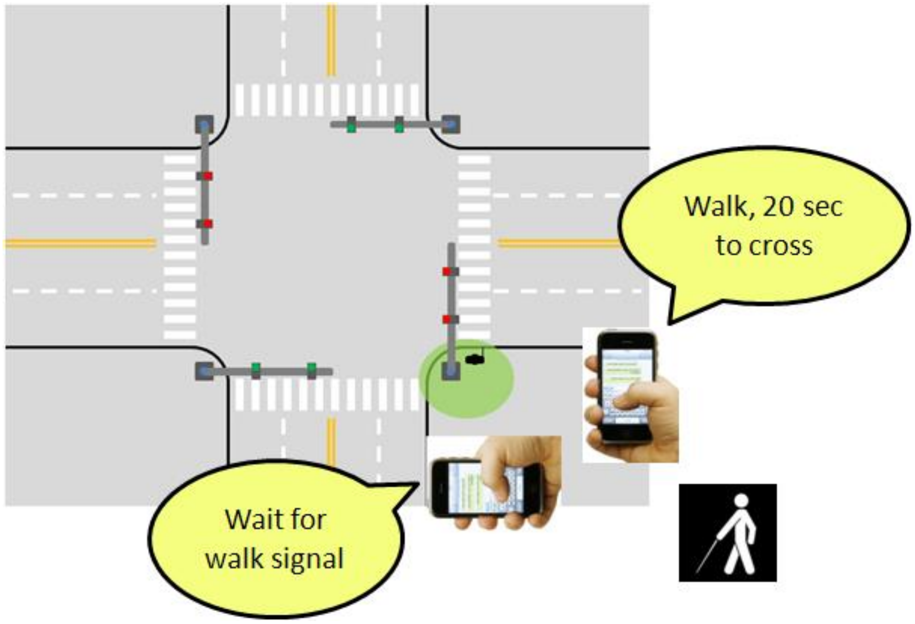

Figure 3-12 Double-Tap to Confirm Crossing and Obtain Signal Information

3.6.2 Design Flowchart

The system design flowchart of the smartphone app is illustrated in Figure 3-13. Intersection-related features on the left column of Figure 3-13 were previously developed to provide signal timing information to the visually impaired at signalized intersections. For work zone applications, the smartphone app, running as a service in the background, continuously scans for Bluetooth beacons in the nearby environment in discovery mode. The Bluetooth functionality on the smartphone is activated in order to detect Bluetooth beacons in the environment.

When a Bluetooth MAC address is detected and identified in the spatial database, the smartphone vibrates for about 1 second to alert users. The app then announces corresponding audible message associated with the Bluetooth beacon to smartphone users using the TTS (Text to Speech) technology. After the initial message was announced, users can repeat the message, if needed, by performing a single tap on the smartphone screen. The smartphone app redirects its process to the smartphone screen and waits for potential user input whenever a match in the database is found for a Bluetooth beacon. In case no Bluetooth beacons are found from the spatial database, the phone simply announces "*No Information Present*".

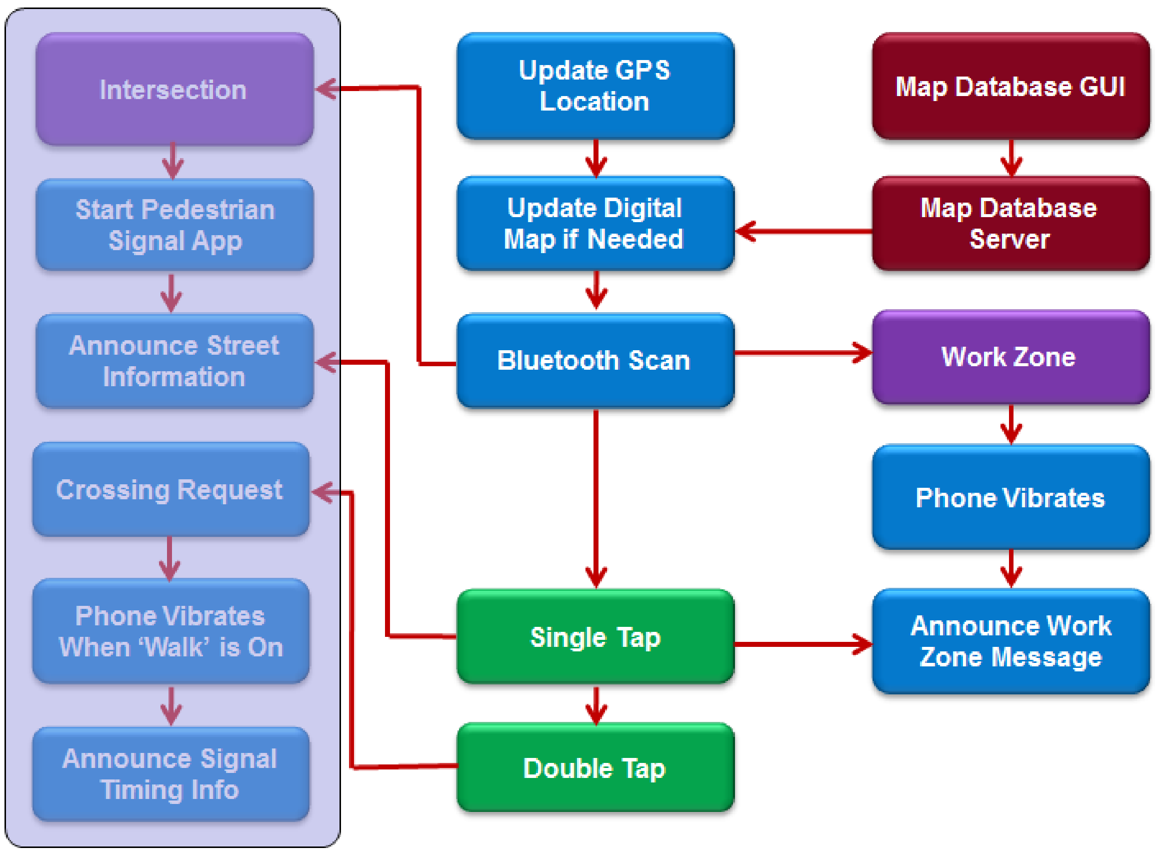

Figure 3-13 Flowchart of Work Zone Navigation Smartphone App

3.7 Performance Measures

Subjective and objective measures were developed to evaluate the user's satisfaction, usefulness, trust and confidence of using the MAPS.

3.7.1 Subjective Measures

Subjective measures include: sufficient information needed to cross the intersection, sufficient time to cross, feel safe during crossing, usefulness and satisfaction of the MAPS system and trust of using the smartphone based system. Questionnaires for both intersections are listed in Appendix B.1, section d & e. Questionnaire in Appendix B.2 surveys participants' opinions about the MAPS system they used at intersection #2. Questionnaire in Appendix B.3 evaluates participants' level of agreement with the statement in relating to the system they used. Complete users survey protocol and questionnaire are included in Appendix B.

3.7.2 Objective Measures of Users Behavior

Objective measures, including walk speed, initial alignment to the crosswalk at beginning of crossing, time to step into crosswalk when walk phase is on, number of veering actions, number of assistance needed from O&M specialist, were developed. These measures are extracted from the recorded video data.

- Walking speed – Compare the walking speed of a visually impaired traveler on a sidewalk vs. in a crosswalk.
- Initial alignment to crosswalk – This measure defines the orientation differences between the direction of the crosswalk zebra and a traveler's heading while waiting at the beginning of an crosswalk
- Time to step into crosswalk – The parameter defines the time lag after a walk signal is turned on to the time when a traveler actually steps into crosswalk.

- Number of veering actions – This measure defines how many times a visually impaired pedestrian steps outside the crosswalk path

3.8 Other Potential Applications

The Governors Highway Safety Association[27] (GHSA) estimates that the number of pedestrian fatalities jumped by 10 percent in 2015[28], a year-to-year increase that comes after a 19 percent increase from 2009 to 2014. A recent survey by the Pew Research Center found that Americans have grown comfortable using their mobile devices in public and 77% of the survey participants said it was okay to use mobile devices while walking down the street (Halsey, 2015). The primary reasons more people on foot are dying track closely with trends in three areas: economic, social and electronic (Halsey, 2016). According to the statistics from GHSA, California, Florida, Texas and New York accounted for 42 percent of the overall pedestrian deaths. California ranked first with 347 pedestrian fatalities. Based on the number killed per 100,000 residents, Florida has the highest pedestrian fatality rate of 1.35[29].

Milian (2016) from Palm Beach Post in Florida recently reported that the number of pedestrians injured while using their cellphones doubled. According to a national study conducted by Nasar & Troyer (2013) from Ohio State University, over 1,500 pedestrians were estimated to be treated in emergency rooms in 2010 for injuries related to using a

[27] Governors Highway Safety Association, http://www.ghsa.org/
[28] Pedestrian Fatalities Projected to Spike 10% in 2015, http://www.ghsa.org/html/media/pressreleases/2016/20160308peds.html
[29] Pedestrian Traffic Fatalities by State: 2015 Preliminary Data, http://www.ghsa.org/files/pubs/spotlights/spotlight_ped2015.pdf

mobile phone while walking. The number of such injuries has more than doubled since 2005. The study found that young people aged 16 to 25 were most likely to be injured as distracted pedestrians. They expect the problem of distracted pedestrians is likely to get worse. A new term '*pedtextrian*' is frequently used to describe a person who is texting while walking, and is completely unmindful of things happening around them. A lawmaker from New Jersey proposed to fine pedestrians and/or bicyclists who use electronic devices that are not hands-free on public roads[30].

In addition to providing the walk signal at signalized intersections and work zone bypassing information to the visually impaired pedestrians, the MAPS system can incorporate several other potential applications, such as alerting distracted pedestrians (Figure 3-14) while they are approaching an intersection and providing transit stop and arrival information.

When a Bluetooth tag is placed at a corner of an intersection, the MAPS smartphone app can detect the tag and display an audio and visual alert to the pedestrian while they are texting and walking toward a crosswalk. Similarly, when a Bluetooth tag is attached to a transit stop, our app automatically detects the tag and provides corresponding bus route or arrival information to the visually impaired. A similar approach can be applied to inform pedestrians regarding the entrance of a skyway, subway, or business building.

[30] N.J. lawmaker wants fines for 'distracted walking', https://www.washingtonpost.com/politics/2016/03/26/d24651a4-f389-11e5-89c3-a647fcce95e0_story.html

Figure 3-14 An App to Alert Distracted Pedestrian near an Intersection

3.9 Summary

In this chapter, we conducted two surveys (one for street crossing and the other for work zone bypass routing) to assess user's needs from individuals who are blind or visually impaired. The objective of the first survey is to better understand the challenges experienced by the visually impaired pedestrians and the types of information they use at intersection crossings. The purpose of the second survey is to understand what message elements are important and useful for the visually impaired while navigating around work zones. We then developed a smartphone based wayfinding system, called the Mobile Accessible Pedestrian System (MAPS), by incorporating the results from both surveys in our system design. The intent of our system is not to replace the orientation and mobility (O&M) skills that people with vision impairment have already learned. They will continue to use the O&M skills for obstacle avoidance as they travel along the pathways.

The objective of the MAPS app is to provide navigation information they need at key decision locations (e.g., beginning of a crosswalk, work zone, subway entrance, etc.) while traveling in a transportation network (e.g., at signal crossings or work zones).

We also developed a simple user interface to take user's input and provide appropriate information at different levels that will not overwhelm the visually impaired user with unnecessary cognitive load while interpreting information. A cloud based geospatial database that contains the location and geometry of an intersection is integrated with the MAPS app to provide corresponding navigation information to assist wayfinding for the visually impaired. Subjective and objective measures were also developed to evaluate the user's satisfaction, usefulness, trust and confidence of using the MAPS in a field experiment which is discussed in the following chapter.

In addition to providing the walk signal at signalized intersections and work zone bypassing information to the visually impaired pedestrians, We believe, the MAPS system can also incorporate other potential applications, such as alerting distracted pedestrians while they are approaching an intersection and providing transit stop and arrival information.

CHAPTER 4 SYSTEM VALIDATION AND EXPERIMENTS AT SIGNALIZED INTERSECTIONS AND WORK ZONES

This chapter first describes the design of street crossing experiments at two signalized intersections. The experiments involving 18 visually impaired participants and an orientation and mobility (O&M) instructor were conducted at two signalized intersections. After 15-minute of training, the participants were asked to perform street crossing task twice at one of the two intersections with and without using the MAPS system. A set of subjective and objective performance measures were developed to validate system performance, and measure the acceptance and usefulness of the MAPS.

We learned from the street crossing experiments that the GPS solution is not always reliable even in an open sky. We incorporated the Bluetooth technology on smartphones and introduced a Bluetooth beacon that can be placed in an environment to reliably identify a pedestrian's location. In addition to the street crossing experiments, work zone experiments were also conducted to validate the MAPS app when GPS solution is not reliable.

In section 4.1, we describes the methods for our experiment design. Experiment procedures and instructions given to participants at the first intersection (equipped with APS) and the second intersection (without APS installation) were presented in section 4.2 and 4.3, respectively. Experiment results at both intersections are discussed in section 4.4. Section 4.5 includes the test results of using Bluetooth beacons to trigger work zone messages for bypass routing. Finally, system validation and experiment results at intersections and work zones are summarized in section 4.6.

4.1 Methods

Two intersections in Golden Valley west of the City of Minneapolis were identified and recommended by an orientation and mobility (O&M) specialist for field experiment. Crossing experiments at intersection #1 and #2 were conducted on separate Fridays on April 13 & 20, 2012, respectively.

Upon the approval of the IRB review, recruiting ads were posted and announced at Vision Loss Resources (VLR) in Minneapolis and through word of mouth to the visually impaired communities. Participants were required to meet the following criteria.

- Be 18 to 64 years of age,
- Have completed orientation and mobility training,
- Be proficient in using a cane or a guide dog,
- Be willing to have audio and/or video recorded during the interview and intersection crossing tasks.

During one month of recruitment, thirty individuals who are visually impaired contacted the research team and expressed their interests in participating in this research study. Twenty people were selected randomly but finally eighteen individuals responded and agreed to participate. Consent agreement (included in Appendix A) was read to each individual by one of the research team members while a witness was present. A Braille version of the consent form was also available to the participants. All participants provided their written consent for participating.

Eleven male and seven female individuals participated in the experiment, with mean age 44.2 years, standard deviation 15.2 years. Two participants are veterans. Ten participants have total peripheral blindness and the others have low vision. Thirteen of the participants use a long cane and five use a dog. All participants have completed orientation and mobility training during their lives. Regarding intersection crossing frequency, nine of the participants cross more than four intersections a day, five of them cross one to two intersections a day, two of them cross one to four intersections a week, and the other two participants cross less than one intersection a week. Nine of the participants own and use a smartphone, eight of them have a ‘dumb’ cell phone, and one individual does not have a mobile phone.

The experiment at intersection #1 took place near a commercial area during light rain on a day from 7:40 AM to 5:30PM. The experiment at intersection #2, two blocks away from the first intersection, took place on a bright sunny day from 7:40 AM to 5:30PM. Sidewalk areas were clear with no obstacles at both locations. However, the sidewalk surface, at a few spots, was a bit uneven at intersection #2. A traffic data collection unit (DCU) and a relay IO module were installed in the controller cabinet at intersection #2 to provide signal information to smartphone users. Survey questionnaire regarding usability, acceptance, and trust of the smartphone based traffic signal system was read to each individual and their responses were recorded on the questionnaire. See Appendix B for questionnaire details.

At each location, participants were asked to perform crossing tasks and then interviewed by a research team member before and after each crossing task. The crossing tasks and interviews focus on the participants' experiences while crossing signalized intersections, using audible pedestrian signals, or a smartphone based accessible pedestrian signal beacon provided by the research team.

For each crossing task, a certified O&M specialist brought each participant to a starting point which was located about 100 to 200 feet (north) away from the north-east corner of the intersection, as illustrated in Figure 4-1. Visually impaired participants were asked to travel along the sidewalk using their own navigational skills to reach the corner of the intersection. While at the intersection, the visually impaired participants need to find and use the pushbutton to request a pedestrian walk signal or use the smartphone based pedestrian signal beacon to determine when it is possible to cross. Participants then cross the street that is perpendicular to the sidewalk they just travelled and arrive at the other side of street.

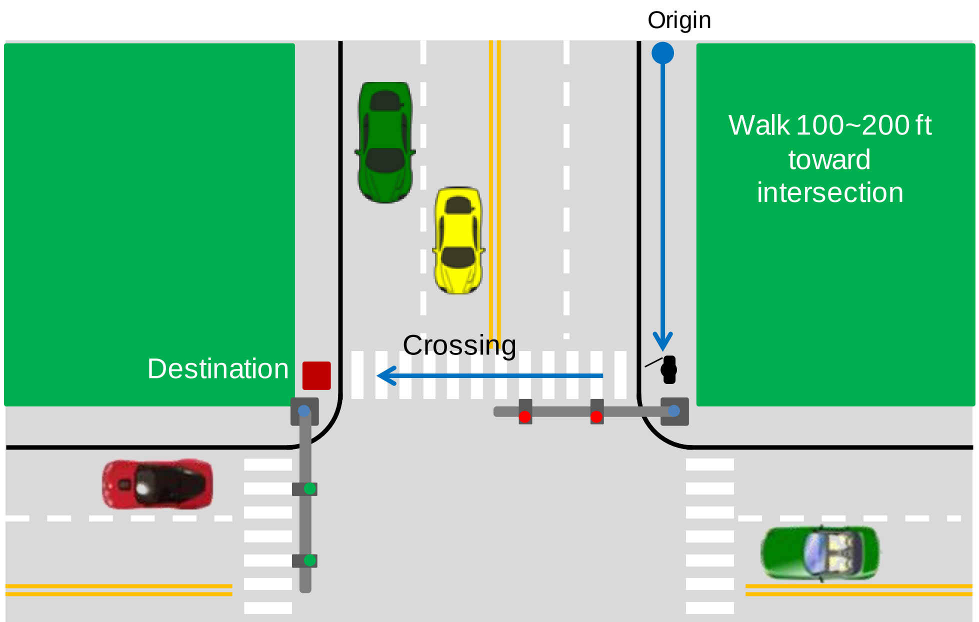

Figure 4-1 Crossing Path

The pre and post-experiment questionnaires covered the following topics:

- Vision,
- Ability to orient by themselves,
- Experience crossing intersections,
- Usage and opinions of the new technology,
- Opinions of the smartphone based pedestrian crossing system,
- Usability and acceptance of the smartphone based pedestrian signal system,
- Trust of the smartphone based traffic information system, and
- Other demographic information.

Each experiment session lasted approximately 30 minutes for each participant. The field experiment and interviews were recorded using video and audio equipment to effectively capture participants' responses and intersection crossing performance, for example, walking speed, in-position time and time to step into crosswalk when walk sign is on.

Results from survey questionnaires and performance measures derived from recorded video data of 18 visually impaired participants were compiled, analyzed and discussed in section 4.3. System verification for work zone application and condition-aware infrastructure monitoring were presented in section 4.4.

GPS solution on a smartphone is not always reliable. In order to identify a pedestrian's location correctly, we took advantage of the Bluetooth technology readily available on smartphones to detect Bluetooth beacons placed in an environment. We incorporated the Bluetooth interface for the MAPS app for a work zone bypass routing application. A geo-spatial database that includes information of Bluetooth beacon placed in a work zone was developed and integrated in the MAPS. System validation of the MAPS for work zone routing application is discussed in section 4.5.

4.2 Experiment Procedures at Intersection #1

Intersection #1 is located at Winnetka Avenue and Golden Valley Road. Winnetka Avenue consists of four lanes and is aligned in the north-south direction. Golden Valley Road consists of four lanes and is aligned in the east-west direction. An APS system manufactured by Polara Engineering, Inc.[31] is installed at this location.

[31] http://www.polara.com/

4.2.1 Instruction Given to Participants at the Beginning of the Task

The O&M specialist walked with each participant across Winnetka Ave. from the NW to the NE corner and turned north, then walked about 100 feet to the starting point. The O&M instructor had each individual turn 180 degrees around and said to the participants the following.

"*This is the starting point and you are facing South, Winnetka is your parallel street. Please walk straight about 100 feet to the intersection, locate the pushbutton, turn right and cross Winnetka Ave., a 5-lane street. It is a print letter L shaped route. The APS will say, 'The walk sign is now on to cross Winnetka Ave.' Any questions? Let me know when you're ready and I will give a signal to the camera man. OK. Go when you are ready.*"

4.2.2 Instruction Given When Participant Veers

If participants were veering and in danger, the O&M instructor spoke to them "*walk to your right, do you hear your traffic?*" For some clients, the instructor tapped their right shoulder and said, "*Walk this way*". In a situation where 2 cars blocked the crosswalk, the O&M instructor said, "*there is a car in the crosswalk either go around in the front of the car or the back, another car is in the cross walk*", when the participant encountered the second car in the crosswalk.

No messages were communicated to participants when participants press the wrong pushbutton.

4.3 Experiment Procedures at Intersection #2

Intersection #2, two blocks away from the first intersection is located at Rhode Island Avenue and Highway 55 (Olson Memorial Highway). Rhode Island Avenue consists of four lanes and is aligned in the north-south direction. Highway 55 consists of seven lanes and is aligned in the east-west direction. This intersection does not have an APS system installed. Pedestrians are asked to use the existing pushbutton or the MAPS to cross the intersection.

4.3.1 Crossing without MAPS

The O&M specialist walked with the subject approx. 1/8 mile to a starting point 238 feet north of the NE corner of Rhode Island Ave. and Highway 55. Then the following instruction was given to the participants.

"*This is the starting point and you are facing south, Rhode Island Ave. is your parallel street. Please walk straight about 200 feet to the intersection, locate the pushbutton, turn right and cross Rhode Island Ave., which is a 4-lane street. It is like a print letter L shaped route. Pushing the button will give you enough time to cross, it will not talk. Any questions? Let me know when you're ready. I will give a signal to the camera man. OK. Go when you are ready.*"

For most of participants, the O&M specialist told them the pushbutton is located behind the wheel chair ramp and to their left.

4.3.2 Crossing with MAPS

The O&M specialist walked approximately 1/8 mile to the starting point 238 feet north of the NE corner of Rhode Island Ave. and Highway 55. The O&M specialist said the following to the participants.

"*This is the same starting point and you are facing south, Rhode Island Ave. is your parallel street. Please walk straight about 200 feet to the intersection and line up to cross turning right, use the smartphone tap once to locate the direction west, adjust the phone direction if you do not hear the correct geometry information such as 'facing west, Rhode Island Ave. 4 lanes.' Next, double tap the smartphone and listen for the phone to speak, 'walk sign is now on to cross Rhode Island Ave.' Use your hearing, useable vision and O&M techniques to cross safely. Use the phone as secondary information. Any questions? Let me know when you're ready. I will give a signal to the camera man. OK. Go when you are ready.*"

4.3.3 Instruction Given When Participant Veers

The O&M specialist only had to cue a few participants when they were veering out of the crosswalk. The O&M specialist tapped the shoulder of participants on the left side to signal walk to the left or on the right shoulder to walk towards the right.

4.4 Results from Intersection Crossing

Subjective measures were collected from pre- and post-experiment surveys. Objective measures were obtained by extracting data from the video data.

4.4.1 Self-Assessment

The participants' self-reported travel skills and navigation assistance preference participants were reported in the self-assessment questionnaires (multiple choices) prior to the field experiment. The results displayed in Figure 4-2 indicated that white cane was selected as the most preferred method of assistance (44%) followed by asking other people (26%) and using a guide dog (22%).

With regard to the travel skills of the visually impaired participants, 5 participants (28%) responded that their general sense of orientation is about average, while 12 people (66%) responded that their general sense of orientation is above (4 participants, 22%) or well above average (8 participants, 44%) as shown in Figure 4-3. For travel independence, 4 participants (22%) responded that they are average independent travelers, and 14 participants (78%) considered their independent travel skill to be above (5 participants, 28%) or well above average (9 participants, 50%) as illustrated in Figure 4-4. Figure 4-5 shows that 4 participants (22%) considered their skills in crossing signalized intersection as average, and 14 individuals (78%) considered their street crossing skills above (7 participants, 39%) or well above average (7 participants, 39%).

To summarize the self-assessment, almost all participants consider themselves to have a good sense of direction. They are independent travelers, and generally have no problem in crossing signalized intersections.

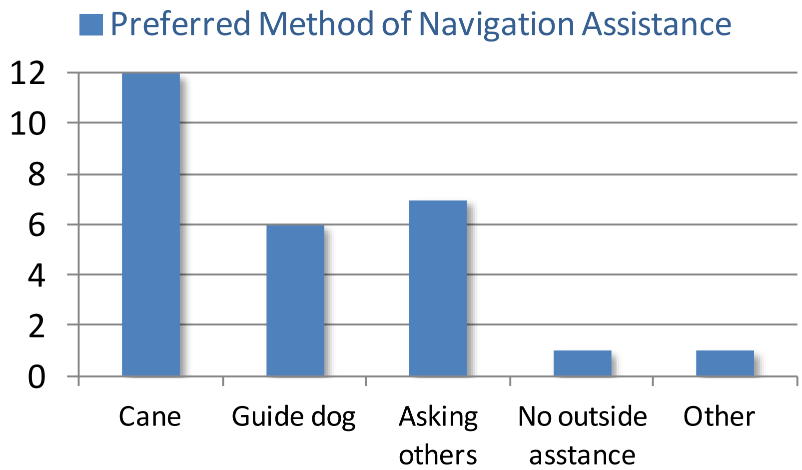

Figure 4-2 Preferred Method of Navigation Assistance

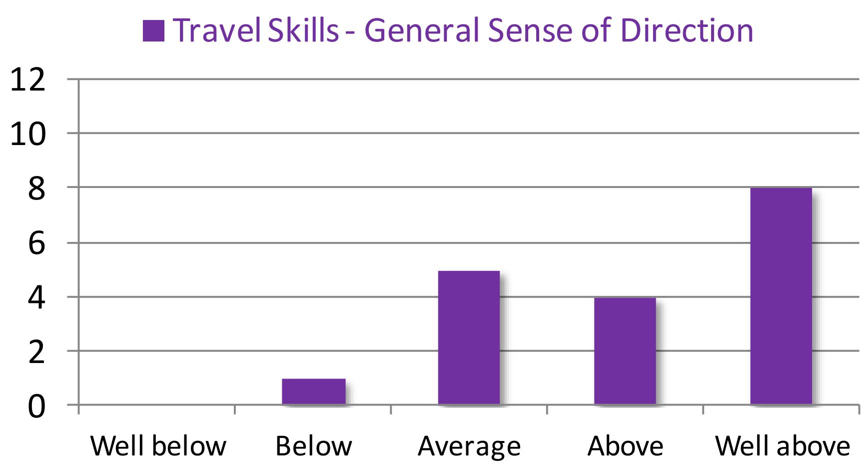

Figure 4-3 General Sense of Direction

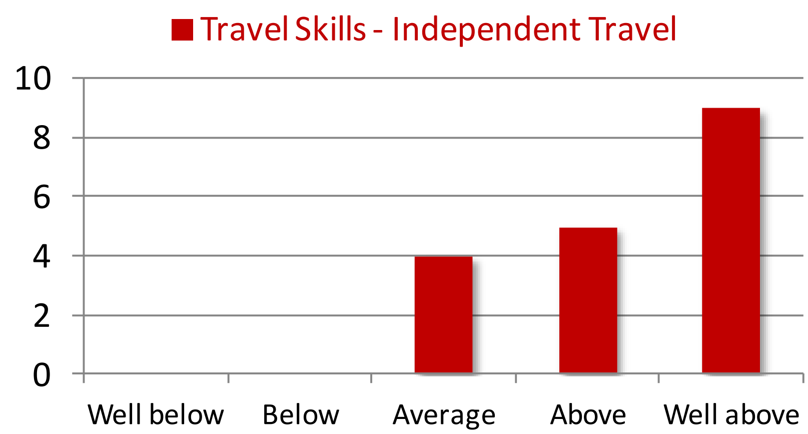

Figure 4-4 Independent Travel

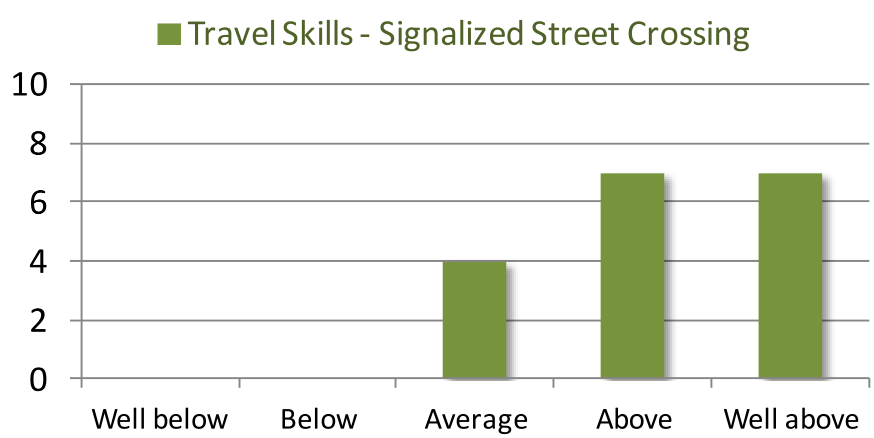

Figure 4-5 Signalized Street Crossing

4.4.2 Objective Measures

Video data collected at both intersections were analyzed to compare participants' travel speed on a sidewalk versus a crosswalk, and the time to step into the crosswalk. Table 4-1 lists the objective measures for both intersections. Crossing task #1 was performed at intersection #1 where APS is present. Crossing task #2 and #3 were conducted at intersection #2 where no APS is installed. The participants were asked to perform crossing task #2 using the existing pushbutton at the intersection, and task #3 using our MAPS app.

As listed in Table 4-1, the crosswalk length at intersection #1 (APS equipped) and #2 are 94 ft (28.7 meter) and 111 ft (33.8 meter), respectively. The APS pushbutton is required at intersection #1, operated under actuated signal control plan, to call for a walk signal. At intersection #2, participants were asked to use the existing pushbutton to request crossing in the first task and then to use our beacon for a crossing request and assistance for the second crossing. The participants' travel speed on the sidewalk (2.5 mph) was slower (statistically significant) than the speed on the crosswalk (2.9 mph) using a paired t-test (p-value = 0.01). However, the travel speed difference on the sidewalk and crosswalk at intersection #2 was not significant using a paired t-test (p-value = 0.06 and 0.77, respectively).

On average, the visually impaired participants spent 7.8 seconds (SD 6.1 sec) in searching for the APS pushbutton at intersection #1. The standard deviation is large, mostly due to the difference of participant's personal mobility skill to locate the pushbutton by listening to the beeping tone from the APS. At intersection #2, where no pushbutton-locating tone is available for visually impaired pedestrians, the participants spent 26.6 seconds (SD 56.5 sec), on average, to locate the regular pushbutton. The pushbutton stub pole at intersection #2 is located behind the ADA ramp; it took several participants more than 2 minutes to locate the pushbutton. Four participants veered outside the crosswalk path at both intersections. The research team also observed that guide dog can easily be distracted by people close by and thus guided the visually impaired participant toward a person nearby. For example, two guide dogs led the participants toward the camera man during the last quarter of the crosswalk instead of staying on the crosswalk path.

Table 4-1 Comparison of Objective Measures for 3 Experiments

Intersection ID	1	2	
Intersection Type	**APS**	**Non APS**	
Crosswalk Length, meter (ft)	28.7 (94)	33.8 (111)	
Crossing Task #	1	2	3
Sample Size (N)	18	17	17
Ped Call	APS Pushbutton	Regular Pushbutton	MAPS
Crosswalk Speed, Average (mph)	**2.91**	**3.36**	**3.33**
Crosswalk Speed, SD (mph)	0.44	0.82	0.60
Sidewalk Speed, Average (mph)	**2.54**	**3.11**	**3.30**
Sidewalk Speed, SD (mph)	0.37	0.54	0.64
Sidewalk vs. Crosswalk Speed Comparisons (p-value)	0.01	0.06	0.77
Pushbutton Search Time, Average (sec)	**7.8**	**26.6**	NA
Pushbutton Search Time, SD (sec)	6.1	56.5	NA
In-Position Time, Average (sec)	**14.5**	**34.8**	**9.8**
In-Position Time, SD (sec)	7.5	57.2	6.7
Time to Step Into Crosswalk, Average (sec)	**3.1**	**7.1**	**5.5**
Time to Step Into Crosswalk, SD (sec)	1.5	4.7	3.2
Number of Veers Outside Crosswalk	4	2	4

The in-position time is defined as the time duration from the participant passing the pushbutton pole to a waiting location at the beginning of the crosswalk. The average in-position time at intersection #1 was 14.5 sec (SD 7.5sec). At intersection #2, the average in-position using MAPS system was 9.8 sec (SD 6.7 sec) as compared to the average in-position time of 34.8 sec (SD 57.2) while using a regular pushbutton. The MAPS allows the visually impaired users to orient and position themselves in the ready position at the beginning of a crosswalk when there is no need to find the pushbutton.

At intersection #1, the average time to step into the crosswalk is about 3.1 seconds (SD 1.5 sec). At intersection #2 without the APS beacon, participants wait about 7.1 seconds (SD 4.7 sec) to step into the crosswalk. Without audio notification of when the walk sign is on, the visually impaired pedestrians usually have to listen to the sound from parallel traffic surges. In the experiment, the participants were asked to cross in parallel to Highway 55, which is a busy state highway with Annual Average Daily Traffic (AADT) of 33,500 vehicles (See intersection layouts and the signal controller timing plan in Appendix C). The average time for the visually impaired participants to step into the crosswalk at a non-APS equipped intersection will vary depending on the parallel traffic because the visually impaired travelers were taught to judge possible time to cross by listening to the traffic.

When using the MAPS system, the participants waited on average about 5.5 seconds (SD 3.2 sec) to step into the crosswalk. This is about 2.5 seconds longer than the time observed at an APS intersection (#1). The extra two seconds is probably incurred by, (a) the data communication between the smartphone app and the signal controller (1 sec), and (b) the announcement duration of 'walk sign is ON, xx seconds left' from the smartphone app when users were trying to listen and understand what the message meant before stepping into the crosswalk. In addition, the visually impaired pedestrians are more familiar with existing APS system and messages. The APS system has a simple message type (e.g., ‘wait’ or ‘walk’) that may contribute to the shorter step-into-crosswalk responding time. We expect the average step-into-crosswalk time will drop when users are more familiar with the MAPS system. Detail objective measures derived video data are included in Appendix D.

4.4.3 Subjective Measures

Intersection #1 and #2 are couple blocks away. However, the geometry layout for both intersections is similar. Intersection #1 is equipped with APS system to assist the visually impaired with street crossing. Intersection #2 uses a regular pushbutton to request crossing.

Intersection #1

Survey results from intersection #1 were analyzed and are listed in Table 4-2. Most of the participants (89% or 16 out of 18) do not use any GPS beacon for navigation. 16 participants had experienced intersection crossing using an APS beacon previously. At the APS equipped intersection, participants (94% or 17 out of 18) preferred the pushbutton to activate the walk signal request. 14 participants did not have difficulty in locating the pushbutton. However, 3 participants had difficulty locating the button during busy traffic. Most of the participants (11) felt that the APS system provide sufficient information to support their street crossing task. Two participants commented that the audible message was announced in all directions when the walk sign is on and the APS system does not provide street width (e.g., number of lanes) information. 11 participants

(61%) felt the length of the walk phase is sufficient, but the other 7 participants (39%) indicated they would need more time for the walk signal. 14 participants felt they were aligned at the beginning of their crossing. Four individuals veered outside the crosswalk path during the crossing task #1 (See last row of Table 4-1).

