GuideBeacon: Beacon-Based Indoor Wayfinding for the Blind, Visually Impaired, and Disoriented

Seyed Ali Cheraghi, Vinod Namboodiri
Department of Electrical Engineering and Computer Science
Wichita State University, Wichita, KS, USA
Email: sxcheraghi@shockers.wichita.edu, vinod.namboodiri@wichita.edu

Laura Walker
Envision Research Institute
Wichita, KS, USA
Email: laura.walker@envisionus.com

***Abstract*—There are currently few options for navigational aids for the blind and visually impaired (BVI) in large indoor spaces. Such indoor spaces can be difficult to navigate even for the general sighted population if they are disoriented due to unfamiliarity or other reasons. This paper presents an indoor wayfinding system called GuideBeacon for the blind, visually impaired, and disoriented (BVID) that assists people in navigating between any two points within indoor environments. The GuideBeacon system allows users equipped with smartphones to interact with low cost Bluetooth-based beacons deployed strategically within the indoor space of interest to navigate their surroundings. This paper describes the technical challenges faced in designing such a system, the design decisions made in building the current version of the GuideBeacon system, the solutions developed to meet the technical challenges, and results from the evaluation of the system. Results presented in this paper obtained from field testing GuideBeacon with BVI and sighted participants suggests that it can be used by the BVID for navigation in large indoor spaces independently and effectively.**

I. Introduction

Wayfinding can be defined as knowing where you are in a building or an environment, knowing where your desired location is, and knowing how to get there from your present location. For outdoor environments, recent advances in global positioning systems (GPS) and mapping technologies provide accurate and simple to use means for wayfinding. For indoor environments, reading and following signs still remains the easiest and most reliable option because GPS and associated advances for outdoor environments do not apply. This has, however, meant that indoor wayfinding has remained a challenge for the blind and visually impaired (BVI) in our society. Indoor environments can be geographically large and intimidating such as grocery stores, airports, sports stadiums, large office buildings, and hotels. Visual directions provided in these large indoor spaces can be difficult, if not impossible, for persons with low vision to follow. Increasing automation has led to a decrease in the number of human personnel used in occupations such as security guards at the entrance or within indoor spaces; such personnel in the past would have been able to anticipate the special needs of the BVI and provide navigational assistance. Thus, there is a great need to provide a low-cost, easy to use, and reliable indoor wayfinding system to serve BVI persons. With recent medical advances increasing the survival of prematurely born babies and the lengthening of adult lifespan, the number of individuals with vision loss continues to grow. The National Eye Institute (NEI) estimates that there are currently about 3 million people with low vision in the US alone and that figure is expected to rise to nearly 9 million people by 2050 [1]; the global low vision and blind numbers already exceed 275 million [2]. A solution to the indoor wayfinding problem for the BVI also has broad applications for the sighted population. In unfamiliar, large indoor spaces, it is common for even typically sighted people to be disoriented and have trouble finding their way around. This could be due to the lack of well marked signs and maps, or not being familiar with the conventions or language used on these signage, or just the fact that the layout of the space is disorienting.

The most accurate and usable indoor wayfinding systems (e.g. [3]–[5]) currently available to persons with low vision rely on the use of radio frequency identification (RFID) tag technology. This solution however is not very flexible when it comes to changing embedded information on tags; furthermore, the tag reader technology is expensive and can be difficult to integrate into current mobile systems. Other mechanisms that provide audible directions such as TalkingSigns [6] still need each user to possess special audio frequency devices capable of acting as receivers. In general, most approaches to solve this challenge require special hardware to be carried by the user. Such limitations have created barriers for widespread use and adoption for indoor wayfinding. Recent published work has developed a system of wayfinding for the BVI using low-cost, stamp-size Bluetooth Low Energy (BLE) "beacon" devices embedded in the environment [7] that interact with smartphones carried by users; however, many technical challenges in beacon placement and mutual interference remain unsolved.

This paper presents the design (and subsequent evaluation results) of the *GuideBeacon* indoor wayfinding system using beacons deployed within indoor spaces that BVID persons can use with a smartphone. The technical contribution and novelty of the work presented in this paper lies in taking an emerging technology (beacons) that is being developed and ubiquitously and inexpensively deployed for sighted users [9] and harnessing it for accessible wayfinding for disoriented sighted users and those who are blind or visually impaired. This paper presents the technical challenges in designing indoor wayfinding systems for the BVI, describes the solutions implemented as part of the GuideBeacon system, and provides feedback gathered on the effectiveness of the system through

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field evaluations by BVID users. Quantitative evaluations show that GuideBeacon can cut the time required for the BVI to navigate unfamiliar indoor spaces by 30-50% and cut the associated distance walked by more than 50% in most cases. Qualitative evaluations show a general satisfaction with the UI design and navigation functions while providing valuable feedback for future improvement. These results were from a relatively small indoor space and it can be expected that they can only get better when tested in larger indoor spaces and make a big impact even for sighted but disoriented users. With a user of the GuideBeacon needing only a smartphone device and software apps to interact and gain benefits from the system, it can provide entities managing large indoor spaces with the tools to extend their space to accommodate BVID end users. It is possible that even some current beacon installations for other applications such as proximity based advertising [9], [10] can be re-purposed to allow the use of GuideBeacon.

II. System Objectives and Challenges

This section provides a formal overview of the objectives of the GuideBeacon indoor wayfinding system for the BVID and the challenges it would need to address to meet these objectives. This section begins with an overview of BLE beacons and their technical characteristics.

