IDEA

Innovations Deserving Exploratory Analysis Programs

*Transit IDEA Program*

# Transit Information Access for Persons with Visual or Cognitive Impairments

Final Report for
Transit IDEA Project 71

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*OF THE NATIONAL ACADEMIES*

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## ACKNOWLEDGMENTS

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# EXECUTIVE SUMMARY

Public transportation is key to independence for individuals who, for various reasons, cannot drive. Unfortunately, independent use of public transportation can be challenging for large portions of the society. This project addressed some of the unmet needs of passengers with visual impairments and of passengers with cognitive disabilities, who may be unable or unwilling to use public transportation. People who are blind are disadvantaged when using public transit as they cannot access printed information at a bus stop; cannot read the number of a bus arriving at a bus station; and, once on a bus, may miss the desired stop if the bus driver does not call all stops, or if the ADA-mandated audible announcement cannot be heard due to loud background noise. Individual with cognitive disabilities may have problems organizing and executing independent trips, may need to hear transit information (e.g., which bus line to take) multiple times, and may need to be instructed as to when to call a stop and exit the bus. For both communities, improved access to information during a trip is key to independent and safe travel using public transportation.

The project team has explored a novel approach to real-time, customizable, multi-modal travel-related information access. Unlike previous research addressing a similar problem, this system does not require continuous access to the Internet. Information is pushed to one's own smartphone from Wi-Fi Access Points (APs). This approach also obviates the need for continuous utilization of the Global Positioning System (GPS) in the user's smartphone, an operation that could quickly drain the cell phone's battery. In this system, APs are placed both at bus stops and within bus vehicles. These APs are programmed to communicate with the user's smartphone through Wi-Fi, providing information that is then presented to the user in accessible form. In the prototype implementation, Wi-Fi APs are embodied in TP-LINK systems, running different types of server software, depending on whether the AP is placed at a bus stop or inside a bus vehicle. The APs communicate with a client application implemented in a Nexus 7 tablet, operated by the user. Needless to say, the same application could be deployed on a variety of other tablets or smartphones.

In a typical applications scenario of the project team's system, the user would first walk to a bus stop and start the mobile application on his or her smartphone. If the smartphone is within the transmission range of the AP in the bus stop, the application prompts the user to connect to the AP in order to receive transit information. If more than one instrumented bus stop is nearby (e.g., two stops facing each other across the street), the application asks the user to select the AP he or she wants to connect to. Upon connection, the application provides information to the user as to the bus lines that go through that stop, and asks the user to select a desired one. Once a selection has been made, the user is again prompted to select a final destination for his or her trip from a list of bus stops that are traversed by the chosen bus line. After the user has selected the destination stop, this initial interaction phase is completed, and the user is instructed to wait for the bus to arrive. While waiting, the user can interrogate the system and ask to hear the remaining estimated time till bus arrival. Once the next bus vehicle of the chosen line arrives, and as soon as the user's smartphone is within Wi-Fi range of the AP inside the bus, the client software switches connection to this AP, and informs the user of the arrival of the desired bus. The user then enters the bus and finds a seat. The client application, now connected to the in-bus AP, receives information about the current bus location, and informs the user about upcoming stops as they are approached by the bus. The user can review the last information produced by

the application at any time, and have the application repeat this information multiple times if desired. When the bus is approaching the stop before the final destination, a special announcement is produced; this is specifically designed to give the user ample time for all actions required before exiting the bus (pulling the cord to call the stop, getting up and moving towards the door, etc.). Finally, before the bus reaches the final destination, the user is prompted to get ready to exit the bus. Once the user has left the bus and the bus vehicle has departed, the system disconnects from the bus and puts itself into sleep mode, ready to be awakened when desired and to start the process again.