Table 4-2 Intersection #1 Survey Responses

Intersection #1 Responses	No	Yes	Don't Know
Use GPS Navigation Previously	16	2	0
Have Prior APS Experience	2	16	0
Prefer Pushbutton (PB) over No PB	1	17	0
Have Difficulty in Locating PB	14	3	1
APS Provides Sufficient Info	2	16	0
Have Sufficient Time to Cross	7	11	0
Feel Aligned to Crosswalk	2	14	2

Intersection #2

Survey responses from the second intersection were analyzed and are listed in Table 4-3. Most of the participants (11 or 65%) preferred not to locate the pushbutton as compared to using the smartphone to activate the walk signal request automatically. 8 participants (47%) had difficulty in locating the pushbutton because of the non-standardized pushbutton location. Most participants (15 or 88%) reported that the existing crossing time is sufficient. 15 participants aligned themselves well at the beginning of the crosswalk; however, 2 participants wavered off the crosswalk during the crossing task #2 (see last row of Table 4-1).

During the crossing task #3 while using the MAPS system at intersection #2, a few participants experienced unreliable GPS signals that led to their being confused with the result of MAPS. Due to a poor GPS signal, MAPS considered that the participant was already on the other side (NW corner) of the intersection. The inconsistent GPS positioning solution caused the MAPS to provide incorrect information. Subjective measures in the following discussion included users' comments while using the MAPS with incorrect GPS positioning.

As compared to the two crossing tasks at intersection #2, eleven participants felt (65%) the MAPS system provide sufficient information, 14 (82%) people responded that MAPS provides helpful geometry information, but only 10 participants (59%) felt the MAPS provides helpful signal information.

Table 4-3 Intersection #2 Survey Responses

Intersection #2 Responses	No	Yes	Don't Know
Prefer Pushbutton over MAPS	11	4	1 - Both 1 - Neither
Have Difficulty in Locating Pushbutton	9	8	0
Have Sufficient Time to Cross	2	15	0
Feel Aligned to Crosswalk	2	15	0
MAPS Provides Sufficient Info	6	11	0
MAPS Provides Helpful Geometry Info	3	14	0
MAPS Provides Helpful Signal Timing Info	6	10	1

Note: One participant did not show up at the second intersection.

4.4.4 Usability and Acceptance

In addition to the objective and subjective measures discussed in previous sections, we also would like to evaluate the usability and acceptance of the MAPS to the participants. We use a reliability index, Cronbach Alpha, to measure the consistence of feedback from the participants. The Cronbach's Alpha (α), a coefficient of reliability, is commonly used as a measure of internal consistency and reliability of a psychometric test score for a sample of subjects (Cronbach, 1951). It describes how closely related a set of items are as a group. Cronbach's Alpha (α) is defined as follows.

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{K}\sigma_{Y_i}^2}{\sigma_X^2}\right) \quad (4\text{-}1)$$

Where,

K is the number of components, items or testlets,

σ_X^2 is the variance of the observed total test scores, and

$\sigma_{Y_i}^2$ is the variance of component *i* for the current sample of subjects.

In general, a test with a Cronbach's Alpha (α) of 0.85 indicates the test is 85% reliable in practice. A commonly accepted rule of thumb for describing internal consistency using Cronbach's Alpha (α) is listed in Table 4-4 (George & Mallery, 2003). Results from the usability and satisfaction questionnaire among the 17 visually impaired participants have a Cronbach's Alpha (α) value of 0.96, a relatively high internal consistency and reliability.

Table 4-4 Cronbach's Alpha Values for Internal Consistency

Cronbach's Alpha	Internal Consistency
$\alpha \geq 0.9$	Excellent
$0.9 > \alpha \geq 0.8$	Good
$0.8 > \alpha \geq 0.7$	Acceptable
$0.7 > \alpha \geq 0.6$	Questionable
$0.6 > \alpha \geq 0.5$	Poor
$0.5 > \alpha$	Unacceptable

Van der Laan et al. (1997) developed a simple procedure to measure the perceived satisfaction and usefulness of a new system. The technique consists of nine items rated on a 5-point adjective scale. These scales are summed to generate separate scores for the perceived satisfaction and usefulness measures. In the survey listed in Appendix B.2, the score of individual item ranges from -2 to 2. Survey question 3, 6, and 8 are mirrored as compared to the other questions. The usability score is calculated as the average of item 1, 3, 5, 7, and 9. The satisfaction score is computed as the average of item 2, 4, 6, and 8. Survey results from each participant on usability and acceptance are listed in Table 4-5.

Table 4-5 Usability and Satisfaction Survey Results

Question #		1	2	3	4	5	6	7	8	9		
Subject ID	Guidance Type (Dog/Cane)	Useful	Pleasant	Good	Nice	Effective	Likeable	Assisting	Desirable	Raising Alertness	Usefulness (1,3,5,7,9)	Satisfying (2,4,6,8)
6	Dog	2	2	0	2	0	2	0	1	2	0.8	1.8
8	Cane	0	0	0	0	-1	0	0	0	0	-0.2	0.0
26	Cane	2	2	1	2	0	2	2	1	1	1.2	1.8
13	Dog	2	1	1	1.5	2	2	2	1	1	1.6	1.4
23	Cane	2	2	2	2	2	2	2	2	2	2.0	2.0
27	Cane	1	2	-1	1	0	1	0	1	1	0.2	1.3
4	Cane	2	2	0	2	0	2	2	2	2	1.2	2.0
21	Cane	1	0	0	0	2	0	1	2	2	1.2	0.5
2	Cane	1	2	1	2	1	2	2	1	2	1.4	1.8
18	Dog	0	-2	-1	-2	-1	-1	0	-1	1	-0.2	-1.5
17	Cane	1	2	2	2	2	2	2	2	1	1.6	2.0
10	Cane	2	2	2	2	2	2	2	1	2	2.0	1.8
19	Cane	2	1	1	1	1	2	2	2	2	1.6	1.5
15	Dog	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2.0	-2.0
12	Cane	2	2	2	2	2	2	2	2	2	2.0	2.0
16	Cane	2	2	2	2	2	2	2	2	1	1.8	2.0
1	Cane	0	NA	0	-2	-1	-2	0	NA	1	0.0	-2.0
AVERAGE		1.18	1.13	0.59	0.91	0.65	1.06	1.12	1.06	1.24	**0.95**	**1.04**

Note: NA – Participant did not answer

As shown in Table 4-5, the average scores for the perceived satisfaction and usefulness are 1.04 and 0.95, respectively. The results indicate that the participants are moderately satisfying with the MAPS prototype system. Out of the 17 subjects, 13 participants (76%) felt the MAPS is useful to assist intersecting crossing. Results of the usability questionnaire indicated that the visually impaired participants considered the MAPS to be moderately useful and satisfying to use as shown in Figure 4-6.

As shown in Figure 4-6, four participants (data with negative values in the lower left quadrant of Figure 4-6) rated the MAPS unsatisfying or less useful. We learned that these 4 participants experienced unreliable GPS signals that led to their being confused with the result of MAPS during the crossing task #3. Due to a poor GPS signal, MAPS considered that the participant was already on the other side of the intersection. The inconsistent GPS positioning solution caused the MAPS to provide incorrect information. We plan to incorporate Bluetooth beacons at each corner of an intersection to reliably determine a pedestrian's location and provide the correct signal timing information at the right location. More discussion about using the Bluetooth for positioning is presented in Chapter 5.

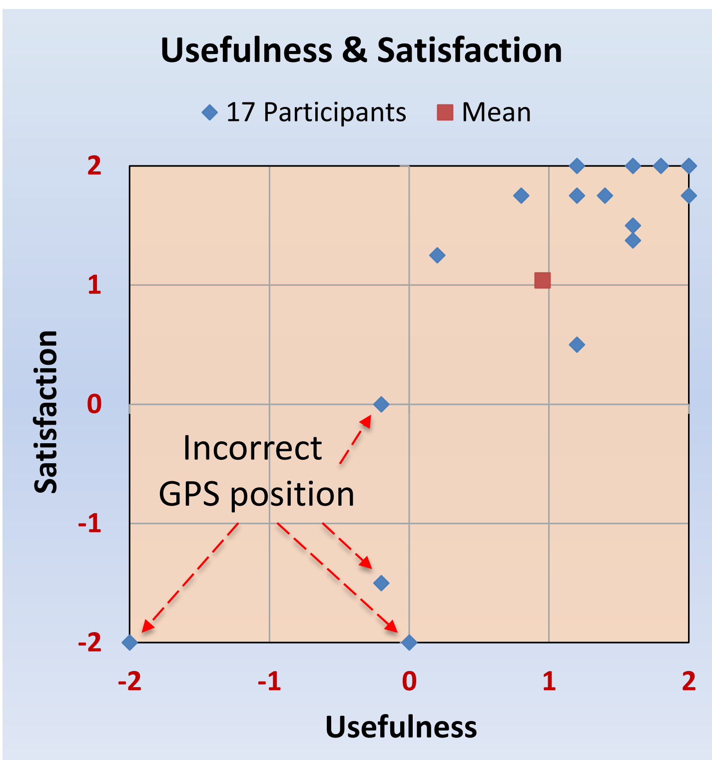

Figure 4-6 System Usability and Acceptance

Additional comments (in *italic* type) from the participants and responses from the research team are listed as follows.

"*Like the beacon. Feel it will be helpful.*", "*Like the automation of pushbutton.*"

"*Not sure how system would react when touch it while crossing.*"

The MAPS system announces corresponding direction and geometry information when a single tap is performed.

"*Louder.*", "*No crispy sound when crossing w/o mobile beacon.*"

The speaker volume was turned to the highest. However, due the traffic noise at busy intersection, it may be difficult to hear the auditory message. Possible alternatives are to, (1) bring the phone closer to one's ears after performing single or double tap on the screen in desired direction, (2) use a Bluetooth ear bud in one ear, or (3) use a Bluetooth micro portable speaker that can be attached to the collar of a traveler's shirt.

"*Make it hands free.*"

Potential solution is to wear the smartphone around neck using a strap with a phone holder.

“*Make it vibrate more often while crossing.*”, “*User configurable settings.*”, “*Provide alignment and wavering info.*”

These will be on our to-do list for next generation of MAPS.

“*Wrong info.*”

The MAPS was confused by incorrect GPS positioning information. Bluetooth geo-ID is needed to ensure 100% positioning reliability.

4.4.5 Trust and Confidence

In addition to the usability and acceptance measures discussed in previous sections, we also would like to evaluate participants’ trust and confidence while using the MAPS for crossing intersections. We use the trust and confidence measures developed by Lee & Moray (1992). The trust questionnaire (Appendix B.3) was used to measure different dimension of trust: purpose, process, performance, and overall trust (Lee & Moray, 1992). Questions 1 and 4 deal with performance, question 2 and 5 deal with process, question 7 and 8 deal with purpose, question 3 and 9 are overall questions, and question 6 deals with confidence. As shown in Figure 4-7, the performance index measures the expectation of consistent, stable and desirable performance of the system. The process index represents the understanding of underlying qualities that govern the system behavior. The purpose index is the underlying motives or intent of the system. Survey results on system trust and confidence are shown in Figure 4-7.

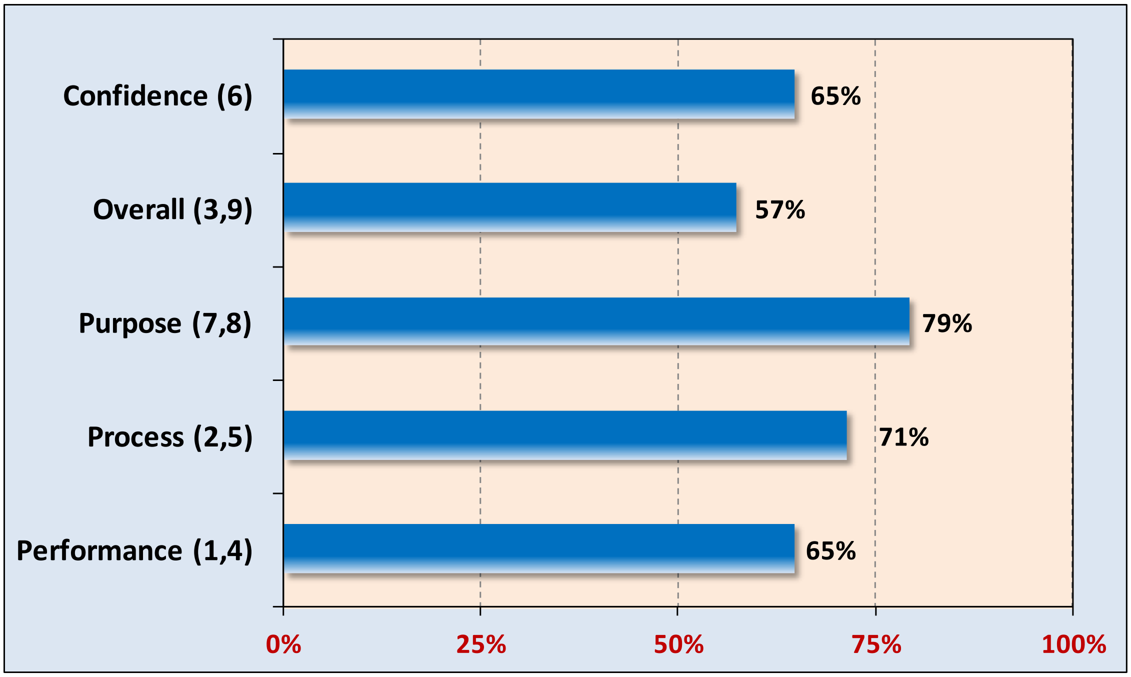

Figure 4-7 System Trust and Confidence

On average, the participants reported 65% of trust in system performance and confidence. Participants reported 79% and 71%, respectively, in understanding the purpose of the system and its underlying behavior. In overall, the visually impaired participants reported 57% of system trust. The survey results regarding system trust and confidence are not as good as expected (90% or higher). However, we feel this is acceptable for a prototype system, particularly when they receiving only 15 minutes of training on how to using the MAPS app.

Additional comments (in *italic* type) from the participants are listed as follows.

- "*Cool and nice to use.*"
- "*Told a couple of people about it.*"
- "*Like the idea of the project and very supportive of this idea.*"

- "*A well done job.*"
- "*System was slow.* "
- "*Not fair to evaluate for only using for 5-min*."
- "*Not sure how it turns on.*"
- "*It took multiple attempts.*"
- "*Need better volume*."

4.4.6 Lessons Learned

Through our interaction with the O&M specialists and the visually impaired during the field experiments, we learned that,

1) Guide dog can be distracted by O&M specialist or other research team member nearby the intersection.
2) The single- and double-tap user interface may seem relatively easy for the visually impaired participants. However, 15-minute of tutorial on how to properly use the beacon may not be sufficient for some participants. There is still a learning curve for some users to understand how the system works. For example, in order to hear the auditory message clearly at a busy intersection, the participants usually point the phone to a desired direction and immediately bring the phone to their ears before the orientation measurement from the digital compass is stabilized.
3) The system was tested at experiment site for several without GPS signal reception issue. However, a few participants experienced incorrect GPS solution due to the fact that the MAPS app was confused by the user's actual location. A Bluetooth

beacon is needed to reliably identify a user's location at an intersection.

4) In the future, design the experiment to evaluate participants' performance 3-month later. This is to evaluate the usefulness of the MAPS system and user's knowledge retention in learning new technology.

4.5 Work Zone Bypass Routing

We learned from the street crossing experiments that the GPS solution is not always reliable even in an open sky. It is absolutely important to provide correct information to people with vision impairment at the right locations. In order to reliably identify a pedestrian's location, we incorporate the Bluetooth technology on smartphones and use cost-effective Bluetooth beacons that can be placed in an environment. The Bluetooth beacons will serve as geo references when detected by the MAPS app. A geo-spatial database that includes the Bluetooth beacon information was incorporated into the MAPS. The repeatability of the Bluetooth communication range was tested and system validation at two sidewalk construction sites were performed and presented as follows.

4.5.1 Bluetooth Communication Range

<u>Bluetooth 2.0 with Extended Data Rate (EDR)</u>

A Bluetooth 2.0 with Extended Data Range (EDR) module operating in a receiving mode was programmed and installed at the corners of an intersection to serve as a geo-reference tag which can be detected by the work zone smartphone app to identify a user's location. When operating in the receiving mode, the Bluetooth module consumes minimal power ranging from 15 to 50 milliwatts (mW). The Bluetooth module can be either connected to the battery of a barricade flasher or operated using a very small solar panel. Currently, the Bluetooth beacon prototypes were powered by 3 AA batteries. A prototype and its enclosure are displayed in Figure 4-8.

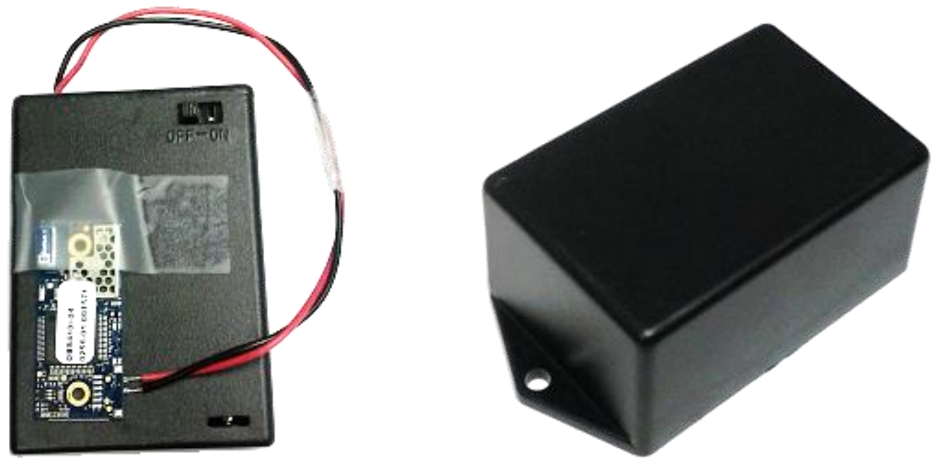

Figure 4-8 Bluetooth Beacon (2.0+EDR) and Enclosure (78mmX50mmX38mm)

In order to reduce the power consumption and to avoid coverage overlap among Bluetooth beacons, the antenna range of the OBS410i Bluetooth module (typically 246 to 496 feet, or 75 to 150 meters) used in our experiments was programmed (AT*AMMP = 100, see Appendix E for details on the AT*AMMP command) to cover a smaller area such as a 5 meter radius.

Figure 4-9 illustrates the configuration for testing the Bluetooth beacon in four different directions. Table 4-6 lists the results from tests of the Bluetooth communication ranges when the smartphone detects the Bluetooth beacon. The average communication distance when approaching the Bluetooth beacon from the left direction is 4.9 feet (1.5 m) with a standard deviation of 1.8 feet (0.5 m). The average communication distance when approaching the Bluetooth beacon from the right direction is 8.7 feet (2.7 m) with a standard deviation of 5.5 feet (1.7 m). The average communication distance in front of the Bluetooth beacon is 8.7 feet (2.7 m) with a standard deviation of 3.3 feet (1 m). The average communication distance in the rear direction of the Bluetooth beacon is 13.1 feet (4 m) with standard deviation of 6.3 feet (1.9 m).

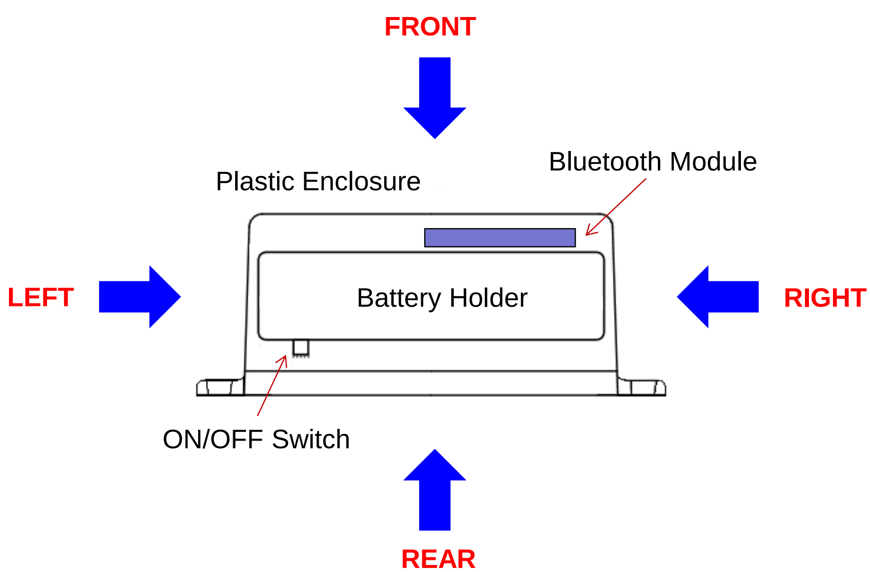

Figure 4-9 Configuration of Bluetooth Communication Range Testing

Table 4-6 Test Results of Bluetooth Communication Range

Approach	Trial	1	2	3	4	5	6	7	8	9	10	AVG	SD
LEFT	Range (ft.)	3	5	2	6	4	5	8	4	7	5	4.9	1.8
RIGHT		7	11	3	1	12	17	17	9	5	5	8.7	5.5
FRONT		8	10	11	14	12	7	10	7	3	5	8.7	3.3
REAR		9	10	9	15	7	7	23	19	9.5	22	13.1	6.2

We worked with MnDOT and the City of St. Paul to identify pedestrian work zones for our tests. The objective is to verify the effectiveness of using Bluetooth beacons as geo-references to provide location based messages to the visually impaired while navigating around a work zone. The experiments tested the reliability of the Bluetooth beacon detection and communication between the Bluetooth message database and the MAPS app.

4.5.2 Construction Site #1

As illustrated in Figure 4-10, the north sidewalk along the Martin Luther King Boulevard was closed as a result of temporary parking lot construction in the north mall area. Four Bluetooth beacons were each attached to a street light post near the junction of the crosswalk and sidewalk in each corner as shown in Figure 4-11. Audible messages associated with each Bluetooth beacon were programed as follows.

BT#1 Message

Attention eastbound Martin Luther King Boulevard pedestrians.

You are at the north side of Martin Luther King Boulevard.

Sidewalk is closed on this side for 100 feet.

Cross Martin Luther King Boulevard for additional information about bypass.

BT#2 Message

Attention eastbound Martin Luther King Boulevard pedestrians.

You are at the south side of Martin Luther King Boulevard.

Sidewalk on the other side is closed for 100 feet.

Use sidewalk on this side.

BT#3 Message

Attention westbound Martin Luther King Boulevard pedestrians.

You are at the south side of Martin Luther King Boulevard.

Sidewalk on the other side is closed for 100 feet.

Use sidewalk on this side.

BT#4 Message

Attention westbound Martin Luther King Boulevard pedestrians.

You are at the north side of Martin Luther King Boulevard.

Sidewalk is closed on this side for 100 feet.

Cross Martin Luther King Boulevard for additional information about bypass.

A sighted research student was informed to start at a location about 100 feet west of the Bluetooth beacon #1 (BT1 as shown in Figure 4-10) walking toward the sidewalk closure site during the construction period. The validation result confirms that the smartphone vibrated for about 1 second and announced the corresponding audible message to the traveler as he or she was walking toward a Bluetooth beacon located about 15 feet away. The person was informed to follow each audible message to bypass the work zone closure area through the suggested path (BT1 → BT2 → BT3 → BT4). The right photo in Figure 4-11 illustrates a pedestrian approaching the sidewalk construction site #1 using the app we developed.

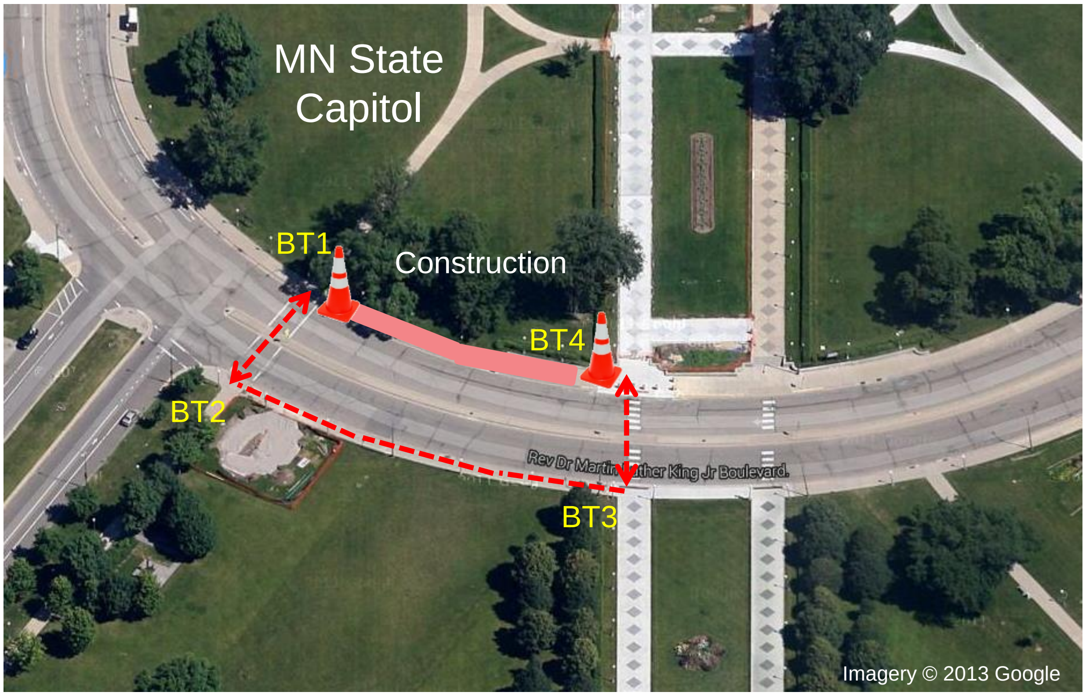

Figure 4-10 Test at State Capitol North Construction Site – N. sidewalk closed (Background Image from Google Inc.)

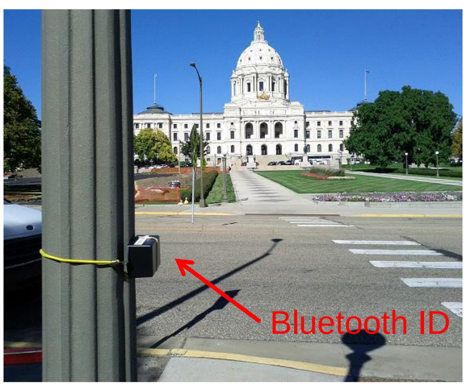

Figure 4-11 Installation of Bluetooth Beacon at Field Test Site (N. Sidewalk)

4.5.3 Construction Site #2

As illustrated in Figure 4-12, the south sidewalk along the Martin Luther King Boulevard was closed for another parking lot construction after the north sidewalk reopened. Four Bluetooth beacons were each attached to a light post near the junction of the crosswalk and sidewalk in each corner as displayed in Figure 4-13. The four Bluetooth beacons were placed at the same locations as in the north sidewalk closure scenario. Audible messages associated with each Bluetooth beacon were reprogramed as follows.

BT#1 Message

Attention eastbound Martin Luther King Boulevard pedestrians.

You are at the north side of Martin Luther King Boulevard.

Sidewalk on the other side is closed for 100 feet.

Use sidewalk on this side.

BT#2 Message

Attention eastbound Martin Luther King Boulevard pedestrians.

You are at the south side of Martin Luther King Boulevard.

Sidewalk is closed on this side for 100 feet.

Cross Martin Luther King Boulevard for additional information about bypass.

BT#3 Message

Attention westbound Martin Luther King Boulevard pedestrians.

You are at the south side of Martin Luther King Boulevard.

Sidewalk is closed on this side for 100 feet.

Cross Martin Luther King Boulevard for additional information about bypass.

BT#4 Message

Attention westbound Martin Luther King Boulevard pedestrians.

You are at the north side of Martin Luther King Boulevard.

Sidewalk on the other side is closed for 100 feet.

Use sidewalk on this side.

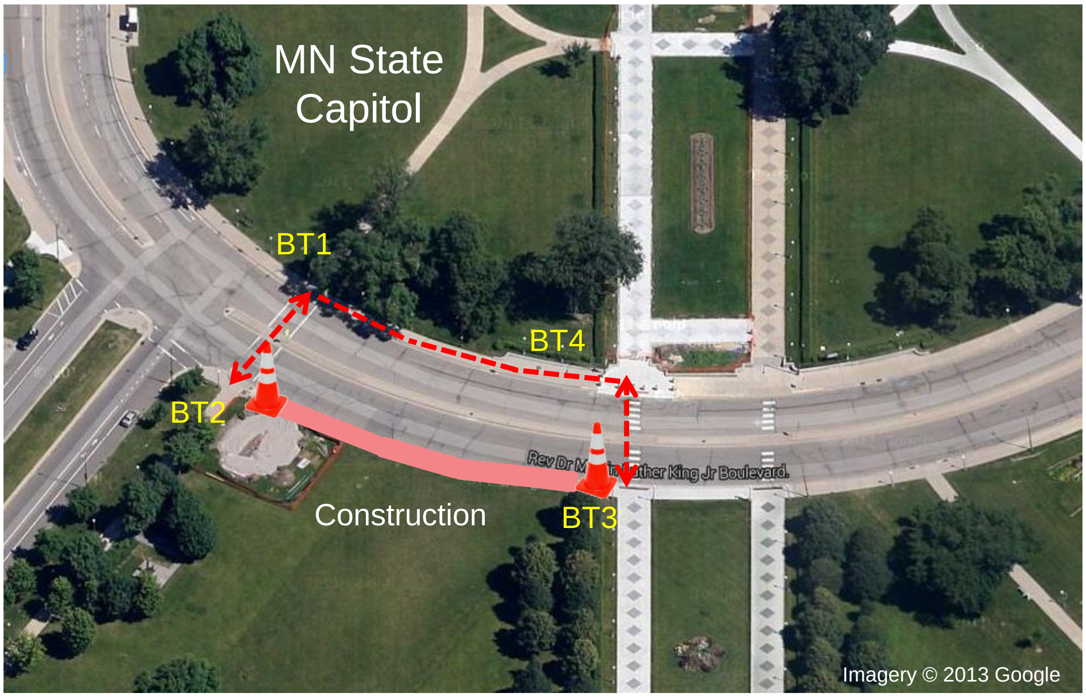

Figure 4-12 Test at State Capitol South Construction Site – S. Sidewalk Closed (Background Image from Google Inc.)

Figure 4-13 Installation of Bluetooth Beacon at Field Test Site (S. Sidewalk)

A research student was informed to start at a location about 100 feet south of the Bluetooth beacon #2 (BT2 as shown in Figure 4-12) walking toward the sidewalk closure site during the construction period. The validation result confirms that the smartphone vibrated for about 1 second and announced the corresponding audible message to the traveler as the person was approaching each Bluetooth beacon about 15 feet away. The test subject then followed each audible message to bypass the construction closure through the suggested path (BT2 → BT1 → BT4 → BT3).

4.6 Summary

In this chapter, we described the design of street crossing experiments at two signalized intersections. The experiments involving 18 visually impaired participants and an orientation and mobility (O&M) instructor were conducted at two signalized intersections in Golden Valley, MN. After basic training, the participants were asked to perform street crossing task twice at one of the two intersections with and without using the MAPS system. A set of subjective and objective performance measures were derived from video data to validate system performance, and measure the acceptance and usefulness of the MAPS.

Our results indicated that the MAPS enables the visually impaired users to orient and position themselves quickly in the ready position at the beginning of a crosswalk when there is no need to find the pushbutton. We also observed that guide dog can easily be distracted by people close by and thus guided the visually impaired participant toward a person nearby. When using the MAPS system, the participants waited on average about 2.5 seconds longer than the time observed at an APS intersection to step into the crosswalk. The extra two seconds is probably contributed by, (a) the data communication between the smartphone app and the signal controller (1 sec), and (b) the announcement duration of '*walk sign is ON, xx seconds left*' from the smartphone app when users were trying to listen and understand what the message meant before stepping into the crosswalk. We expect the average step-into-crosswalk time will drop when users are more familiar with the MAPS system.

We learned that guide dogs can be distracted by an O&M specialist or other research team member near the intersection. The single- and double-tap user interface may seem relatively easy for the visually impaired participants. However, there is still a learning curve for some participants to understand how the system works. We also learned from the street crossing experiments that the GPS is not always reliable even when the sky is open. In order to reliably identify a traveler’s location, we incorporated the Bluetooth technology on smartphones and programmed Bluetooth beacons that can be placed in an environment to reliably identify a pedestrian’s location. Work zone experiments were conducted to validate the MAPS using Bluetooth beacons as geo references when GPS solution is not reliable. Results from the work zone experiments indicated that the MAPS successfully detects Bluetooth beacons in a work zone and correctly announces the corresponding message associated with each Bluetooth beacon to alert the travelers.

When Bluetooth beacons are placed at an intersection or in a work zone, it is important to ensure that the beacons remain at their original locations and function properly. We need a self-aware infrastructure that the beacons can monitor their neighboring peers and detect a change of a BLE beacon when it is removed or disappears (e.g., due to vandalism or lost power) from a network. The development of a self-monitoring infrastructure is discussed in the following chapter.

CHAPTER 5 A SELF-MONITORING INFRASTRUCTURE

In Chapter 3, we discussed a smartphone based system to assist the visually impaired navigate streets. And in Chapter 4, we showed how the visually impaired are misled if the position information is not sufficiently accurate. The assistive information is only useful if the visually impaired can trust the information that it is valid and robust. A satellite based position solution on a smartphone is not always accurate for pedestrian navigation, particularly when a user is traveling in a GPS-denied environment (e.g., an urban canyon). Our experiments showed that there were position localization problems with smartphones even where no buildings were nearby. We need a more reliable position sensing and a "self-aware" infrastructure--i.e., a system that can self-monitor and make sure that the information provided is up-to-date.

We propose a method that provides more reliable sensing as to where a pedestrian is positioned. This method uses the ability of a smartphone with Bluetooth to sense the proximity of Bluetooth modules, and their ability to sense each other. Typical location estimation schemes includes triangulation, computer vision based scene analysis, proximity, and fingerprinting. This chapter first focuses on developing algorithms for ranging estimation based on the received Bluetooth signal strength. Multi-regression and triangulation methodologies are used to explore a positioning solution. A Statistical Process Control (SPC) method and several wireless signal fingerprinting techniques are also presented to monitor any changes of relative distance among beacons in a local Bluetooth network. We then discuss the analysis results from using positioning and infrastructure monitoring methodologies based on the Received Signal Strength

Indication (RSSI) measurements from Bluetooth Low Energy (BLE) beacons.

We developed a standalone Bluetooth smart beacon based on a commercial off-the-shelf (COTS) BLE module. Commercially available BLE beacons in the market usually operate in the “advertising” mode. The “advertising” mode of operation is a one-way discovery mechanism that allows a BLE to be discovered by a scanning device (such as a smartphone). As opposed to the “advertising” mode of operation, we reprogramed the BLE beacons to alternate its operation between scanning (master) and advertising (slave) modes for our self-aware infrastructure. After reprogramming the firmware, these BLE beacons can monitor their neighboring peers and detect when other beacons are not functioning or have been removed or vandalized. To monitor infrastructure and ensure information integrity, statistical methodologies were developed based on the Bluetooth received signal strength indication (RSSI) for positioning and self-monitoring.