A. BLE Beacons

Bluetooth low energy (BLE) (also called Bluetooth Smart or Version 4.0+ of the Bluetooth specification) is the power- and application-friendly version of Bluetooth that was built for the Internet of Things (IoT) [11]. BLE communication consists primarily of “advertisements”, “notifications” or small packets of data, broadcast at a regular interval by beacons or other BLE-enabled devices. BLE advertising/notifications is a one-way communication method where beacons that want to be discovered’ can broadcast, or advertise self-contained packets of data in set intervals. These packets are meant to be collected by mobile devices such as smartphones or tablets, where upon receipt a variety of mobile applications can facilitate triggering of push messages, app actions, or prompts. Typical broadcast intervals of notifications vary from 50ms to several seconds; broadcasting more frequently uses more battery life but allows for quicker discovery by smartphones and other listening devices. Standard BLE has a broadcast range of up to 100 meters, but this can be configured to be lower for more accurate proximity detection. A smaller range also can make it more difficult for a beacon to be detected, thus there is a trade-off that needs to be managed based on the application and expected user behavior. A BLE transmits in the 2.4 GHz industrial, scientific, and medical (ISM) band with 40 channels each 2.0 MHz wide [12]).

B. Problem Formulation

Assume that each point of interest such as doorways, amenities, and rooms/offices/locations in an indoor space are marked by the presence of a BLE beacon. These beacons and the network of paths that can be taken between these beacons can be modeled as a graph $G(V, E)$ where V is the set of vertices represented by beacons and E is the set of edges representing paths that exist between all beacons. Each path to be taken by a BVID user between two beacons, represented as (u, v) in $G(V, E)$ can be represented with a certain level of difficulty or weight, $w(u, v)$ that could be a function of one or more of a combination of distance between two beacons, the ease of walking between these points based on path surface characteristics, obstacles, pedestrian congestion etc. The GuideBeacon system’s objective is to find the shortest end-to-end path from a given starting point s to a desired destination point d in $G(V, E)$ and provide navigational instructions for the user to traverse along this route.

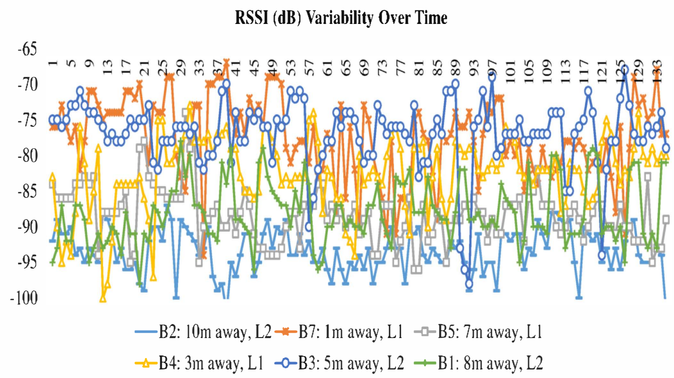

Fig. 1: Variability of RSSI for six beacons placed at different distances away. Beacons are labeled B1, B2, B3, B4, B5, and B7 and these are either on level 1 (L1) or level 2 (L2) of the building represented in Figure 3.

C. Challenges

While the promise of just running a shortest-path algorithm to route from one point to another sounds simple, there are many challenges to realizing indoor navigation for the BVID. The rest of this section describes these challenges; the later sections of the paper will then describe how GuideBeacon attempts to solve many of these challenges and an evaluation of the effectiveness of the system.

Challenge 1: Localization

Knowing where a user is at anytime in an indoor location is a big challenge. Proximity to beacons provide a range as to where a user may be. However, the variability of wireless signal strengths (due to mobility of user, building materials and their impact on fading, multi-path, interference from other wireless devices on the ISM bands etc.), presence of possibly multiple beacons in a vicinity, and heterogeneous gaps between beacons (when balancing cost of dense deployment with coverage needs) all contribute to this challenge. Figure 1 shows the variability of RSSI signals from six different beacons, with the data collected from a location on level 1 of the indoor space. It can be seen that (i) RSSI values from all beacons are highly variable with time with little correlation, and (ii) RSSI levels from the closest beacon is not always

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the highest. An example of the complexity of identifying the closest beacon as beacon 7 is when beacon 3's signal exceeds it during many time periods. This was due to the fact that beacon 3 from level 2 was above the receiver on level 1 across an open, unobstructed balcony possibly providing a very clear path in spite of being farther away. Though there has been a lot of work done in the area of indoor localization, even with beacons (as described later in Section V), the challenge of localization for indoor wayfinding is different in that accurate user location is not required at all points within the space, but only in proximity to points of interest and at points where turns need to be made. As a result, beacon deployment density is not a major parameter of interest for the success of the application; application success is dictated more by the ability of the system to detect beacon proximity in a timely and accurate manner for a given distribution of points of interest and turns in an indoor space.

Challenge 2: Accurate Indoor Maps
Mapping techniques used outdoors such as imagery from cars driven on streets do not work in indoor environments. Indoor mapping thus tends to typically rely on architectural drawings and individuals or robots moving through the indoor spaces [13], [14]. The approach of using architectural drawings fails to capture three dimensional features that may be necessary, especially locations of furniture. Using humans or robots moving to collect imagery for mapping can be time consuming and costly to employ. Crowdsourcing using people moving around the spaces that need to be mapped can be an effective way to create high quality maps as reported recently [15], [16]. With such efforts only being employed recently, there aren't enough published results or data sets available to use or reproduce such efforts and achieve adequate quality maps.