Special care was taken for the design of a user interface that could be easily accessible without sight. The application communicates with the user via synthetic speech, with short sentences that convey information clearly and effectively. The user can input selections from menus (e.g., which bus stop AP to connect to or the final destination bus stop) by simple gestures such as screen taps and swipes. In addition, specific menus are triggered by a tap-and-hold gesture.

For the project team's user studies, the team instrumented three bus stops and one bus vehicle in the UC Santa Cruz (UCSC) campus. Four blind participants tested the system during February and March of 2015. Each participant underwent the full procedure described above twice, operating the Nexus 7 tablet and interacting with the system. The Principal Investigator (PI) and a graduate student supervised all user studies and took accurate notes (including video recordings) of the whole procedure. In addition, each participant completed a semi-structured interview at the end of the study, which highlighted relevant accessibility issues with the current public transit system, recurring problems experienced by blind travelers, and perceived benefits and shortcoming of the proposed new technology.

## IDEA PRODUCT

This project envisioned a new location-based information access system with the potential to increase safety and comfort for people with visual or cognitive impairment taking public transportation. Transit-related information is broadcast through Wi-Fi access points located at bus stations and inside bus vehicles (see Figure 1a). Users can subscribe to this system by simply downloading an app for their smartphone. The app automatically connects to the in-station Wi-Fi access point when the user is in the vicinity of the bus stop, and initiates an interaction between the user and the system through accessible modalities. The system also seamlessly manages the connection transfer between the in-station access point and the Access Point in an incoming bus of the desired line. Through this always-connected modality, the user is able to access a plethora of information that is specific to his or her bus ride, including the time till the next bus, the current location of the bus, and specific warnings when the bus is approaching the desired stop. The interface modalities can be customized to ensure easy access to the information.

By providing personalized transit information to each user, regardless of possible sensorial or cognitive impairments, the proposed system has the potential to increase ridership to large segments of the community who are currently unable or unwilling to travel independently. Some of these individuals currently prefer to resort to Paratransit rather than taking a bus, resulting in unnecessary high costs for the transit agencies. The proposed system encourages and facilitates independent use of public transportation, which has the potential to increase revenues for transit services.

## CONCEPT AND INNOVATION

Improved information access for cognitively or sensorially impaired travelers is the object of intense research (*1, 3, 4*). Most germane to this project is the work of Bolechala et al. (*1*) ("Travel Assistance Device," or TAD), also funded by IDEA. TAD relies on the GPS in the user's smartphone to determine the user's position and to alert the user when the bus is approaching the desired bus stop. Users (or possibly their parents or guardians) can plan their trip using a dedicated web site. While the project team's system accomplishes the main tasks for which TAD was designed (specifically, warning the user in advance that a bus stop is approaching), it differs from TAD in three main aspects:

1. It is designed to assist the user not only within the bus vehicle, but also at a bus stop, providing information about all bus lines through the stops, and bus arrival times.
2. It does not require the user to pre-plan trips on a website. The user can select the desired destination at a bus stop through an accessible interactive modality.
3. The system does not use the GPS in the user's phone, nor does it require continuous Internet connectivity. The GPS in a smartphone is not always reliable, especially in so-called "urban canyons," where tall buildings obscure view of the satellite. In addition, GPS sensors use a substantial amount of power, resulting in reduced battery life of the smartphone. For what concerns Internet connectivity, it should be noted that continuous Internet access is not always available with all carriers. For example, a major carrier such as T-Mobile has extremely limited connectivity in the UC Santa Cruz (UCSC) campus, where the project team's system was tested.

# INVESTIGATION

At the beginning of the project, the project team realized that a technical modification to the original proposal (namely, the use of Wi-Fi, or IEEE 802.1, wireless protocol rather than Bluetooth, the wireless technology discussed in the team's proposal) would greatly simplify the design and implementation of the proposed system. Wi-Fi radios are integrated in all modern smartphones, and there is much wider availability of hardware and software libraries for Wi-Fi than for Bluetooth. The project team thus decided to implement the prototype system using Wi-Fi Access Points (AP), which communicate with a client embodied in an Android tablet.