The system block diagram of the self-aware infrastructure is illustrated in Figure 5-1. A Multivariable Regression (MR) model (described in section 5.4.1) is used to model the range and Bluetooth Received Signal Strength Indication (RSSI) relationships among BLE tags, forming a model of the geometric relationship of the BLE network. The MR model takes the RSSI as input and finds optimal weighting parameters that best describe the geometry relationship of the BLE network. A Singular Value Decomposition (SVD) technique (discussed in section 5.4.2) is introduced to remove RSSI range noise to estimate the range from a smartphone to other BLE tags. It takes the weighting from the MR model as input and generates range estimates. An Extended Kalman Filter (EKF), described in section 5.5, is formulated to determine the position of a user's smartphone. The EKF takes the range estimates from the MR and SVD combined model to determine the location of a smartphone with respect to a selected local coordinate system.

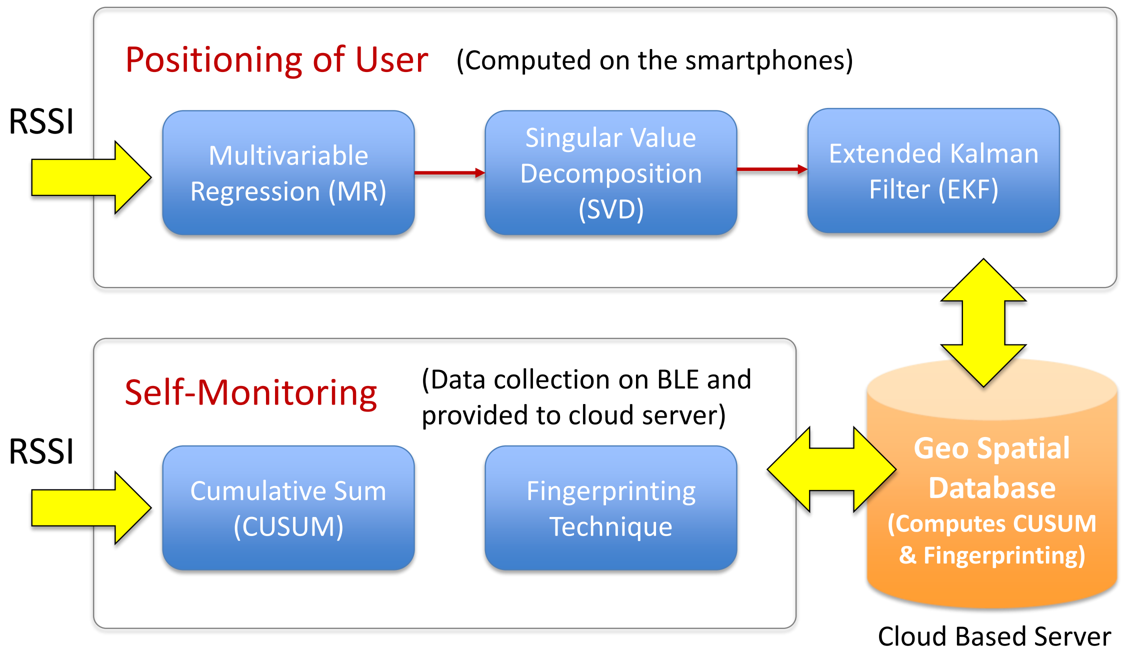

Figure 5-1 System Block Diagram of a Self-Aware Infrastructure

For positioning the user, we investigated several methodologies to find a more robust positioning solution to identify a user's relative location near an intersection. For self-monitoring, a statistical process control technique, called Cumulative Sum (CUSUM), is implemented to monitor if the location of one or multiple BLE beacons in a network is changed based on Bluetooth RSSI measurements. In addition, two wireless signal fingerprinting techniques, based on the Jaccard and Normalized Weighted Signal Level Change (NWSLC) indices, are introduced to detect geometry changes of a BLE network.

A crowdsourcing approach was used to update the status of BLE beacons and update BLE messages associated with each beacon. That is, the RSSI network information and corresponding messages of beacons in a BLE network are updated through the available wireless communication on a user's smartphone.

5.1 Introduction

Most of the BLE beacons on the market are pre-programmed to pair up with a smartphone app for a specific application. The BLE beacons operate in broadcasting mode, which means they are waiting for a master device, such as a smartphone, to scan, detect and communicate with them. When a wireless data communication is desired between a master device (e.g., a smartphone) and a slave BLE beacon, a pairing protocol is used to establish a wireless connection for data exchange.

One key feature of our system is that we re-programed the firmware of the COTS BLE beacons to operate both as a master (central) and as a slave (peripheral). Our BLE beacon operates in the scanning mode for a few seconds to detect its neighboring devices and records the corresponding Media Access Control (MAC) ID and RSSI measurements. The BLE beacons then switches to broadcasting mode for one minute. The cycle time of switching between scanning and broadcasting modes can be configured differently to preserve battery power.

A self-monitoring sensor network refers to a class of sensor networks used for monitoring or surveillance. Algorithms have been developed for local coordination and active probing (Hsin & Liu, 2006) and for optimizing network topology (Dong et al., 2011).

For example, consider a class of Bluetooth wireless sensor network, S, which consists of n sensor nodes where $B(i) \in S \text{ } and \text{ } i \in [1, n]$. Each node, e.g., $B(i)$, is able to scan and detect its neighbor's ID, e.g., $B(j)$, and the corresponding range, $d(i, j)$, where $i, j \in [1, n] \text{ } and \text{ } i \neq j$. We use the unique Media Access Control (MAC) address of each BLE beacon as the ID and the Received Signal Strength Indication (RSSI) as a measure of range between two BLE beacons.

Figure 5-2 illustrates an example of strategic placement of proposed BLE-master beacons near a non-orthogonal intersection. Each BLE beacon is associated with a corresponding message to inform a user's location and other information at that particular location. The square dots represent the BLE beacons placed at each corner of an intersection (on light posts) or at decision locations where pedestrians may approach the intersection. The placement of the BLE beacons allows the system to form a local map using a trilateration algorithm. The relative position of the BLE beacons to each other can be monitored by the system in case a BLE beacon is malfunctioning or is removed. The audible message associated with a BLE beacon will not be available to the visually impaired pedestrian if the beacon was removed from the previously formed local map. This mapping method is used to ensure that the correct audible information (such as those related to signal timing and intersection geometry information at an intersection or wayfinding information at a skyway) is provided to users at the right location.

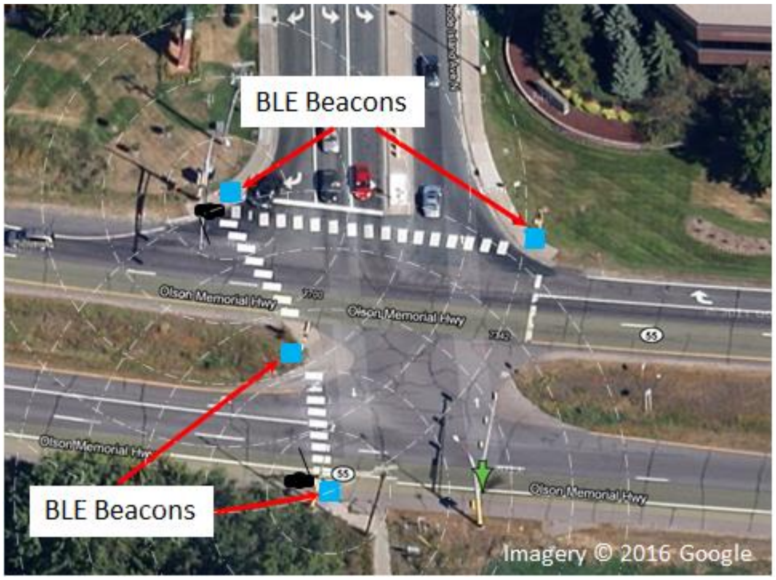

Figure 5-2 Illustration of a Self-Monitoring BLE Network at an Intersection

5.2 Using Bluetooth Beacons for Location Identification

Bluetooth technology has been used in recent years as an inexpensive and reliable way to collect travel time information on roadways (Martchouk et al., 2011). Anonymous travel time monitoring is performed by matching the unique MAC addresses of Bluetooth beacons embedded on cell phones or GPS navigation systems. Bluetooth technology uses a radio or broadcast communications system thus it does not require line of sight. However, its signal attenuation may be influenced by physical obstacles in the environment.

The GPS satellite positioning system provides relatively accurate positioning solution in an open space. However, in urban canyons or indoor environments, the position solution is unavailable or degraded due to signal strength, reflections, multipath, and other factors.

The purpose of using Bluetooth beacons as smart beacons is to identify a pedestrian's location more accurately and reliably at a decision location or a point of interest (for example, corner of an intersection, bus stop, or entrance of a building, etc.). We will discuss several scenarios for using the Bluetooth beacons for identifying a traveler's location at decision points.

For example, an outdoor scenario for a pedestrian who is blind traveling from an origin to a destination involves the following steps: (1) walk from an origin to an intersection, (2) cross the intersection to arrive at a bus stop, (3) get on the bus and travel to a destination bus stop, and (4) get off the bus and walk across an intersection prior to arriving at a destination.

In this scenario, the boarding/alighting bus stops and the intersection corners are considered as decision points equipped with Bluetooth beacons as illustrated in Figure 5-3. Smart Bluetooth beacons can be placed at intersection corners, or at key decision points near a work zone to provide more accurate position and guidance information as shown in Figure 5-4. Corresponding audible message can provide appropriate bypassing or detouring information to the visually impaired travelers.

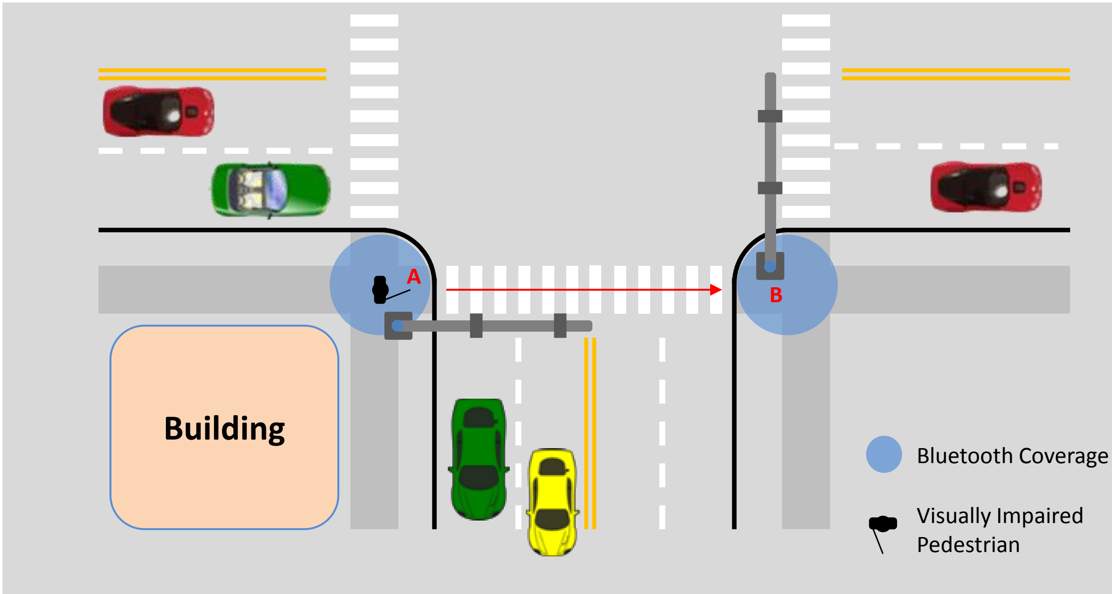

Figure 5-3 Illustration of Bluetooth Beacon Placement at an Intersection

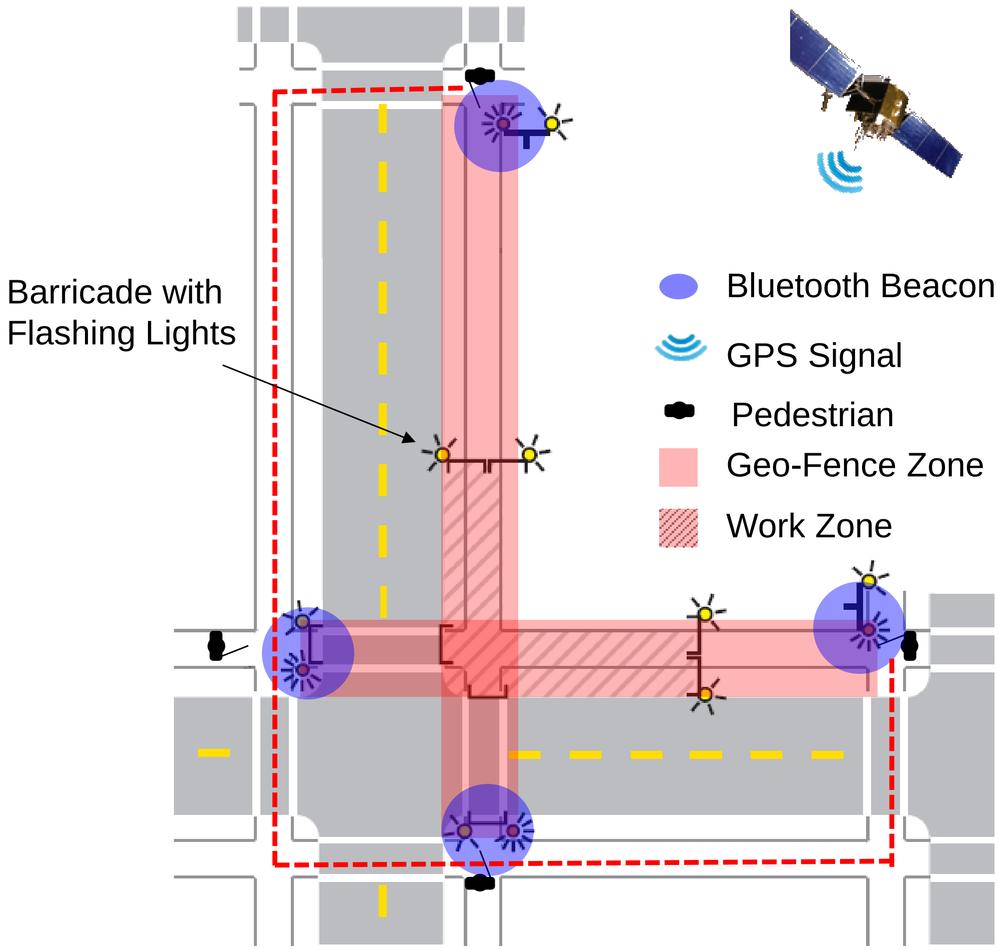

Figure 5-4 Bluetooth Beacon Placement at Decision Points around a Work Zone

A Bluetooth beacon operating in discovery or broadcasting mode can be installed at decision points to serve as geo-reference IDs which can be detected by the smartphone application to identify the user's location. When operating in the receiving mode, the Bluetooth module consumes minimal power ranging from 15 to 50 milliwatts (mW). The Bluetooth module can be either connected to the battery of a barricade flasher or operated using a very small solar panel. Figure 5-5 shows a Bluetooth Geo-ID prototype based on earlier Bluetooth 2.0 technology with Extended Data Rate (EDR) powered by a pack of 3 AA batteries.

In order to reduce power consumption and avoid coverage overlap among Bluetooth beacons, the range of the Bluetooth antenna (typically 75 to 150 meter for a classical Bluetooth 2.0+EDR module) can also be adjusted to cover a smaller area such as 5 meters radius.

Figure 5-5   A Bluetooth Beacon Prototype Powered by 3 AA Batteries

The development of new low power Bluetooth 4 technology, as shown in Figure 5-6, allows Bluetooth beacons to operate on a single “coin-style” cell battery. The low power consumption feature of Bluetooth beacons running in discovery mode for the proposed work zone application could extend the battery life significantly. The compact size of BLE beacons makes it even easier to deploy by attaching the Bluetooth beacons to barricades, traffic cones, or flashers in a work zone.

Figure 5-6 Smart Beacon using Bluetooth 4.0 Technology

5.2.1 Bluetooth Low Energy (BLE) Technology

A newer generation of smartphones on the market is now equipped with BLE technology. For example, iBeacon from Apple uses BLE technology to identify locations which trigger an action on the iPhone. According to an article "*Mobile Telephony Market*", the Bluetooth Special Interest Group (SIG)[32] predicts that more than 90 percent of Bluetooth-enabled smartphones will support the low energy standard by 2018.

BLE technology typically has a wireless communication range up to 50 meters based on line of sight, according to its specifications. (If the tag is located underneath the dash or in the car's fuse box (not within line of sight), the range is reduced.) Commercially available BLE tags are usually configured as non-paired and discoverable Bluetooth beacons. A BLE equipped smartphone App can continuously scan for BLE beacons in the environment. The BLE tag can "*broadcast*" its service name or other information. When the smartphone app receives the wireless signal from a BLE tag, it also receives a Received Signal Strength Indicator (RSSI) value with that broadcasted message. The

[32] https://www.bluetooth.com/

RSSI is used to evaluate distance from the tag. Commercially available tags are about the size of a US dollar coin. Some BLE products are even smaller. These BLE tags, primarily designed to be detected or discovered, do not communicate with each other.

5.2.2 Received Signal Strength Indication (RSSI) and Ranging

Many indoor localization methodologies using Bluetooth technology have been studied in the literature. Because of the signal noise, it is usually not a good idea to perform a distance estimate based on a single RSSI measurement. When examining the raw RSSI of beacon packets, the signal level is very noisy.

Zhu et al. (2014) modeled the RSSI values in a Gaussian distribution and introduced a weighted sliding windows filtering technique to remove the noise of the RSSI signals for indoor positioning. Their results indicate an 80 percentile position accuracy of 1.5 meters. Suárez et al. (2010) compared the performance of a Kalman filter and a gradient filter in handling the communication holes of RSSI values. However, Dong & Dargie (2012) investigated the reliability of RSSI for indoor localization. They calibrated and mapped RSSI to distance through a series of experiments. They concluded that the RSSI values give a considerable fluctuation in a mobile scenario and thus are not reliable for the indoor sensor localization.

Jung et al. (2013) used a simple low-pass filter (LPF) to reduce RSSI noises. However, the LPF is not effective. Subhan et al. (2015) presented an extended gradient filter and predictor to address the communication holes of the RSSI caused by signal attenuation, signal loss, and multipath effects. Their results using both simulated and actual data indicated that the extended gradient filter and predictor perform better than the gradient filter and also work better than a Kalman filter and Kalman smoother. Faragher and Harle (2014) investigated the positioning accuracy of Bluetooth Low Energy beacons in advertising mode for signal fingerprint-based indoor position schemes. They concluded that the positioning accuracy increases with the number of beacons per fingerprint, up to 6–8 beacons.

Ideally, a RSSI value can be converted to receive power level if both the upper and lower power thresholds are known. A simple log-distance model proposed by Kotanen, et al. (2003) is described as follows.

$$P_{RX} = P_{TX} + G_{TX} + G_{RX} + 20\log(\lambda) - 20\log(4\pi) - 10nlog(d) - X_a \tag{5-1}$$

Where,

P_{TX} and P_{RX} are the power level of the transmitter and receiver,

G_{TX} and G_{RX} are the antenna gain of the transmitter and receiver,

λ is the wavelength (about 0.12 m for 2.441 GHz Bluetooth channels),

d is the distance between the transmitter and receiver,

n is a factor that describes the influence of environmental obstacles, and

X_a is the noise.

Or, the received Bluetooth power level can be expressed in a simplified model (Zhu et al., 2014) based on the radio propagation model as shown in equation (5-2) which describes the relationship between the signal received and distance. The received power decreases logarithmically with distance, where $P(d)$ is the received signal power, $P(d_0)$ is the signal strength at a reference point d_0, and γ is the path loss exponent (typically between 1 and 4).

$$P(d) = P(d_0) - 10\gamma\log\left(\frac{d}{d_0}\right) \tag{5-2}$$

We evaluated the RSSI of the Bluetooth Low Energy (BLE) beacons mounted in different orientations in an outdoor environment and modeled the RSSI-range relationship first using a simple Logarithmic Curve Fitting (LCF) technique. Figure 5-7 and 5-8 display the relationship if RSSI vs. distance of a BLE module mounted vertically (see photo in Figure 5-7) and horizontally (see photo in Figure 5-8) on a lamp post. The RSSI values have a large range of variation at a given distance. The median and average RSSI values are relatively close to each other. The RSSI and distance relationship was modelled using a logarithmic least square fitting technique with R-square value of 0.83 and 0.84, respectively.

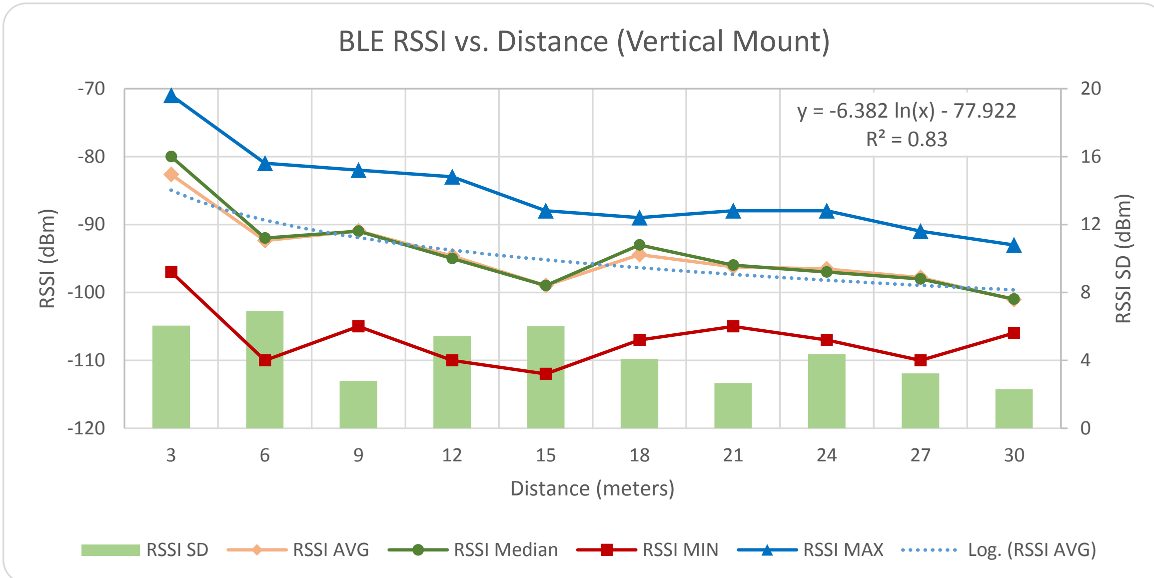

Figure 5-7 BLE Signal Strength Indication vs. Distance (Antenna Faces Front)

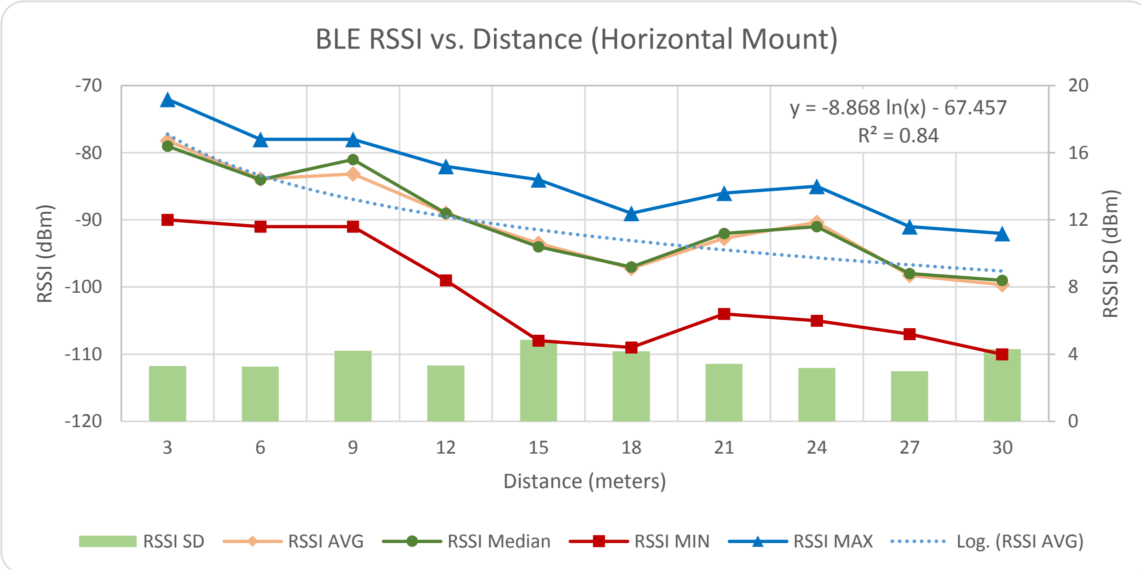

Figure 5-8 BLE Signal Strength Indication vs. Distance (Antenna Faces Up)

As our results indicated, the Bluetooth RSSI values exhibit high variability in space and time, mostly because of the randomness of the radio signals. So we need to develop a method to remove or reduce the noise of the Bluetooth RSSI.

5.3 Noise Reduction for Received Bluetooth Signal

The RSSI measurements can be expressed as a vector in a D-dimensional space with noise and pure signal lying in orthogonal subspaces. A Hankel matrix (Hermus et al., 1999) is constructed for the RSSI measurements for altering its singular spectrum. The high energy components are supposed to contain a pure signal, whereas the low energy components are supposed to contain only noise. The RSSI measurements y consisting of the pure signal x and the noise n can be expressed as follows.

$$y(i) = x(i) + n(i) \tag{5-3}$$

Where i representes the index of BLE beacons, $y(i)$ and $n(i)$ represent the RSSI values and environment noise from the i-th BLE beacon, respectively.

Therefore, we create overlapping frames of D samples of the RSSI measurements, $Y = [y(0), y(1), y(2), \ldots, y(D-1)]^T$. A Hankel-form matrix, H_Y, is expressed as,

$$H_Y = \begin{bmatrix} y(0) & y(1) & \ldots & y(M-1) \\ y(1) & y(2) & \ldots & y(M) \\ \vdots & \vdots & \ddots & \vdots \\ y(K-1) & y(K) & \ldots & y(D-1) \end{bmatrix} \tag{5-4}$$

The dimension H_Y is $K \times M$, where $K \geq M, and\ M + K = T + 1$.

According to the assumption of additive noise, we can also write,

$$Y = X + N \tag{5-5}$$

Where, Y, X, and N are the raw RSSI measurement, pure RSSI signal and noise vectors, respectively.

5.3.1 Singular Value Decomposition (SVD)

Using the SVD technique, the matrix H_Y can be decomposed and expressed as,

$$H_Y = U\,\Sigma\,V^T \tag{5-6}$$

Where,

$U \in \mathcal{R}\,(K \times K)$ is the orthonormal left singular vectors,

$V \in \mathcal{R}\,(M \times M)$ is the orthonormal right singular vectors, and

$\Sigma = \text{diag}\,(c_1, c_2, \ldots, c_p)$, and $c_1, c_2, \ldots, c_p$ represent the singular values of the matrix, H_Y, where $c_1 \geq c_2 \ldots \geq c_p \geq 0$ and $p = \min(K, M)$.

5.3.2 SVD Reconstruction

The largest singular components in equation (5-6) capture almost only signal information whereas the smallest ones contain almost only noise. The noise reduction can be obtained by adapting a diagonal weighting matrix W to equation (5-6).

$$H_{\hat{X}} = U\,(W\Sigma)\,V^T \tag{5-7}$$

Matrix $H_{\hat{X}}$ is no longer in the Hankel form. However, the non-diagonal components of $H_{\hat{X}}$ can be averaged to extract the improved signal $\bar{X} = [\hat{x}(0), \hat{x}(1), \hat{x}(2), \ldots, \hat{x}(D-1)]^T$.

A Least Square (LS) estimation or rank reduction approach is applied to select the weighting matrix W. We assume the pure RSSI signal X consists of r complex components such that the rank of $H_{\hat{X}}$ is r. The LS estimates of H_Y is obtained by setting the $M - r$ smallest eigenvalues to zero.

$$H_{Y,r} = \begin{bmatrix} U_r & U_{M-r} \end{bmatrix} \begin{bmatrix} \Sigma_r & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_r^T \\ V_{M-r}^T \end{bmatrix} \tag{5-8}$$

Where Σ_r contains the r largest singular values, and $H_{Y,r}$ is the best rank-r estimation of H_Y.

5.3.3 Validation

The SVD based RSSI noise reduction discussed in section 5.3.1 & 5.3.2 were implemented and tested using the raw RSSI signal as illustrated in Figure 5-9. Figure 5-9 displays the results of the filtered RSSI signal using LS estimation with rank $r = 2$. The resulting singular values found in this case are $c_1 = 4{,}473, c_2 = 49$. We further reduce the rank to 1 because the two largest singular values differ by two orders of magnitude. Figure 5-10 shows the results of the filtered RSSI signal using the LS estimation with rank $r = 1$. Without completely removing information from the signal, we use rank $r = 2$ in our model for better range estimation as described in the following section.

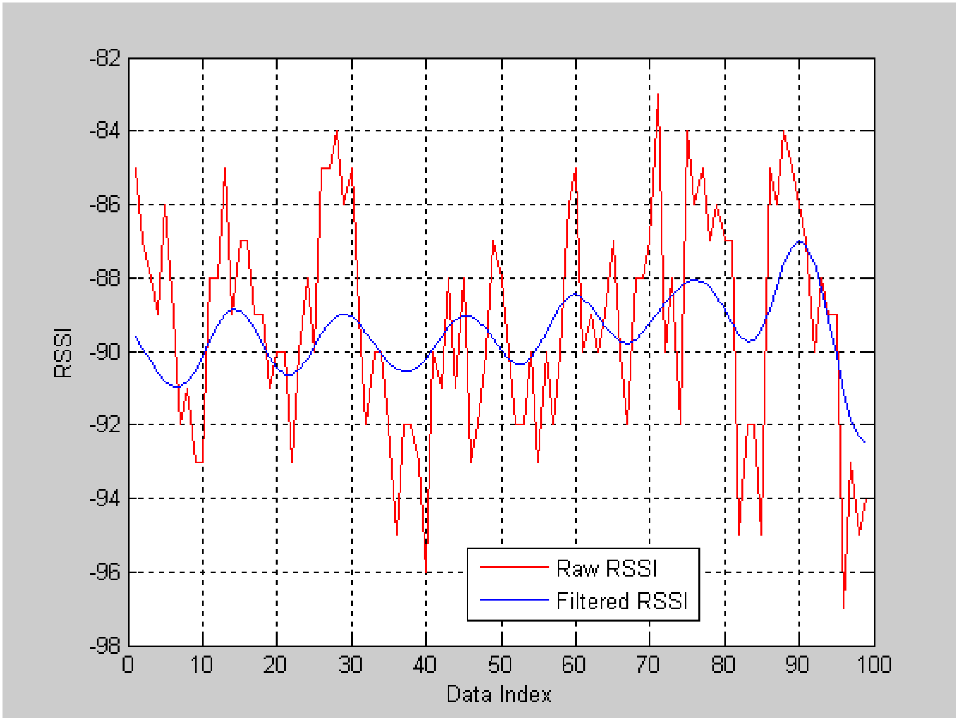

Figure 5-9 RSSI Noise Reduction Using SVD ($r = 2$)

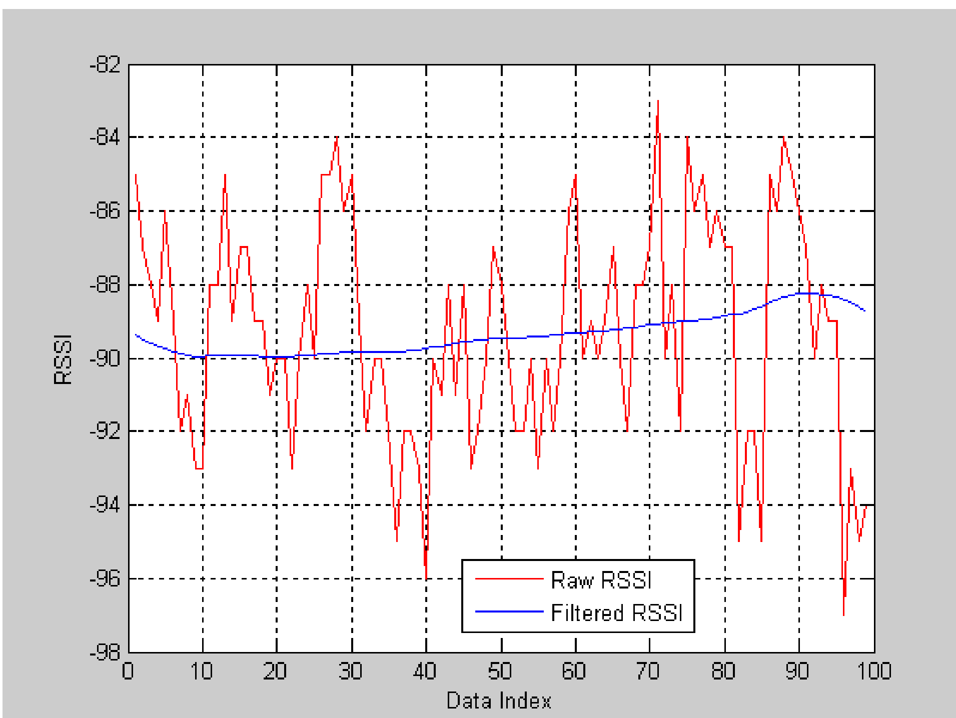

Figure 5-10 RSSI Noise Reduction Using SVD ($r = 1$)

5.4 Enhanced Bluetooth Range Estimation

Fan et al. (2015) proposed a SVD-based Multivariable Regression (MR) approach by including signal strength from multiple Access Points (AP) in a cellular network for mobile beacon localization. Due to the environmental dynamics, the nature of the Bluetooth wireless medium and the uncertainties in the power-distance model as described in section 2.3, we adopted the approach proposed by Fan et al. (2015) for a Bluetooth Low Energy (BLE) network. The goal is to create a mapping between RSSI and distance using an MR-based approach in real-time to better characterize the RSSI-distance relationship at an intersection. Our approach is used to better estimate the distances between a smartphone and BLE beacons based on a local mapping of the received Bluetooth signals. The estimated distances between a smartphone and BLE beacons are then incorporated into an Extended Kalman Filter (EKF), which is described in the following section, for positioning estimation.

5.4.1 Multivariable Regression (MR) Model

A Multivariable Regression (MR) model is selected to map the distance from a BLE to all the other BLE beacons to be described by a weighted combination of RSSI values from all BLE beacons. The MR model is expressed as,

$$\log(d_i) = S_i W_i + \varepsilon_i \tag{5-9}$$

Where,

$D_i = [d_1, d_2, \dots, d_n]$ is n distance matrix from the i-th BLE to the n-th BLE beacons,

$d_i = [d_{in}^1, d_{in}^2, \dots, d_{in}^m]^T$ is a vector of m measurements of distance from the i-th to the n-th BLE beacons,

S_i refers to the input variables of the i-th BLE,

$W_i = [w_0, w_1, \dots, w_n]^T$ is the weighting matrix, and

ε_i is an error term.