Challenge 3: Beacon Placement
Beacon placement needs to balance the cost of installation and the effectiveness of the navigation experience. Although each beacon is inexpensive (around $5), the costs are not negligible when scaled up and will require occasional maintenance such as replacing batteries. Thus, each beacon should be placed judiciously based on its utility to the overall navigation goal. More beacons can possibly improve the accuracy and effectiveness of the navigation experience (if deployed carefully), but will also require adequate provisions to deal with resolving beacon proximity conflicts where the user device receives messages from more than one beacon.

Challenge 4: Route Advancement
To guide users in any particular direction, the use of a compass on smartphones is necessary. A compass, however, is not always accurate (especially indoors) and needs additional fall-back mechanisms for re-routing when compass direction estimates are incorrect. Guiding sighted users to follow instructions can be as simple as saying walk straight, left, right etc. However, when dealing with the BVI this is not that simple. For example an instruction to turn left by itself may not be enough as the user may not know if they have turned enough to take the next appropriate path, especially when there are multiple paths from a point separated by only a small angular distance. In such scenarios, additional tactile or auditory feedback may be needed to confirm that a user followed the received instruction correctly.

Challenge 5: System User Interface
Any system for the BVI needs to eliminate the need for vision to interact with the system. This requires that the entire navigation process be conducted through other sensory mechanisms such as hearing or touch. Due to the varying levels of visual impairments, users may exhibit different levels of comfort in interacting with these mechanisms in any designed user interface. Thus the UI may need to confirm more actions by users than typical UIs designed for sighted people before registering inputs. The UI must also be of high quality, tested to work with various accents and perfected over time.

III. System Overview

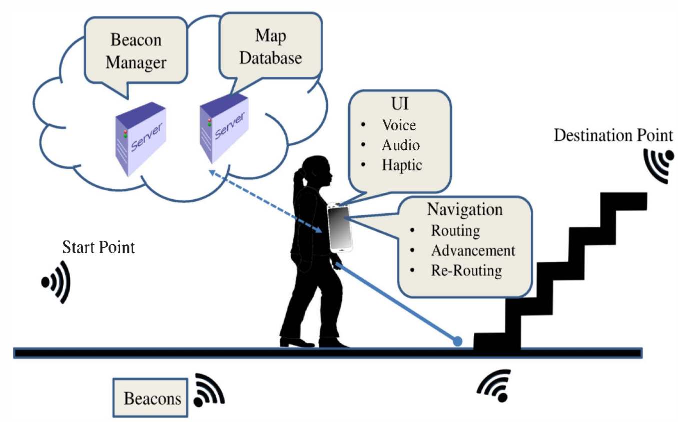
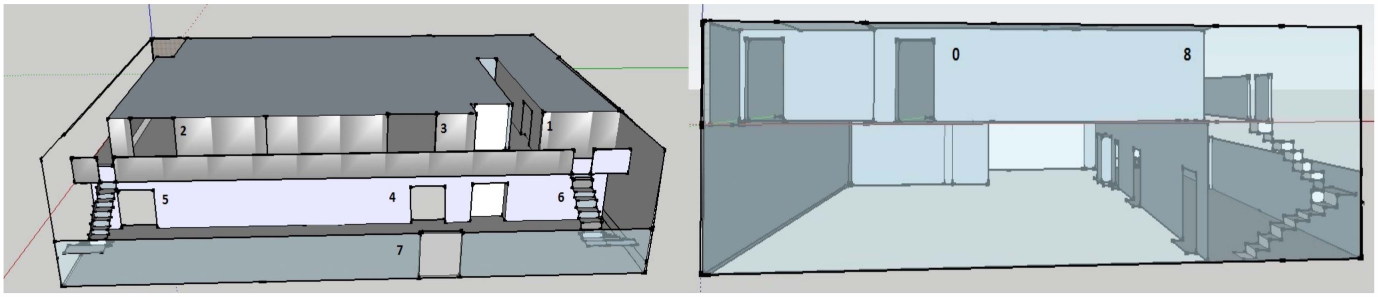


Fig. 2: Building blocks and interactions of the GuideBeacon system.

Upon entering an indoor space for the first time, the GuideBeacon app on a smartphone (upon activation) announces the name of the indoor space and prompts the user to provide the desired destination. The phrase from the user is then looked up in a database of points of interest (PoIs) in the indoor space (provided typically by beacon manufacturer's platform as a beacon manager on a server); if matches are found, they are listed out to the user one by one until the user confirms one of them. Upon confirmation that there is a match for the desired destination, the system then downloads the map of the building (by connecting to a server controlled by GuideBeacon system administrators) and calls the routing algorithm with the starting and destination points. The calculated end-to-end route is then used within the navigation module. Each of the main modules/components are described next along with the solutions implemented to meet some of the challenges outlined in the previous section. The overarching components involved in the GuideBeacon system are shown in Figure 2.

A. User Interface

The user interface of GuideBeacon is built upon the SpeechRecognizer class within the Android OS and the Text-



(a) Front view (facing North). (b) View from the left (West) facing East.

Fig. 3: Beacon deployments inside a building - 3D view.

to-Speech application from Google. User input is captured through voice and converted to text for searching within the database of possible locations of interest. Responses and navigational instructions are presented in an audio format for the user to comprehend. When navigational instructions are provided to the user, additional tactile/haptic and audio feedback is provided to the user through a vibrating audio beep to ensure they are oriented in the right direction for the next path to be taken. This is important because instructions such as "turn left" or "turn slight left" are difficult for BVI users to follow correctly. This tactile feedback is again implemented using standard Android APIs. If the user is not blind or visually impaired, they have the ability to turn off voice-based inputs and outputs and rely on reading text from the screen and using the touch interface. With most BVI using a cane or guide dog, they cannot have more than one hand free to interact with the smartphone. Thus, the user interface of GuideBeacon is designed such that a user can begin interaction with a double tap with one finger, after which voice input is enough to interact with the application.

