SafeExit4All: An Inclusive Indoor Emergency Evacuation System for People With Disabilities

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ABSTRACT

Indoor wayfinding has remained a challenge for people with disabilities in unfamiliar environments. With some accessible indoor wayfinding systems coming to the fore recently, a major application of interest is that of emergency evacuation due to natural or man-made threats to safety. Independent emergency evacuations can be particularly challenging for persons with disabilities as there is usually a requirement to quickly gather and use alternative wayfinding information to exit the indoor space safely. This paper presents the design and evaluation of an inclusive emergency evacuation system called SafeExit4All that empowers people with disabilities (in addition to the general population) to independently find a safe exit under emergency scenarios. The SafeExit4All application drives an underlying accessible indoor wayfinding system with the necessary emergency evacuation system parameters customized to an individual's preferences and needs for exiting safely from a premise. Upon receiving an emergency alert, a user accesses the SafeExit4All system through an app on their smartphone that has access to real-time information about the threat, and simply follows on-screen turn-by-turn navigation instructions towards the closest safe exit. Human subject evaluations show SafeExit4All to be effective not just in terms of reducing evacuation time, but also in providing guidance that results in users taking deterministic, shorter, and safer paths to the exit most suitable for them.

CCS Concepts

•**Human-centered computing** → **Accessibility;** *Accessibility systems and tools;* Accessibility technologies; Interaction design;

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Keywords

Accessibility; visual impairments; alternative input.

1. INTRODUCTION

Wayfinding remains a challenge for people with disabilities in our communities. For outdoor environments, recent advances in satellite-based technologies (e.g. GPS) along with the pervasiveness of smartphones provide an accurate and simple to use means for wayfinding. However, wayfinding remains a challenge in many indoor environments, especially those that are geographically large, such as grocery stores, airports, sports stadiums, office buildings, and hotels.

Reading and following signs remains the predominant mechanism for receiving indoor wayfinding information. This puts people who are blind or visually impaired (BVI) at a great disadvantage. Similarly, for people with mobility impairments requiring the use of wheelchairs or walkers, the determination of accessible pathways to a destination remains inefficient by following visual cues. For example, upon entering indoor spaces, wheelchair-accessible paths or exits, if marked, are not necessarily visible from a distance. For older adults with cognitive impairments, it may be difficult to comprehend signage and find their way around in unfamiliar areas [11, 18]. A solution to the wayfinding problem for people with disabilities in our communities also has broad applications for the rest of the general population in unfamiliar, disorienting spaces.

A major application of interest for accessible indoor wayfinding is that of emergency evacuation (EE). Such a need can arise due to natural events such as tornadoes and earthquakes, or the break-out of a fire or a shooting incident. EEs of the general population can itself be difficult in such situations, but this can be particularly challenging for a person with disabilities (PWDs). A blind individual in an unfamiliar building may not know where the nearest safe exit is. A person using a wheelchair may not know of alternate routes if elevators cannot be used and what other exits are accessible. A person with cognitive impairments may not be able to react to the situation adequately and find a safe route.

While there has been recent work in accessible indoor wayfinding (e.g., [6, 9, 17]), the area has not matured enough to consider individual applications such as EE and the specific requirements of such applications. Furthermore, indoor wayfinding efforts have generally considered one particular type of disability at a time and have not considered how the same application and its associated infrastructure can serve people of different disabilities simultaneously.

This paper presents the design and evaluation of an inclusive EE system called SafeExit4All that empowers PWDs (in addition to the general population) to independently find a safe exit under emergency scenarios. SafeExit4All is built as an application layer on top of an existing beacon-based indoor accessible wayfinding system. The SafeExit4All application layer drives the lower accessible indoor wayfinding system with the necessary EE system parameters customized to an individual's preferences and needs for exiting safely from a premise. Upon receiving an emergency alert, a user accesses the SafeExit4All system through a smartphone app and simply follows on-screen turn-by-turn navigation instructions towards the closest safe exit. SafExit4All is capable of incorporating real-time updates about a situation and compute safe routes. For dynamically developing situations like fires or shootings, entire "danger" zones can be blocked off when computing routes, ensuring users exit through the safest possible route known at that time.

Evaluations of SafeExit4All were conducted with a diverse group of human subjects (with sensory and/or physical disabilities, use of different types of assistive technologies/mobility aids) in an unfamiliar indoor space. Results showed that SafeExit4All was effective in reducing evacuation times of almost all participants except those with usable vision. More importantly, SafeExit4All was able to provide stress-free, personalized, turn-by-turn guidance to safe exits for all participants using paths that were often much shorter than those taken when the app was not used.

2. LITERATURE REVIEW

EE basics

An EE within an indoor space is required when a certain building or certain floors of a building, or a zone within a floor of a building is deemed unsafe. It refers to the procedures that people need to follow after emergency situations arising from tornadoes, fires, earthquakes, shootings, bomb threats, etc. For some emergencies, such a tornadoes, policies dictate moving to a shelter within the building, preferably in a basement. For other emergencies where the threat is from within the building, exiting the building is considered the best action. In cases where exiting a building or a floor is not possible due to lack of time or capability, guidelines for relocations and in-place measures are typically available. Most modern (and many older) buildings currently are equipped with visual and/or audio alarm systems (from within or outside) to alert occupants when an EE is needed, at least for many of the common threats. However, these alarm systems are rarely capable of specifically providing instructions on the safest path to be used for the specific emergency at hand.