For m RSSI records received by the i-th BLE, the corresponding d_i and S_i matrices are expressed as the following, respectively.

$$D_i = \begin{bmatrix} d_{i1}^1 & d_{i2}^1 & \dots & d_{in}^1 \\ d_{i1}^2 & d_{i2}^2 & \dots & d_{in}^2 \\ \vdots & \vdots & \ddots & \vdots \\ d_{i1}^m & d_{i2}^m & \dots & d_{in}^m \end{bmatrix} \quad (5\text{-}10)$$

$$S_i = \begin{bmatrix} 1 & s_{i1}^1 & \dots & s_{in}^1 \\ 1 & s_{i1}^2 & \dots & s_{in}^2 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & s_{i1}^m & \dots & s_{in}^m \end{bmatrix} \quad (5\text{-}11)$$

Where,

d_{in}^m refers to the m-th distance measurement between the i-th and the n-th BLE, and

s_{in}^m is the m-th RSSI value received by the i-th BLE from the n-th BLE beacon.

The matrix D_i $(m \times n)$ contains m regress outputs, indicating m estimated distances from multiple RSSI values. The matrix S_i is a $m \times (n+1)$ matrix. The weighting W_i represents a regression by which the RSSI values are combined to determine distance. The weighting W_i can be obtained by using a linear MR approach to minimize the sum of squared errors (SSE) which is defined as,

$$SSE_i = \varepsilon_i^T \varepsilon_i = [\log(d_i) - S_i W_i]^T \, [\log(d_i) - S_i W_i] \tag{5-12}$$

To minimize SSE_i, we can take the derivative of SSE_i with respect to W_i,

$$\frac{\partial(SSE_i)}{\partial(W_i)} = 0 \tag{5-13}$$

Therefore,

$$\partial(-\log(d_i)^T S_i W_i - {W_i}^T {S_i}^T \log(d_i) + {W_i}^T {S_i}^T S_i W_i) / \partial(W_i) = 0 \tag{5-14}$$

Applying matrix differentiation propositions (Golub & Van Loan, 2012), the results from equation (5-14) can be expressed as,

$$-\log(d_i)^T S_i - \log(d_i)^T S_i + 2{W_i}^T {S_i}^T S_i = 0 \tag{5-15}$$

And, the solution to equation (5-15) is computed as,

$$W_i = (S_i^T S_i)^{-1} \, S_i^T \log(d_i) \quad (5\text{-}16)$$

The RSSI mapping is created by considering the RSSI values from all BLE beacons in a local network where a smartphone is located. This mapping is updated dynamically to reflect the current environment. As a result, it can better characterize the RSSI-distance relationship in a target area.

5.4.2 BLE Range Estimation Using SVD

As previously discussed, the large variation of Bluetooth RSSI resulting from noise causes bias error in the RSSI-distance mapping. To improve the robustness of the proposed mapping, we use the SVD method as discussed in Chapter 5.3 by defining a mapping relationship as $H_i = [W_1, \dots, W_n]$, where W_i is the regression weights from equation (5-16). With SVD technique, H_i can be decomposed as,

$$H_i = U \, \Sigma \, V^T \quad (5\text{-}17)$$

Where,

$U \in \mathcal{R} \, (n+1) \times (n+1)$ is the orthonormal left singular vectors,

$V \in \mathcal{R} \, (n \times n)$ is the orthonormal right singular vectors, and

$\Sigma = \text{diag}\,(c_1, c_2, \dots, c_n)$, $c_1, c_2, \dots, c_n$ are the singular values of the matrix, H_i.

$c_1 \geq c_2 \dots \geq c_n \geq 0$

The largest singular components in equation (5-17) capture almost only signal information whereas the smallest ones contain almost only noise. The noise reduction can be obtained by adapting a diagonal weighting matrix Γ to equation (5-17).

$$\widehat{H}_i = U\ (\Gamma\Sigma)\ V^T \tag{5-18}$$

Equation (5-18) represents a reconstructed matrix $\widehat{H}_i$ with enhanced RSSI-distance mapping. The weighting matrix Γ can be selected using the least square method by considering the first p singular values as clean mapping and the last $(n - p)$ singular values representing the noise.

$$\Gamma = \begin{bmatrix} \mathrm{I}_p & 0 \\ 0 & 0 \end{bmatrix} \tag{5-19}$$

Where,

I_p is a $p \times p$ identity matrix.

The distance from a smartphone (u) to a BLE beacon (i) can be estimated as,

$$\hat{d}_{u,i} = \exp(S_u \widehat{H}_i) \tag{5-20}$$

Where,

$\hat{d}_{u,i}$ is the estimated distance from the smartphone (u) to a BLE beacon (i),

$S_u = [1, s_{u1}, s_{u2}, \dots, s_{un}]$,

s_{un} is the RSSI value from the smartphone (u) to a BLE beacon (n), and

$\widehat{H}_i$ is the enhanced RSSI-distance mapping.

5.4.3 Comparison of Range Estimation Methodologies

Figure 5-11 displays the raw RSSI values received on a smartphone from four BLE beacons in a network. The data index in the X axis represents the sequence of received signal strength for a 5-sec scan. The location of the smartphone is fixed during the period of data collection. The distance from the smartphone to each BLE beacon is estimated using the Logarithmic Curve Fitting (LCF) model described in Chapter 5.2.2. The range estimation using the LCF model is plotted in Figure 5-12 for each BLE beacon. As illustrated in Figure 5-12, beacon #1, which is farther away from the smartphone, has the highest variation in range estimation. The range estimations of the four BLE beacons in the network using the SVD-based Multivariable Regression (MR) method as previously described in section 5.4.1 & 5.4.2 are shown in Figure 5-13.

When a Bluetooth network is formed, the SVD-based MR model use the RSSI measures among the BLE beacons to determine the optimal weighting parameters ($\widehat{H}_i$, as shown in equation 5-20) for range estimates. Using equation 5-20, the range estimates shown in Figure 5-13 are computed using optimal weighting parameters ($\widehat{H}_i$) and the raw RSSI measures (S_u) from a smartphone to four BLE beacons in a network (as shown in Figure 5-11). The regression model successfully improves the range estimation by removing the RSSI fluctuations based on the mapping of the RSSI and distance relationship of the BLE network. The BLE beacons displayed in Figure 5-13 are the same set of beacons as those in Figure 5-11 & 5-12.

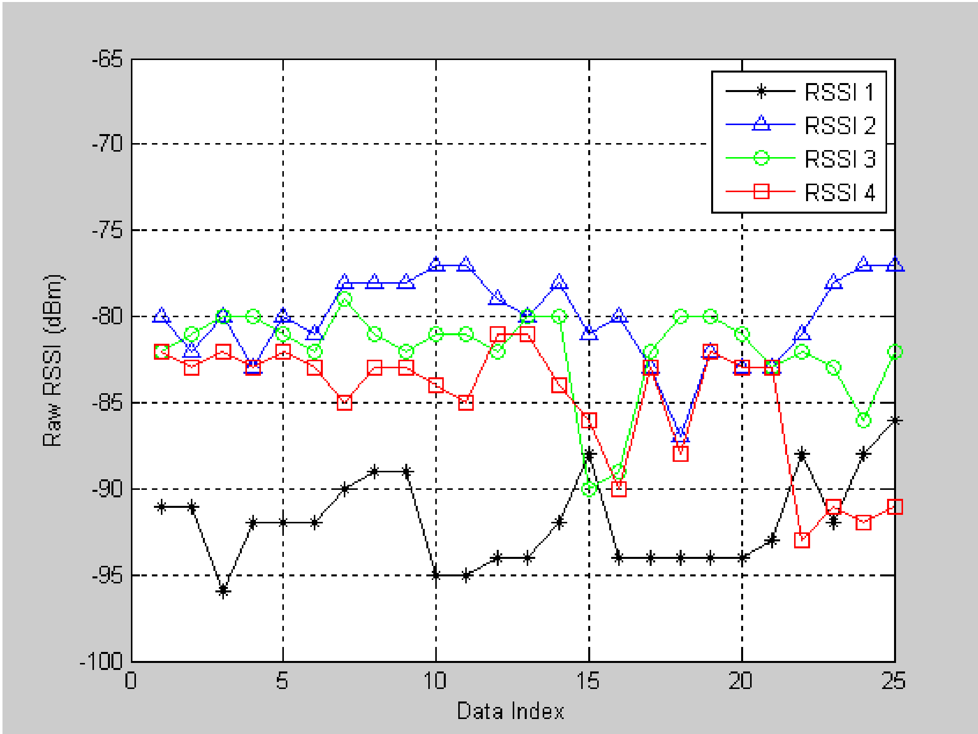

Figure 5-11 Raw RSSI Data from a Smartphone to 4 BLE Beacons

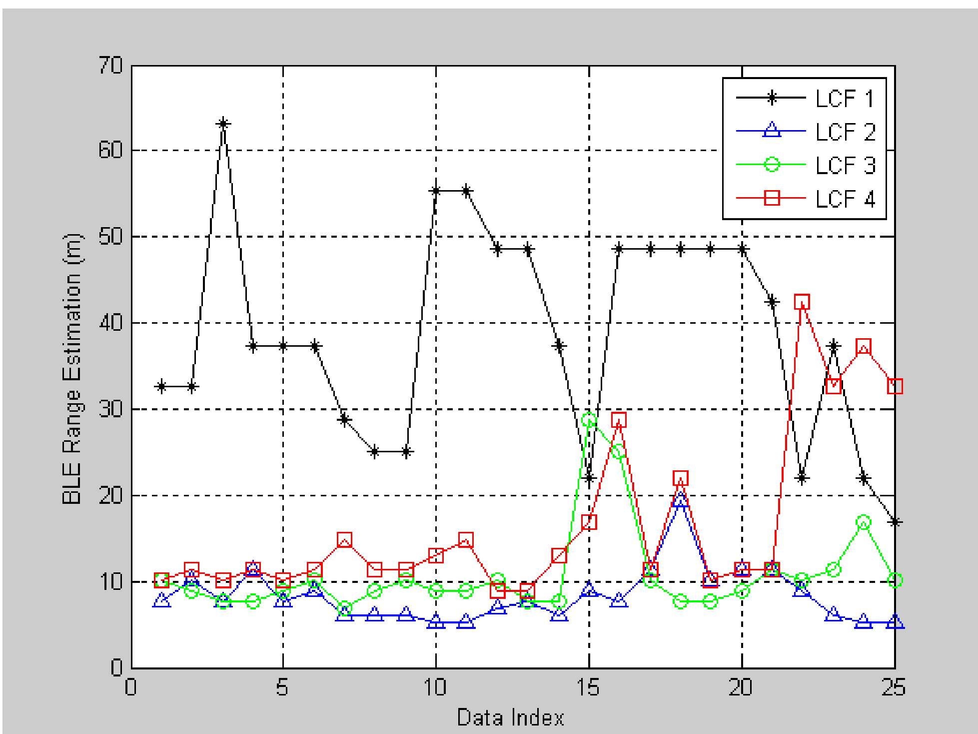

Figure 5-12 RSSI Range Estimation Using the LCF Model

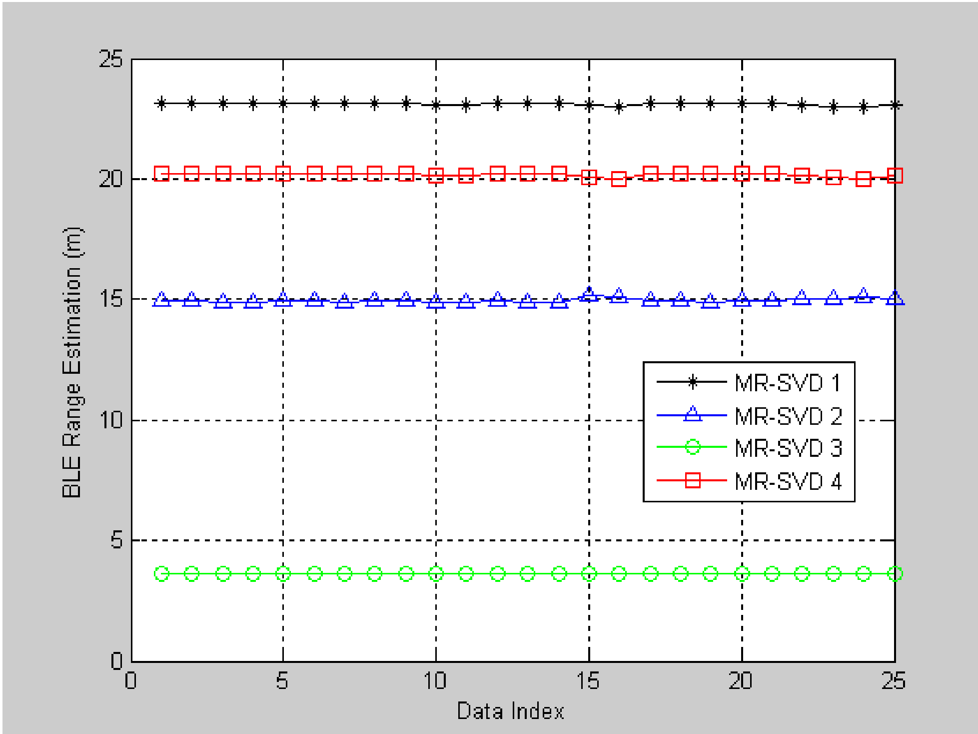

Figure 5-13 RSSI Range Estimation Using the MR-SVD Model

This network based mapping and mapping algorithm eliminates the need of updating the RSSI-distance relationship for each user. For example, Figure 5-14 illustrates how the RSSI mapping is updated when a person approaches a BLE network. The customized BLE firmware running in each beacon periodically scans its vicinity and stores the MAC ID and RSSI values of neighboring node in its local memory. When a user (with a smartphone running our app) arrives at an intersection, the smartphone app detects the beacons within the wireless communication range and immediately connects to the nearest beacon (e.g., node A illustrated in Figure 5-14). It then downloads a list of MAC IDs and RSSI values (e.g., $RSSI_{BA}$, $RSSI_{CA}$, $RSSI_{DA}$) from the connected beacon (A) and transfers the data to a central database server through a cellular or Wi-Fi network. That is, the RSSI mapping information of a BLE network is updated through the available wireless network on a user's smartphone.

The MR-SVD based method offers better Bluetooth range estimation between a smartphone and BLE beacons. It is incorporated into an Extended Kalman Filter (EKF), which is described in the following section, for positioning estimation.

The stored RSSI values between BLE beacons in the database server are used to provide a positioning and mapping solution and to monitor location changes of BLE beacons or network geometry changes. Methodologies to detect beacon location and network geometry changes are discussed in Chapter 5.6.

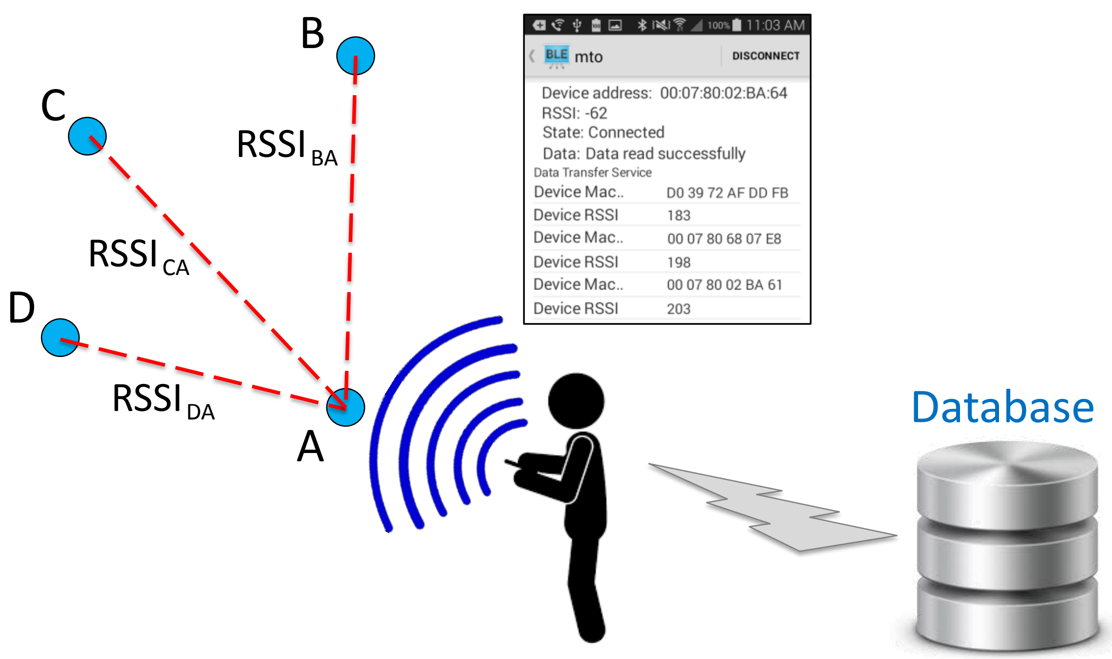

Figure 5-14 Illustration of Updating RSSI Mapping

5.5 Position Estimation Using Extended Kalman Filter (EKF)

R. E. Kalman (1960) developed a recursive solution to estimate unknown variables based on a series of measurements containing noise and other inaccuracies over time. The Kalman Filter (KF) has been broadly used for guidance, navigation, system control of vehicles, and numerous other applications in engineering industries (Bageshwar et al, 2009). The KF method was selected to optimally fuse current position estimates with the most recent measurements. We use the KF approach to estimate the location of a Bluetooth scanner based on the received signal strength measurement from its neighboring Bluetooth beacons. Based on the knowledge about the uncertainties of the current position estimates and the measurement, the KF combines the information to minimize the estimation error. The geometric relationship between a node and other neighboring nodes can be described by equation (5-21) as follows.

$$(X - X_i)(X - X_i)^T = r_i^2 \tag{5-21}$$

Where,

X is the location of a BLE scanner (e.g., a smartphone),

X_i is the location of BLE beacon i, and

$\boldsymbol{r_i}$ is the distance between scanner $\boldsymbol{X}$ and sensor $\boldsymbol{X_i}$, $i \in [\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{n}]$.

The extended Kalman filter (EKF) was used for the non-linear system. The location of a smartphone beacon (X) was selected as the state variables which can be modeled in the following discrete form.

$$X_{k+1} = X_k + w_k \tag{5-22}$$

Where,

X_k (3×1) is the position of BLE scanner at time step t_k,

w_k (3×1) is assumed to be a uncorrelated sequence with known variance $E[w_k w_k^T] = Q_k$.

The observation or measurement of the above discrete process is assumed to occur at discrete points in time according to the following relationship.

$$Z_k = h(X_k) + v_k \tag{5-23}$$

Where,

v_k $(m \times 1)$ is random measurement noise with variance $E[v_k v_k^T] = R_k$,

Z_k $(m \times 1)$ is the range measurement at time step t_k,

m is the number of neighboring Bluetooth beacons.

The elements of $h(X_k)$ are the distances between a smartphone beacon and its neighboring beacons, which can be rewritten from equation (5-21) as,

$$h_i(X_k) = \sqrt{(X_k - X_i)^T (X_k - X_i)} \tag{5-24}$$

Where,

$h_i(X_k)$ is the distance between the scanner and the i^{th} neighboring Bluetooth beacon,

i is the index of neighboring beacon, and

X_i is the location of the neighboring beacon.

The measurement equation (5-23) needs to be linearized in order to use the discrete KF. The current state estimate is selected as the reference trajectory about which the equations are linearized. Assume $\Delta X_k$is a small difference between the actual position X_k and the current estimate, $\hat{X}_k$. Using the Taylor's series expansion with first order form, the $h(X_k)$ can be linearized as,

$$h(X_k) = h(\hat{X}_k) + H_k \, \Delta X_k \tag{5-25}$$

$$H_k = \left[\frac{\partial h}{\partial X}\right]_{X=\hat{X}_k} \tag{5-26}$$

The rows of the linearized H_k matrix represents a sensor measurement which can be expressed based on the measurement equation (5-24) as follows.

$$h_i^T = \left(X_i^T - \hat{X}_k\right)^T / \, h_i(\hat{X}_k)$$

Based on the theory presented in (Brown & Hwang, 2012), we assume that at an initial time, t_k, all estimates were based on knowledge prior to t_k. This prior (or priori) estimate can be denoted as $\hat{X}_k^-$. Therefore the estimation error can be calculated as,

$$e_k^- = X_k - \hat{X}_k^- \tag{5-27}$$

And the associated error covariance matrix is,

$$P_k^- = E[e_k^- e_k^{-T}] = E[\left(X_k - \hat{X}_k^-\right)\left(X_k - \hat{X}_k^-\right)^T] \quad (5\text{-}28)$$

A linear blending of the prior estimate and the noisy measurement can be formulated using the following equation.

$$\hat{X}_k = \hat{X}_k^- + K_k(Z_k - H_k\hat{X}_k^-) \quad (5\text{-}29)$$

Where,

$\hat{X}_k$ is the updated estimate

K_k is a blending factor which can be expressed as follows (Brown & Hwang, 2012).

$$K_k = P_k^- H_k^T (H_k P_k^- H_k^T + R_k)^{-1} \quad (5\text{-}30)$$

This particular K_k, namely the one that minimizes the mean square estimation error, is called the Kalman gain. The covariance matrix associated with the optimal estimate can therefore be computed as,

$$P_k = (I - K_k H_k) P_k^- \quad (5\text{-}31)$$

The Kalman filter can be initialized by setting the $\hat{X}_0$ and P_0 to constant values. The first measurement update is evaluated iteratively until a predefined converge criteria is satisfied.

Based on the range estimation discussed in section 5.4, the EKF method is incorporated with the MR-SVD model to identify the location of a traveler's smartphone in a BLE network. The EKF uses the MR and SVD combined model to find the range estimates from a smartphone to the BLE beacons. The estimates of the range from the phone to each beacon are used to determine the location of the smartphone with respect to a selected local coordinate system.

5.6 Detection of Location and Network Geometry Changes

Figure 5-15 illustrates a simple BLE network in which each BLE beacon has the capability to scan and receive the Bluetooth signal from the other BLE beacons. Statistical methodologies are investigated to detect changes of the location of a BLE beacon within its network configuration.

A cumulative summation (CUSUM) method and two location change indices were introduced to test what happens if the location of a BLE module is changed or the configuration of the BLE network is altered. The CUSUM technique is used to evaluate the location changes of a single BLE module. The Jaccard index and a normalized weighted signal level change (NWSLC) index were used to evaluate the geometry configuration of a local BLE network.

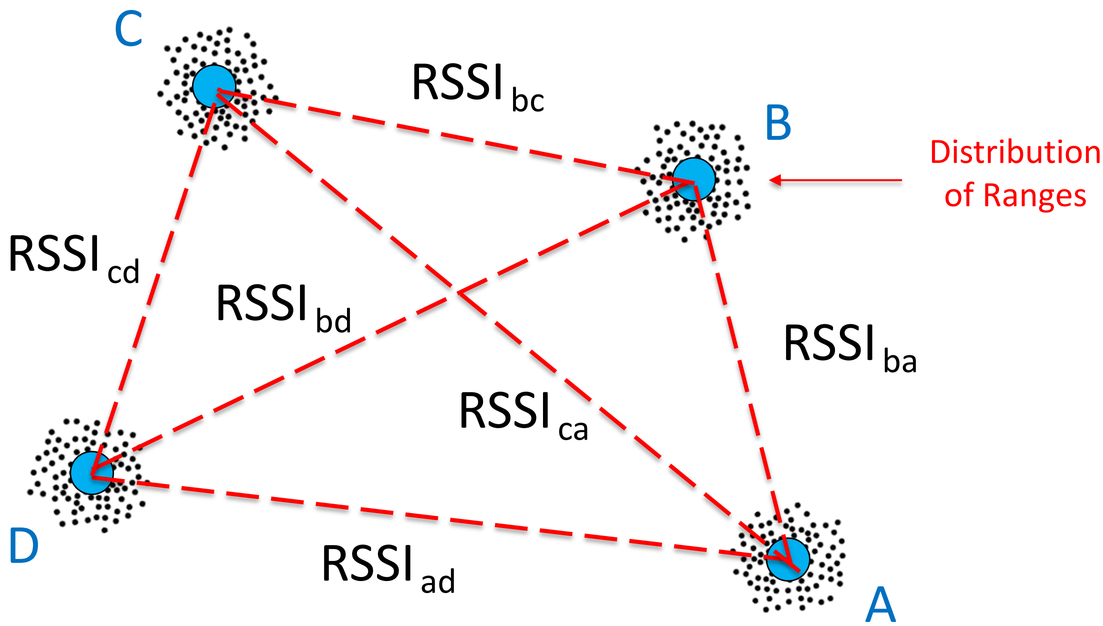

Figure 5-15 Illustration of Monitoring RSSI in a BLE Network

5.6.1 Statistical Process Control (SPC)

A Statistical Process Control (SPC) method known as Cumulative Sum (CUSUM), can be performed to detect and identify any changes of BLE locations. The CUSUM chart is a commonly used quality control method to detect deviations from benchmark values. Hawkins & Olwell (1998) used the CUSUM charts and charting as the SPC tools for quality improvement. Luceño (2004) used generalized CUSUM charts to detect level shifts in auto correlated noise. Lin et al. (2007) developed an adaptive CUSUM algorithm to robustly detect anomalies. The cumulative sum of difference between each measurement and the benchmark value is calculated as the CUSUM value. The CUSUM is expressed as follows.

$$C_n = \sum_{i=1}^{n}(X_i - \mu) \quad (5\text{-}32)$$

Or in the recursive form,

$$C_n = C_{n-1} + (X_i - \mu) \tag{5-33}$$

Where,

X_i is the ith data reading from BLE modules,

μ is the data mean, and

C_n is the sum of independent normal $N(0, \sigma^2)$ quantities.

The CUSUM equations (5-32 & 5-33) can also be standardized to have zero mean and unit standard deviation as follows.

$$U_i = (X_i - \mu)/\sigma \tag{5-34}$$

$$S_n = \sum_{i=1}^{n} U_i \tag{5-35}$$

Or in recursive form,

$$S_n = S_{n-1} + U_n \tag{5-36}$$

Where,

U_i is the difference of measurement from mean in unit of standard deviation,

S_n is the cumulative difference in unit of standard deviation, and

σ is the standard deviation of a data set.

The cumulative distribution function and the normal inverse cumulative distribution function (illustrated in Figure 5-16) were used to normalize the deviation statistics before calculating CUSUM. The following equations can be used to calculate the adjusted CUSUM.

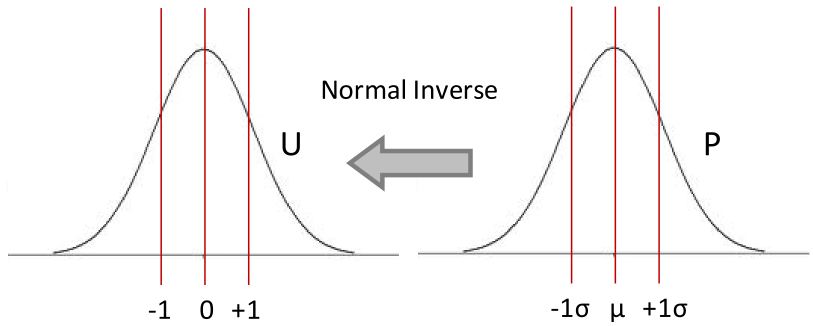

Figure 5-16 Illustration of Normal Inverse Cumulative Distribution Function

$$\bar{x}_1 = \frac{\sum_{i=1}^{n_0} \mu_i}{n_0}$$

$$w_1 = \sum_{i=1}^{n_0} (\mu_i - \bar{x}_1)^2$$

$$\bar{x}_{j+1} = \bar{x}_j + \left[\frac{(\mu_{j+n_0} - \bar{x}_j)}{j+n_0}\right]$$

$$w_{j+1} = w_j + (j + n_0 - 1)\left[\frac{(\mu_{j+n_0} - \bar{x}_j)^2}{j+n_0}\right]$$

$$\sigma_j^2 = \frac{w_j}{j+n_0-1}$$

$$T_j = \frac{\mu_{j+n_0} - \bar{x}_j}{\sigma_j}$$

$$p_j = tcdf\left(T_j.\sqrt{\frac{j+n_0-1}{j+n_0}}, j + n_0 - 2\right)$$

$$U_j = norminv(p_j, 0, 1)$$

$$adj.cusum_j = \sum_{k=1}^{j} U_k$$

Where,

n = number of measurements,

$n_0 = 3$, initial number of measurements,

w_j is sum of squared difference between individual data and mean,

σ_j^2, is the variance,

$m = n - n_0$,

μ is an array of RSSI average,

$p = tcdf(x, v)$ is the student's t cumulative distribution function (CDF).

The result, p, is the probability that a single observation from the t distribution with ν degrees of freedom falls in the interval [–∞, x), and

$U = norminv(p, \mu = 0, \sigma = 1)$ is the normal inverse cumulative

distribution function. It computes the inverse of the normal CDF with parameters μ (mean) and σ (standard deviation) the corresponding probabilities in p.

The standardized CUSUM form, S_n (Eq. 3-6), can be used to directly interpret random walks and linear drifts of a process mean. The Decision Interval (DI) of CUSUM is proposed by Hawkins & Olwell (1998) to detect a process shift in mean that changes from general horizontal motion to a non-horizontal linear drift. For example, a particular slope k and leg height h can be specified to test a shift. The sequence to monitor an upward shift in mean is defined in equation (5-37 & 5-38) as follows.

$$S_0^+ = 0 \qquad (5\text{-}37)$$

$$S_n^+ = \max(0,\ S_{n-1}^+ + U_n - \mathrm{k}) \tag{5-38}$$

It signals an upward shift in mean if $S_0^+ > h$. Similarly, the sequence to monitor a downward shift in mean is defined in equation (5-39 & 5-40) as follows.

$$S_0^- = 0 \tag{5-39}$$

$$S_n^- = \min(0,\ S_{n-1}^- + U_n + \mathrm{k}) \tag{5-40}$$

It signals a downward shift in mean if $S_0^- < -h$. The constant k represents a reference value or allowance, and constant *h* is the decision interval. Hawkins & Olwell (1998) described in detail how to choose an appropriate reference value k for the shift in the mean of a normal distribution. The k value is chosen for optimal response that the CUSUM process will detect a shift of 2×k standard deviations.

We used the CUSUM method to monitor the changes of RSSI between to two BLE beacons. The CUSUM method allows us to test what happens if the location of a BLE module is changed. In addition, we also would like to monitor the configuration of a formed BLE network. Two signal fingerprinting techniques are discussed in the following section to monitor any changes of relative distance among beacons in a local Bluetooth network.

5.6.2 Wireless Signal Fingerprint

Trilateration techniques have been used by GPS, radar, or other sensors to determine the location of an object. Another positioning technique is called fingerprinting, which is a localization process that represents a radio transmitter by the unique ID and the signal strength at the current location. Wi-Fi fingerprinting has often been used for indoor positioning due to unavailable GPS signals. It requires a robust Received Signal Strength Indication (RSSI) database which is used for generating signal strength maps as well as for identifying locations. Each location reference point includes signal strengths measured from all accessible Access Points (AP). Live RSSI data can then be compared to the find the closest match from the database which stores the location of each reference point (Navarro et al, 2011).

Wireless location fingerprinting consists of two phases: the off-line data training and online positioning. We use the wireless fingerprint positioning process to determine the *change* in location of a BLE module, which allows for a much more efficient use of BLE data (Liao et al., 2016). Importantly, our approach does not require the additional layer of complexity incurred by the need to form and maintain external RSSI databases as well as querying them for each location determination. In particular, the BLE module can record the wireless fingerprint when the network is installed. The scanned BLE signals are stored in the cloud and are used as a reference signature. When a BLE module detects any suspicious movement using the CUSUM method, the app on a user's smartphone informs the server to compare the current BLE signal fingerprint with the stored reference to determine and validate if the location of a BLE module has changed.

Each record from the BLE scan result list includes a MAC address and Received Signal Strength Indication (RSSI). The MAC address is a unique identifier associated with each BLE module. The RSSI is the received signal strength from the corresponding BLE module. The RSSI is expressed in dBm which is defined as the power ratio in decibels (dB) of the measured power referenced to one milliwatt (mW) as displayed in Equation (5-41).

$$dBm = 10log_{10}\frac{Power}{1mW} \tag{5-41}$$

The RSSI signal strength in dBm can be converted into a discrete *N*-level signal indication (where $N = 5$ is a commonly used value), often displayed using bars on smartphone screens. The Android API provides a function to compute signal strength level based on the RSSI,

$$SigLevel = WifiManager.calculateSignalLevel\,(RSSI, N) \tag{5-42}$$

Where,

RSSI is the measured signal strength in dBm,

N is the total number of signal levels, and

$SigLevel \in \{0,1,\dots,\mathrm{N}-1\}$.

We use the MAC ID and Received Signal Strength Indication (RSSI) as elements of the BLE fingerprint. That is, a BLE fingerprint F_x of at given location x is represented as $F_x =$

{ (MAC_i, $RSSI_i$) }, where each tuple (MAC_i, $RSSI_i$) indicates a specific (i^{th}) BLE network (ID and signal strength) visible at location x. Both the Jaccard and a normalized weighted signal level change indices are discussed as follows.

Jaccard Index

The Jaccard index, or similarity coefficient, was previously developed by Paul Jaccard to compare regional floras. The similarity index is also widely used in data-mining (Rajaraman and Ullman, 2011) for comparing the similarity and diversity of a finite number of sample sets. Specifically, similarity of two sets S_1 and S_2 is defined as:

$$J(S_1, S_2) = \frac{|S_1 \cap S_2|}{|S_1 \cup S_2|} \in [0,1] \qquad (5\text{-}43)$$

In our case, S_1 and S_2 are the reference MAC ID list and the current MAC ID list, respectively. More specifically, given two Wi-Fi fingerprints F_1 and F_2 from two different locations, S_1 and S_2 are defined to include MAC IDs of only those networks that have signal level (ranging from 0 to 4) equal or greater than 1 for Jaccard index calculation. Formally,

$$S_i = \{\ MAC\ ID \mid (MAC\ ID, RSSI) \in F_i, SigLevel\ (RSSI, 5) \geq 1\ \},\ \text{for } i = 1, 2. \qquad (5\text{-}44)$$

That is, this approach uses the changes in the fingerprint of the strong-signal networks (with signal strength of 1 or higher) for location change determination. By definition, the value of $J(S_1, S_2)$ is always between 0 and 1. We define that the location of a smartphone is changed when the Jaccard index drops below some threshold $J_{threshold}$, i.e., $J(S_1, S_2) < J_{threshold}$, which essentially indicates that the overlap between two sets of Wi-Fi networks from scans F_1 and F_2 is minimal.

The Jaccard index has an initial value of 1 when no signal strength changes occur in a network. However, it is sensitive to the initial signal strength of a wireless network. The changes of Jaccard index of a network with stronger initial signal strength among beacons (i.e., the Wi-Fi access points in a wireless network are close to each other) is less significant than the changes of a wireless network with weaker signal strength initially (i.e., the distances between Wi-Fi access points in a wireless network are farther apart).

Normalized Weighted Signal Level Change (NWSLC) Index

We introduced an alternative measure called the normalized weighted signal level change (NWSLC) index for detecting a beacon location change detection, because the Jaccard index approach was inadequate. NWSLC index describes the changes of a network signature by weighting the signal level differences between the reference (from F_1 scan) and current (from F_2 scan) signal level with its reference signal strength and then taking the normalized average. It is defined as follows.

$$A = \frac{1}{Nn} \sum_{i=1}^{n} SigLevel_{ref_i} \times \left| SigLevel_{cur_i} - SigLevel_{ref_i} \right| \qquad (5\text{-}45)$$

Where,

A is the NWSLC index,

n is the number of intersection samples (i.e., $n = | F_1 \cap F_2|$),

N is the total number of signal levels (i.e., $N = 5$ in our case),

$SigLevel_{ref_i}$ is the signal level of reference BLE i (from scan F_1), and

$SigLevel_{cur_i}$ is the signal level of current BLE i (from scan F_2).