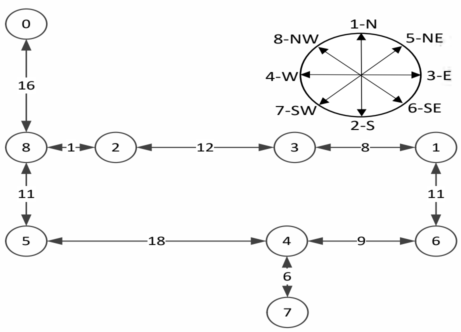


Fig. 4: Building beacon deployment of Figure 3 modeled as a graph showing vertices, edges, and weights. The top right also shows a numeric code assigned to various possible compass orientations.

B. Beacon Placement

Any indoor space is prepared for beacon placement as follows. All possible points of interest (PoIs) are marked as beacon locations. Lines are drawn through the middle of all walking paths (including stairs) in the indoor space on a 3D-basis. Elevators are marked vertically as a walking path. All intersection points between lines are marked as beacon locations. On each line where marked beacon locations are more than x feet apart, mark additional beacon locations every $\frac{y}{\lceil \frac{y}{x} \rceil}$ from one of the PoIs, where y is the current separation of PoIs in feet before this step. At the end of these steps, the indoor space has all beacon locations marked out at which beacons can be placed at a location most convenient near to it. Under the current version of the system under test, all beacons are taped to the closest walls at about 6 feet from the ground. In future deployments, it can be expected the beacons become a more permanent part of an indoor space and are deployed as such on celings (if low), walls around (if close), or embedded on the floor; this aspect is discussed in more detail in our discussion later in Section VI.

The current system uses manually constructed 3D-maps of indoor spaces represented as strings. Each beacon location, the outgoing paths and their directions, and transitions across floor levels are represented in these strings. Each path is also given a weight cost, currently set to be the walking distance on this path. Beacons are organized in numeric order starting from 0 and a unique prefix string identifying the building. For each beacon, a description (that can be used when searching for it or when providing update on current location) is saved along with the beacon number.

Figure 3 shows a 3D representation of an indoor space from two different angles. It also shows the assignment of 9 beacons numbered from 0 through 8. Figure 4 illustrates a conversion of the 3D space and its beacon to a directed graph with beacons serving as vertices and paths serving as edges. The edge weights are the distances on the paths between beacons. The figure also shows a numeric code representing orientation; each possible direction is placed into one of either different bins of size 45° centered at the positions shown. This results in approximations with errors bounded at 22.5° which we found to be acceptable in our system tests. The compass used in smartphones tend to not be perfectly accurate as well, and the margin of error allowed ensures the system assigns a direction with reasonable confidence.

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C. Localization of User

The current implementation of GuideBeacon relies on using received signal strength indicators (RSSI) values from beacons to estimate proximity to beacons in addition to directional information from a compass. If the RSSI values indicate that a user is not near a PoI, the system requests the user to move to the nearest PoI (could be an easily found one by BVI such as a doorway) to begin the navigation process.[1] The current direction information is used to let the user know in what direction they must move from the starting position PoI s to progress towards the intended destination d. The system identifies a beacon as within proximity using the Proximity Detection Algorithm (Algorithm 1). The Proximity Detection Algorithm is used continuously throughout the route to confirm if a user is moving through the points on the computed route, or to re-route the user if they have strayed off path.

The Proximity Detection Algorithm's task is to signal to the system that a user is within proximity of a specific beacon. As a user walks in an indoor space, there are often times one or more beacons are detected by the receiver on the smartphone. It is very important to identify the beacon that is closest (but only if within a short distance, say, 2m) while ignoring those that are farther away. Due to various multi-path effects, RSSI values can vary dramatically for the same beacon for a stationary user as seen previously in Figure 1. To mitigate the impact of variability, the PD algorithm uses a weighted moving average (WMA) over a window size of last n advertisement RSSI's seen. The weights of WMA decrease in arithmetical progression; for a n-RSSI Window WMA, the latest RSSI value has weight n, the second latest $n-1$, etc. down to one as shown in Equation 1.

$$\text{WMA}_M = \frac{nRSSI_M + (n-1)RSSI_{M-1} + \cdots + RSSI_{(M-n+1)}}{n + (n-1) + \cdots + 2 + 1} \tag{1}$$

If the resulting WMA value is below a threshold PRX_THR1, then that beacon is considered a "candidate" for proximity detection. As many beacons are likely to be detected at any time, this threshold ensures that only "serious" beacons are considered candidates. Within the candidate set, a beacon is identified as within proximity if K out of the last n advertisement RSSI values meet a threshold value of PRX_THR2, with PRX_THR2 $>$ PRX_THR1. RSSI thresholds of PRX_THR1 and PRX_THR2 can be chosen to balance the speed of detection with the accuracy of proximity of beacons. A larger value of window n provides more confidence on chosen candidates, while taking more time to gather these samples. Similarly, a larger value of K provides more confidence that the beacon announced as within proximity is actually close, at the possible expense of taking more time to confirm proximity. The PD algorithm only considers a beacon from which n samples have been received in the last $2n * BI$ seconds, where BI is the beacon interval at which advertisements are sent out. Some advertisements are expected to be lost over the wireless medium, but this check ensures that very old received advertisement RSSI values aren't considered in proximity detection.