Limitations of the best evacuation systems

Directional Sound Evacuation (DSE) beacons [1], where present, attempt to help people find an exit from a geographic location. As a sound-based system, DSE is very useful for BVI individuals as well as sighted users in smoke-filled areas where emergency exits and signs are impossible to locate by sight. However, DSE does not provide additional information about the type as well as the location of an emergency incident, if applicable. Unlike DSE, active shooter detection system (ADSD) [4] tries to provide information regarding specific danger zones. It can spot a shooter, alert the police, and provide the location of the shooter through the building's floorplan to people within the building in real time. Although this system is very useful for sighted users to avoid the shooter while they evacuate the building, it is very specific to one type of emergency and is not built keeping the needs of PWD for evacuation. Both DSE and ADSD systems are static systems that are not able to suggest the best egress route to people based on their current location and congestion on paths. Lack of dynamic capabilities to find the best available egress route can lead to emergency exit blockage, or even occupant injury from crowding [16, 19].

Requirements for inclusive EE systems

In addition to emergency-specific and dynamic evacuation instructions, most current EE systems lack personalized evacuation instructions based on an individual's mobility characteristics, abilities, and preferences. The latter aspect is very important when PWD are considered. Individuals with visual impairments may not be able to independently find the nearest safe exit in a timely manner, especially if the exit paths they know of are not available anymore. Mobility-impaired individuals, who may be used to elevators to arrive at a floor, may not know of alternate routes that they can use. In a stressful situation like an emergency, cognitively impaired individuals may not be able to process what needs to be done and determine where a safe exit may be. According to Shi et al.[20], upon being alerted to an evacuation need, most people favor the closest exit door, and the rest either follow the crowd or favor an exit which they are familiar with regardless of the path availability. Therefore, an efficient EE assistance system needs to not only navigate people through what was thought to be a safe path at the time the alarm was raised, but also must be able to continuously update with any available information and take corrective action with guidance provided. With such features, an EE system can be used in zoned evacuation scenarios where evacuation must be planned based on the location of an incident. According to the Life Safety Code [3], it is permitted to not activate the alarm system throughout the entire building if the total evacuation is impractical, or if it is important to keep evacuation exits empty for individuals close to an incident (e.g., fire or shooting) location. Danger zones are defined by experts [2] who know the building structure as well as the safety codes defined by NFPA.

One of the key building blocks of an evacuation assistance system is to know each user's movement speeds and preferences on different surfaces. Prior work has shown individuals who use walking frames and those who use wheelchairs, respectively, take two and three times longer than people without an extra device [8]. The work in [8, 20, 15, 10] investigated the movement speed of people with different disabilities and age-groups on various indoor surfaces. Based on these findings, different surfaces do not affect movement speed of those without disabilities with the exception of movement on stairs. It can also be inferred from these findings that making turns of 90°or more is time consuming for wheelchair or walking frame users. Any inclusive EE system must allow for factoring in such characteristics.

Current accessible indoor wayfinding systems

In spite of progress on GPS-based outdoor wayfinding, indoor wayfinding has still remained a big challenge. There have been many recent efforts in the area utilizing wireless devices,such as radio-frequency identification or Bluetooth-low energy (BLE), or computer vision to provide location information and context within indoor spaces [14, 5, 9, 6, 7, 5]. In addition to the application to wayfinding, the use of computer vision promises to serve as the "artificial eye" allowing a BVI person to capture and analyze images using a smartphone and identify text and objects around them as captured within images [17], which potentially can be used for wayfinding applications too. These same systems can be used by the sighted population and PWD in general due to their ability to provide customized information about indoor locations and associated context. Thus, with these welcome developments in indoor accessible wayfinding, it is now possible to assume that there are means to have a PWD independently navigate even in indoor environments. Thus, it is opportune to design EE systems or applications that leverage such accessible indoor wayfinding systems for safe evacuations for PWD in addition to the general population. Unfortunately, there have been almost no efforts in designing such systems, possibly due to the fact that accessible indoor wayfinding is only an emerging development. The only related work that we are aware of is from Hashemi et al. [12] who propose an accessible wayfinding algorithm to find the optimal evacuation route considering building components for people with disabilities. They proposed a personalized wayfinding algorithm for wheelchair users that takes preferences into account [13] in computing best egress routes, but is not a system that facilitates EE for PWD in general.

SafeExit4All unique contributions

The SafeExit4All system is designed to be an inclusive EE system that provides personalized, real-time instructions for a PWD to independently evacuate to safety in a variety of emergency scenarios. SafeExit4All is built as an application layer on top of a currently deployed accessible indoor wayfinding system, and by simply following instructions on a smartphone app, users can evacuate any indoor premise with such a deployment. SafeExit4All has many features that current accessible indoor wayfinding systems do not have such as (i) the ability to dynamically provide personalized paths for users taking into account any specific disability needs and mobility characteristics, (ii) the ability to dynamically change routes as threat zones change in size or location, and (iii) the ability to monitor their current location in real-time for the evacuating user and/or those outside interested in the user's whereabouts.

3. FOUNDATIONS OF SAFEEXIT4ALL

This section provides an overview of the objectives of the proposed SafeExit4All EE system and the challenges it would need to address to meet these objectives. Given that SafeExit4All is built as an application on top of an accessible indoor wayfinding system, this section begins with an overview of an indoor wayfinding system and its technical characteristics, deployment details, and utilization for EE.