We determine that the location of a beacon is changed when the NWSLC index is larger than a certain threshold $A_{threshold}$, i.e., $A \geq A_{threshold}$, which takes into account not only the change in visible Wi-Fi networks but also the relative change in their signal strength.

The NWSLC index performs better than the Jaccard index. It normalizes the changes of a signal based on its initial signal states. As a network geometry configuration changes, the NWSLC index increase proportionally to the amount of changes with respect to its initial signal strength.

5.7 Analysis Results

We reprogrammed the firmware of commercial off-the-shelf Bluetooth Low Energy (BLE) beacons for our experiments. The characteristics of the Received Signal Strength Indication (RSSI) were examined. Four BLE beacons were installed at an intersection to evaluate the positioning and mapping method as discussed previously using RSSI. Statistical methodologies discussed in Chapter 5.6 were also tested to validate the capability of a self-aware BLE network.

5.7.1 Program Bluetooth Low Energy (BLE) Beacons

We developed a standalone Bluetooth smart system (called BLE-master) that integrates a commercial off-the-shelf BLE module operating in dual modes (master/slave or scanning/broadcasting) with necessary interface elements to sense other BLE-master beacons within its range of communication. The BLE-master units periodically scans the other BLE-master beacons in their communication range to ensure the integrity of the local map and to provide correct positioning information in an environment.

A Texas Instruments (TI) CC2540 development kit (including CC debugger) was acquired and used to program the BLE modules (as illustrated in Figure 5-17).

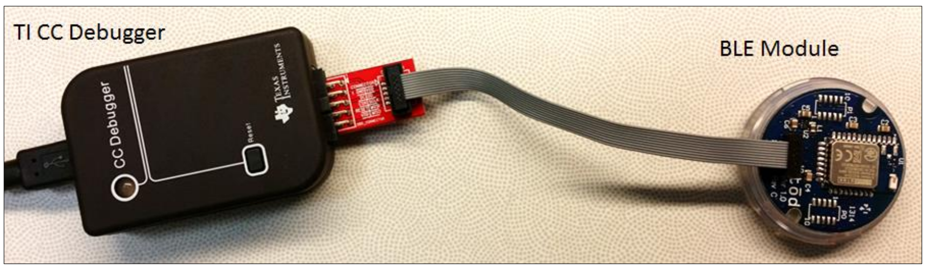

Figure 5-17 CC Debugger and a BLE Module

The generic attribute (GATT) layer of the Bluetooth 4.x protocol stack is used by the application for data communication between two BLE beacons when one of them acts as a GATT server and the other as a GATT client. A GATT server consists of one or more GATT services, which are collections of data to accomplish a particular function or feature. “Characteristics” are values that are used by a service, along with properties and configuration information. GATT defines the sub-procedures for discovering, reading, and writing attributes over a BLE connection. The characteristic values, along with their properties and their configuration data (also known as “descriptors”) on the GATT server are stored in the attribute table. Figure 5-18 illustrates our implementation (in parenthesis) of the GATT server and service on each BLE beacon. Each BLE beacon is programmed to be in central mode (master) for 10 seconds after which it switches to peripheral mode (slave) and remains in that role for 50 seconds. When in central mode, the application searches for surrounding BLE beacons that are programmed for our application and gets their corresponding MAC addresses and RSSI values and stores them locally. When in peripheral mode, the application hosts a GATT server with the GATT service and is ready to be connected to a central beacon. The GATT service hosts the sensor's MAC addresses and RSSI values previously read in the central mode. A central BLE beacon (for example, a smartphone) can now connect to the beacon in peripheral mode and read the values of MAC addresses and RSSI values of its neighboring BLE beacons from the GATT server.

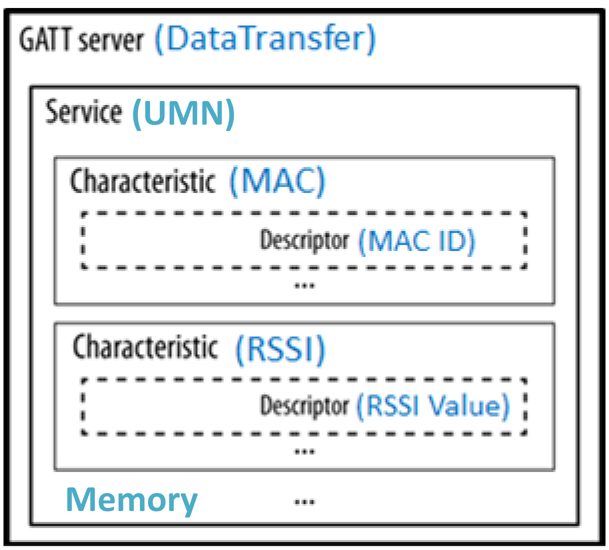

Figure 5-18 GATT Services Running on Each BLE

A smartphone app was also developed for data collection and testing. The results are shown in the smartphone screen image of Figure 5-19. It illustrates one of the BLE beacons when operating in master/scanning mode when it detects 3 other BLE beacons in its vicinity.

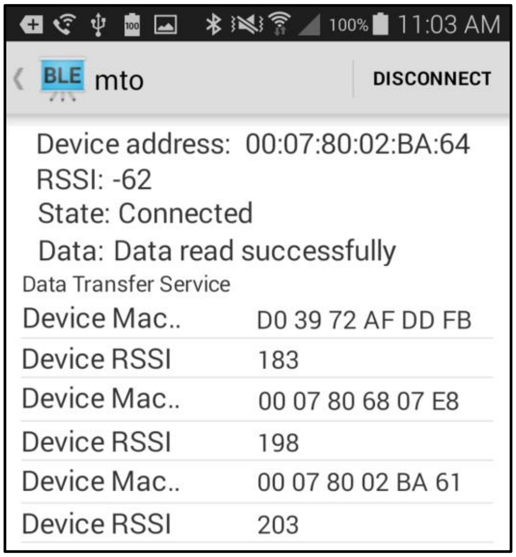

Figure 5-19 Sample Results in a Screen Image from a Smartphone BLE Scan

We tested the reprogrammed BLE beacons and explored the relationship between actual distance and the RSSI values in the atrium of the Ralph Rapson Hall (Figure 5-20a) on the University of Minnesota east bank campus. A layout of the reference points and placement of four BLE beacons (located at A, D, M & P) are illustrated in Figure 5-20b. The relationship between the RSSI reading and actual distance to each Bluetooth beacon from all locations as shown in Figure 5-20b is plotted in Figure 5-21. The results suggest a logarithmical relationship between the measured RSSI and actual distance. However, the distance estimation based on measured RSSI has a relatively low coefficient of determination (R2 = 0.14). The distance estimation based on the raw RSSI measurement is not reliable. We therefore cannot use the distance estimates to determine whether beacons have moved.

We used the NWSLC based BLE fingerprinting technique to monitor the changes of RSSI values received from other Bluetooth beacons. The RSSI variation of Bluetooth beacons at each test location is displayed in Figure 5-22. Figure 5-22 displays the average RSSI measures of 4 beacons at A, D, M & P from location A to U. When a Bluetooth beacon is operating in scanning (master) mode and monitoring its neighboring beacons, the measured RSSI from all the other Bluetooth beacons within its range of communication are stored in local memory. If one of the neighboring Bluetooth beacons is moved, vandalized or malfunctions, the signal pattern at that particular location will be different from the historical pattern. Therefore, an alert can be triggered to inform the system administrator.

For example, the average RSSI measurements from a smartphone placed at location F to the other four Bluetooth beacons are displayed in a column chart as shown in Figure 5-23. The four BLE beacons are 49.4 ft (15 m) apart from each other in both the longitudinal and lateral directions. The smartphone, when placed at location F, exhibits a range of 23 ft (7 m), 36 ft (11 m), 47 ft (14 m), and 38 ft (12 m) to beacons #7, #8, #9, and #10, respectively. The red ticks plotted on each column represent the RSSI value of one standard deviation above and below the average measurement.

Similarly, the fingerprint of the RSSI values and corresponding variations with the smartphone placed at location G (Figure 5-20b) shown in Figure 5-24. Location G is about 17 feet (5.2 m) east of location F as illustrated in Figure 5-20b. The smartphone, when placed at location G, exhibits a range of 37 ft (11 m), 46 ft (14 m), 37 ft (11 m), and 24 ft (7 m) to beacons #7, #8, #9, and #10, respectively. Each of these signal patterns is used to determine if any of the neighboring Bluetooth beacons (labeled MTO-07 to

MTO-10) has been removed or has stopped functioning. When a user approaches the BLE beacon with the smartphone app running in the background, the BLE signal pattern is automatically transferred to a database server through the wireless services on the smartphone.

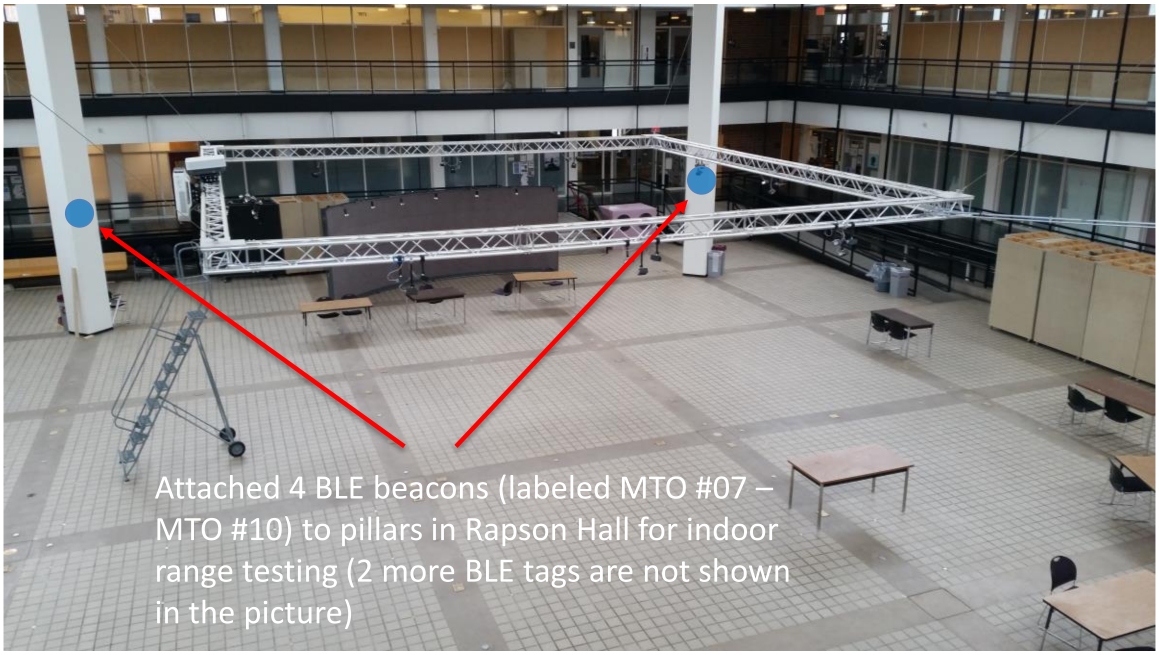

Figure 5-20a Photo of BLE Beacons Installed at Rapson Hall Atrium

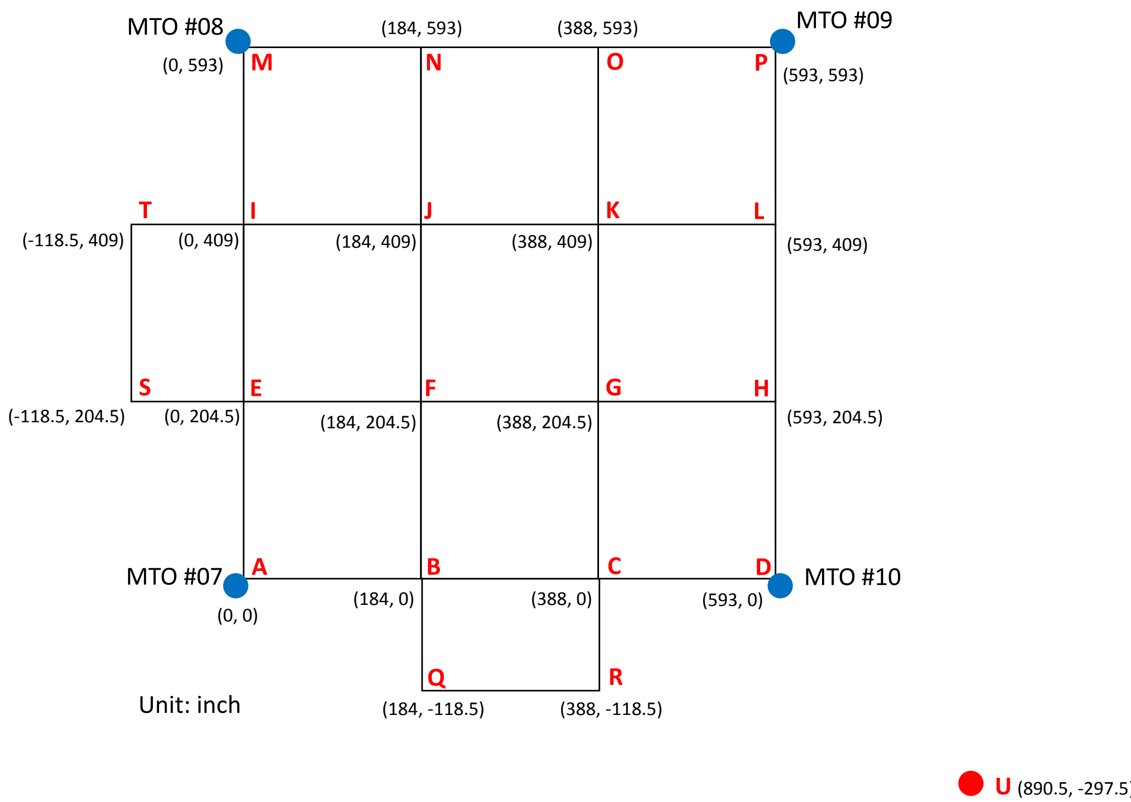

Figure 5-20b Layout of BLE Beacons and Digitized Test Locations (Indoor)

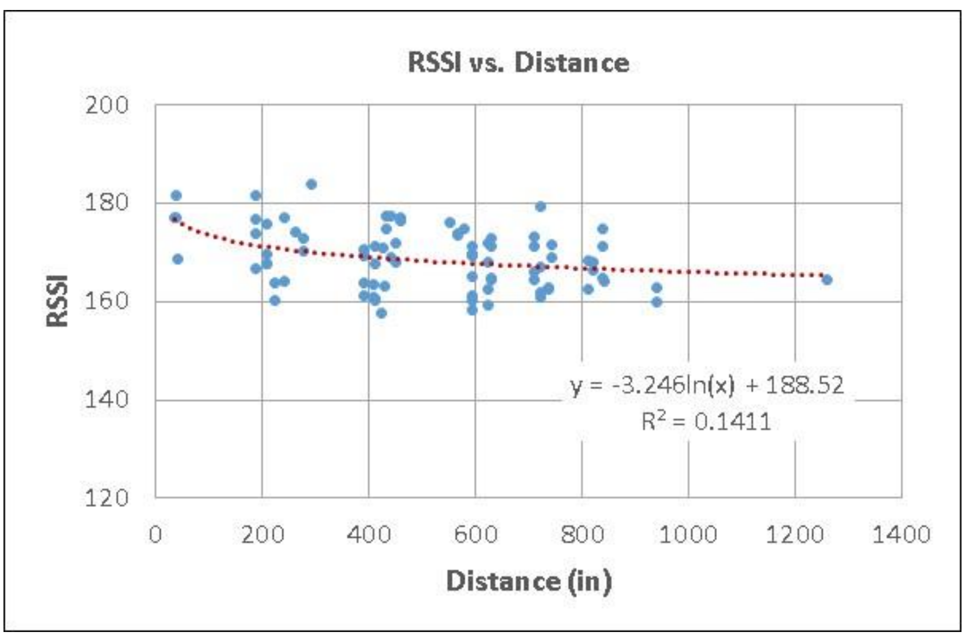

Figure 5-21 Raw RSSI Measurement vs. Distance (Indoor)

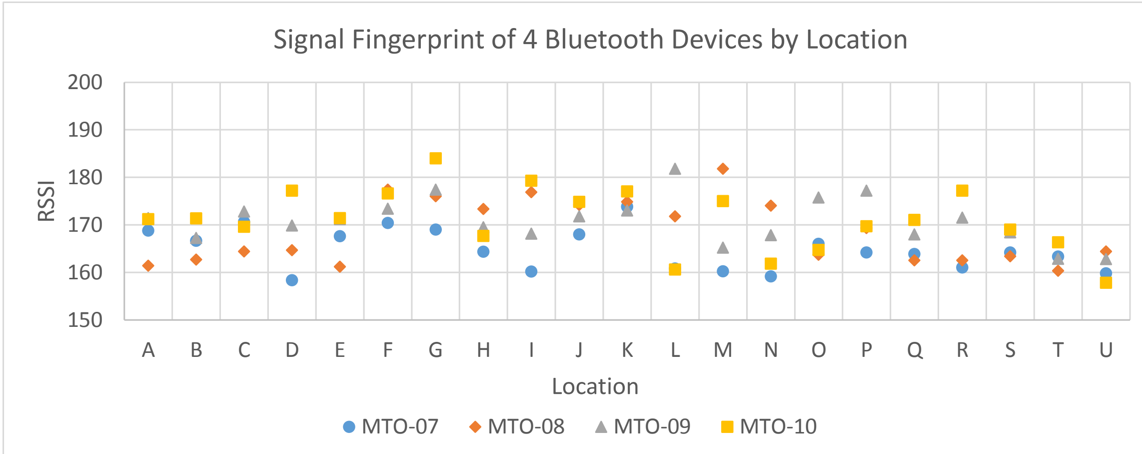

Figure 5-22 Average RSSI Measurements of 4 Bluetooth Beacons by Location

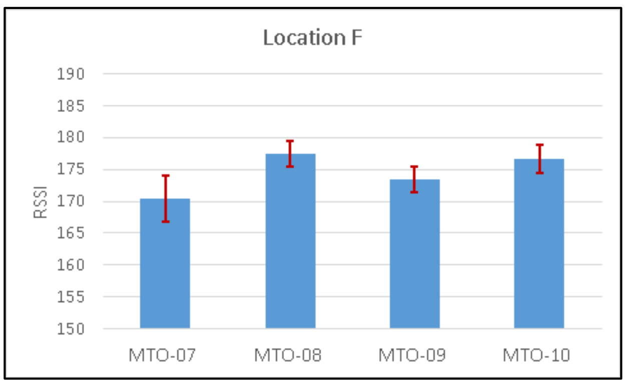

Figure 5-23 RSSI Measurement and Variation of 4 BLE Beacons at Location F

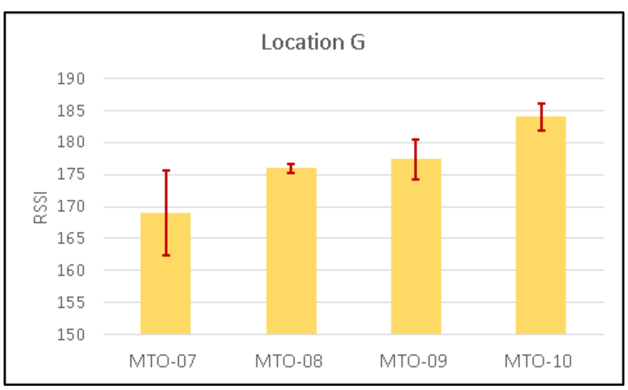

Figure 5-24 RSSI Measurement and Variation of 4 BLE Beacons at Location G

A similar analysis for 12 BLE beacons placed in an outdoor environment was also conducted to examine the RSSI-distance relationship as displayed in Figure 5-25. The beacons were placed at fixed locations and a user with a smartphone walked to multiple locations to collect the RSSI data. The RSSI measurements from BLE beacons may vary by location due to the environmental dynamics and nature of the Bluetooth wireless medium.

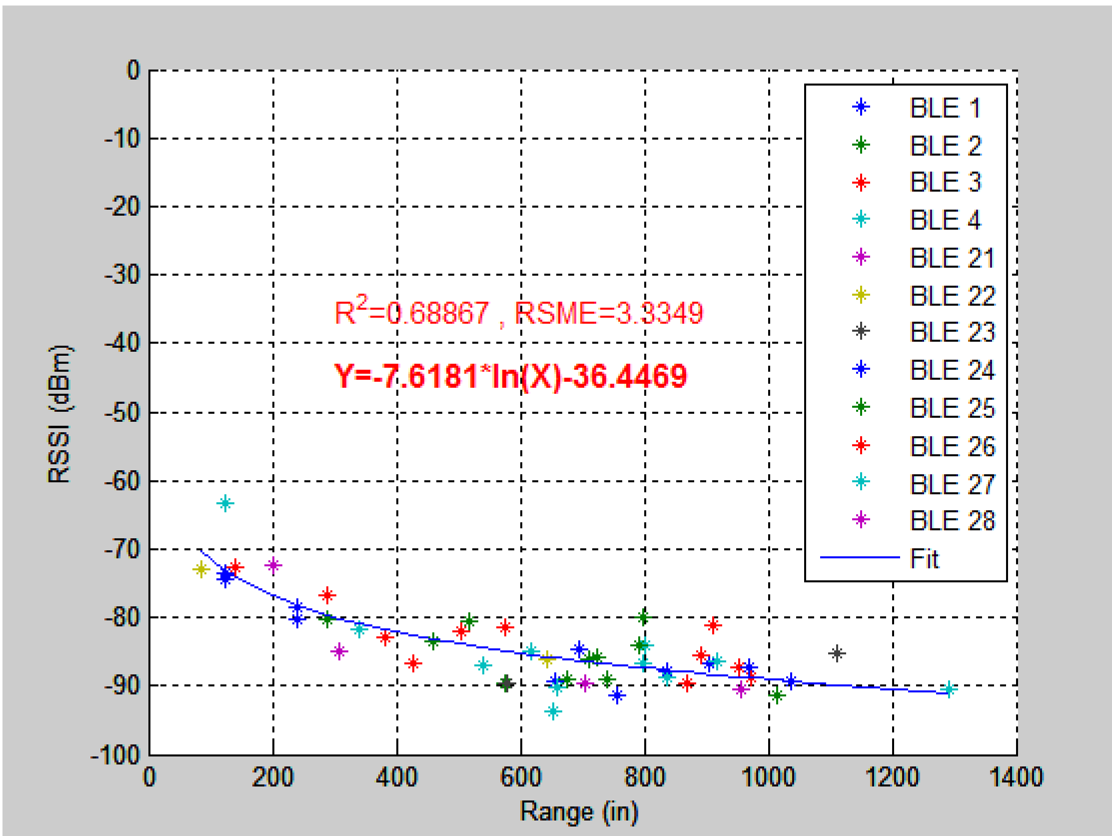

Figure 5-25 RSSI vs. Distance Relationship (Outdoor)

5.7.2 Geospatial Database

A geospatial database that contains the location and corresponding message of each BLE beacon was developed to provide information to a smartphone app. As illustrated in

Figure 5-26, the BLE network was superimposed upon a street network. Each BLE parent node includes an ID, latitude, longitude and information of its neighboring nodes which may be located on the other side of the street or the next block. The relation between a parent and a child node describes relative orientation, direction, crosswalk and street information. The goal is to provide reliable situation awareness and corresponding navigation information to assist wayfinding for the visually impaired. The spatial relationship is to ensure that correct audible information (such as signal timing and intersection geometry) is provided to users at the correct location. Table 5-1 display a sample list of RSSI values received by each Bluetooth node when it scans its neighboring nodes. Each node ID is represented by the MAC ID of the Bluetooth beacon.

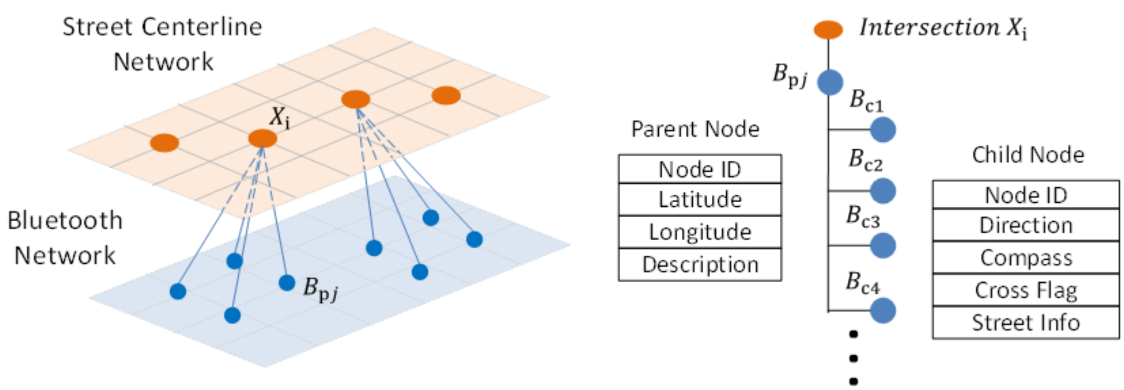

Figure 5-26 Geospatial Database

Table 5-1 Sample List of Bluetooth RSSI Data

Intersection ID	Node ID	Neighboring Node ID	RSSI
101	00:12:F3:0B:4A:11	00:12:F3:0B:4A:27	-93
101	00:12:F3:0B:4A:27	00:12:F3:0B:49:A6	-87
101	00:12:F3:0B:49:A6	00:12:F3:0B:49:4C	-108
101	00:12:F3:0B:49:4C	00:12:F3:0B:4A:11	-95

5.7.3 RSSI Mapping and Positioning Experiment at Intersection

Four Bluetooth low energy beacons were installed at an intersection (Judson Ave. and Underwood St.) in St. Paul as illustrated in Figure 5-27. Nine reference points (location A to I) were selected as position references where a smartphone was located in order to collect RSSI measurements from four BLE beacons (BLE #21-24 as shown in Figure 5-27). Figure 5-28 displays a sample of raw (noisy) RSSI signals received from 4 other BLE beacons (BLE #21 - #24) from a smartphone placed at location G (as shown in Figure 5-27).

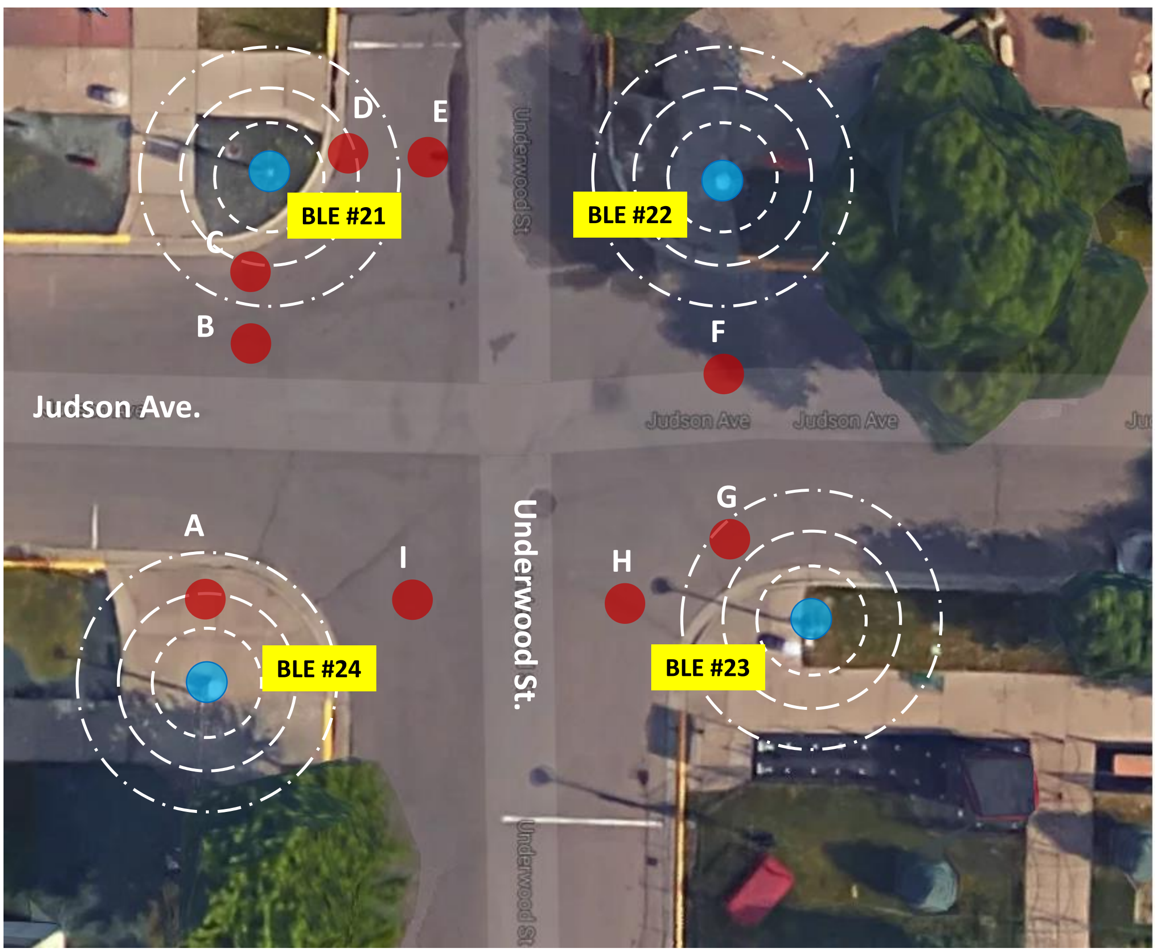

Figure 5-27 A Simple Bluetooth Network
(Background Image from Google Maps)

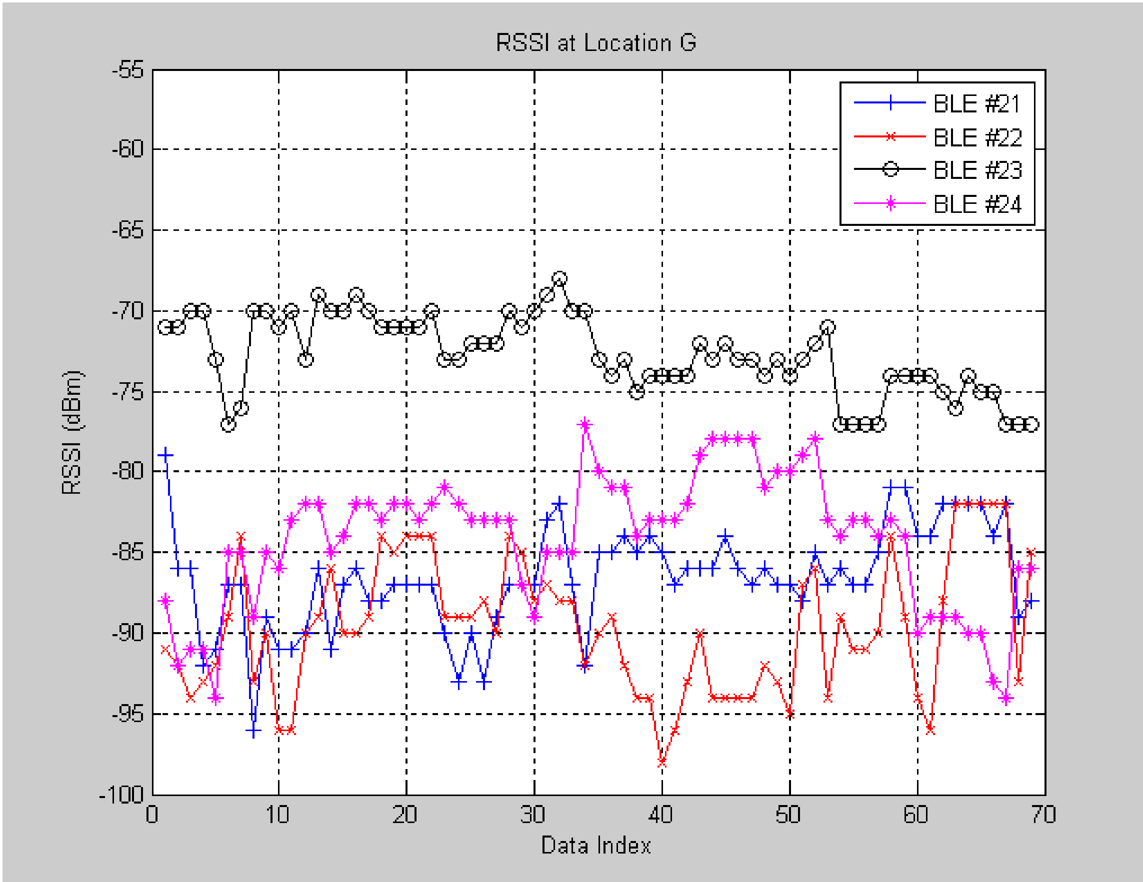

Figure 5-28 Sample RSSI Received from 4 BLE Beacons at Location G

We first implemented the Logarithmic Curve Fitting (LCF) based RSSI-range model (discussed in Chapter 5.2.2) for range estimates, but the results were not acceptable. We then implemented the Multivariable Regression (MR) model (discussed in Chapter 5.4) to estimate the actual distance between BLE beacons. One minute of RSSI data was collected at all 9 locations (A to I) using a smartphone app at the test site as illustrated in Figure 5-27. Each collected dataset include RSSI received from all other neighboring BLE beacons. The estimated distance between the smartphone and each BLE beacon is then provided to the Extended Kalman Filter (EKF) (previously discussed in Chapter 5.5) to determine the location of a smartphone.

We collected RSSI measures from a smartphone at 9 locations (A to I as shown in Figure 5-27) near the intersection to validate our methodologies. We used equation (5-10) and (5-11) for our data modeling and analysis. The number of BLE beacons is 4 ($n = 4$) and number of RSSI measurements for the MR model is 20 ($m = 20$). The first two ($p = 2$) singular values are selected in equation (5-19) for the weighting matrix Γ to improve the range estimates.

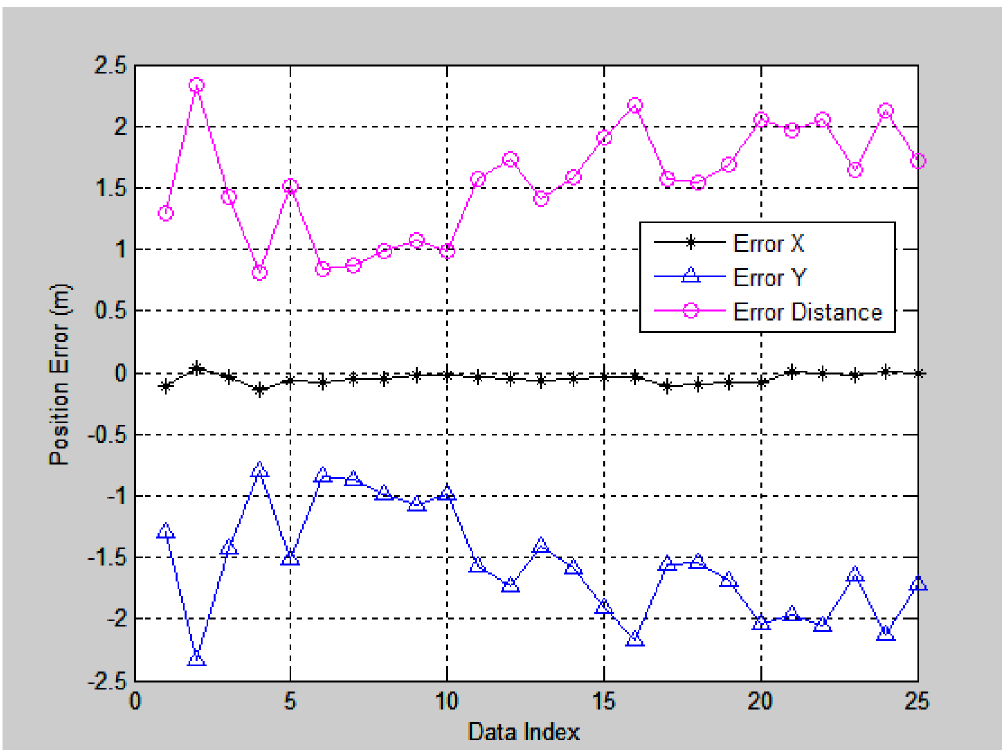

Figure 5-29 Position Error at Location A Using MR-SVD-EKF Method

Figure 5-29 to 5-32 respectively display the position error in both X and Y directions at location A, D, F and H (as indicated in Figure 5-27), respectively. Table 5-2 compares the average position error of the 9 locations for both models. The LCF and EKF combined model has an average position error of 7.3 m (X axis) and 9.5 m (Y axis), respectively. The MR and EKF combined model improves the position error by about 44% with an average position error of 4.1 m (X axis) and 5.4 m (Y axis), respectively, for all 9 positions. At some locations, such as A & C, the average position errors are less than 2 m. However, the position errors at location D & H are almost 5 m. The average positioning accuracy is illustrated in Figure 5-33.