[1] This initialization process is very similar to how a GPS system takes time to pinpoint coordinates accurately upon initialization. In section VI we discuss additional mechanism to improve the initial location detection.

Algorithm 1 Proximity Detection (PD) Algorithm

Store received advertisement j from beacon i with RSSI value r_{ij}
if we have received n samples from beacon i in the last $2n * BI$ seconds **then**
  Compute the WMA for i over last n samples using equation 1
  if $WMA \geq PRX\_THR1$ **then**
    Consider i a proximity beacon candidate
    Count number of values k from set $\{r_{ij}, r_{i(j-1)}, \cdots, r_{i(j-n+1)}\}$ that are $\geq PRX\_THR2$
    if $k \geq K$ **then**
      Identify beacon i as proximity beacon
    end if
  end if
end if

D. Navigation Module

The navigation module is comprised of the following sub-parts.

1) Routing: For routing, we use the Dijkstra's shortest path algorithm with distances between PoIs used as the weight. Once a map is obtained upon entering the building, all aspects of constructing the graph representation to run a routing algorithm can be extracted. The list of paths to be taken is then used as input for the route advancement module. As users can benefit from hearing the entire end-to-end path (similar to how a bystander may provide route information) before starting out, the GuideBeacon system provides a route preview option that narrates the entire path to the user. To ensure this path narration is useful, it is only done in cases where the end-to-end route has no more than 5 intermediate beacons. The path narration typically takes less than 15 seconds for paths with no more than five intermediate beacons, and is a feature that can be turned off by the user or configured to be active for a user-specified number of intermediate beacons.

2) Route Advancement: Route advancement consists of the use of compass for directional guidance, a tactile and audio feedback system for confirming direction taken, and a combination of accelerometer and RSSI values for conflict resolution.

The system currently uses the compass found on smartphones accessed through standard Android APIs, with 0° as North. Using the current direction faced by the user, and that of the next beacon on the destination route, the system guides the user to move in that direction. As the user moves on the path to the next beacon, an accelerometer is used to count the

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steps taken.[2] As soon as the next beacon on the provide route is detected through the PD algorithm, the UI announces the next beacon location's name as "approaching" and guides the users on what next move they must make. This is intentionally done just before the next beacon as BVI users may need additional time to process the instructions and take appropriate actions. If they are using a cane or dog, these tend to be a few steps in front and earlier notifications are really useful based on our discussions with BVI orientation and mobility specialists.

3) Re-routing: This subroutine is called when it is confirmed that a user has strayed off the computed path provided by the system. This happens when the system is expecting to reach the proximity of a beacon x_e, but instead arrives in proximity of a beacon x_u. This triggers a call to the routing module with x_u as the new starting location while retaining the original user-specified destination. The user is again given a route preview after which the system moves to route advancement routines.

IV. System Evaluation

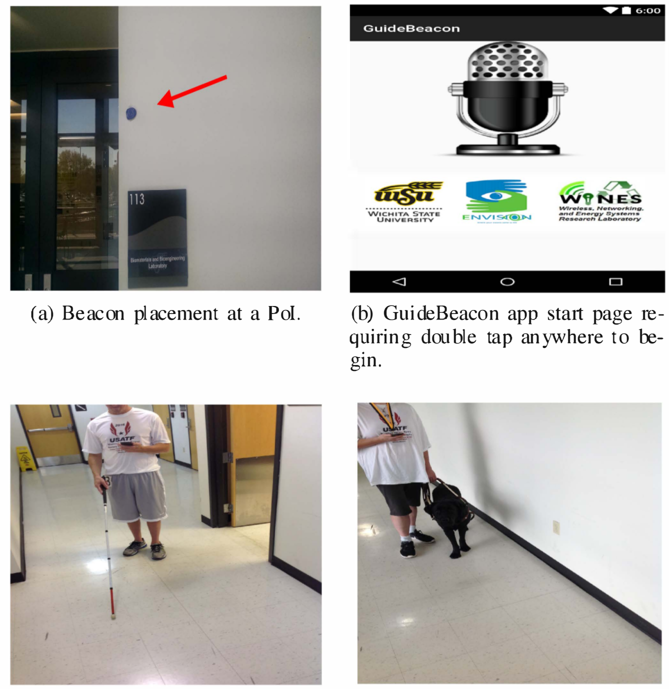
A. Objective

The main objective of the GuideBeacon system's evaluation was to measure its effectiveness in assisting BVID users in navigating unfamiliar indoor spaces. In addition, the user interface and navigation components were evaluated individually to isolate their impact (positive or negative) on the effectiveness of the overall system.

B. Methodology

To test GuideBeacon we used human subjects to navigate from the entrance of a building on the Wichita State University campus to a research lab located on the second floor of the building. The representation in Figure 3 was actually of this indoor space with users having to go from beacon 7 (entrance) to beacon 0 (lab on second floor northwest from entrance). This indoor space and start destination points provided some challenge in finding the destination as it is not apparent from the entrance which direction to go and what turns to make. It was however also not so challenging that the destination could not be found after a few false paths were explored and eliminated. Eight human subjects with varying degrees of vision were recruited for the study after obtaining appropriate Institutional Review Board (IRB) approvals. These participants fall into three different categories of interest: normally sighted users, users with severe vision impairments and using a cane, and users with severe vision impairments and using a guide dog. Participants were recruited through an open call that specified the objectives of the study and what to expect. All participants were unfamiliar with the evaluation site where they were asked to navigate, but were smartphone users on a day-to-day basis.