3.1 Accessible indoor wayfinding systems

The goal of any accessible indoor wayfinding system is to route users from one point to another, preferably with turn-by-turn instructions. For BVI individuals, such a system should be easy to interact with and provide the intended destination and receive instructions. For a mobility impaired individual, the system's primary utility may be in routing through the shortest accessible path. For others, turn-by-turn instructions in an unfamiliar space may itself be very useful. To provide such instructions, an indoor space and its various paths are typically represented as a connected graph data structure (say $G(V, E)$) upon which shortest-path algorithms are executed. Points of Interest (POIs) within the space typically represent the set of vertices V while paths between these POIs represent the set of edges E. Weights on the edges are typically distances between each pair of endpoints, but can incorporate other metrics such as congestion on a path, features or characteristics of the path, etc. See Figure 1a for an example graph representation. The most challenging aspect of such systems tend to be localizing a user within the space as they move around. Approaches used to localize indoors include the use of Bluetooth Low Energy (BLE) beacons, Wi-Fi, computer vision, RFID, or a combination of these (e.g., [14, 5, 9, 6, 7, 5, 21, 17]).

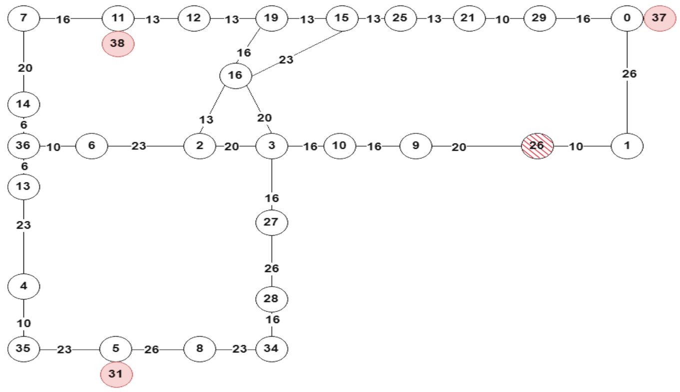
Regardless of how an indoor wayfinding system is implemented, they usually comprise three layers: localization layer, indoor wayfinding layer and an instruction delivery layer. The localization layer is responsible for locating the user within the indoor space and tends to be a very important component in any navigation application. Once a user's current location is known (used as the source point s), an accessible indoor wayfinding layer's objective is to find the best end-to-end path from a source s to a destination d on $G(V, E)$. The top most layer is the user interface layer which provides navigational instructions for the user to traverse along the route. In order to equip an accessible wayfinding system with an EE component - such as SafeExit4All - another layer has to be inserted in between the user interface layer and the wayfinding layer; see Figure 1b. Upon activation of an EE situation, with a user at some location $s^{'}$, SafeExit4All determines the safest exit point as $d^{'}$ (keeping in mind the nature of the emergency, user characteristics, latest information, available paths and exits), computes the best path for a specific user, and begins guiding them.

3.2 Challenges in realizing an accessible EE system

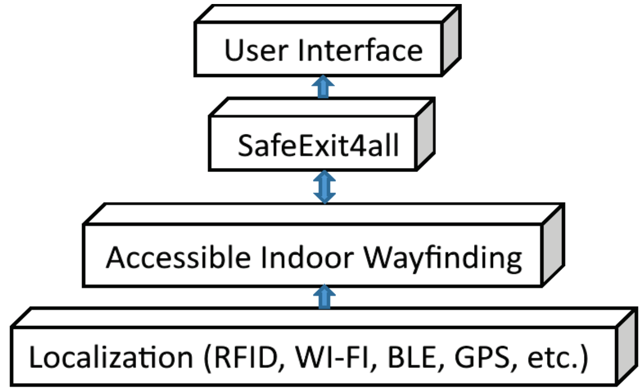
To equip any accessible indoor wayfinding system with an EE layer, several modifications are needed. These modifications are in addition to picking an exit as the destination point and running a shortest path algorithm to route from a user's location to the selected destination. The rest of this sub-section describes some important challenges that need to be addressed to add an EE layer into any indoor accessible wayfinding system to make it inclusive in terms of usability.

Challenge 1: Route Advancement

The proposed accessible EE system harnesses the compass found on smartphones to navigate individuals in the correct direction. Since the compass is not always very accurate and users are in hurry to evacuate the building as fast as possible, re-routing as a fallback mechanism is important to add in case a incorrect path is taken by an individual. This same mechanism can be used if an emergency update is received while a user is being guided through a previously computed path. To guide users in any particular direction, various approaches must be utilized. Guiding sighted users to follow instructions can be as simple as saying walk straight, left, right etc. in addition to providing visual location/map information on the app. However, when guiding BVI users, additional tactile or auditory feedback may be needed. Fur-

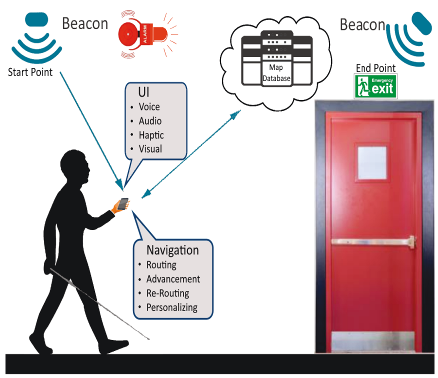


(a) Floorplan from Figure 3 modeled as a graph showing vertices, edges, and weights as well as compass orientations.

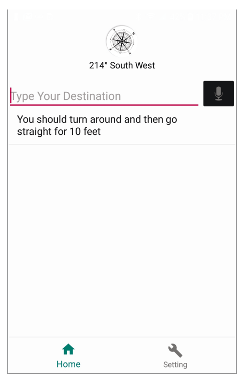


(b) SafeExit4All layer inserted between user interface and accessible indoor wayfinding system layers.