The positioning solution from the combined MR and EKF method is significantly better than the LCF and EKF combined approach. Although, the positioning performance is not sufficient for detecting a pedestrian veering at crosswalks. It provides acceptable positioning to identify a person's location at a corner of an intersection in a GPS unfriendly environment.

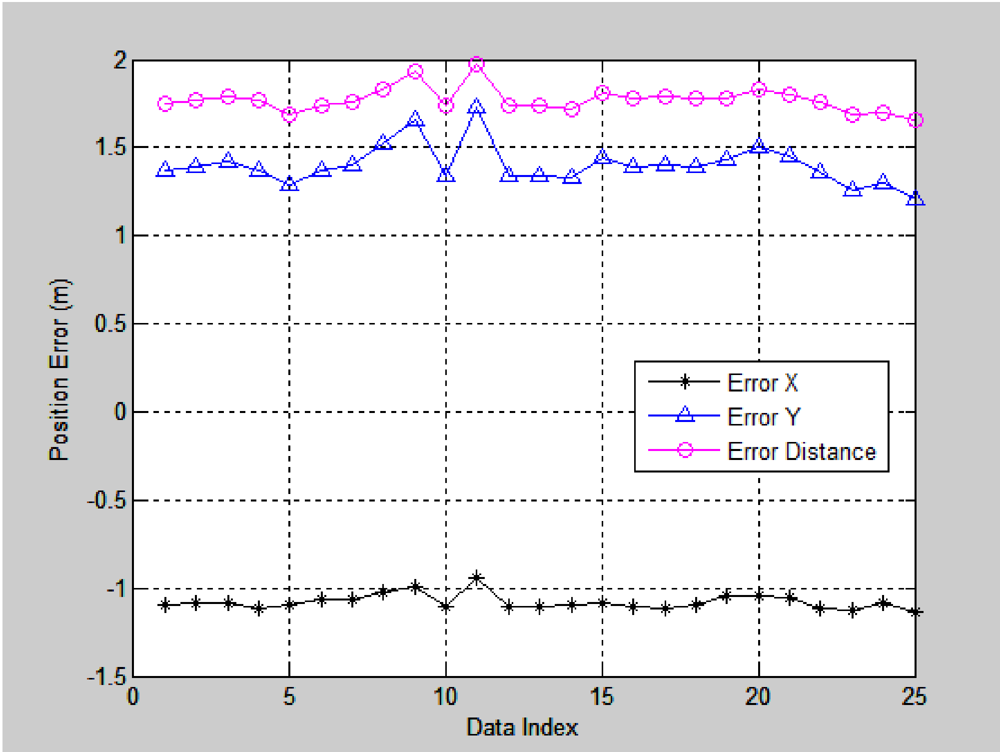

Figure 5-30 Position Error at Location C Using MR-SVD-EKF Method

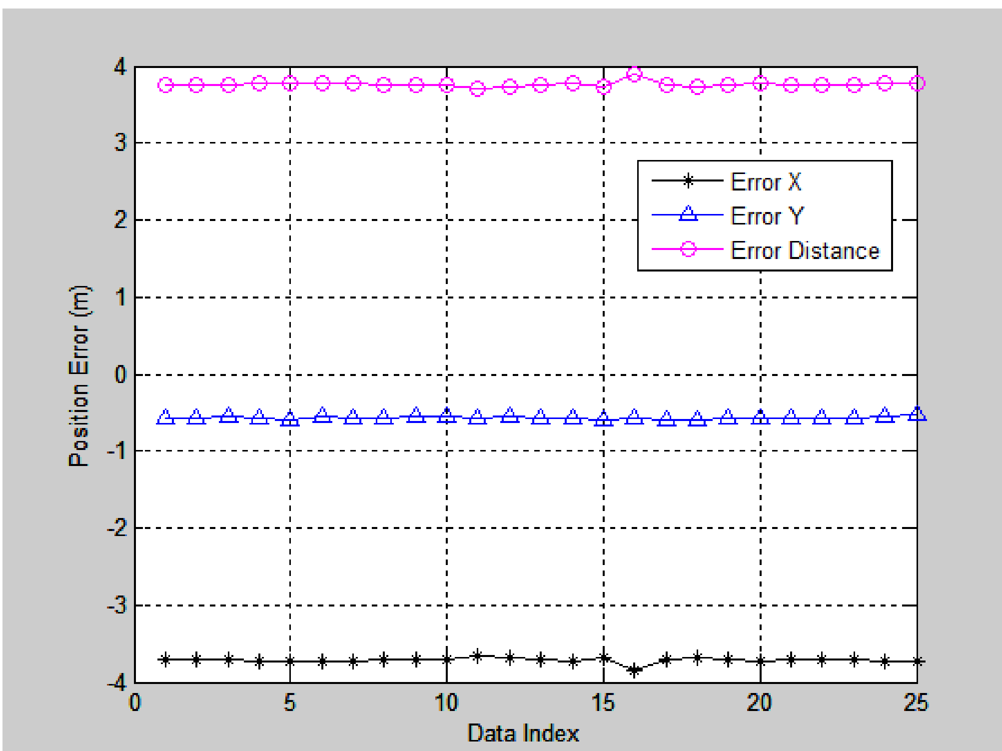

Figure 5-31 Position Error at Location D Using MR-SVD-EKF Method

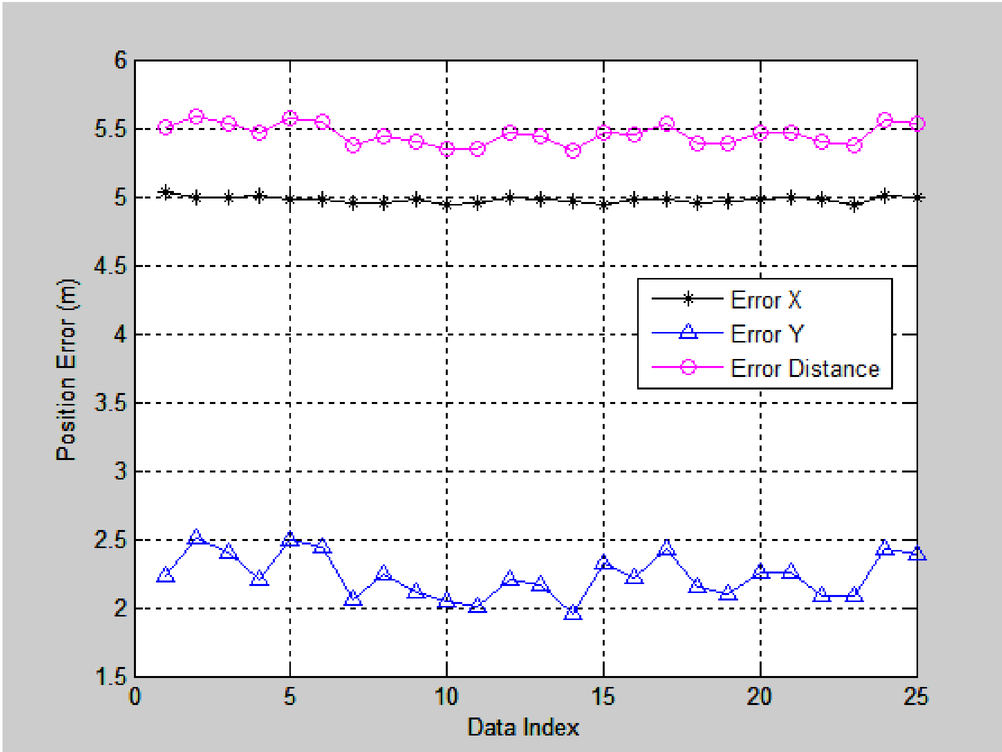

Figure 5-32 Position Error at Location H

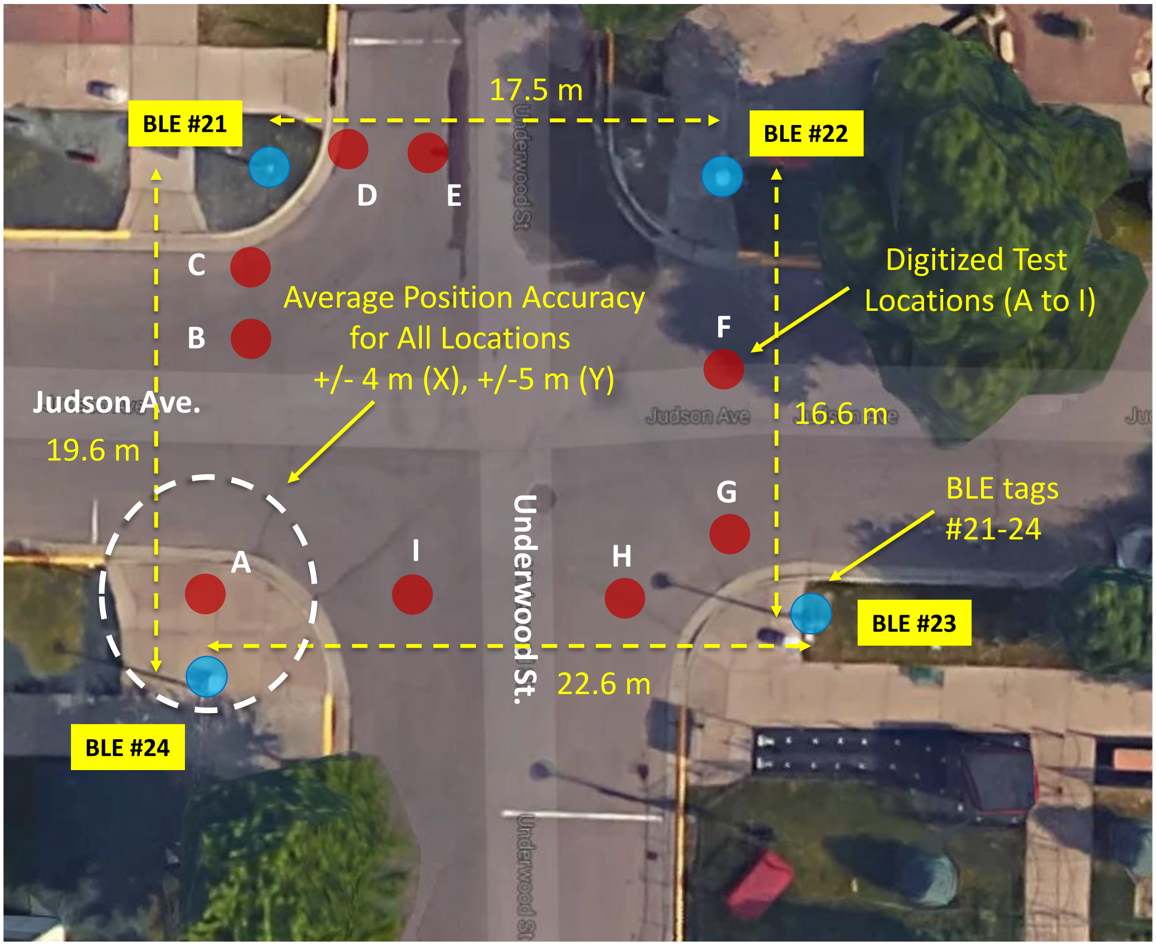

Figure 5-33 Schematic Showing Position Accuracy of a BLE Network (Background Image from Google Maps)

Table 5-2 Comparison of Average Position Error

Absolute Position Error (m)			Standard Deviation (SD)	
Direction	X	Y	X	Y
LCF + EKF	7.3	9.5	5.7	6.2
MR + EKF	4.1	5.4	3.8	4.4
% Change	-44.1%	-43.6%	-33.3%	-29.0%

5.7.4 CUSUM Analysis for Detecting BLE Location Changes

In order to detect the location change of a BLE beacon or changes of a BLE network geometry, the methodologies described in Chapter 5.6 were used for validation. Experiments were conducted by moving one of the BLE beacon at 3 meter increments in both the lateral and longitudinal directions. Figure 5-34 displays the CUSUM and Decision Interval (DI) plots when a BLE beacon (for example, BLE #22, as shown in Figure 5-34) was moved away from its neighboring node (BLE #21) for about 6 meters after 50 seconds (250 samples). The CUSUM algorithm is able to detect changes of RSSI shortly after BLE #22 beacon is removed as indicated by the down arrow shown in Figure 5-34.

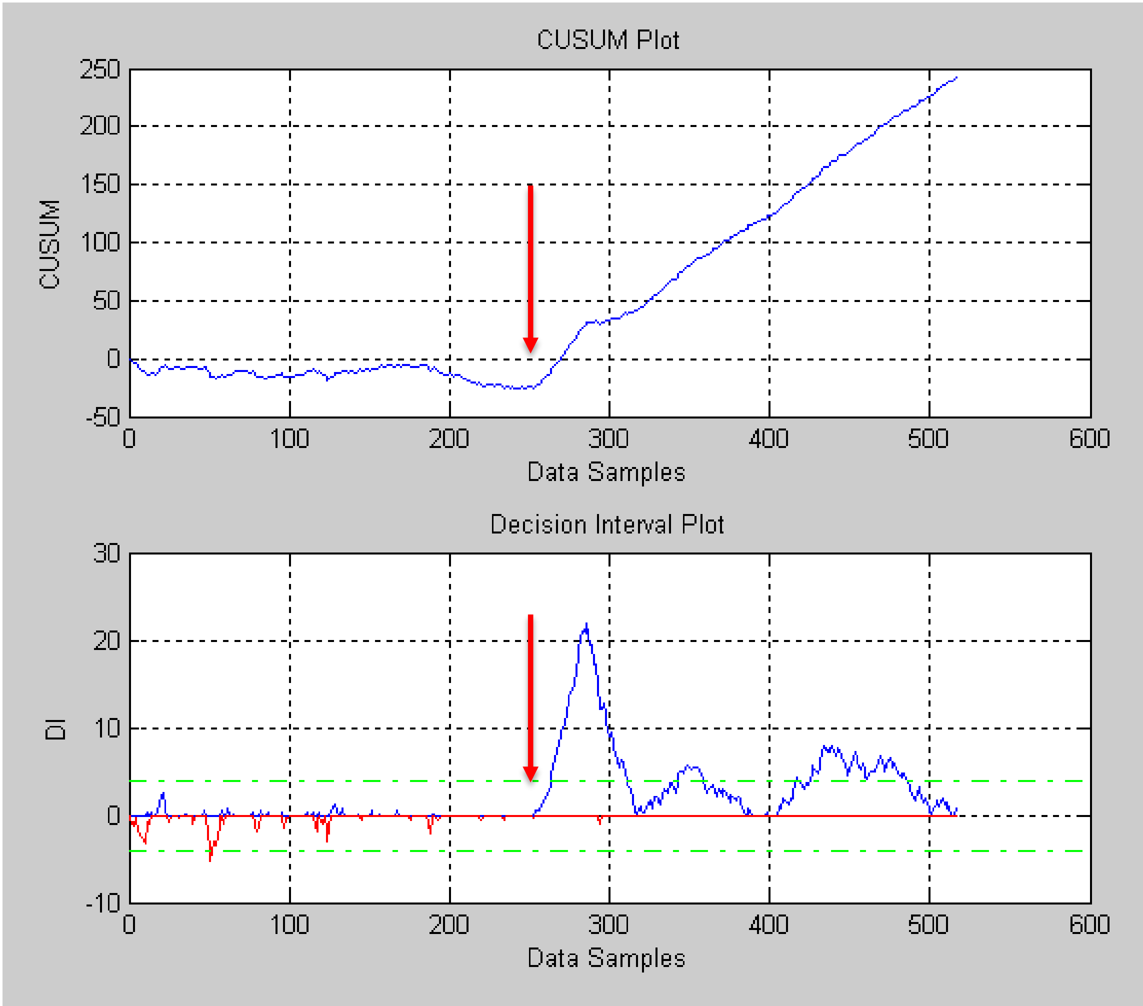

Figure 5-34 CUSUM and DI Plots of Moving a BLE Beacon

Test results of moving the BLE beacons are listed in Table 5-3. Table 5-3 lists the results of a BLE beacon being initially placed at a location from 3 to 33 meters (with 3 meter increments) away from a smartphone with BLE technology. The RSSI measurements were recorded on the smartphone for CUSUM analysis. The BLE beacon is first moved 3 or 6 meters toward from the smartphone. The beacon is then moved 3 or 6 meters away from the smartphone to evaluate the success rate of CUSUM detection. Our results indicate that the CUSUM detection algorithm is able to detect the location changes of a peer BLE beacon at 3 meters range 86% of the times. The CUSUM detection rate increases to 100% when a BLE tag is moved over 6 meters away from its original location.

Table 5-3 Success Rate of CUSUM Test for Detecting BLE Location Change

CUSUM Detection	Move away from a peer		Move toward a peer	
Starting Location (m)	+3 meters	+6 meters	-3 meters	-6 meters
3	Yes	Yes	NA	NA
6	No	Yes	Yes	Yes
9	Yes	Yes	No	Yes
12	Yes	Yes	Yes	Yes
15	Yes	Yes	Yes	Yes
18	Yes	Yes	Yes	Yes
21	Yes	Yes	Yes	Yes
24	Yes	Yes	Yes	Yes
27	Yes	Yes	Yes	Yes
30	Yes	Yes	No	Yes
33	Yes	Yes	Yes	Yes

5.7.5 RSSI Fingerprint for BLE Network Configuration Changes

We validated both RSSI signal fingerprint techniques, the Jaccard and the NWSLC index, as discussed in Chapter 5.6.2. Figure 5-35 shows the Jaccard index signature of the Judson Ave. and Underwood St. intersection as displayed in Figure 5-27 when all 4 BLE beacons are mounted at their original locations. The initial Jaccard signature is based on 196 sets of RSSI measurements. When BLE #21 is removed from the network, the RSSI fingerprint changes and the average Jaccard index drops from 0.98 to 0.82 as shown in Figure 5-36. Similarly, the average Jaccard index drops from 0.98 to 0.53 (as plotted in Figure 5-37) when BLE #21 is returned back to its original location and BLE #23 is removed from the network.

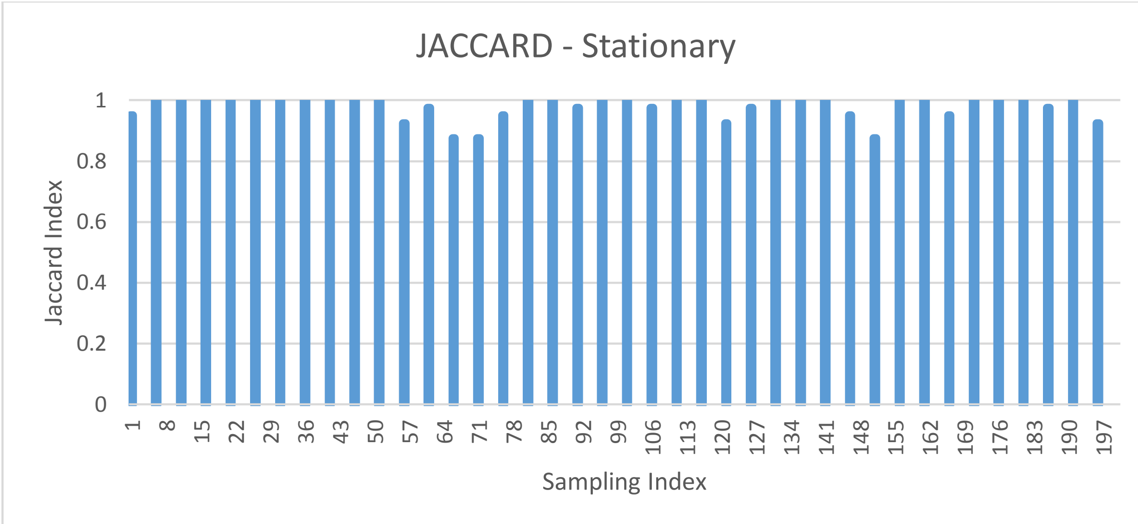

Figure 5-35 Jaccard Index

(Average value of Jaccard index is 0.98)

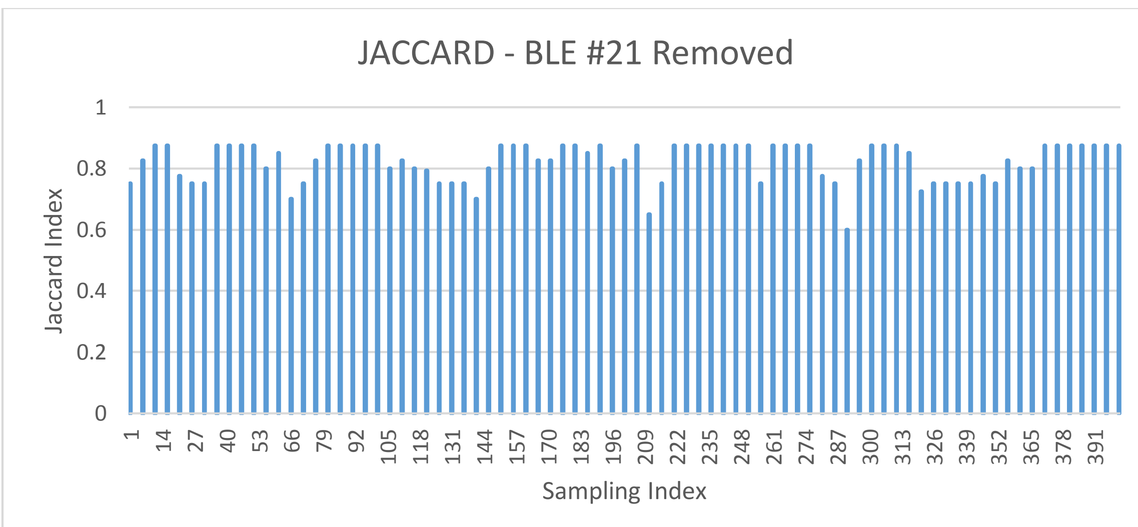

Figure 5-36 Jaccard Index When BLE #21 is Removed

(Average value of Jaccard index is 0.82)

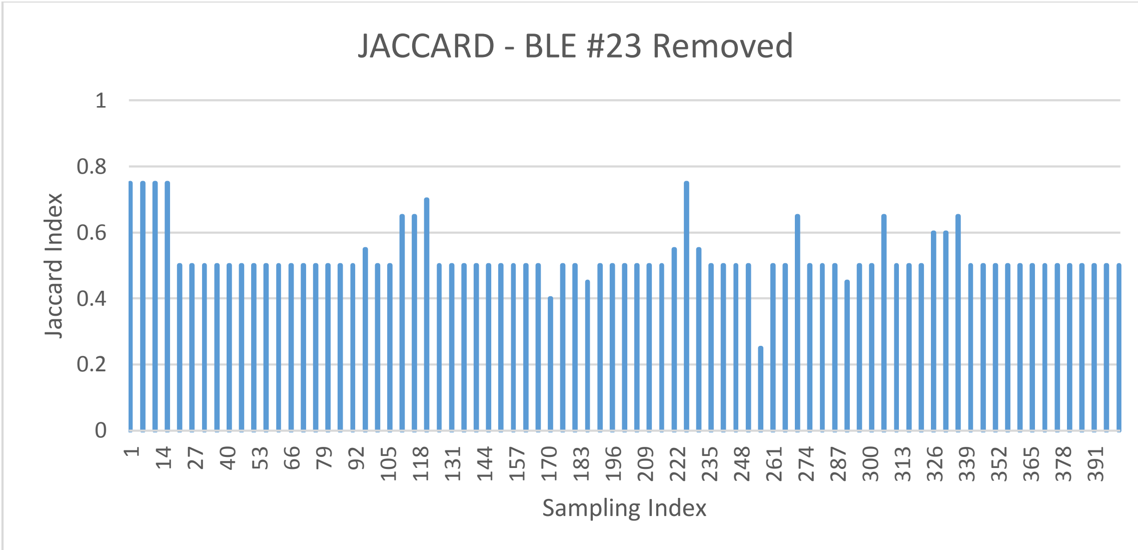

Figure 5-37 Jaccard Index When BLE #23 is Removed
(Average value of Jaccard index is 0.53)

The NWSLC index (from equation 5-45) is also examined at the same intersection. Figure 5-38 illustrates the NWSLC index when all BLE beacons are at their original locations based on 196 sets of RSSI measurements. The average NWSLC is 0.15 with a standard deviation (SD) of 0.09. When the BLE #23 is moved 5 meters away, the NWSLC signature changes with an average index increased to 0.62 and its SD is 0.24, as shown in Figure 5-39. Our fingerprint method used a two-tailed t-test (at the 95% confidence interval) to confirm a significant change of the NWSLC index pattern. Similarly, the NWSLC index in Figure 5-40 increases to 0.91 in average with a SD of 0.28 when the BLE #23 beacon is removed from the self-monitoring BLE network.

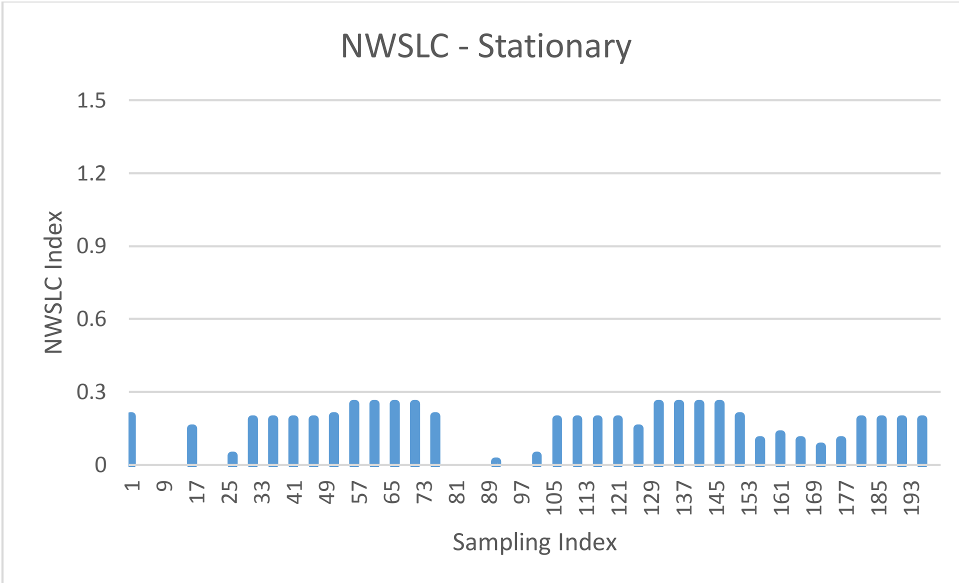

Figure 5-38 NWSLC Index
(Average value of NWSLC index is 0.15)

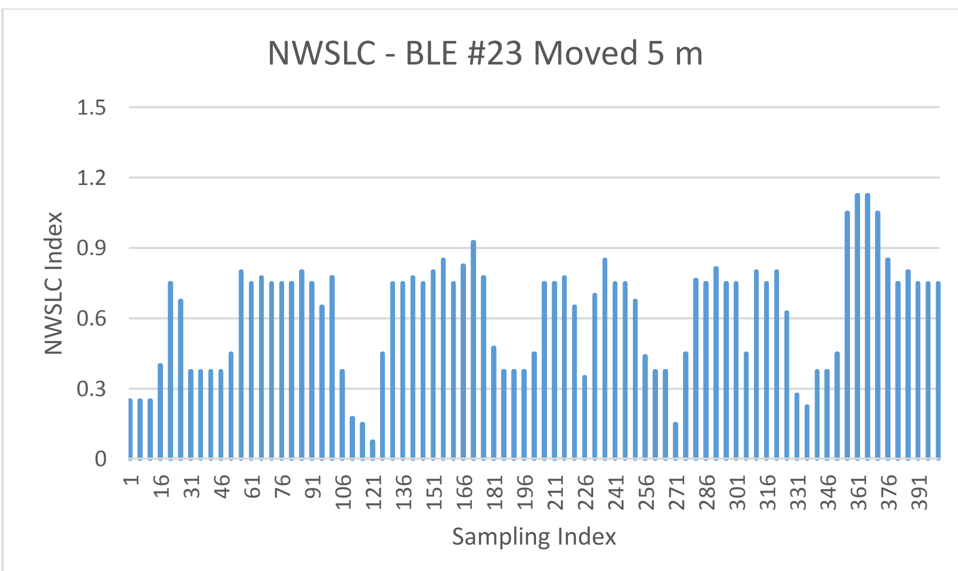

Figure 5-39 NWSLC Index When BLE #23 is Moved by 5 m
(Average value of NWSLC index is 0.62)

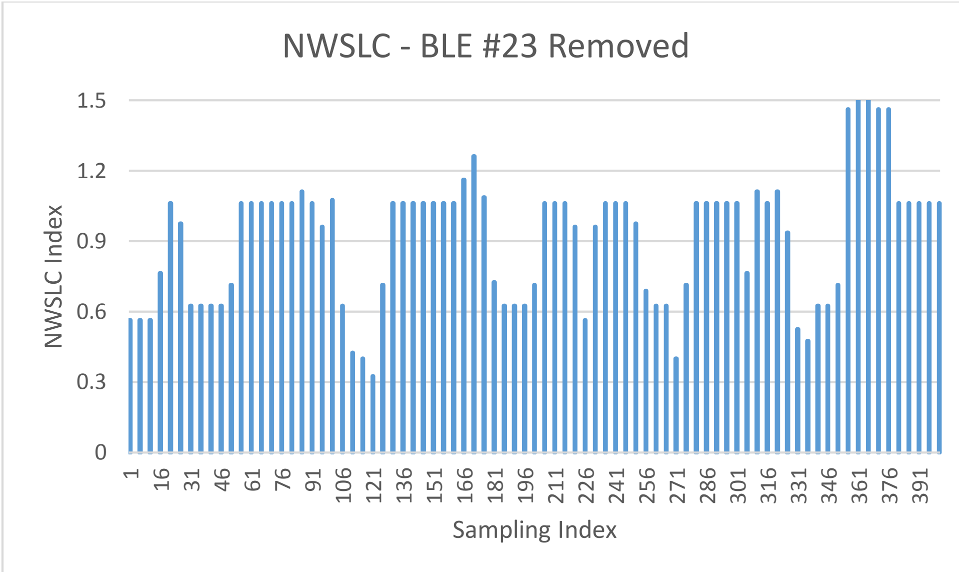

Figure 5-40 NWSLC Index When BLE #23 is Removed
(Average value of NWSLC index is 0.91)

5.8 Summary

In this chapter, we described a position sensing and a self-monitoring infrastructure to ensure information provided to the visually impaired is up-to-date and at right location. We developed a method that uses the ability of a smartphone with Bluetooth to sense the proximity of Bluetooth modules, and their ability to sense each other. For positioning and mapping, we evaluated two methodologies, Logarithmic Curve Fitting (LCF) and Multi Regression (MR), to find a robust positioning solution to identify a user's relative location near an intersection. Our results indicated that the Multivariable Regression (MR) method using Singular Value Decomposition (SVD) algorithm outperforms the LCF method in modeling the relationship between Received Signal Strength Indication (RSSI) and the actual ranging distance in an outdoor environment. The MR-SVD approach successfully reduces the environmental uncertainty and dynamic nature of the

RSSI measurements. The range output from the MR-SVD model is integrated with an Extended Kalman Filter (EKF) model to determine a user's location.

Due to the significant noise associated with the RSSI measurements, the LCF model has large position errors (7.3 and 9.5 m in X and Y axis, respectively). The MR-SVD and EKF combined model improves the position error by about 44% (to 4.1 and 5.4 m in X and Y axis, respectively). Because of the low power characteristics of the BLE beacons, the received signal strength is subject to influences from many external parameters. Although, the positioning performance of the MR-SVD and EKF combined method is not sufficient for detecting pedestrian veering at crosswalks, it provides reasonable positioning to identify a person's location at a corner of an intersection in a GPS unfriendly environment.

To create the self-monitoring infrastructure, a Cumulative Sum (CUSUM) technique is implemented to monitor if the location of one or multiple BLE beacons in a network is changed based on Bluetooth RSSI measurements. Our results indicate that the CUSUM detection algorithm is able to detect the range changes of a peer BLE beacon of 3 meters 86% of the time. The CUSUM detection rate increases to 100% when a BLE tag is moved over 6 meters away from its original location.

In addition, we evaluated two wireless signal fingerprinting indices, the Jaccard and Normalized Weighted Signal Level Change (NWSLC) indices, to detect geometry changes of a BLE network. Both indices were able to successfully detect the change of a

BLE beacon when it was moved over by 3 to 6 meters away, removed or disappears (e.g., due to vandalism or lost power) from a network. However, the NWSLC index performs better than the Jaccard index. It normalizes the changes of a signal based on its initial signal states. As a network geometry configuration changes, the NWSLC index increases proportionally to the amount of change with respect to its initial signal strength.

The MR-SVD and EKF combined method is incorporated in our system for positioning. The CUSUM and NWSLC techniques are both incorporated in our system for self-monitoring infrastructure. The CUSUM is used to detect changes between 2 BLE beacons. And, the NWSLC index is used to monitor the changes of BLE network geometry.

CHAPTER 6 DISCUSSION AND CONCLUSION

In this chapter, we review the development of a mobile accessible pedestrian system that supports wayfinding and situation awareness for people with vision impairment while traveling in a transportation network. We summarize the results and findings from our study. We include lessons learned from the field experiments while interacting with the O&M specialists and the visually impaired. Furthermore, we discuss the implementation guideline, benefit and potential impacts of our effort. Finally, we discuss our system limitations, future opportunities and directions to further our research in this area.

6.1 Dissertation Summary

People with vision impairment use white cane as their primary mobility and obstacle detection tool for navigation and wayfinding. They usually gather as many environmental cues (e.g., auditory, olfactory, or tactile) as possible to support their decision making at various levels of navigation and situation awareness. However, due to differences in spatial perception as compared to sighted people, they usually encounter physical and information barriers that limit their transportation accessibility and mobility. This dissertation aims to improve their mobility, accessibility and level of confidence in using the transportation system by removing not only the physical barriers but also the information barriers that could potentially impede their mobility and undermine safety. A smartphone based system was designed, developed, and tested to provide transportation information to assist people with vision impairment navigate streets. In addition, a self-monitoring infrastructure using Bluetooth Low Energy (BLE) sensors was also developed to ensure information provided to the users is correct at right location.