## TASK 1: PROTOTYPE DEVELOPMENT

The project team's system consists of two units: a client and a server. The server is the Access Point (AP) application that communicates with the client to transmit relevant bus information. It was designed to transmit specific information when a client is within its transmission range and the user has requested information. Two types of APs were reprogrammed and reconfigured: a bus stop AP and an in-bus AP. Bus stop APs send bus routes numbers, arrival times, and other information such as the address or the name of the bus stop. In-bus APs, which are placed inside a bus, send the bus identifier and information about the bus stops encountered in the route. Users of the team's system interact with the client application to input data and receive information. The system was designed to accomplish a number of tasks in order to safely and efficiently guide the user to their destination:

1. *Destination selection*: Upon arrival at the bus station, the system informs the user of nearby bus stations and prompts the user to select a bus stop if more than one is within range. Once connected to the desired bus stop AP, the system provides necessary information for the user to select the final destination.

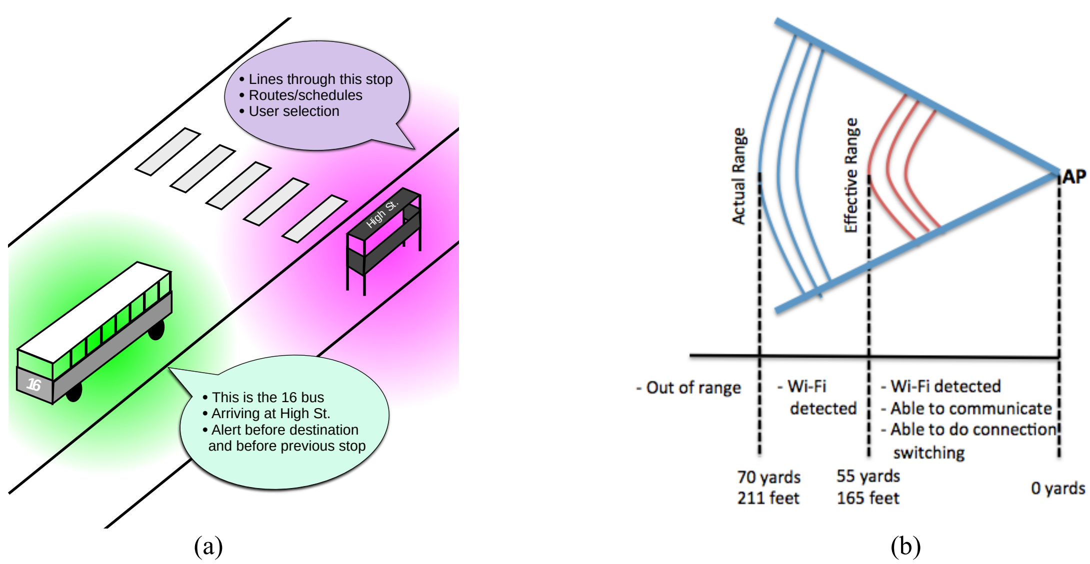


**FIGURE 1 (a) Conceptual system representation. Wi-Fi access points are placed at a bus stop and inside a bus, providing different types of information to a user through a client application on a mobile device. (b) Transmission range of the project team's TP-LINK access point. The *effective range* is the maximum distance at which the client is able to connect to the server, send information and remain connected. The *actual range* is the maximum distance at which the client is able to detect the server but can neither connect nor transmit information. An AP located at a distance greater than 211 ft is considered out of range.**