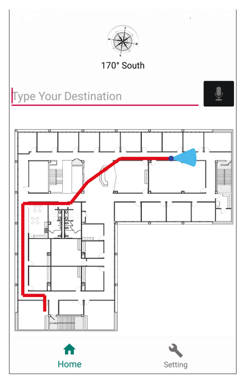
Figure 1: Modeling indoor spaces through a graph representation and how SafeExit4All is built as an application layer.



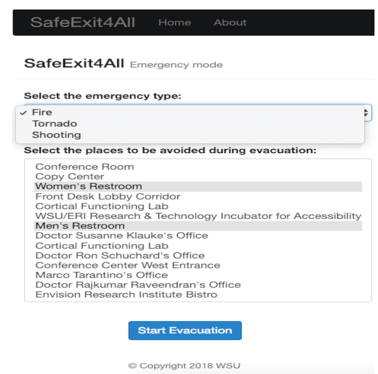
(a) Building blocks and interactions of the SafeExit4All system.



(b) User interface for BVI users.



(c) Graphical User Interface for sighted users.



(d) Administration tool for building administrators/first responders.

Figure 2: System components, user interface and administration tool snapshots.

thermore, unlike typical wayfinding systems, content such as advertisements, information about POIs passed, etc. must be suppressed with emphasis placed on the actions (steps, directions) to be taken until a safe location is attained. Instructions must also be short and informative to maximize movement speeds and reduce congestion on pathways. Another important feature to provide is a mechanism to update users as soon as egress routes get updated. Current evacuation systems usually are based on predefined evacuation paths, regardless of where an incident occurs. Non-adaptive guidance can lead individuals to locations that are not safe or dead ends; hence it is required to have a mechanism to keep track of the status of the building and update users based on acquired information.

Challenge 2: System User Interface
To the best of our knowledge, current accessible wayfinding systems have been designed to only cater to the needs of individuals with a specific type of disability. An inclusive EE system will need a multimodal user interface that is usable across the disability spectrum. Such a system requires the elimination of visual perception of information for BVI users while retaining it for other users. To address the needs of BVI individuals, there must be a capability to conduct the entire navigation through a combination of audio and tactile information delivery. For individuals who are deaf or hearing impaired, without the ability to process audio information, there is a need for dynamic graphical interfaces that are able to convey prioritized information and attract adequate attention visually. Both BVI and deaf/hard of hearing individuals can benefit from tactile cues to keep them on the evacuation path and provide another mode to alert them to important information. A mobility or cognitively impaired user may prefer to have both audio and graphical user interfaces in addition to voice command-based menu operation.

Challenge 3: Personalized Routing
Personalized routing is an intelligent feature which equips an accessible wayfinding system to change application behavior based on a user's needs. It enables the application to provide the fastest route feasible for each user to follow considering their needs. To enable such personalized routing, an indoor space's features such as the number of turns on paths, surface type, width, length, number and type of doors, etc. need to be gathered and incorporated as part of the connectivity graph $G(V, E)$ of the space. For example, the shortest path to an exit point may be the perfect egress route for a person with cognitive impairments, but it

may not be the best path for a BVI or wheelchair user if it consists of many direction changes (turns).

4. THE SAFEEXIT4ALL SYSTEM

4.1 Overview

Upon detecting a hazard such as fire, shooting, etc. within a building, occupants are informed through an audio alarm. After getting notified, the application on a smartphone (upon activation) detects the user's current location, downloads the map (represented as a graph) of the building with POIs closest to the danger zone marked as unsafe vertices, calls the routing algorithm with the user's current location as the starting point and the computed safe exit as the destination point. Subsequently, it announces the best available path from the user's location to one of the exit points. The calculated end-to-end route is then used within the navigation module of the system that is responsible for turn-by-turn instructions to advance the users till the exit. Each of the main modules/components of SafeExit4All is described next along with the solutions implemented to meet some of the challenges outlined in the previous section. The overarching components involved in the system are shown in Figure 2a.

The current implementation of SafeExit4All is on top of a BLE beacon-based indoor wayfinding system called GuideBeacon [9]. Beacons are affixed near each POI, and as users comes in proximity of a beacon, a unique identifier is received from the beacon at the smartphone. This identifier is then translated to relevant context and location information with the assistance of a beacon manager/server. The floorplan of the indoor space of interest is paired with the connected graph data structure (as described in the previous section) to enable navigating the space.

4.2 Administration Tool and Danger Zones

Danger zones in this research study refer to areas that users must avoid during evacuations due to causes such as fire, the presence of a shooter, gas or chemical leakage, etc. Such zones defined must be done by experts who are familiar with a building's layout. As soon as such a building's administrator defines danger zones within the evacuation area, the EE system must be informed. To enable such definitions, an administration tool is designed to be part of the SafeExit4All system to inform users within a building about the type of an emergency event as well as inform the SafeExit4All database about danger zones. This information is subsequently used to mark beacons and paths adjacent to them as ones to avoid (or blocked) in computation of paths to safe exit points. Figure 2d illustrates the administration tool used in this project to block different nodes. Further, this tool can also be used by emergency responders to detect locations of those who cannot leave a building either due to locations of danger zones around them or due to a disability.

4.3 User Interface

The SafeExit4All app's user interface provides a flexible means to address diverse user needs. It allows users to configure various options including (i) the option to choose among various modes of interaction and combinations according to preferences and needs, (ii) the option to choose how to receive directional orientations (clock notation or left-right-straight-turn back notation with additional intermediate points), (iii) the option to choose units of distance to next point along a path (feet, meters, steps). Additionally, sighted users have the option to choose the use of graphical user interface to get updates about their surrounding environment through maps and other contextual information available. The user interface of the app is equipped with built-in accessibility tools of smartphones. For the Android OS, TalkBack provides a text-to-speech functionality that allows BVI users to utilize traditional text-based GUIs. Turn-by-turn directions are displayed as a list on the screen in addition to audio narration, which enables users to hear current and upcoming instructions. Audio and haptic feedback is provided to every user through vibrations, audio beep, and text-to-speech to ensure they are oriented in the right direction for the next path to be taken. Figures 2b and 2c illustrate user interfaces used in the app for BVI and sighted users respectively.