Prior to designing a system to assist navigation and wayfinding for the visually impaired, we conducted two surveys to better understand the challenges they face and the types of information that are useful while crossing streets and navigating around work zones. We then incorporated the recommendations from the surveys and developed a smartphone based assistive wayfinding system, called the Mobile Accessible Pedestrian System (MAPS). The intent of our system is not to replace the orientation and mobility (O&M) skills that people with vision impairment have already learned. The objective of the MAPS is to provide navigation information they need at key decision locations (e.g., beginning of a crosswalk, work zone, subway entrance, etc.) while traveling in a transportation network.

The MAPS system integrates GPS, an accelerometer, a digital compass and a Text-To-Speech (TTS) interface that are readily available on a smartphone together with a digital map database we developed to determine a user's location and orientation. A smartphone app was developed to provide necessary information at a decision point (e.g., at an intersection crossing or at a work zone) by communicating with a cloud server based on the user's location.

A simple user interface using single- or double-tap on the screen of the smartphone was implemented to take user's input and provide appropriate information at different levels that will not overwhelm the visually impaired user with an unnecessary cognitive load while interpreting information. Intersection geometry information is communicated to the users through the single tap interface. The double-tap interface allows the visually impaired pedestrians to request street crossing and receive pedestrian signal timing at a crosswalk through an audible feedback. For work zone bypass applications, the MAPS uses the Bluetooth technology on a smartphone to continuously scan for any Bluetooth beacons installed near a work zone, determine a user's location based on the Bluetooth signal strength measurements, then provide corresponding navigational guidance instructions accordingly.

We conducted field experiments at two signalized intersections with 18 visually impaired participants to evaluate the MAPS. Participants were given a brief tutorial on how to use the smartphone app including pointing in different directions for geometry and signal timing information. Participants were asked to perform 1 crossing task at the first intersection already equipped with an APS system and 2 crossing tasks at the second intersection with and without the use of the MAPS system. Experiment protocols and objective measures were developed to evaluate the users' street crossing and wayfinding performance with and without the assistance of the MAPS. We also evaluated the usability of the MAPS system to better understand the users' perceptions of workload, satisfaction, usefulness, and willingness to use the information presented by the smartphone app.

Results from the field experiments are promising. However, four participants experienced incorrect positioning information from the MAPS due to the fact that the GPS receiver on the smartphone does not always identify a user's location correctly. As a result, a

Bluetooth geo-ID was included as part of the MAPS to reliably determine the user's location at a GPS unfriendly environment. Enhancements, such as reducing the latency of signal data communication and adaptively learning available pedestrian walking time from the signal controller, were made to the existing system after the field experiment.

We presented our field experiment results to the O&M instructors who attended the Association for Education and Rehabilitation (AER) orientation and mobility (O&M) conference in 2013. They understood the objective of MAPS is to provide information assistance to the visually impaired but not to replace their existing wayfinding skills. Many instructors preferred the personal approach of providing transportation information through the smartphone. They liked the idea of including intersection signal timing info, transit and work zone information in one app. However, they had questions over the smartphone ownership in the visually impaired community.

According to a research survey conducted by the Pew Research Center in 2015, 64% of cell phone owners say that their phone is a smartphone. Smartphone ownership in the visually impaired community is lower than that in the general population. But, the smartphone ownership in the visually impaired community is rising. Five of the ten visually impaired participants we surveyed own a smartphone. It is expected that smartphone ownership will continue to grow as the mobile technology advances in the future.

Satellite based position solution on a smartphone is not always accurate for pedestrian navigation, particularly when a user is traveling in a GPS unfriendly environment (e.g., subway or urban canyon). In order to ensure the location based information provided to the user is accurate and reliable at a user-specific location, we developed a method that uses the ability of a smartphone with Bluetooth to sense the proximity of Bluetooth beacons, and their ability to sense each other. We re-programed the firmware of the commercial off-the-shelf (COTS) BLE beacons to operate both in scanning (master) and broadcasting (slave) mode.

Four BLE beacons were installed at an intersection to collect data and validate our methodologies. Our results indicated that the Multivariable Regression (MR) method using Singular Value Decomposition (SVD) algorithm outperforms the Logarithmic Curve Fitting (LCF) method in modeling the relationship between Received Signal Strength Indication (RSSI) and the actual ranging distance in an outdoor environment. The MR-SVD approach successfully reduces the environmental uncertainty and dynamic nature of the RSSI measurements. The range output from the MR-SVD model is integrated with an Extended Kalman Filter (EKF) model to determine a user's location.

The MR-SVD and EKF combined model improves the position error by about 44% (to 4.1 and 5.4 m in X and Y axis, respectively) as compared to the LCF method. Although, the positioning performance of the MR-SVD and EKF combined method is not sufficient for detecting pedestrian veering at crosswalks, it provides reasonable positioning to identify a person's location at a corner of an intersection in a GPS unfriendly environment. The positioning solution can be improved by adding additional beacons in a Bluetooth network.

To develop a self-monitoring infrastructure, a Cumulative Sum (CUSUM) technique is implemented to monitor if the location of one or multiple BLE beacons in a network is changed based on Bluetooth RSSI measurements. Our results indicate that the CUSUM detection algorithm is able to detect the location changes of a peer BLE beacon at 3 meters range 86% of the times. The CUSUM detection rate increases to 100% when a BLE tag is moved over 6 meters away from its original location.

In addition, we evaluated two wireless signal fingerprinting indices, the Jaccard and the Normalized Weighted Signal Level Change (NWSLC) index, to detect geometry changes of a BLE network. Both indices were able to successfully detect the change of a BLE beacon when it was moved over by 3 to 6 meters away, removed or disappeared (e.g., due to vandalism or lost power) from a network. However, the NWSLC performs better than the Jaccard index. It normalizes the changes of a signal based on its initial signal states. As a network geometry configuration changes, the NWSLC index increase proportionally to the amount of changes with respect to its initial signal strength.

The MR-SVD and EKF combined method is incorporated in our system for positioning. The CUSUM and NWSLC techniques are both incorporated in our system for self-monitoring infrastructure. The CUSUM is used to detect changes between 2 BLE beacons. And, the NWSLC index is used to monitor the changes of the BLE network geometry.

6.2 Lesson Learned

We learned much from the field experiments while interacting with the O&M specialists and the visually impaired. They are listed as follows.

a) For planning new experiments with visually impaired subjects, a guide dog may be distracted by the O&M specialist or other research team member nearby the intersection.

b) The single and double tap user interface may seem relatively easy for the visually impaired participants. However, a 15-minute tutorial on how to properly use the beacon is not sufficient. There is still a learning curve for the users to understand how the system works. For example, in order to hear the auditory message clearly at a busy intersection, the participants usually point the phone in a desired direction and immediately bring the phone to their ears before the orientation measurement from the digital compass is stabilized. A Bluetooth wireless speaker can be attached to a user's collar so they can hear the messages clearly in a noisy environment.

c) A follow-up experiment is needed to evaluate the participants' performance again a few months after introducing MAPS to people with vision impairment. This is to evaluate the usefulness of the MAPS system and user's knowledge retention in learning a new technology.

d) For a given intersection, a minimum of 4 BLE beacons are needed to provide information at each corner of the intersection and establish the self-monitoring BLE infrastructure.

e) For indoor applications, such as a tunnel or skyway, a standalone BLE beacon can be placed at each terminal of a pathway segment to provide information to the visually impaired (but unless more BLE beacons, no self-monitoring is possible).

f) For indoor applications in a concourse, such as an airport terminal, based on our experiments, the BLE beacons should be placed 98 to 164 ft (30-50 m) apart for positioning and mapping because of limitations in the BLE beacon transmission range.

6.3 Implementation Guidelines

Implementation and deployment guidelines are discussed in this section. For a larger scale implementation, it makes more sense to access the real-time traffic signal information from a city's central traffic controller. Often, a city-wide GIS database of sidewalks is not available or incomplete. The digital map for MAPS is overlaid on the street network (Figure 6-1) with intersection signal information. Battery power consumption and power sources for the BLE beacons when installed in an infrastructure require additional consideration for deployment.

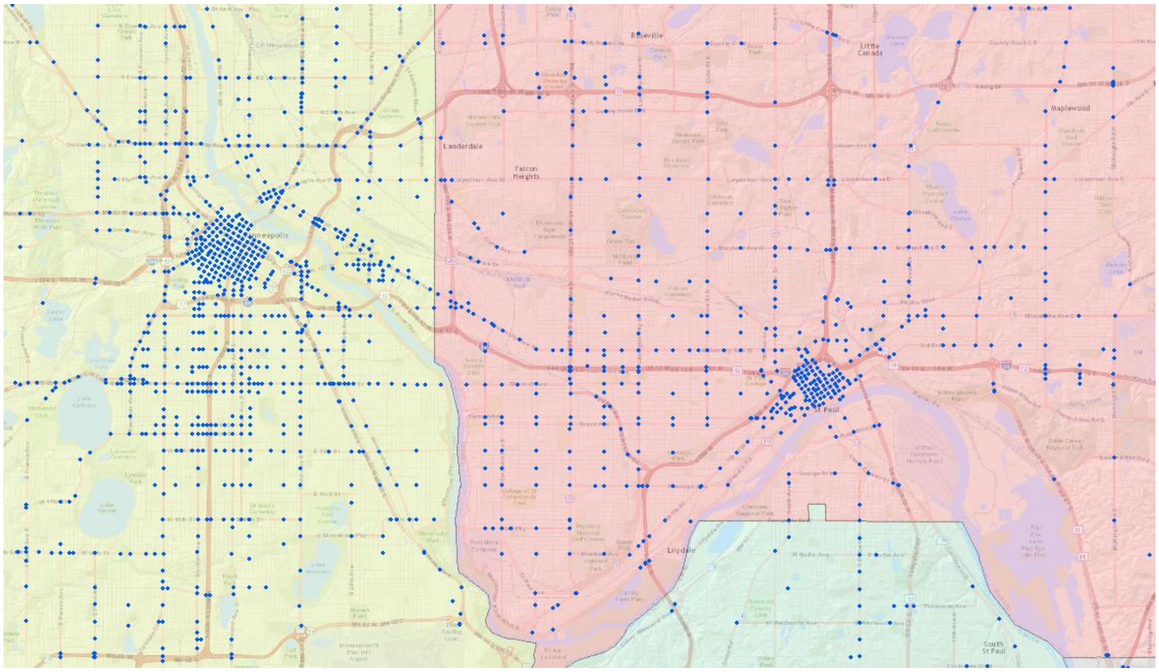

Figure 6-1 Signalized Intersections in Minneapolis and St. Paul, MN

In order to accommodate the dynamic nature of the transportation network (e.g., sidewalk closures), Figure 6-2 illustrates a proposed system design to manage the text-to-speech (TTS) information that is stored on a server by the local jurisdiction. The proposed system can be implemented in a three-tier data management architecture for data security. The data exchange between the database and the clients are handled through a Java servlet application which takes care of the user authentication and authorization.

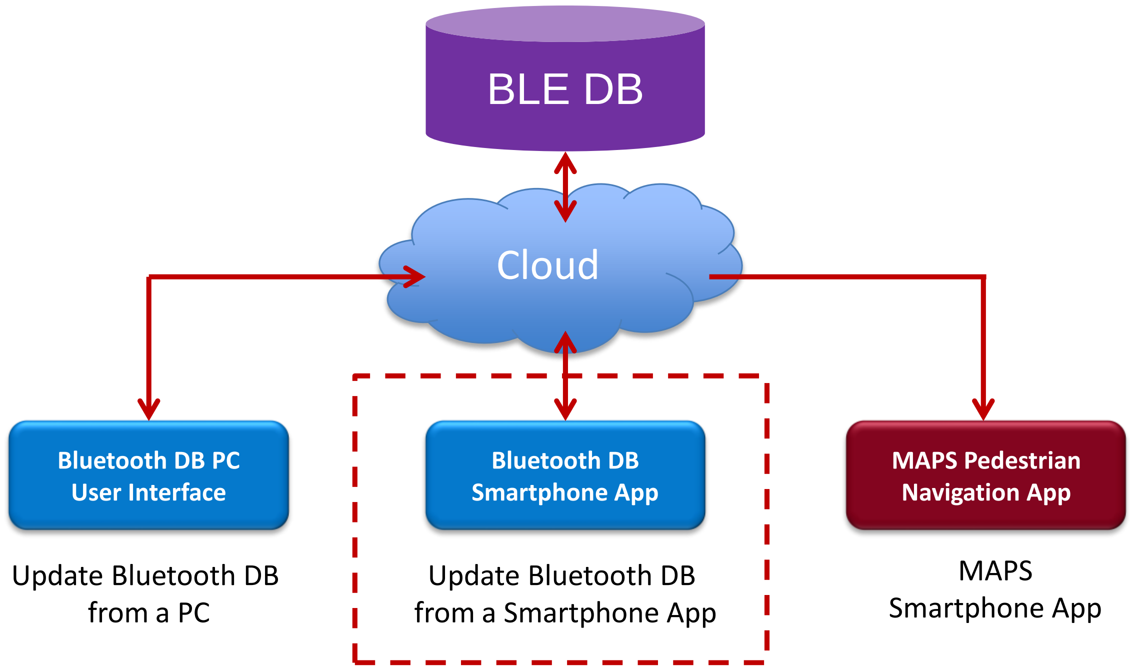

Figure 6-2 Proposed System Architecture for Future Implementation

In order to reduce the effort required in the placing the Bluetooth beacons at an intersection or a construction site, a smartphone app (inside the rectangle with dash lines) was developed for project engineers at a construction site. This app allows the engineers to enter the messages at the location where a Bluetooth beacon is installed. The proposed app (a screen image is shown in Figure 6-3) can determine current latitude/longitude location of the smartphone beacon, scan for Bluetooth beacons in the vicinity, and then list identified Bluetooth MAC IDs. After the field engineer enters the corresponding text messages and an authorized security code, the smartphone app then submits the data to the central database through the servlet application running on a remote server. This approach allows construction workers to easily reconfigure the sidewalk closure in a work zone as needed and to update the audible messages in a timely manner.

Figure 6-3 A Screen Image of a Smartphone App to Update Database Onsite

6.4 Benefit and Impacts

More than one billion people worldwide live with a disability, according to the world disability report published by the World Health Organization (WHO). The WHO fact sheet (2013) stated that there are about 285 million people who are visually impaired worldwide, 39 million of them are blind, and 82% of people living with blindness are aged 50 and above. We believe that the methods developed here will significantly help the visually impaired to get around including to and from their employment, to and from health care, and to be more self-sufficient.

We believe the MAPS system can be deployed on a larger scale and in a more cost effective manner than described here. Its long-term impact will be determined by the usability and acceptance of the system by blind pedestrians, and by the availability and reliability of the information that is provided.

In order to address the usability and acceptance of the assistive system, we focused our initial effort on understanding the needs and challenges of blind pedestrians at intersection crossings. We believe, the advent of even better technologies related to position localization, Location Based Services (LBS), advanced traffic signal controllers, and wireless technologies, will enhance the performance and reliability of the proposed system.

Many smartphone apps use GPS and other sensors on the phone to provide location information. However, the GPS on a smartphone doesn't work in GPS denied environments. The benefit of our system is that it uses the BLE beacons to identify a user's location and uses a digital map of the important features as represented by the BLE beacons residing in a network to support wayfinding.

The local position and mapping information can be monitored and updated regularly from a central database system accessible to the pedestrian's smartphone. Appropriate messages can be referenced to each BLE beacon when detected by a smartphone app. The approach described here is different from all other BLE applications that have been described in the literature or public press.

The positioning and mapping method based on the BLE beacons can also be incorporated into a geospatial database or a reference map for indoor navigation and guidance. Another smartphone app was developed for the project engineers to reduce the effort required in placing the BLE beacons at a field site. This app allows the engineers to enter the messages at the location where a Bluetooth beacon is installed. This app, for example, allows construction workers to easily reconfigure the sidewalk closure in a work zone as needed and to update the audible messages in a timely manner.

6.5 System Limitations

The MAPS is intended to use the smartphone as a personal assistive device to provide transportation information to people with vision impairment. However, it does not account for the differences in personal understanding and perception of an environment. Possible system limitations include:

1. When using the smartphone as a pointer to survey the environment for geometry information, the users may not point the phone in the same direction as they are facing.
2. The user's cognitive understanding of the environment and provided messages may vary.

These will need to be investigated in future studies.

6.6 Future Opportunities

The Federal Communications Commission (FCC) allocated 75 MHz of spectrum in the 5.9 GHz band for use by Intelligent Transportations Systems (ITS) vehicle safety and mobility applications. Dedicated Short Range Communication (DSRC) based communications is a major research priority of the Joint Program Office (ITS JPO) at the USDOT. The cross-modal program is conducting research using DSRC and other wireless communication technologies to ensure safe, interoperable connectivity to help prevent vehicular crashes of all types and to enhance mobility and environmental benefits across all transportation system modes. As part of the Connected Vehicles (CV) pilot deployment program[33], the USDOT announced the selection of three connected vehicle deployment sites (http://www.its.dot.gov/press/2015/ ngv_tech_announcement.htm). The deployment in New York City[34] will use dedicated short range communications (DSRC) among intersections to improve vehicle flow and pedestrian safety in high-priority corridors. Potential applications related to pedestrians include providing pedestrians with signalized intersection warning and improving the safety of the visually impaired pedestrians at signalized intersections.

For example, Figure 6-4 illustrates an example of a smartphone app using DSRC technology to communicate with other devices in range. The DSRC radio is paired with a smartphone through Bluetooth for communications between vehicles and pedestrians. It is envisioned that a smartphone can become a personal safety beacon for pedestrian to vehicle (P2V) communication, i.e., pedestrians broadcast their presence to vehicles when

[33] CV Pilot Implementation Program, http://www.its.dot.gov/pilots/cv_pilot_plan.htm
[34] NYC Concept of Operations, http://www.its.dot.gov/pilots/pdf/NYC_ConOpsWebinar.pdf

appropriate, or vehicle to pedestrian (V2P) communication, i.e., pedestrians receive safety / emergency messages from vehicles. Qualcomm[35], a San Diego based semiconductor company, is testing chips for smartphones that can incorporate the DSRC technology without adding external hardware. Honda and Qualcomm leverage DSRC technology so vehicles can communicate with smartphones to preempt a possible collision between a pedestrian (with a smartphone) and an approaching vehicle (Wu et al., 2014). They are conducting extensive lab and field tests to enable DSRC technology on both Qualcomm reference design phones and all other commercially available smartphones (Borroni-Bird, 2013).

Figure 6-4 A Smartphone App Uses DSRC Radio for Communications[36]

In the near future, when users' smartphones are equipped with DSRC technology, the driver of the vehicle or the vehicle can automatically detect and avoid collision with a

[35] Enabling Connected and Electric Vehicles, https://www.itu.int/en/fnc/2014/Documents/S3P5-Chris-Borroni-Bird.pdf
[36] GM Develops Portable In-Vehicle Device That Creates a Wireless 'Safety Net', http://www.automotive-fleet.com/news/story/2011/10/gm-develops-portable-device-and-app-that-creates-a-wireless-safety-net.aspx

pedestrian. For future research, additional experiments with visually impaired subjects are needed by involving visually impaired subjects to validate the self-monitoring infrastructure and the latest system reliability and usefulness of the MAPS at a larger scale. An implementation study is essential and should include sufficient numbers of participants. Experiments will need to be conducted on different street networks with different configurations to evaluate the scalability of the MAPS system.

We have identified the following tests that are still needed prior to full deployment.

- Test robustness, scalability and usability in a larger complex region (for example, a commercial business district) with multiple transit stops covering areas with good, poor and no GPS availability.
- Evaluate test areas which combine grid and non-grid intersection geometry.
- Conduct experiments with multiple simultaneous users over longer time frames.
- Incorporate access to signal phase and timing (SPaT) from a central database at the traffic management center.
- Develop a message architecture that can handle more complex navigation tasks, e.g. how do messages change if one approaches intersection from different directions.
- Develop methods for handling veering issues and assess the possibility of false positives or false negatives.
- Integration of GPS and BLE positioning for outdoor and indoor navigation.
- Develop a better Human Machine Interface (HMI) for orientation compensation (for example, inform users to turn by angle or left/right direction).

- Evaluate a set of Android smartphones to assess their sensing and resolution capability for our application.

In the future, it will be interesting to explore and investigate alternatives to make the system hands-free and include user configurable settings (e.g., selectable vibration pattern, message frequency, and TTS speech rate) based on participants' preferences. With the advance of the Internet of Things (IoT) and innovations in consumer electronics, we are interested in exploring wearable technology for providing assistive transportation information to people who are blind or visually impaired.

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APPENDIX A: PARTICIPANT RECRUITMENT AD AND CONSENT FORM

A.1 Recruitment Ad

BLIND AND LOW-VISION VOLUNTEERS NEEDED

Researchers at the University of Minnesota have developed a Mobile Accessible Pedestrian Signals (MAPS) that provide signal timing and intersection geometry information to people who are visually impaired at signal intersections. They are recruiting individuals who are visually impaired to participate in an experiment at two locations involving signalized intersection crossing. Participants will be asked to cross signalized intersections with Accessible Pedestrian Signals (APS) and with a MAPS beacon that provide signal and geometry information. The participants will be followed by a certified orientation and mobility (O&M) specialist as a shadow at each location. The participants will have one-on-one discussions with a researcher before and after each crossing task to understand how blind and low vision individuals orient/navigate as a pedestrian, what types of information cue they use, and evaluate the usefulness of information provided by the MAPS beacon at intersection crossings.

Experiment will be conducted at two signalized intersections the Twin Cities Metro Area. It will require approximately 1 hour for each location. Participation in both locations is required for each participant and each participant will be paid $30 for each session.

There is no additional risk of injury to participants as compared to crossing existing signalized intersections. In the event that this research activity results in an injury, treatment will be available, including first aid, emergency treatment and follow-up care as needed. Care for such injuries will be billed in the ordinary manner to you or your insurance company.

To participate, individuals must:

- **Be 18 to 64 years of age,**
- **Have at best 20/70 acuity with correction in their better eye,**
- **Have completed orientation and mobility training,**
- **Be proficient in using a cane or guide dog,**
- **Be willing to have audio and/or video recorded during the interview and intersection crossing tasks.**

If you fit these criteria, you may be eligible to participate in the study. If you are interested, please contact

Linda Spaulding
Email: thekidisgood1@comcast.net, Phone: (651) 247-5553

Or, Chen-Fu Liao
Email: cliao@umn.edu, Phone: (612) 626-1697

Please provide your name and a phone number where you can be reached during the day.

A.2 Consent Form

Title of Study: Spatial Cognition of the Blind and Visually Impaired While Using a Mobile Accessible Pedestrian System (MAPS) at Signalized Intersections

You are invited to participate in a research study to evaluate the usefulness of a smartphone based traffic signal system designed for the visually impaired pedestrians. You were selected because you are considered legally blind or to have low vision, you have completed orientation and mobility training, and have experience orienting on your own. We ask that you listen to/read this form and ask any questions you may have before agreeing to be in the study.

This study is being conducted by Chen-Fu Liao who is a research staff at the University of Minnesota and assisted by Linda Spaulding who is a certified orientation and mobility (O&M) specialist. This study is sponsored by U.S. Department of Transportation through the University Transportation Center program at University of Minnesota.

Background Information
The purpose of this study is to provide intersection geometry and traffic signal information to the blind and visually impaired while waiting at a signalized intersection. The traffic information will be wirelessly broadcasted to a smartphone beacon that was developed by the research team.

Procedures
If you agree to be in this study, we would ask you to participate in an experiment involving crossing two signalized intersections in the metro area. At each location, you will be asked to perform crossing tasks and will be interviewed before and after the crossing. The crossing tasks and interviews will focus on your experiences while crossing signalized intersections, using audible pedestrian signals, and a smartphone based accessible pedestrian signal beacon provided by the research team.

For each crossing task, a certified O&M specialist will bring you to a starting point which will be located about 50~100 feet away from an intersection. You will be asked to travel along the sidewalk using your own navigational skills to reach the corner of the intersection. While at the intersection, you will need to find and use the pushbutton to request a pedestrian walk signal or use our smartphone based pedestrian signal beacon to determine when it is possible to cross. You will then cross the street that is perpendicular to the sidewalk you just travelled and arrive at the other side of street.

The pre and post experiment interviews will allow for follow-up questions and will cover the following topics:

1. Your vision,
2. Your ability to orient by yourself,
3. Your experience crossing intersections,
4. Your usage and opinions of the new technology,
5. Your opinions of the smartphone based pedestrian crossing system,

6. Usability and acceptance of the smartphone system,
7. Trust of the smartphone based traffic information system, and
8. Demographic information.

Each session should last approximately one hour. The experiment and interviews will be recorded using video and/or audio equipment to record your responses and intersection crossing performance.

Risks and Benefits of being in the Study
There are no direct risks or benefits associated with this experiment. A certified O&M specialist will shadow each subject during each intersection crossing in order to provide assistance if needed or in case of emergency.

Research Related to Injury
In the event that this research activity results in an injury, treatment will be available, including first aid, emergency treatment and follow-up care as needed. Care for such injuries will be billed in the ordinary manner to you or your insurance company. If you think that you have suffered a research related injury, let the study staffs know right away.

Compensation
You will receive $30 for participating in each session. Compensation ($60 in total) will be paid after the completion of both experiment sessions.

Confidentiality
The records of this study will be kept private. In any report we might publish, we will not include any information that will make it possible to identify participants. Research records will be stored securely and only researchers will have access to the records. Audio and video recordings will only be accessible to researchers on this project. Portions of these recordings may be used when presenting findings at internal project meetings or at scientific meetings. Your name and identifying information will never be linked to these recordings.

Voluntary Nature of the Study
Participation in this study is voluntary. Your decision whether or not to participate will not affect your current or future relations with the University of Minnesota or with Vision Loss Resources. If you decide to participate, you are free to not answer any question or withdraw at any time without affecting those relationships.

Contacts and Questions
The researcher conducting this study is: Chen-Fu Liao. He is assisted by Linda Spaulding who is a certified O&M specialist. You may ask any questions you have now. If you have questions later, you are encouraged to contact Chen-Fu Liao at 500 Pillsbury Drive SE, Minneapolis, MN 55455, (612) 626-1697, or cliao@umn.edu.

If you have any questions or concerns regarding this study and would like to talk to someone other than the researcher(s), you are encouraged to contact the Research Subjects' Advocate Line, D528 Mayo, 420 Delaware St. Southeast, Minneapolis, Minnesota 55455; (612) 625-1650.

You will be given a copy of this information to keep for your records.

Statement of Consent

I have listened to/read the above information. I have asked questions and have received answers. I consent to participate in the study.

Signature:____________________________

Date: ________________________________

Signature of Investigator:

____

Date: ________________________________

IRB Code Number: **1112S07962**
Approved on Feb. 2, 2012

APPENDIX B: EXPERIMENT PROTOCOL AND INTERVIEW QUESTIONNAIRES

B.1 Experiment Protocol

Experiment Protocol

Thank you for agreeing to help us with our research on technology that may assist the mobility of blind and low vision pedestrians. You will be asked to cross two signalized intersections. Two trips at each intersection will be conducted. In each experiment, you will be asked to travel from an origin which is about 50~100-ft away from the intersection.

The first intersection is equipped with accessible pedestrian signal (APS). You will cross the intersection twice (with and without the use of pushbutton). The second intersection is a regular intersection that you will cross with and without the assistance of a mobile beacon. The purposes of these experiments are to compare the performance of intersection crossing with or without using the pushbutton and a mobile assistive beacon.

In order to observe and capture multiple measurements and parameters in each experiment, we will video record each trip to better understand the potential challenges people who are visually impaired may encounter. A certified orientation and mobility (O&M) specialist will follow a few steps behind you in case of emergency or assistance needed during each task. The role of the O&M specialist is to ensure your safety during the crossing. If at any time during the experiment, you feel uncomfortable or unsafe, please let the O&M specialist know.

I. Pre Experiment Interview Protocol

We would like to design technology that helps meet your needs on a daily basis and because of this your participation and input is important. Your answers will be completely confidential. If you feel uncomfortable answering any question, you may pass (leave it blank). If at any time you would like a break or to stop, please let the interviewer know.

a. Demographic information.

1. Age: ___________ years

2. Gender: ☐ Male ☐ Female

3. What is the highest level of education you have completed?
   - ☐ Some high school – no diploma
   - ☐ High school graduate or equivalent
   - ☐ Some college or Associate degree
   - ☐ Bachelor's degree
   - ☐ Advanced degree (MBA, PhD, etc.)
   - ☐ Other, please specify ______________________________________

4. In average, how often do you cross a signalized intersection?
   - ☐ More than 4 intersections a day
   - ☐ 1~2 intersections a day
   - ☐ 1~4 intersections a week
   - ☐ Less than 1 intersection a week

b. Self-ratings: Technology

5. Do you currently use a mobile phone?
   - ☐ No
   - ☐ Yes ➔ ☐ Smartphone ☐ Non-Smartphone

6. Do you currently use a mobile navigation assistant / GPS?
   - ☐ No
   - ☐ Yes

7. Have you experienced an Accessible Pedestrian Signal before? These signals give you audio or tactile information about the state of the light at the intersection or the location of the crosswalks in addition to a light signal.
   - ☐ No
   - ☐ Yes

c. Navigation & mobility

8. How long have you been using the following methods of assistance (if at all)?
   - ☐ Cane ___________________ years
   - ☐ Guide dog ________________ years
   - ☐ Other _____________________ years

9. What is your preferred method of assistance while navigating to a destination?
   - ☐ Cane
   - ☐ Guide dog
   - ☐ Asking other pedestrians I pass
   - ☐ No outside assistance
   - ☐ Other ____

10. How proficient are you are at each of these travel skills (on the scale from 1 to 5)

(Golledge et al. 2004)	Well below average 1	Below average 2	Average 3	Above Average 4	Well above average 5
General sense of direction	☐	☐	☐	☐	☐
Independent travel	☐	☐	☐	☐	☐
Signalized street crossings	☐	☐	☐	☐	☐

II. Post Experiment Interview Protocol

We would like to collect feedback from your intersection crossing experiences. Your answers will be completely confidential. If you feel uncomfortable answering any question, you may pass (leave it blank). For multiple-choice options, please select one answer per question.
If at any time you would like a break or to stop, please let the interviewer know.

d. APS intersection crossing (Intersection #1)

11. Do you prefer using a pushbutton for requesting walk phase at signalized intersection?
   - ☐ No
   - ☐ Yes
   - ☐ Don't know

12. Do you have difficulty locating the pushbutton?
   - ☐ No
   - ☐ Yes
   - ☐ Don't know

13. Does the APS system provide sufficient information to assist your intersection crossing?
   - ☐ No
   - ☐ Yes
   - ☐ Don't know

14. Do you feel you have sufficient time to cross this intersection?
   - ☐ No
   - ☐ Yes
   - ☐ Don't know

15. Do you feel you stay alignment with the crosswalk?
   - ☐ No
   - ☐ Yes
   - ☐ Don't know

e. Non-APS intersection crossing (Intersection #2)

16. Do you prefer using a pushbutton or the mobile assistive beacon for requesting walk phase at signalized intersection?

- ☐ No
- ☐ Yes
- ☐ Don't know

17. Do you have difficulty locating the pushbutton?
    - ☐ No
    - ☐ Yes
    - ☐ Don't know

18. Do you feel you have sufficient time to cross this intersection?
    - ☐ No
    - ☐ Yes
    - ☐ Don't know

19. Do you feel you stay alignment with the crosswalk?
    - ☐ No
    - ☐ Yes
    - ☐ Don't know

20. Does the mobile assistive beacon provide sufficient information to assist your intersection crossing?
    - ☐ No
    - ☐ Yes
    - ☐ Don't know

21. Do you feel the mobile beacon provide helpful information about the intersection geometry to support your wayfinding?
    - ☐ No
    - ☐ Yes
    - ☐ Don't know

22. Do you feel the mobile beacon provide helpful information about the intersection signal timing to support your intersection crossing?
    - ☐ No
    - ☐ Yes
    - ☐ Don't know

B.2 Acceptance and Usability

MOBILE ACCESIBLE PEDESTRIAN SIGNAL (MAPS)
SYSTEM USABILITY

What is your opinion about the system you just used? Please rate your opinion for each descriptive item below (please tick one box for each item):

For example, if you thought the system was very easy to use but required a lot of effort to learn, you might respond as follows:

Easy	☒	☐	☐	☐	☐	Difficult
Simple	☐	☐	☐	☒	☐	Confusing

Please continue to rate your opinion of the system for each descriptive term below:

	5	4	3	2	1	
Useful	☐	☐	☐	☐	☐	Useless
Pleasant	☐	☐	☐	☐	☐	Unpleasant
Good	☐	☐	☐	☐	☐	Bad
Nice	☐	☐	☐	☐	☐	Annoying
Effective	☐	☐	☐	☐	☐	Superfluous
Likeable	☐	☐	☐	☐	☐	Irritating
Assisting	☐	☐	☐	☐	☐	Worthless
Desirable	☐	☐	☐	☐	☐	Undesirable
Raising Alertness	☐	☐	☐	☐	☐	Sleep-inducing

Thank you for completing this questionnaire.

B.3 Trust

SYSTEM TRUST QUESTIONNAIRE

Below are statements relating to the system you just used, please indicate your level of agreement with the statement on the scales below each one.

1. The performance of the system enhanced my safety at signalized intersection crossings.

Strongly Disagree				**Strongly Agree**
0	25	50	75	100
☐	☐	☐	☐	☐

2. I am familiar with the operation of the system.

Strongly Disagree				**Strongly Agree**
0	25	50	75	100
☐	☐	☐	☐	☐

3. I trust the system.

Strongly Disagree				**Strongly Agree**
0	25	50	75	100
☐	☐	☐	☐	☐

4. The system is reliable.

Strongly Disagree				**Strongly Agree**
0	25	50	75	100
☐	☐	☐	☐	☐

5. The system is dependable.

Strongly Disagree				**Strongly Agree**
0	25	50	75	100
☐	☐	☐	☐	☐

6. I have confidence in this system.

Strongly Disagree				**Strongly Agree**
0	25	50	75	100
☐	☐	☐	☐	☐

7. The system has integrity.

Strongly Disagree				**Strongly Agree**
0	25	50	75	100
☐	☐	☐	☐	☐

8. I am comfortable with the intent of the system.

Strongly Disagree				**Strongly Agree**
0	25	50	75	100
☐	☐	☐	☐	☐

9. I am confident in my ability to cross a signalized intersection without the system.

Strongly Disagree				**Strongly Agree**
0	25	50	75	100
☐	☐	☐	☐	☐

B.4 Audible Messages

Today we are evaluating different messages that could be used to provide information to support wayfinding for the visually impaired in or around work zones. We will play you a message and repeat once assuming you are approaching a work zone. We will then ask you questions about the information you heard. Do you have any questions?

a. Audible Message Details

1. Do you prefer a brief message in a familiar location?

   ☐ No ☐ Yes

2. Does the following message provide sufficient information in a familiar location?

   "Attention Snelling Avenue pedestrians. East sidewalk closed for 6 blocks between Marshall and Summit."

   ☐ No ☐ Yes

   If "No", what information would you like to know more about?

   ____

   ____

3. Do you prefer a more detailed message in an unfamiliar location?

   ☐ No ☐ Yes

4. Does the following message provide sufficient information in an unfamiliar location?

   "Attention southbound Snelling Avenue pedestrians. Sidewalk closed from Marshall Ave for 6 blocks. Cross Snelling at Marshall. Use sidewalk on the other side. Return to original side of street if desired"

   ☐ No ☐ Yes

   If "No", what information would you like to know more about?

   ____

   ____

b. Message #1

"Attention eastbound Dolphin Street pedestrians. Construction ahead on sidewalk between 2nd and 6th Avenue. Use alternate route."