2. *Bus arrival notification*: Once the destination has been selected, the user waits for the bus to arrive. When the correct bus approaches the bus station, within approximately 20 ft from the user, the system alerts the user via synthetic speech that the designated bus is arriving.
3. *Bus stop name announcement*: Once the user has boarded the bus, the bus alerts the user of upcoming bus stations by announcing the bus station name. The announcement is made before the bus reaches the bus station, approximately 60–100 ft away.
4. *Upcoming final destination notification*: As the bus makes its way through its designated route and approaches the destination selected by the user, the system alerts the user via synthetic speech that their destination is within vicinity by announcing that (1) the bus is one stop away from the destination, and (2) the bus is about to arrive at the destined bus station.
5. *Departed bus notification*: Once the user has exited the bus and the bus has left the bus station, the system reminds the user that the system is still on by announcing that the bus has left the bus station (the bus is out of range), and that the system is going to be set in idle mode and needs to be awakened in order to select a new destination.

The servers consist of TP-LINK routers (shown in Figure 2b) reprogrammed with OpenWrt, a Linux-based operating system that provides a writable root file system with package management and other configurable scripts and tools. The main tool of interest for this project is the package manager, *opkg*, which allows for installation of any software written in the C programming language. After changing the TP-LINK router's firmware to OpenWrt, a program that uses the socket inter-process communication was written and installed in each of the routers. In addition, the routers were configured as Access Points, and a global static primary IP address was hardcoded into each of the APs. This IP address is used along with a port number to allow the client access to the AP and


(a) (b) (c)

**FIGURE 2 (a) The Nexus 7 tablet used as a client device. (b) The TP-LINK router functioning as access point (server). (c) TP-Link Access Point hosted in a plastic case and secured at a bus stop. Note the printed signs informing passers-by of the test in progress.**

transmission of data wirelessly. In general, the client opens the socket specified by the IP address and port number, connects to it, and sends a Hello or Data request to the server. The server then listens for the connection, accepts it, sends the data requested, and closes the connection.

There are two types of requests that the server listens for: Hello and Data requests. Hello requests are used to acknowledge that the server is functioning and able to send data. Data requests are only sent after the Hello requests and AP information such as name, type, and address of the access point are returned. AP data are stored using data object definitions, with a compact format inspired by the NASA's Planetary Data Systems (PDS) standard to store all of the data sent back from planetary missions and telemetry measurements. It allows for rapid data access and communication to the client.

The client subsystem consists of an Android application that incorporates the following hardware and software technologies: Wi-Fi, touch and gesture detection, text-to-speech (TTS) engine, socket and message communication protocols, database management system (DBMS), and Android services. The Wi-Fi technology is used for wireless connectivity between the client and the server and the transmission of pertinent public transportation information; the touch and gesture detection is used to obtain input from the user as he or she navigates through the different options provided by the app; the text-to-speech engine provides real-time voice feedback to instruct and guide the user as he or she navigates through the app; the socket and message communication protocols are used to connect and transmit information between the server APs and the client app; the database management system is used to query a local timetable database and to calculate the bus arrival time; and the Android services are used to manage several threads to listen for in-bus access points, connect, disconnect and switch between bus stop and in-bus access points, stay connected to an access point, listen for other bus stop or in-bus access points, and more. In the project team's prototype, the client software is implemented in a Nexus 7 tablet (shown in Figure 2a).

A number of experiments were conducted to verify that the Wi-Fi connection between APs and the client application was reliable, and that *connection switch* (switching between connection to bus stop AP and the AP of an incoming bus for the desired route) was quick and seamless. Indeed, the user never notices that the client has switched connection: as far as the user is concerned, the application is "always connected" from the first connection with the bus stop AP. The project team also took careful measurements of the AP's *effective range* (the maximum distance at which the client is able to connect to the server, send information and remain connected) as well as the *actual range* (the maximum distance at which the client is able to detect the server but can neither connect nor transmit information). Figure 1b illustrates both quantities.

## TASK 2: USER INTERFACE DEVELOPMENT

The client interface was designed to effectively communicate proper instructions to blind users through intuitive usage modalities. It uses multi-touch interaction techniques and text-to-speech feedback. The user inputs data through single screen taps, tap-and-hold, and right or left swipes. Interaction is facilitated by the use of simple instructions and information via synthetic speech. Each user gesture is confirmed by a suitable short sentence uttered by the system.