4.4 Navigation Module

The navigation module has the following sub-parts.

4.4.1 Personalized Routing

The personalized routing feature of SafeExit4All has the objective of combining user characteristics/needs such as physical abilities, mobility device, etc. with those of the indoor space from which evacuation must be done to find the most fastest end-to-end evacuation route for a given user. To find the best available route suitable for each individual, the following criteria are considered: (a) number of turns between the start point s to the destination point d, (b) the accessibility of exit doors based upon user characteristics, (c) surface type and passage width, and (d) walking distance between POIs. When the map of the indoor space is downloaded in the form of a graph representation with user's current location as the source s, weights related to nodes within a radius r of the danger zone are altered to infinite (∞) to discourage them from being used in computed egress routes. Furthermore, weights on edges (paths) provided to the modified Dijkstra's shortest path algorithm incorporate a user's characteristics and preferences so that a shortest path that is computed factors in these details specific to each user. For example, turning $90°$for a wheelchair user may take the same amount of time as traveling y meters for a BVI or sighted user; therefore, for each turn, a cost corresponding to walking y meters will be added to the weight on the specific edge. Table 1 illustrates movement speed for individuals with various mobility capabilities and characteristics; this information is used to arrive at user-specific weights on the graph before end-to-end paths for evacuation are computed. Proximity of users to POIs is assessed continuously (utilizing a beacon proximity detection algorithm first used in [9]) throughout the route to confirm if a user is moving through the points on the computed route. Every time a user is within proximity of a specific beacon, the current danger zone information is looked up to determine if the in-progress route guidance needs to be modified. Given that each user's characteristics and needs is different, they may have certain priorities in terms of preferable exits; this prioritization is used to narrow down potential exits.

4.4.2 Route Advancement

The system currently uses the compass found on smartphones accessed through standard Android APIs. Using the current direction faced by the user, and that of the next

Type of impairment	90° turn Seconds	Horizontal surface (m/s)	Exits without automatic door (Mean time pull-push in second)	Stairs (upward-downward) (m/s)
Without disabilities	2.6	1.25	4.6-4.3	0.70-0.70
Motorized wheelchair	3.5	0.89	*-8.6	-
Manual wheelchair	4.2	0.69	4.3-11.6	-
Walking using stick	5.1	0.81	4.9-4.6	0.35-0.32

Table 1: Movement speeds for individuals with and without mobility impairments

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 steps taken.[1] As soon as the next beacon on the computed route is detected, the UI checks the database to find any update regarding the status of the danger zones. In case the status of the emergency incident is altered, the UI goes to the re-routing phase; otherwise the UI only announces what next move they must make. This is intentionally done just before the next beacon as users may need additional time to process the instructions and take appropriate actions. If they are using a cane or a 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. Since individuals who are deaf or hearing impaired are highly dependent on the graphical user interface, a direction beam icon is shown on screen that shows the direction the user is facing on the map. Figure 2c shows the graphical user interface with a blue flashlight beam icon and the path from a starting point to a destination.

4.4.3 Re-routing

This subroutine is called when it is confirmed that either a user has strayed off the computed path provided by the system or the danger zone has changed en route. The former scenario is detected by the system when it is expecting to reach the proximity of a beacon b_u, but instead arrives in proximity of a beacon b_v. The latter scenario of a an update triggers a call to the routing module with current location b_u as the new starting location with b_d as the potential new destination point considering updates to the danger zones(s).

5. SYSTEM EVALUATION

The main objective of the system's evaluation was to measure its effectiveness in assisting individuals with disabilities to find the closest viable exit in emergency scenarios.

5.1 Method

5.1.1 Human subject study details

Ten human subjects falling in various categories of disability (and characteristics/needs) were recruited for the study after obtaining appropriate Institutional Review Board (IRB) approvals. As listed in Table 4, these participants fell into five different categories of interest: users with no impairments, sighted users using a motorized wheelchair, users with both a visual impairment and mobility impairment (using walker), users with severe vision impairments using a cane, and users with severe vision impairments 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. Participants were paid $50 for the study that lasted 60-75 minutes.

User Label	**Vision Category**	**Test Pattern**
A	Blind, cane user	all
B	Light perception (LP) only, cane user	all
C	20/500 one eye, LP other, cane user	only DZ
D	20/150 both eyes, <20° visual field, cane user	only DZ
E	Blind one eye, 20/800 other, dog user	only DZ
F	Blind, cane user, speech impairment too	all
G	LP, cane user	all
H	No visual impairments, motorized wheelchair user	only DZ
I	LP only, walker user	only DZ
J	No visual impairments	only DZ