[2]The step counter data is not used for proximity detection, but can be an additional data point for proximity detection. The step counter data is currently being used to track user movement patterns for post-navigation analysis of the effectiveness of the system as described later in Section IV.



(a) Beacon placement at a PoI.

(b) GuideBeacon app start page requiring double tap anywhere to begin.

(c) Cane user navigating with GuideBeacon.

(d) Dog user navigating with GuideBeacon.

Fig. 5: GuideBeacon application, beacon placement, and user navigation scenarios

Effectiveness of the GuideBeacon system was judged based on *three metrics*, two quantitative (navigation time, navigation distance) and one qualitative (user opinion).

Navigation Time

This metric measures the effectiveness in terms of time in navigating to a desired destination in an unfamiliar space. If a BVID user can navigate to the destination within a reasonable amount of additional time as compared to a sighted user who is familiar with the indoor space, then the system could be termed effective. Similarly, when a user utilizing GuideBeacon can navigate to destinations much faster than other users (who do not use GuideBeacon) with similar visual impairments or lack of orientation in an indoor space, the system can be considered effective.

Navigation Distance

This metric measures the effectiveness in terms of distance (in terms of steps) walked before navigating to a desired destination in an unfamiliar space. This metric removes the impact of walking speed on our results and allows a better understanding of how many false paths were taken in navigating to a destination. If a user does not stray off the navigation path much, it can again be considered as a sign that interaction with the system is easy and the navigational instructions are easy to follow and useful.

Opinion Score

This metric attempts to capture the qualitative aspect of interacting and utilizing the GuideBeacon system. On a standard questionnaire, participants were asked to rate (on a scale from 1 to 10, 10 being the best) the user interface, ease

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User Label	Vision Category	Test Pattern	UI Score	Navigation Score	Need/Adoption Likelihood	Possible Improvements
A	Blind with no LP, Cane user	No assistance, then GuideBeacon	10	6	10	Compass accuracy could be better
B	Only LP, Cane user	No assistance, then GuideBeacon	10	10	10	None
C	Only LP, Cane user	No assistance, then GuideBeacon	10	10	10	None, perfect
D	Only LP, Guide Dog user	No assistance, then GuideBeacon[4]	10	10	10 (unfamiliar spaces)	Pace of walking could be faster
E	Only LP, Cane user	GuideBeacon	8	8	10	Support faster walking speeds
F	Blind with no LP, Cane user	GuideBeacon	5	9	10	Initial delay, voice distortion
G	Only LP, Cane user	GuideBeacon	7	10	10	Timing of instructions
H	No visual impairments	No assistance, then GuideBeacon	9	10	10 (unfamiliar large spaces)	Instructions on demand only

TABLE I: User information and subjective scores (1-10, 10 being best) and feedback. LP is an abbreviation for light perception.

of navigation, and the overall need (and this participant's adoption likelihood) of such a system for navigating unfamiliar spaces. They were also asked for feedback on what can be done to improve the system if anything.

In this work we took an application-level view (BVID navigation) and assumed the accuracy and timeliness of BLE proximity detection were reflected in these three metrics. The beacon density, being dictated more by points of interest and space layouts, was not a parameter of study.[3]

C. System Configuration

The current version of GuideBeacon is based on beacons manufactured by Gimbal [8]. We used the Series 10, the smallest, cheapest and most inexpensive of their beacons in our test. These beacons are lightweight and can be attached to walls or objects easily. All beacons were used at the default transmit power level of 0 dBm and beacon interval (BI) of 645 ms. A MWA window size of $n = 5$ was used which made proximity detection delays to range from 3-6 seconds typically. A smaller value of BI could lower this delay, but at the expense of faster battery life depletion of the beacon. For all our evaluation tests, the route preview option, and use of voice-based interaction was enabled in the UI. The threshold values of $PRX\_THR1 = -75dB$ and $PRX\_THR2 = -72dB$ were used within the PD algorithm as these were found to provide the best balance between accuracy and timeliness/latency of proximity detection for the given deployment scenario through prior testing.[5]

D. Results

Navigation Time

Figure 6 shows the navigation time required by each user tested with and some without the use of GuideBeacon. Each user of course had a different degree of comfort in using the system and understanding the surroundings, and thus expressed an individuality in terms of navigation time needed. Users A, B, C, D, and H show the time required to navigate to the destination without GuideBeacon and then with GuideBeacon. Users A-D being BVI, took a lot of time to find the destination point when given only the room number.[6] They typically strayed off the shortest path many times, and even almost went out the building to another connected building in one case and had to be told how to get back. Even if they were lucky to move in the right directions at first, due to difficulty in knowing where doors and door signs were, often missed the destination and went in the wrong direction. User B even made a mistake in interpreting the braille sign on the destination door only to find it back again later. This showed that finding a location in an unfamiliar place was very difficult to do if the only tool on hand was to touch signs and then guess which direction to go next. Even the sighted user H strayed off the shortest path—which our measurements indicate should have taken about 55-60 seconds for someone who is very familiar with the space—due to unfamiliarity with the indoor space even though this person could easily correct their paths by reading door signs from a distance. Each of the BVI users A-D showed a significant reduction in time to navigate to the destination when asked to do it again using GuideBeacon. It can be argued that these results would be skewed by these users having already made this trip to the destination before using GuideBeacon, though we believe the user's tested had such severe visual impairments that this would have made only a little impact compared to someone who could see the path from a prior trip. The impact of this can be seen by looking at the navigation times of users E-H who directly used GuideBeacon with no familiarity with the space. Their navigation times are only a little bit more than users A-D with GuideBeacon and still a significant reduction than the time taken by users A-D without GuideBeacon. The only user that did not benefit in terms of time using GuideBeacon was the sighted user H. What is interesting is that the navigation time with GuideBeacon shown here includes the 15 seconds needed to narrate the entire route at the beginning, which according to BVI participants was very useful. This additional time if removed from the navigation time of the sighted user, would

[3] For those interested in beacon density and accuracy trade-off studies, [17] and [18] are good sources of information.