*Interaction Scenarios*

Interaction with the system occurs in three main situations:

1. When the user arrives at a bus stop and wants to select a bus line and destination.
2. When the user wants to find more information about the current location, approximate bus arrival time, or last spoken command. This can happen at any time after the user has selected his or her destination.
3. When the user is in the bus and wants to find information about the closest bus stop.

A typical information exchange cycle proceeds as follows: Upon arrival at a bus stop, the client application automatically detects nearby Access Points. If multiple APs have been detected, it lists them to the user and prompts him or her to select one. If no AP is selected, the system goes into idle mode. Otherwise, once a bus stop AP has been selected, the application produces relevant bus information such as bus stop location and the bus lines served by this bus stop. The system then prompts the user to select a bus line and a destination. Once the destination has been selected, the system waits and listens until the desired bus (carrying its own AP) comes within range. The user can at any time interrogate the system, for example asking to hear the remaining waiting time. Once the desired bus is within range, the client application automatically disconnects from the bus stop AP, connects to the in-bus AP, and alerts the user that the bus is arriving. This *connection switch* occurs "behind the scenes"—the user is not aware of it. If for any reason the user does not board the bus, after the bus has departed the client automatically re-connects with the bus stop AP, giving the user the ability to specify a different bus line.

When the user has boarded the bus, the system (which is already connected to the in-bus AP) produces periodic updates such as the next stop name and confirmation of arrival. (Note that the user has already selected the destination bus stop while connecting with the initial bus stop AP.) At each upcoming bus stop in the route, the system generates a text-to-speech notification with the name of the stop. The project team should note that the same information is usually communicated through the bus speakers (as mandated by the Americans with Disability Act, ADA). However, the team believes that producing the same information with this system has additional benefits: the user can listen to it on his or her own smartphone (possibly through an earphone, if desired), and thus is able to hear the spoken text even in the case of loud background noise. In addition, the user can ask the system to repeat this information as many times as desired. This can be especially useful for people with some degree of cognitive impairment, who could benefit from hearing the same information multiple times for confirmation. Since the system is aware of the user's final destination, it can alert the user with proper advance time when the destination stop is approaching. The system produces a special notification when the bus is nearing the bus stop located before the desired one. This is designed to give the user enough time to prepare for the necessary activities before the final stop: pull the signaling cord, get up, and move towards the exit door. When the bus is approaching the final stop, a specific notification is produced. In case the user neglects to exit the bus, the system simply continues to produce notifications about the upcoming bus stops. If the user does exit the bus, as soon as the in-bus AP is out of range, the user is notified that connection with the bus has been terminated. If the destination bus stop has been equipped with an Access Point, the client application again notifies the user, who can choose to connect to this AP and start the process again.

The set of instructions and confirmations that are used to guide the user during interaction with the system have been implemented in a hash map structure to allow for fast and easy retrieval and expansion. The client application sequentially iterates through these sets or dictionaries as a state machine, moving from one state to the next, and speaking the correct instruction, question, or confirmation given the current state of the system. For example, when the user starts the application, he or she is greeted by the system with the sentence "Welcome. The current time is ______. There are # bus stops nearby." The application then asks the user "Would you like to connect to #?," where # is a bus stop name from the acquired list. Depending on the user response, the system provides a proper confirmation, such as "# has been selected," or "# was not selected." At any given state of the system, a phrase or word is fetched from the appropriate dictionary, parsed to fill in any unknown information such as the bus number or the network name, and then sent to the text-to-speech engine, which speaks the phrase or word.