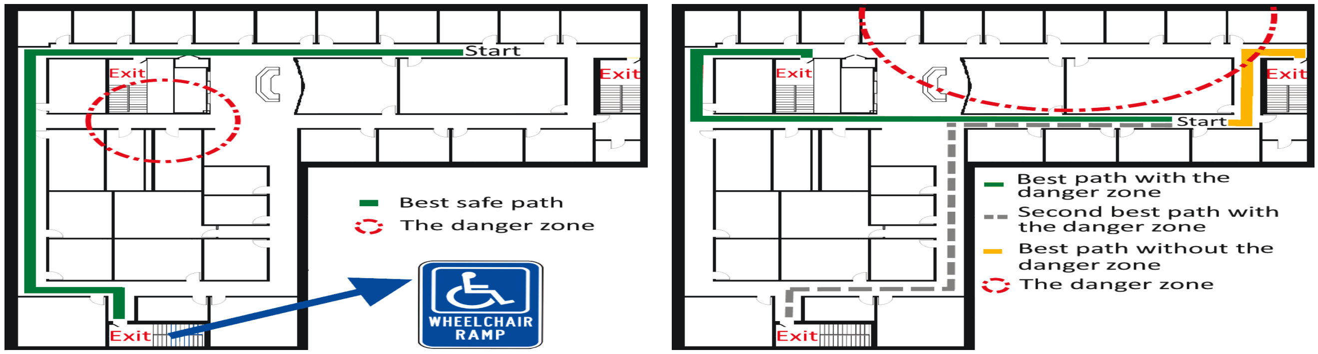
Table 2: User labels and characteristics. LP is an abbreviation for light perception. Test pattern "all" refers to an experimental sequence of (no app, with app) without danger zone, and then (no app, app) with danger zone. Test pattern "only DZ" refers to an experimental sequence of (no app, app) with danger zone.

5.1.2 Test pattern

To test SafeExit4All, we tested participants in two phases: (i) a set of experiments of EE with no danger zones with only BVI participants with significant vision impairments, and (ii) a set of EE experiments involving all participants (BVI, mobility impaired, sighted) for scenarios with danger zones. The two-phase experimentation approach was chosen because the no danger zone scenario presents the greatest challenge to BVI participants. All experiments were conducted on one floor (third) of a building that constituted the Envision Research Institute (ERI). ERI is a facility where individuals with various disabilities often visit for research studies and do not know about any other exits other than the elevator in which they arrive; hence, it serves as an appropriate test location and an eventual deployment location.

For the first phase of experiments with only BVI subjects (A, B, F, G), each participant was asked to navigate from one point within the floor of ERI to the nearest viable exit

[1]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 5.



(a) The scenario to evaluate the SafeExit4All for people with mobility impairments.

(b) The scenario to evaluate the SafeExit4All for the BVIs and sighted users with no impairments.

Figure 3: Scenarios to evaluate the SafeExit4All.

point first without and then with using the SafeExit4All. With no danger zones in consideration, all paths were available for use. The representation in Figure 3b was actually of this scenario. Figure 1a shows the associated graph representation of Figure 3. Results from the no danger zone scenario would apply to emergencies such as tornadoes or earthquakes where users will have to evacuate a higher floor to a designated safe shelter inside the building at a basement or outside. Fires on other floors of a building would lead to the same situation. For this scenario, we assume that users should avoid elevators to exit the building.

For the second phase, all BVI (and the sighted participant) subjects navigated from a starting point to one of the exits first without and then with the SafeExit4All app, with part of the building blocked with a danger zone (marked as beacons 0, 29, 21, 25 and 15 as in Figure 3b). Danger zone evacuation scenarios result for threats like a fire or a shooting incident on the same floor. We chose the specific scenarios and start point to illustrate that although BVI users may be very close to an exit point, they may not be able to find it very fast without getting help from others. To provide a similar challenge for mobility impaired users, we had to slightly modify the test scenario to keep the path complexity similar to BVI subjects, given their need for a wheelchair/walker friendly exit. For participants with mobility impairments we had a slightly modified start point as in Figure 3a to an exit designated to have ramp, first without and then with SafeExit4All, while part of the building has a blocked danger zone. Although all users were provided with room numbers and names of POIs marking the danger zone (as would be expected in a real emergency and a known danger zone), it turned out to be a challenging, but not impossible, task to figure out which paths need to be avoided with supplied information.

5.1.3 Metrics

Effectiveness of the system was judged based on *four metrics*, three quantitative and one qualitative.

Evacuation Time
This metric measures the effectiveness in terms of time in locating a safe exit for evacuation. If a user can evacuate with SafeExit4All faster than without it, then the system could be termed effective.