[4] Being the only guide dog user, we wanted two sets of unbiased data from this person to serve as a reference for dog users. So this person was asked to navigate to two different locations in the indoor space of similar path length/complexity without and with GuideBeacon.

[5] A more rigorous study of these parameter values for different deployment scenarios will be useful in future work.

[6] Each room number was outside a door and could be interpreted by touching the characters or special braille markings.

erase most of the additional time needed with GuideBeacon for this user. Based on these results, it can be expected that a much larger indoor space with more paths on each floor and point of interests hidden deep inside would have shown GuideBeacon to be more useful, even for sighted users.

Navigation Distance

Figure 7 gives another perspective in terms of navigation distance measured as steps walked (Android OS step counter function on the smartphone) for each user tested with and without the use of GuideBeacon. Though step counters are known to be not 100% accurate, we believe that these provide good enough estimates to interpret the navigation time data seen in Figure 6 and can provide additional insight into why a user may have taken a certain amount of time to navigate the distance. It can be seen that for all users that used GuideBeacon, the steps taken are consistent and less; on the other hand the steps taken by users not using GuideBeacon varied a lot, with some users wandering all over the building before they reached the destination. This indicates that those using GuideBeacon had a deterministic path to the destination, with some variability only due to personal walking styles and how they followed the instructions provided. Users A-D, having navigated the path before, found their way to the destination in slightly fewer steps than those who used GuideBeacon directly. This is because the latter were a bit more circumspect about where they were being led and a little unsure about the beginning and orientation of stairs relative to their current positions. The sighted user taking more steps with GuideBeacon than without was a bit of a surprise here, especially considering this person had taken the longer path to the destination without GuideBeacon. This result can be explained by the fact that a sighted user was able to correct wrong paths quickly and move to the destination for the indoor space environment in question. Also, when using GuideBeacon, this user walked very fast and missed turns a couple of times and had to come back.

Opinion Score

The results of subjective opinions from each evaluation participant are shown in Table I. Many users felt that the user interface was excellent and allowed them to provide a destination and receive instructions to get there in a clear and step-by-step fashion. Similarly, many users felt that the navigation was very effective in getting them to their destination as compared to their daily life scenarios where they have trouble finding locations in unfamiliar places. User A had some issues with following the compass directions mainly because this person held the phone at a slight angle vertically and to the left of the directions he faced so the audio output was closer to their ear; this slight angle however makes the compass directions for the user inaccurate with the phone assuming the user to be facing a different direction. User D, being a guide dog user, had a much faster pace to navigation than other cane users, and even sighted users. This meant that she moved ahead of a turn point faster than the smartphone could detect the proximity beacon on a couple of occasions and had to be re-routed back. User F did not like the initial delay where the entire end-to-end path was read out to them (a feature that can be switched off), and felt the voice distortion of the text-to-speech on the application could be reduced. Two other users felt that the instructions could have been given out slightly earlier so their motion flow would not be interrupted. The sighted user felt the system would be useful as well, especially if the indoor space were larger and more disorienting than what they tested in. Additional feedback from sighted users that tested the system over various stages of development was that the UI SpeechRecognizer did not give enough time to talk after a beep prompt; interestingly, but not surprisingly, BVI users were better at latching onto this audio beep to begin talking.