*Specific Interaction Modalities*

The user interacts with the system in one of two modalities: system-prompted or user-prompted. *System-prompted interaction* occurs when the user first reaches the transmission range of an AP at a bus stop, as in the scenario discussed above. In this phase, the user is led through a structured menu and asked to take decisions (select which AP to connect to if multiple are available, select the bus line, select the destination). When selecting an item from a menu, each item in the menu is read aloud via text-to-speech (TTS) in turn, and the user is asked to either single-tap the screen to select the item that was just read, or right-swipe to move to the next item. (If the user right-swipes the last item in the list, the system start again cycling from the first item.) The user may also left-swipe to hear again the last menu item that was read aloud. *User-prompted interaction* is initiated by the user tapping the screen and holding the finger on the screen for three seconds (tap-and-hold gesture). This modality was added to provide the user with access to information at any time. A tap-and-hold gesture triggers a "main menu" with the following items: "Current location"; "Last announcement"; "Start all over" (the last option resetting the interaction cycle). In addition, when the user is waiting at a bus stop, one more item is presented: "Waiting time till the bus arrives". The list of all interaction modalities is presented in the following table.

TABLE 1
INTERACTION MODALITIES PROVIDED BY THE CLIENT APPLICATION

| **Action** | **Functionality** | **Instruction spoken (example)** |
|---|---|---|
| Single tap | Select current option | "Yes" + *<confirmation from dictionary>* *<instruction from dictionary>* |
| Slide to left | Hear last information again | |
| Slide to right | Move to next option | "Next" + *<next instruction in the dictionary>*. Note: if end of dictionary reached, start again from beginning |
| Tap and hold for 3 seconds | Main menu access | "Please select from the following options:" + *<instruction from main menu dictionary>* |
| Press power button Off | Turn device off to preserve battery. Note: the system still runs at all times in the background and produces spoken information when needed | "Device off" |
| Press power button On | Turn device on | "Device on" |

## TASK 3: IN-STATION AND IN-BUS INSTANTIATION

For the project team's experiments, the team instrumented three bus stops in the UCSC campus and one bus vehicle, as described below.

### *In-Station Instantiation*

Figure 3 shows the location of the bus stops in the UCSC campus where APs were placed. Specifically, the project team instrumented two bus stops ("Science Hill—East" and "Science Hill—West") facing each other in the upper part of campus, as well as one bus stop ("East Remote Parking—West") in the lower part of campus (see Figure 4). The reason for instrumenting two bus stops facing each other is that a user located at one bus stop would be in the Wi-Fi range of both APs, and the team wanted to test how easy it would be for the user to select the correct AP and remain connected to it.

The bus stop TP-LINK router was connected to a small battery and placed in a plastic case (shown in Figure 2c), which was then secured to the bus stop shelter by a lock. With this battery, the AP had autonomy of approximately 8 hours. A printed sign (clearly visible in Figure 2c) was placed on the case and on a nearby wall to inform any passersby of the ongoing experiment. This was meant to mitigate any legitimate concerns about the presence of this unattended device at the bus stop. The project team also informed the UCSC Campus Police and the UCSC Department of Transportation and Parking Services (TAPS) about the precise dates of the tests.

*In-Bus Instantiation*

The UCSC campus is served by two different bus systems. TAPS manages a fleet of shuttle busses traversing a loop route, both clockwise ("Eastward") and counterclockwise ("Westward"). The Santa Cruz METRO system manages a number of public bus lines, some of which traverse the UCSC campus through the same routes used by the TAPS shuttles.