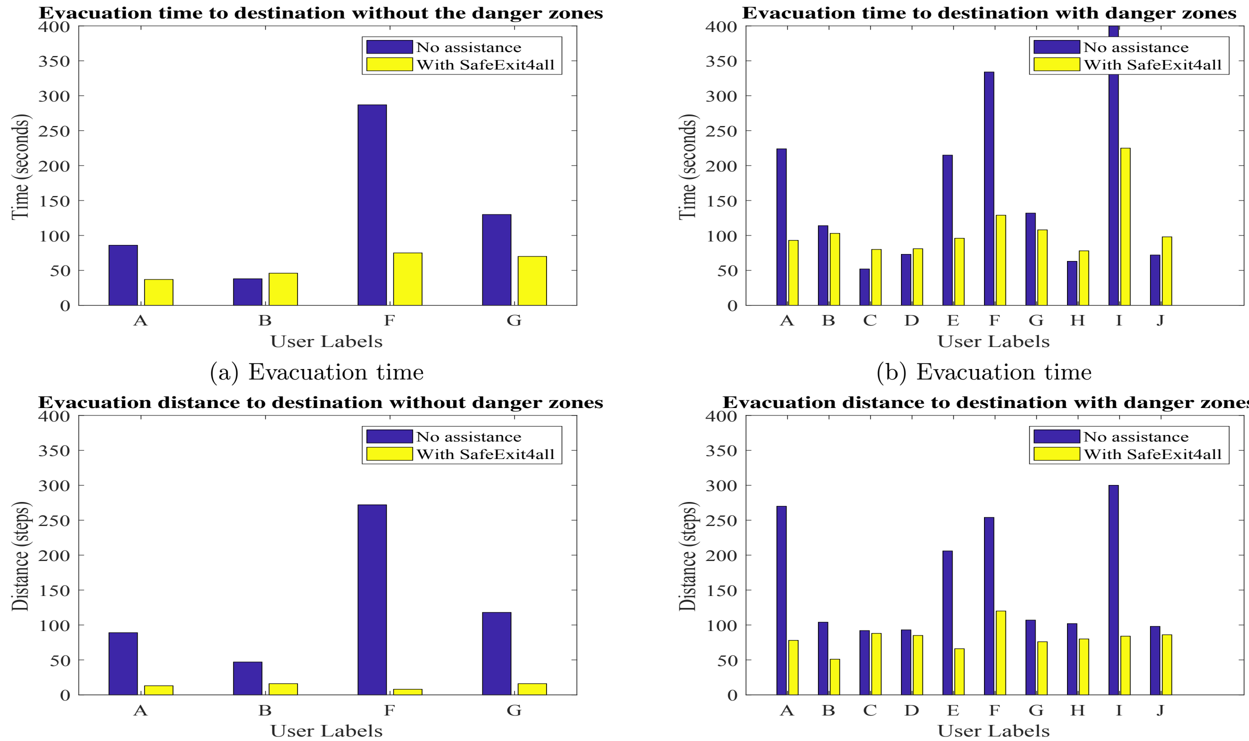
Evacuation Distance
This metric measures the effectiveness in terms of distance (steps) walked in evacuating to an exit. This metric removes the impact of walking speed on results and incorporates the impact of any false paths (if any in addition to best path) attempted before a user reached the exit. This metric (used in conjunction with evacuation time) can convey if the interaction with the system is easy, if the navigational instructions are easy to follow and useful, and how much overhead in terms of time is added for listening to instructions.

Danger Zone Avoidance
This metric measures the effectiveness of the system in helping avoid marked danger zones that, at best, will slow down users in evacuating, and at worst, jeopardize their safety. It captures how many times a user enters danger zones while attempting to evacuate. Without the SafeExit4All app, users need to use their judgement on whether the path they are going on will lead close to the announced avoidance zones; with the app, they just have to follow instructions.

Opinion Score
This metric attempts to capture the effectiveness of the system as perceived by the user. Participants were asked to rate (on a scale from 1 to 10, 10 being the best) how effective the system was in guiding them to a safe exit. This score typically would encompass their positive and negative feelings about the SafeExit4All app, its utility for EE, and their likelihood of adopting it. User comments on this qualitative metric is expected to provide valuable insights on what aspects of the current system implementation are good and should be retained, and what can be improved.

5.2 System Configuration

The underlying GuideBeacon accessible indoor wayfinding system [9] used with SafeExit4All is based on Gimbal Series 21 beacons. The transmit power of beacons were tuned to reduce conflicts with nearby beacons. When multiple beacons were found to be discoverable at a location with a high signal strength, beacon transmit powers of some of the beacons were reduced to a level where all such conflict zones were removed. All POIs on the floor were candidates for beacon placement. In cases where POIs were adjacent to each other, one beacon was used to represent all of them with a description of the relative POI locations provided as part of the beacon's instructions. SafeExit4All was written as an app for the Android OS and can work using its native TalkBack accessibility tool as described earlier in Section 4.3. All tests were conducted on a Samsung Galaxy



(a) Evacuation time (b) Evacuation time

(c) Evacuation distance (d) Evacuation distance

Figure 4: Evaluation results of SafeExit4All with human subjects.

S7 phone that used a Wi-Fi connection to communicate to servers.

5.3 Quantitative results with no danger zones

Evacuation Time

Figure 4a shows the time required to navigate to the closest exit without SafeExit4All and then with SafeExit4All, with no part of the building considered as the danger zones. These individuals, without the app, typically took a lot of time to find the destination, straying off the shortest path often. At times, even when 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 took the shortest time without the app by finding an exit farther away, but in a direct fashion. With the app, all users found direct paths to the closest exit. Variations occurred mainly due to how well they comprehended instructions received. With the app, the total evacuation time includes an initial few seconds of overhead to localize the user and download the floor's map. Overall, there was a 39% average reduction in evacuation times (with a std. dev. of 42) with SafeExit4All.

Evacuation Distance

Figure 4c gives another perspective in terms of navigation distance measured as steps walked (using the step counter function on the smartphone) for each user tested without and with the use of SafeExit4All. Although step counters are known to be not highly accurate, we believe that these provide good enough estimates to act as an additional data point in conjunction with the evacuation time data seen in Figure 4c 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 SafeExit4All, the steps taken are consistent and less; on the other hand the steps taken by users not using SafeExit4All varied a lot, due to users having to wander around to find an exit. This indicates that those using SafeExit4All had a deterministic path to the destination, with some variability only due to personal walking styles and how they followed the instructions provided. Without the app, none of the users found the closest exit, which is where they were guided to when using SafeExit4All; this also shows that familiarity developed due to prior navigation without SafeExit4All is not the reason participants had better results with SafeExit4All. Overall, there was a 84% average reduction in evacuation distances (with a std. dev. of 13) with SafeExit4All.