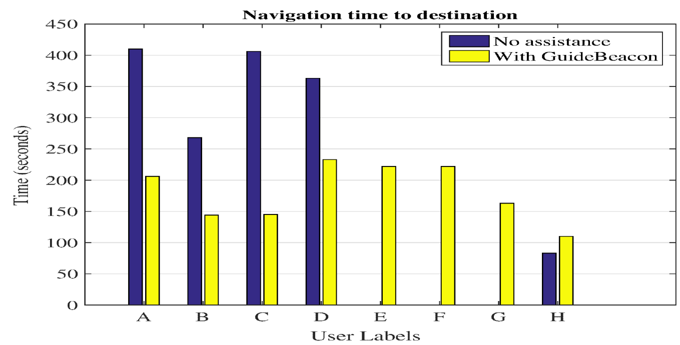

Fig. 6: Navigation time

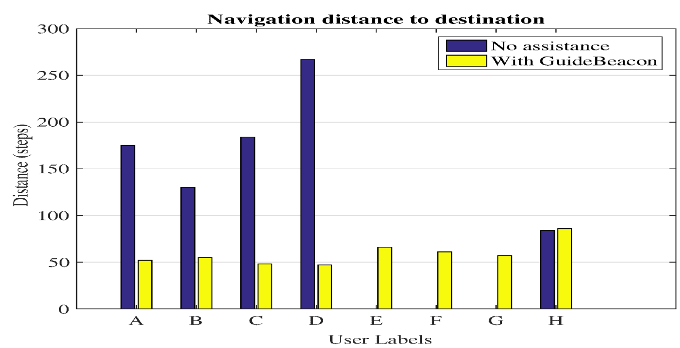

Fig. 7: Navigation distance

V. State of the Art

One of the key building blocks of indoor wayfinding is knowing where a user is at all times in an indoor space. The challenge of indoor localization has been addressed by utilizing existing infrastructure or by adding additional infrastructure. The direction of using existing infrastructure in indoor spaces recently has largely revolved around using Wi-Fi access points (APs) that are already present. Under various assumptions, prior work has shown accuracies within a few meters (for e.g. [19]–[25]). Although this direction achieves indoor wayfinding without any additional infrastructure costs, and allows users to use mobile devices they carry, the assumptions made have many limitations in allowing indoor wayfinding for the BVI. Most of these Wi-Fi based localization schemes require a very high density of Wi-Fi access points (three or more at all times at the point of localization) to be accurate and useful. Furthermore, most of these schemes require additional hardware at the receiving device and/or APs and software mechanisms to be implemented at APs to assist with localization [20]–[22]. Some of the proposed schemes (such as [20]) also have the disadvantage that they require users to make certain device movements (such as rotating their device) for achieving accurate localization; this is difficult for BVI users to do, especially those who already are using a cane or dog and will probably be mounting their smartphone in a pocket or strapping it onto themselves or an accessory. Indoor wayfinding for the BVI does not require knowing the user's location at all times; rather it is more important to identify strategic points within an indoor space that a user should be localized at accurately (within 1-2 m localization error).

The direction of adding additional infrastructure in indoor spaces for localization has been explored in literature, primarily because of their promise of higher accuracies (compared to Wi-Fi based systems for example). Such work has included the use of technologies such as RFID (e.g. [26], [27]), Ultra Wideband (UWB) (e.g. [28]), Ultrasound (e.g. [29]), Infrared (IR) (e.g. [30]), and visible light (e.g. [31]). Many of these technologies (some specific to indoor wayfinding for BVI such as [3], [6]) are not effective for wayfinding indoors (and have rarely been used) because of the requirement of carrying additional hardware on the user, or more expensive or power-inefficient reference nodes in the environment. There have also been many attempts in the field of computer vision (as pointed out in [32]) to assist with wayfinding for the blind and visually impaired; these tend to have high inaccuracies in the information read out when a user is mobile and text is not directly facing the user.

Bluetooth-based indoor localization is not new (e.g. [33]), but it only gained traction after the revision in 2010 and the introduction of BLE. The work in [34] compares BLE-based localization to WiFi-localization and show the the former is far more accurate than the latter. Other work with the Apple iBeacon platform showed accuracies as small as 0.53 m [35] whereas others focused more on the techniques that can be used to improve localization accuracies [36]. In fact, beacons are already being deployed for interaction with smartphone apps to provide real-time location specific information, such as by Gimbal at recent Superbowls [10]. Apple and Google have come up with beacon platforms called iBeacon [11] and Eddystone [37], respectively that can work with beacons made by manufacturers such as Gimbal [8] and Estimote [38]. All these recent trends in using BLE-beacons for localization indicate that the premise of GuideBeacon in using beacons for strategic localization is well-founded. By utilizing the increasing beacon deployments in indoor spaces, the infrastructure costs with GuideBeacon are likely to be lower than a system that can only be used for the BVI.

This work is not the first to consider using BLE beacons for wayfinding for the BVI. The recent work by [7] describes such a system called *StaNavi* with very similar goals of wayfinding in large spaces using BLE beacon deployments. Their system choices are similar in some aspects (voice-based UI, tactile feedback, route preview) while being different in other aspects (use of iOS as opposed to Android OS for GuideBeacon, evaluation methodologies and scale, beacon placement and interference resolution). The *StaNavi* work does not demonstrate how to resolve conflicts among beacons deployed densely with their current approach being the removal of some beacons in some locations to remove conflicts. In this work, a major contribution is a deeper understanding of beacon signal conflicts and resolution through the PD algorithm and how it integrates into the overall wayfinding system along with how to place beacons for strategic localization indoors. The *Wayfindr* project [39] is an effort to develop an open standard for navigation for the visually impaired in outdoor and indoor spaces, including the use of BLE beacons. Although their focus is more on developing a standard than a specific system, we anticipate the standard to prove useful along the deployment path for GuideBeacon.

VI. Discussion and Future Work

Although the GuideBeacon system was found promising and effective, it requires additional improvements, more testing, and infrastructure deployment considerations before it can be provided as a service to the BVID. Some of the improvements needed are with the UI and navigation modules (reducing voice distortion, timing of instructions given), and supporting varying pace of walking. GuideBeacon can be designed to be more configurable by users based upon their personal preferences and characteristics. Additional testing of compass accuracy needs to be done when smartphones (or other wearables in future) are held in various positions or on clothing. Aspects of beacon configuration such as advertisement intervals and transmit powers need to be studied further under a more rigorous framework to determine a generalized set of threshold parameter values. A larger scale test of GuideBeacon in terms of geographic area, beacons, and participants is a logical next step after any system improvements needed are made. This will allow studying the utility of the system over many weeks of deployment and analyzing the infrastructure costs of such a deployment. Such larger scale deployments will require additional work to be done in creating and using adequate resolution indoor maps in an automated fashion. Determining how best to embed beacons permanently in indoor spaces (learning from similar work for RFID such as [40]), but still allowing for convenient battery replacements every few years is another important step in developing GuideBeacon. For the short term, considering the need for such a system amid lack of options for indoor wayfinding, GuideBeacon should be viable in at least all areas where accessibility for BVI is a concern, and perhaps in future all large indoor spaces where sighted persons are disoriented.

Acknowledgement

This work was funded in part by the Carl and Rozina Cassat Regional Institute on Aging at Wichita State University and the Envision Research Institute. We also acknowledge the support of Joy Bodyk in helping recruit participants for our evaluations.

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