1. Do you understand the message?
   - ☐ No
   - ☐ Yes
2. Would you try the suggested route?
   - ☐ No
   - ☐ Yes
3. Based on the information you heard, what action would you take?

   ____

   ____

   ____

   Why? ____

   ____

   ____

4. What path was the message telling you to follow?

5. What type of situation was the message informing you about?

6. How clear is the message (on the scale from 1 to 5)

Very Unclear	Un-clear	Neutral	Clear	Very Clear
1	2	3	4	5
☐	☐	☐	☐	☐

c. Message #2

"Attention southbound Lyndale Avenue pedestrians. East sidewalk closed from 22th to 26th street. Cross Lyndale. Use sidewalk on the other side."

1. Do you understand the message?
   - ☐ No
   - ☐ Yes
2. Would you try the suggested route?
   - ☐ No
   - ☐ Yes

3. Based on the information you heard, what action would you take?
   ____
   ____
   ____
   Why? ____
   ____
   ____

4. What path was the message telling you to follow?

5. What type of situation was the message informing you about?

6. How clear is the message (on the scale from 1 to 5)

Very Unclear	Un-clear	Neutral	Clear	Very Clear
1	2	3	4	5
☐	☐	☐	☐	☐

d. Message #3

"Attention southbound Snelling Avenue pedestrians. Sidewalk closed from Marshall Ave for 6 blocks. Cross Snelling at Marshall. Use sidewalk on the other side. Return to original side of street if desired"

1. Do you understand the message?

   ☐ No

   ☐ Yes

2. Would you try the suggested route?

   ☐ No

   ☐ Yes

3. Based on the information you heard, what action would you take?

   ____
   ____
   ____
   Why? ____
   ____
   ____

4. What path was the message telling you to follow?

5. What type of situation was the message informing you about?

6. How clear is the message (on the scale from 1 to 5)

Very Unclear	Un-clear	Neutral	Clear	Very Clear
1	2	3	4	5
☐	☐	☐	☐	☐

e. Message #4

"Attention southbound Lyndale Avenue pedestrians. You are at southwest corner of Lyndale and Franklin. West sidewalk closed from 22th to 26th street. Cross Lyndale for more bypassing message."

After crossing, receive another update …

"Attention southbound Lyndale Avenue pedestrians. You are at southeast corner of Lyndale and Franklin. West sidewalk closed from 22th to 26th street. Use sidewalk on this side."

1. Do you understand the message?

   ☐ No ☐ Yes

2. Would you try the suggested route?

   ☐ No ☐ Yes

3. Based on the information you heard, what action would you take?

   ____
   ____
   ____
   Why? ____
   ____
   ____

4. What path was the message telling you to follow?

5. What type of situation was the message informing you about?

6. How clear is the message (on the scale from 1 to 5)

Very Unclear	Un-clear	Neutral	Clear	Very Clear
1	2	3	4	5
☐	☐	☐	☐	☐

APPENDIX C: INTERSECTION LAYOUTS

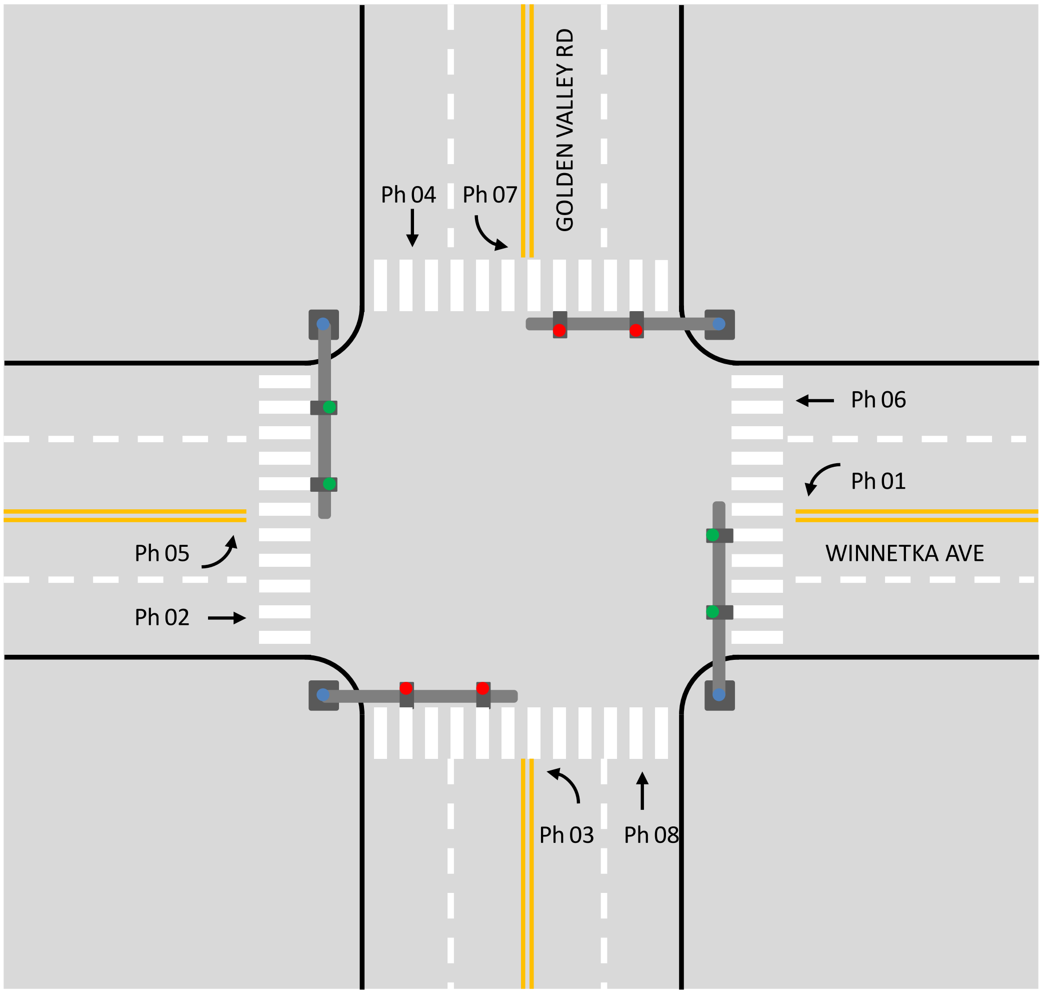

Figure C-1 Controller Phasing Layout at Winnetka Ave and Golden Valley Road

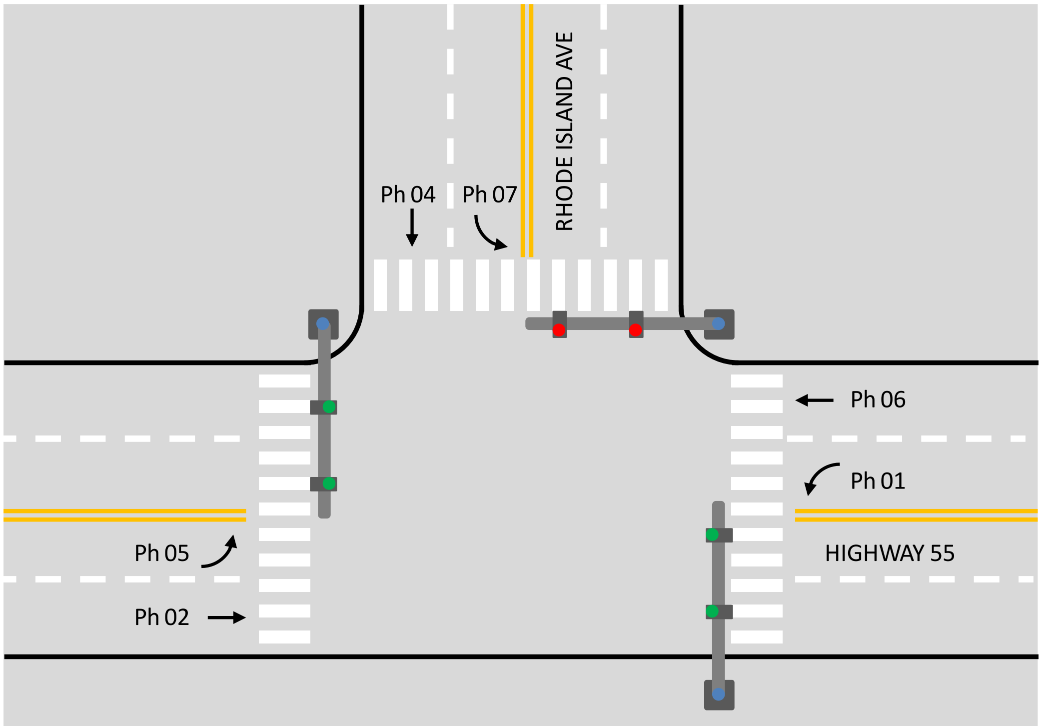

Figure C-2 Controller Phasing Layout at Highway 55 and Rhode Island Ave

Table C-1 AADT of Highway 55 & Rhode Island Avenue

Intersection / AADT	Highway 55	Rhode Island Ave
Highway 55 & Rhode Island Ave	33500	2550

Table C-2 AADT of Golden Valley Road & Winnetka Avenue

Intersection / AADT	Golden Valley Rd	Winnetka Ave
Golden Valley Road & Winnetka Ave	3850	2950

Table C-3 Controller Timing Plan of Highway 55 & Rhode Island Avenue

Controller Timing Plan (MM)2-1 GOLDEN VALLEY - TH 55 & Rhode Island Ave

Plan 1

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Min Green	0	20	0	8	7	20	0	0	0	0	0	0	0	0	0	0
BK Min Green	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CS Min Green	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Delay Green	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Walk	0	0	0	18	0	7	0	0	0	0	0	0	0	0	0	0
Walk 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Walk Max	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ped Clear	0	0	0	15	0	24	0	0	0	0	0	0	0	0	0	0
Ped Clear 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ped Clear Max	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ped CO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vehicle Ext	0.0	5.5	0.0	3.0	3.0	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vehicle Ext 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max 1	0	60	0	40	30	60	0	0	0	0	0	0	0	0	0	0
Max 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DYM Max	0	80	0	0	0	80	0	0	0	0	0	0	0	0	0	0
DYM Stp	0.0	10.0	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Yellow	0.0	5.5	0.0	3.5	3.5	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Clear	0.0	1.5	0.0	3.5	2.0	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Max	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Revert	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
ACT B4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SEC/ACT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max Int	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time B4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cars Wt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
STPT Duc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time To Reduce	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Min Gap	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table C-4 Controller Timing Plan of Golden Valley Road & Winnetka Avenue

Controller Timing Plan (MM)2-1 GOLDEN VALLEY - Winnetka Ave & Golden Valley Rd

Plan 1

Phase	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Min Green	7	12	7	10	7	12	7	10	0	0	0	0	0	0	0	0
BK Min Green	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CS Min Green	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Delay Green	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Walk	0	10	0	10	0	10	0	10	0	0	0	0	0	0	0	0
Walk 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Walk Max	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ped Clear	0	22	0	22	0	22	0	22	0	0	0	0	0	0	0	0
Ped Clear 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ped Clear Max	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ped CO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vehicle Ext	3.5	4.0	3.5	4.0	3.5	4.0	3.5	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vehicle Ext 2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max 1	20	50	20	33	20	50	15	33	0	0	0	0	0	0	0	0
Max 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DYM Max	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DYM Stp	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Yellow	3.5	4.0	3.5	4.0	3.5	4.0	3.5	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Clear	1.0	2.0	1.0	2.0	1.0	2.0	1.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Max	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red Revert	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
ACT B4	0	3	0	0	0	3	0	0	0	0	0	0	0	0	0	0
SEC/ACT	0.0	2.3	0.0	0.0	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max Int	0	20	0	0	0	20	0	0	0	0	0	0	0	0	0	0
Time B4	0	17	0	0	0	17	0	0	0	0	0	0	0	0	0	0
Cars Wt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
STPT Duc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time To Reduce	0	17	0	0	0	17	0	0	0	0	0	0	0	0	0	0
Min Gap	0.0	3.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX D: OBJECTIVE MEASURES

Table D-1 Intersection #1 Objective Measures

Objective Performance Measures	Sidewalk Time (sec) / 102 ft	Pushbutton Search Time (sec)	Time to Step Into Crosswalk (sec)	Crosswalk Time (sec) / 94 ft	In-Position Time (sec)
Dog AVG	30.8	9.0	4.4	23.0	16.2
Cane AVG	27.3	7.8	2.7	22.7	14.3
All AVG	**28.1**	**7.8**	**3.1**	**22.6**	**14.5**
All SD	5.0	6.1	1.5	4.3	7.5
All MIN	23.0	2.0	1.0	18.0	7.0
All MAX	42.0	26.0	6.0	34.0	33.0

Travel Speed Comparisons	Sidewalk Speed		Crosswalk Speed	
	(ft/sec)	(mph)	(ft/sec)	(mph)
Dog AVG	3.4	2.3	4.3	2.9
Cane AVG	3.8	2.6	4.2	2.9
All AVG	**3.7**	**2.5**	**4.3**	**2.9**
All SD	0.5	0.4	0.6	0.4
All MIN	2.4	1.7	2.8	1.9
All MAX	4.4	3.0	5.2	3.6

Table D-2 Intersection #2 Objective Measures (Crossing Task #1)

Objective Performance Measures	Sidewalk Time (sec) / 238 ft	Pushbutton Search Time (sec)	Time to Step Into Crosswalk (sec)	Crosswalk Time (sec) / 111 ft	In-Position Time (sec)
Dog AVG	52.6	70.4	10.5	24.6	79.8
Cane AVG	54.7	29.5	5.5	24.6	37.4
All AVG	**53.5**	**26.6**	**7.1**	**23.8**	**34.8**
All SD	8.5	56.5	4.7	5.6	57.2
All MIN	36.0	2.0	3.0	14.0	6.0
All MAX	69.0	240.0	20.0	36.0	250.0

Travel Speed Comparisons	Sidewalk Speed		Crosswalk Speed	
	(ft/sec)	(mph)	(ft/sec)	(mph)
Dog AVG	4.7	3.2	4.9	3.3
Cane AVG	4.5	3.1	5.7	3.9
All AVG	**4.6**	**3.1**	**4.9**	**3.4**
All SD	0.8	0.5	1.2	0.8
All MIN	3.4	2.4	3.1	2.1
All MAX	6.6	4.5	7.9	5.4

Table D-3 Intersection #2 Objective Measures (Crossing Task #2)

Objective Performance Measures	Sidewalk Time (sec) / 238 ft	Pushbutton Search Time (sec)	Time to Step Into Crosswalk (sec)	Crosswalk Time (sec) / 111 ft	In-Position Time (sec)
Dog AVG	51.4	NA	8.5	23.8	15.0
Cane AVG	50.4	NA	4.5	23.1	7.6
All AVG	**50.7**	**NA**	**5.5**	**23.3**	**9.8**
All SD	8.8	NA	3.2	3.6	6.7
All MIN	36.0	NA	2.0	15.0	4.0
All MAX	62.0	NA	15.0	30.0	34.0

Travel Speed Comparisons	Sidewalk Speed		Crosswalk Speed	
	(ft/sec)	(mph)	(ft/sec)	(mph)
Dog AVG	4.8	3.3	4.8	3.3
Cane AVG	4.9	3.3	5.6	3.8
All AVG	**4.8**	**3.3**	**4.9**	**3.3**
All SD	0.9	0.6	0.9	0.6
All MIN	3.8	2.6	3.7	2.5
All MAX	6.6	4.5	7.4	5.0

APPENDIX E: BLUETOOTH PROGRAMMING INTERFACE

E.1 ConnectBlue™ Programming Interface

A USB programming interface board of the ConnectBlue™ module is illustrated in Figure E-1.

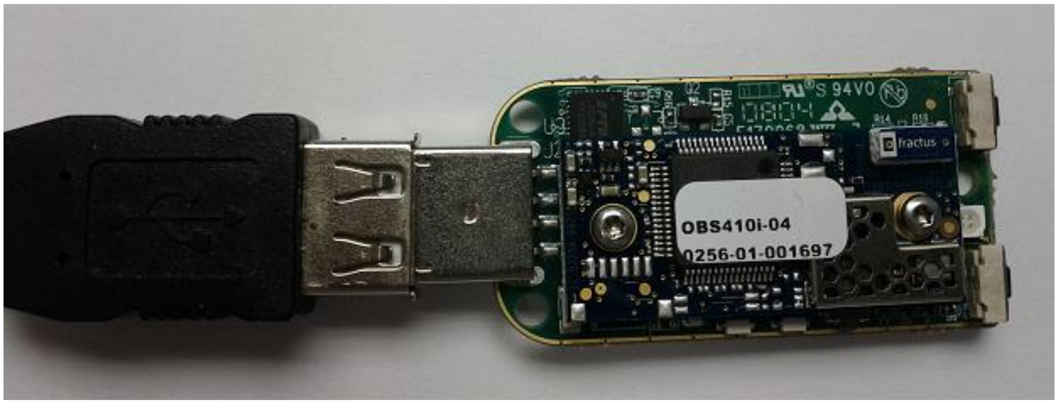

Figure E-1 Connectblue USB Programming Interface

ConnectBlue™ Bluetooth programming software interface is displayed in Figure E-2 to E-4 as follows.

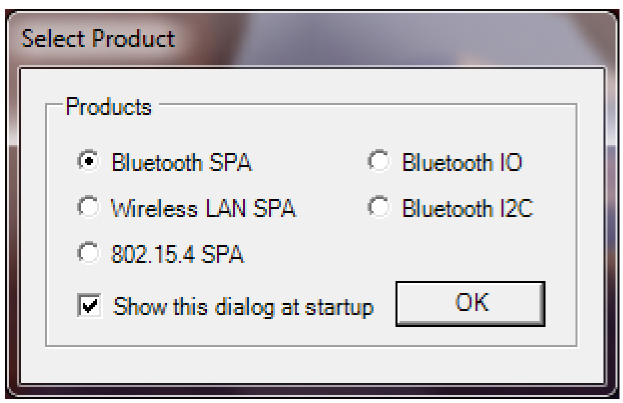

Figure E-2 ConnectBlue™ Graphical User Interface – Select Product

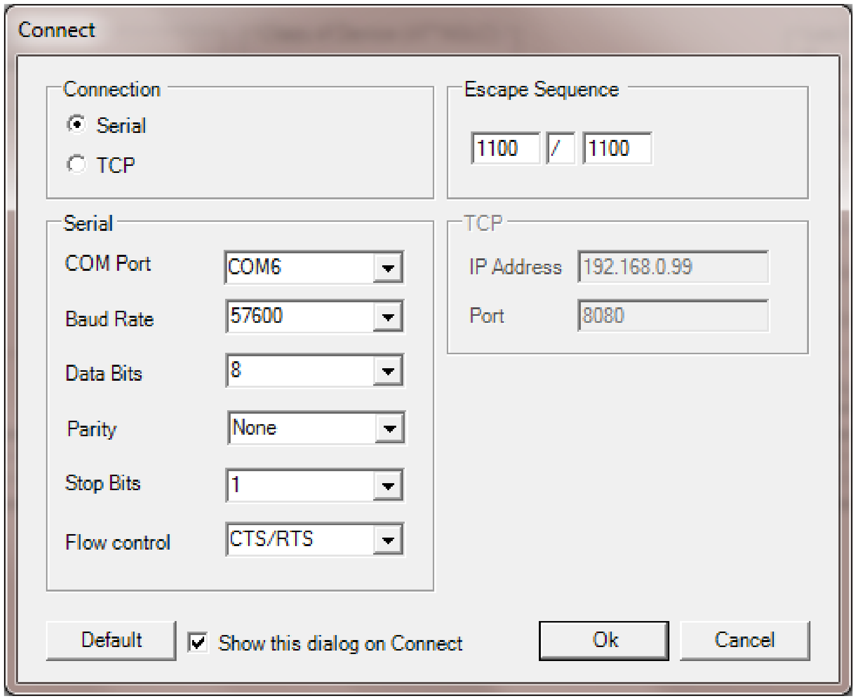

Figure E-3 ConnectBlue™ Graphical User Interface – Connection

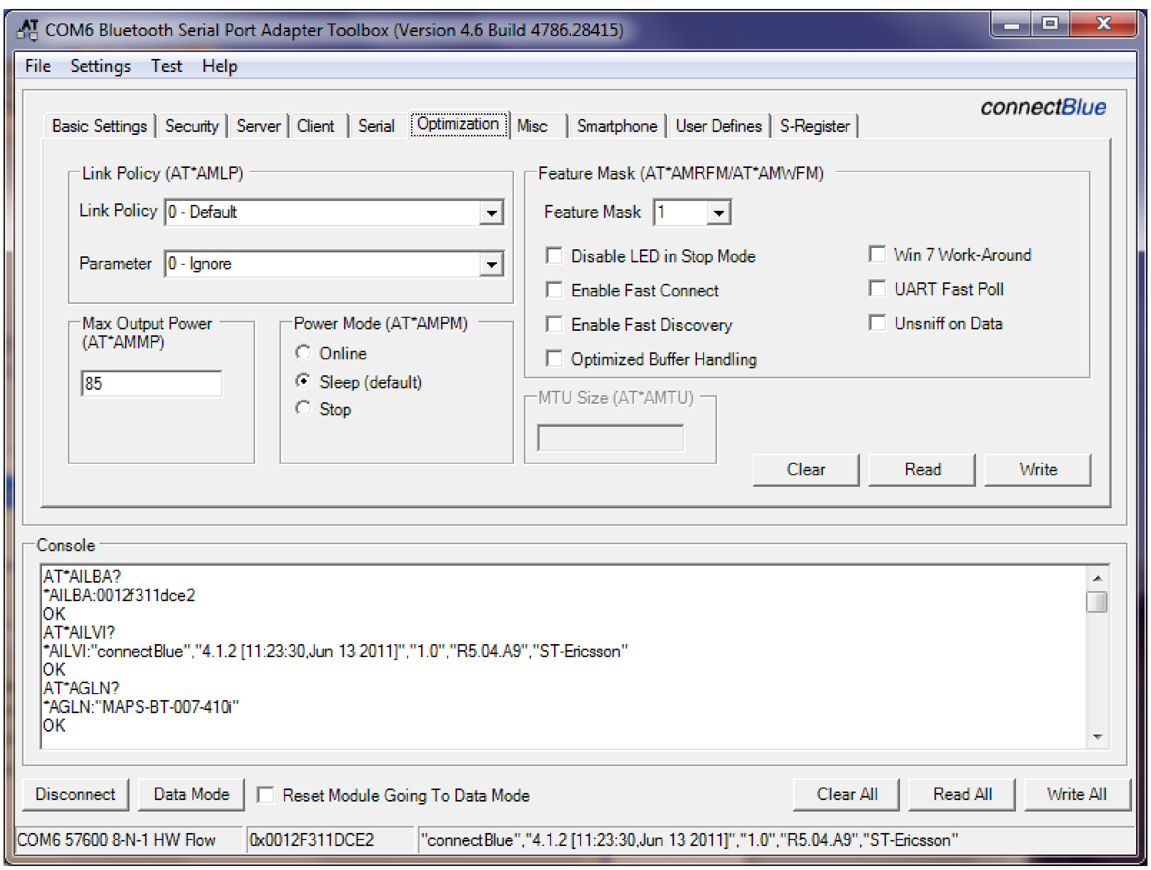

Figure E-4 ConnectBlue™ Graphical User Interface – Programming

E.2 TI CC2540 Programming Interface

A Texas Instruments (TI) CC2540 development kit (including CC debugger) was used to program Bluetooth Low Energy (BLE) modules (as illustrated in Figure E-5). Customized firmware for BLE beacons was loaded to each module using the TI flash programming interface as displayed in Figure E-6.

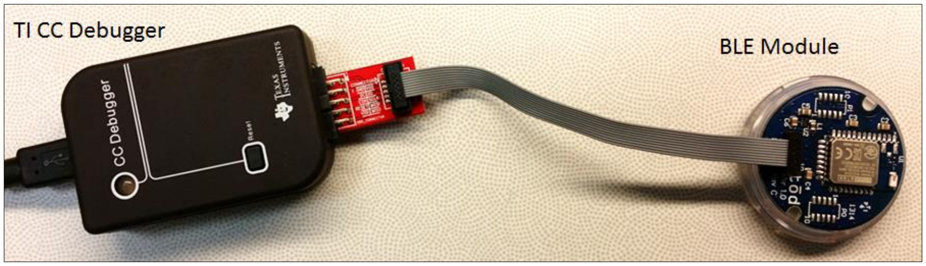

Figure E-5 TI CC Debugger and a BLE Module

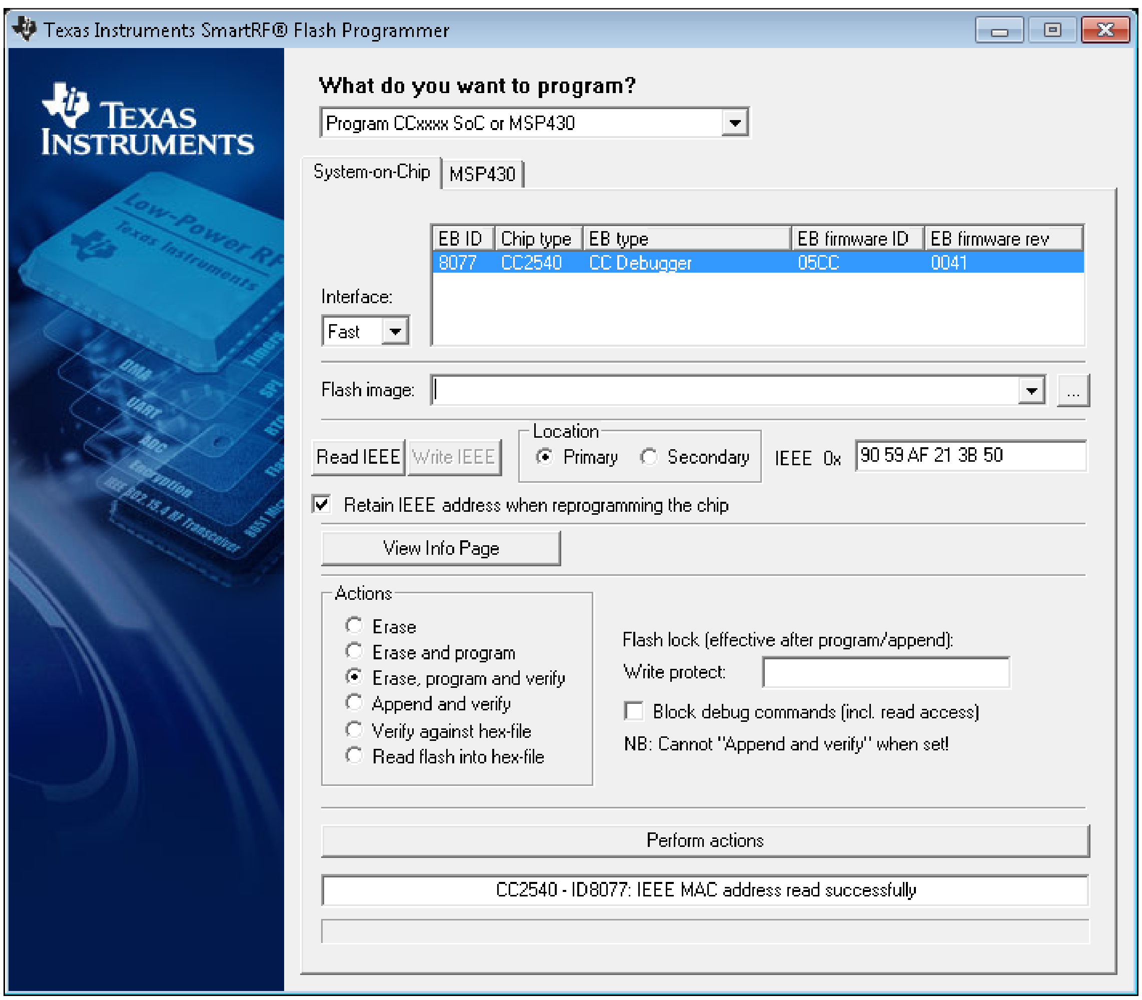

Figure E-6 TI Flash Programming User Interface

APPENDIX F: DATA COMMUNICATION AND CONTROL BEACONS

F.1 Virtual Cabinet

A virtual controller cabinet manufactured by Athens Technical Specialists, Inc. (ATSI), as shown in Figure F-1, was used together with a NEMA traffic controller for testing the signal data transmission through the SDLC interface (http://www.atsi-tester.com/).

The TS2 Virtual Cabinet (TVC-3500) provides the full emulation of a NEMA TS 2 standard cabinet. It connects to an SDLC port (Port 1) of a NEMA TS 2 standard Controller Unit (controller). TVC-3500 receives SDLC frames from the controller, processes those frames and sends responses back to the controller. It also runs a full simulation of TF BIUs 1-4 (Terminals and Facilities), DR BIUs 1-4 (Detector Rack BIU), and an MMU.

Through the interface software (TS2 Virtual Cabinet Interface), the user can change inputs and monitor outputs of the TF BIUs, and simulate detector calls. This allows the user to monitor the controller's "reaction" to various inputs such as emergency vehicle preempt call, pedestrian call on a particular phase or an actuation of any detector call.

The software will also automatically enable inputs/outputs for those BIUs that are programmed in the controller and show which BIUs should be present in the cabinet. This provides a visual presentation of how the controller is setup and what inputs/outputs are available for the given controller configuration.

Figure F-1 TS2 Virtual Cabinet Beacon

F.2 Cellular Modem

A cellular modem manufactured by MultiTech Systems (http://www.multitech.com), as shown in Figure F-2, was used to transmit signal data from traffic controller cabinet to MAPS database server.

Figure F-2 MultiTech Cellular Modem

F.3 USB IO Beacon

An USB I/O beacon, as shown in Figure F-3, was used to activate pedestrian call request in traffic controller cabinet. The USB-IIRO-4 module is manufactured by ACCES I/O Products Inc. (http:// http://accesio.com/),

Model USB-IIRO-4 is an ideal portable solution for adding easy-to-install isolated input and relay output digital I/O capabilities to any PC or embedded system with a USB port. Featuring 16 Form C (SPDT) electromechanical relays and 16 optically isolated digital inputs, the unit is the smallest of its kind for digital monitoring and control using USB.

The isolated, non-polarized inputs may be driven by either DC sources of 3-31 V (or higher by special order) or AC sources at frequencies of 40 Hz to 10 kHz. Optically isolating the digital inputs from each other, and from the computer, assures smooth, error-free data transmission in noisy, real-world environments. The input channels are available via a 34-pin IDC type vertical header. The relay outputs are de-energized at power-up to prevent an unintended control output signal. Data to the relays is latched. The relay contacts are available via a 50-pin IDC type vertical header.

The rugged industrial unit contains an internal, removable screw termination board (USB-STB-84) with onboard removable screw terminals to simplify wiring connections. The USB-STB-84 mounts directly into the vertical IDC connectors of the USB-IIRO-4 PCB. The USB-IIRO-4, like the PC/104 and PCI versions, is excellent in applications where on-board relays are required and inputs must be isolated such as in test equipment, instrumentation, and process control. The USB-IIRO-4 is a USB 2.0 beacon, offering the highest speed available with the USB bus. It is fully compatible with both USB 1.1 and USB 2.0 ports. The OEM version provides just the board without the enclosure and internal screw termination board and is ideal for a variety of embedded OEM applications.

Figure F-3 USB I/O Module

F.4 SMART-SIGNAL DCU

A Smart-Signal DCU (http://www.smartsignaltech.com/), as shown in Figure F-4, was used to obtain signal timing and phasing information from TS2 controller cabinet. The DCU is developed based on a network-enabled 32-bit ARM9 ConnectCore 9M 2443 core module manufactured by Digi International Inc. (http://www.digi.com).

Figure F-4 Smart-Signal DCU

F.5 Field Experiment Setup

Figure F-5 shows the MAPS system installed in a TS2 traffic controller cabinet.

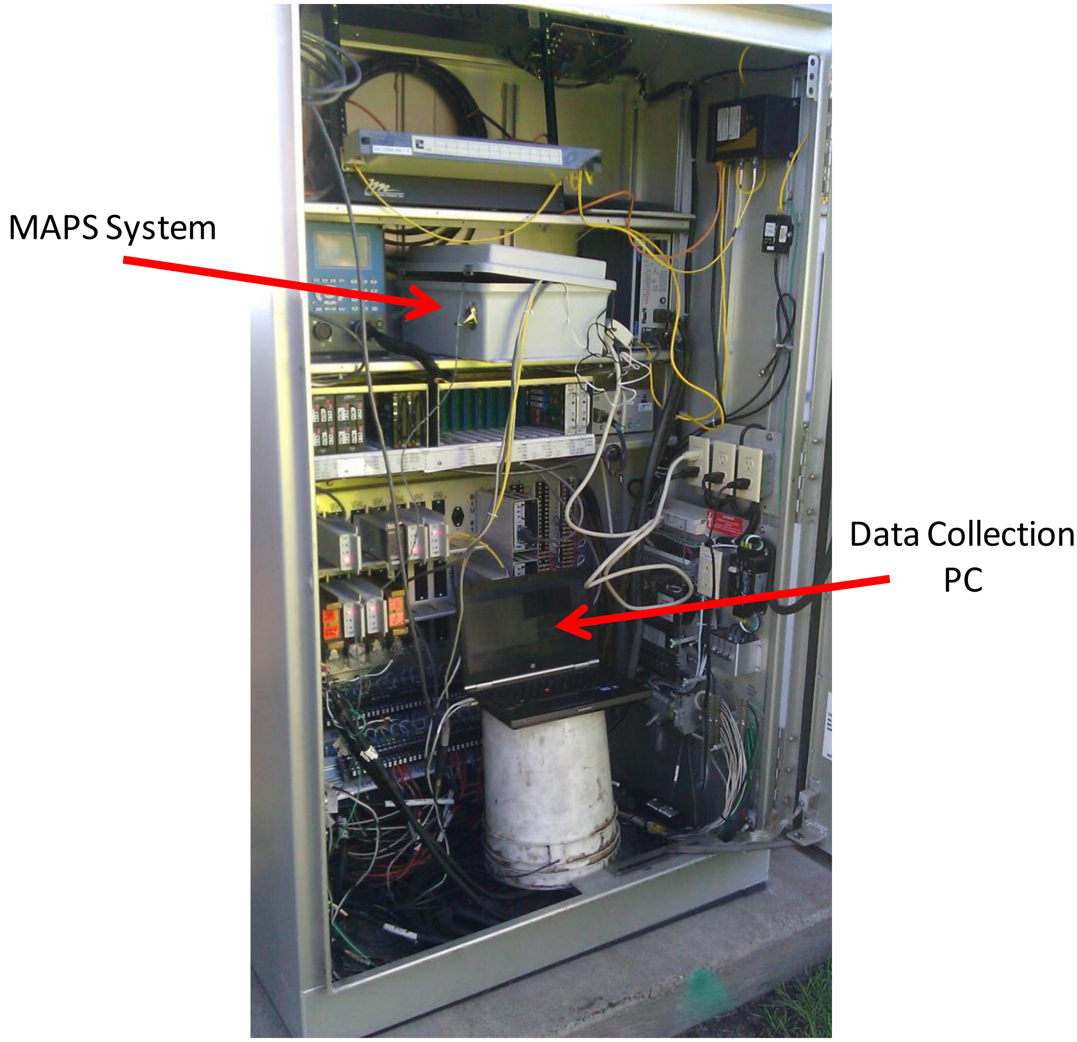

Figure F-5 MAPS installed in a TS2 Traffic Controller Cabinet