5.4 Quantitative results with danger zones

Evacuation time

Figure 4b shows the time required to navigate to the closest exit without SafeExit4All and then with it, while part of the floor is considered as a danger zone. Among users A-G, only user F managed to exit the building using the closest safe exit, but unfortunately after a lot of false paths. Given that none of the users who participated in phase one experiments found the closest exit in a timely fashion without the app, any positive impact of familiarity with paths due to the prior navigation experience can be discounted. This showed that finding the closest exit in an unfamiliar place was very difficult to do if the only mechanism available was to touch signs and then guess which direction to go next. Even the sighted user J strayed off the shortest path due to unfamiliarity with the indoor space and the rush to exit the

User Label	Effectiveness Score	Positives	Possible Improvements
A	7	Useful in university campus buildings that are typically unfamiliar	Wide adoption needed before being useful; emergencies can be rare
B	10	If by myself, very useful to evacuate	Ability to have last instruction repeated along with balance of steps remaining will be an useful addition
C	10	Seems to follow me in real-time; can be very useful to get clear-minded guidance when in panic mode with stress of alarms during an emergency	Tiny lag in one location before instructions were provided
D	9	Made me feel secure in finding an exit, particularly in an unfamiliar place; efficient with instructions	None, initial concerns of unfamiliarity to start with, which went away
E	10	Allows you to stop thinking in an emergency and just follow instructions; helpful for everyone in a shooter situation; avoiding danger zones on my own would not be easy	Additional optional information during navigation may be useful; more location accuracy improvement can improve my speeds even further
F	8	Easy, it would tell me turns and steps, would be difficult to evacuate without it; ready to adopt	Needed one re-route when I overshot a turn
G	10	Gave clear and succinct directions specific to building and floor	iOS version wanted
H	8	It is very useful to see the path from the starting point to the destination on screen	The instructions should be shorter
I	10 (if iOS app)	Virtually impossible to find ramps currently, this does it well; tells you where exactly to go, even if my exit may be different from others; helps me find exits farther away that I may not know	Placing phone on walker not best solution, need a hanging contraption
J	10	It is good that this app shows the shortest path for sighted users who typically are rushing to exits	the app takes a few seconds to find a user's initial location

Table 3: User information and subjective scores (1-10, 10 being best) and feedback.

place, even though the user could easily follow the correct paths by reading door signs from a distance. Those who did not benefit much with SafeExit4All were those whose vision was not impaired (J) or had some usable vision (C and D).

Since exit signs within buildings do not always provide extra information about which exits have ramps outside, mobility impaired users H and I had to check all the exiting points to find whether the exit they found was equipped with a ramp. From the starting point, user H had to check only one incorrect exit before finding the exit with ramp. This result was very interesting because, this participant did not check their closest exit. It is fair to say that when individuals enter an unfamiliar building they are not looking for the exit signs, not expecting an emergency, and this participant was completely unaware of the exit close to it. The other interesting observation is related to the time that user H took to find the ramp with and without using SafeExit4All. Although user H had to check several exits before finding the one with ramp, it took less time than using SafeExit4All. This was because, they took one path and went at the highest wheelchair speed possible, passing exits and eliminating them quickly. with the app, they were forced to wait at each turn to hear full instructions. User H was the only participant who could not find any exit (within a reasonable amount of time for which she tested) possibly due to having two impairments.

Overall, there was a 12% average reduction in evacuation times (with a std. dev. of 42) with SafeExit4All when danger zones are considered; this aggregate result is lowered due to lesser benefits for participants with usable vision.

Evacuation distance

Figure 4d shows that like the case of the no danger zone scenario, participants benefit immensely from deterministic paths to exits. The presence of danger zones can mean that safe exits may be farther away from participants. This results in participants having to move greater distances with or without SafeExit4All. Even though participants C, D, H, and J had taken slightly more time to find a viable exit with SafeExit4All, the distances they had to move was lower in all cases. This indicates that even for those without significant visual impairments, there is a benefit in terms of reduced physical effort to find the exit. This becomes particularly important for people with mobility impairments. These results also highlight that optimizing information provided as part of SafeExit4All could potentially help reduce evacuation time, given that the benefits in terms of evacuation distance moved is greater. Overall, there was a 39% average reduction in evacuation distances (with a std. dev. of 27) with SafeExit4All when danger zones are considered.

Danger Zone Avoidance

Without SafeExit4All, users A, B, E, F, and G entered the danger zone twice each, while user J entered it once. Participants A, B, F, and G chose the exits they knew regardless of the information about the danger zone that was provided to them. This confirms the result seen in previous research studies (for example, [12]), that in case of EE, majority of the people gravitate towards exits that are either close by or they are familiar with. The challenge in avoiding the danger zone may not be limited to BVI users; based on our result, even though the sighted user could see room numbers within the danger zone, they entered the danger zone once while trying to exit the building.

5.5 Qualitative Results

The results of subjective opinions from each evaluation participant are shown in table 3. Almost all users felt that SafeExit4All was very effective in getting them to an exit as compared to scenarios where they may need to independently navigate in unfamiliar buildings.

6. CONCLUSIONS AND FUTURE WORK

As indoor spaces become more accessible, there lies an opportunity to create effective solutions to challenges such as independent EEs from buildings for those with disabilities. This paper presents an EE system called SafeExit4All that allows users with various disabilities to evacuate using just an app on their smartphone. SafeExit4All provides personalized, turn-by-turn instructions to guide each user to their safe exit in a timely manner, also having the ability to take into account real-time information about danger zones that should be avoided. Evaluation results showed that SafeExit4All can cut down evacuation times and distances during emergencies and provide a stress-free experience to people with disabilities. Future work with SafeExit4All will include testing with individuals with additional disabilities beyond those considered in this work. Larger test environments can be used to study evacuations across multiple floors of a building and how congestion on exit paths may be improved. Joint prioritization and routing algorithms also need to be developed to optimally choose between closer, but less preferable exits versus farther, more preferable exits.

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