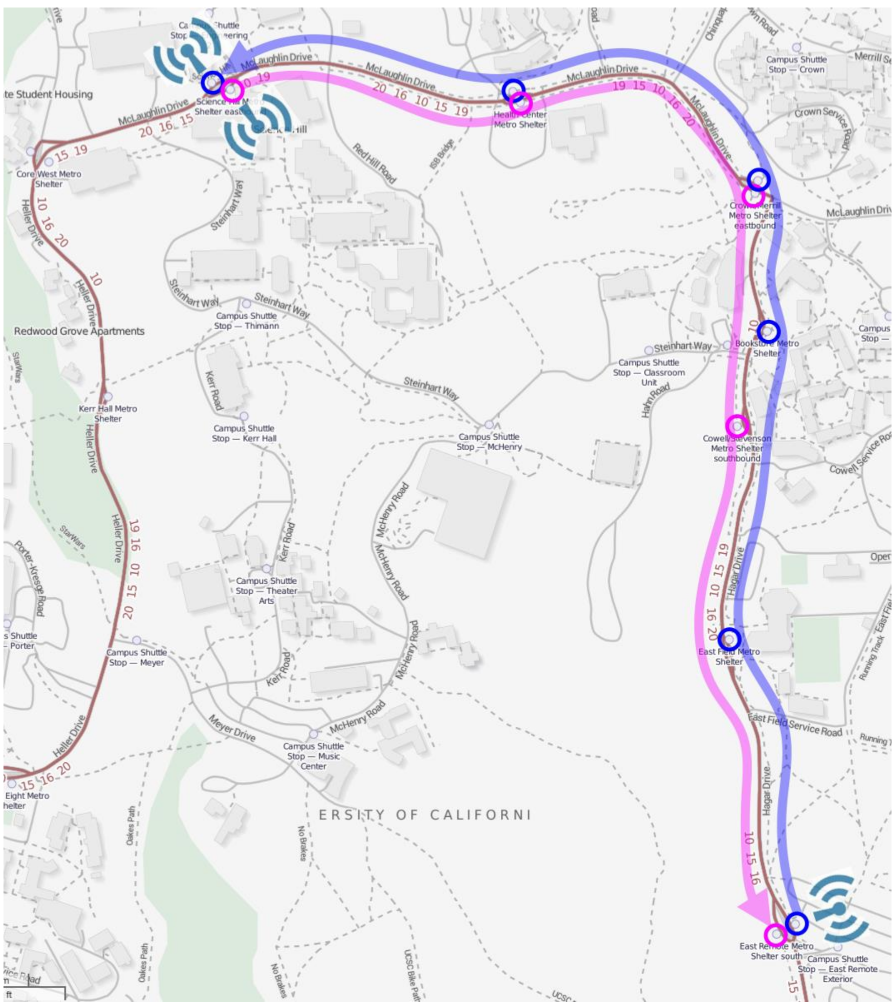


**FIGURE 3 Map of the UCSC campus with bus routes used in the experiments. The Eastward and Westward routes are shown by thick lines, colored in pink and light blue, respectively. The bus stops traversed by the routes are shown by colored circles. The bus stops with Wi-Fi access points are marked with a special symbol.**

During the tests leading to the final user studies, the project team instrumented a TAPS shuttle bus (by permission of the TAPS Director, Mr. Larry Pageler). Specifically, the TP-LINK and connected battery were kept in the front of the vehicle, next to the driver. Since each shuttle bus takes approximately 25–30 minutes to complete a loop, the waiting time at a bus stop for the next instrumented vehicle was reasonably short. Unfortunately, TAPS shuttles do not run on the weekend; this represented a major impediment to using this arrangement for the project team's user studies with blind participants. In fact, the team decided that the user studies should be conducted during weekends, as all campus busses are severely overcrowded with students moving between classes during weekdays, potentially creating serious difficulties with the user studies. Hence, there was no choice but to use vehicles from the METRO system, which runs four bus lines during weekends (Westward: 10, 16, 20; Eastward: 19). However, placing an Access Point within a vehicle in one of these lines would not serve the project team's purpose: the full route of these lines is quite long, and synchronizing the timing of the study with the sporadic arrival at a bus stop of the instrumented vehicle would be excessively complex. To obviate this problem, the project team devised an alternative strategy. A helper (a graduate student in the PI's lab) carried a backpack containing the TP-LINK router and the connected battery. At the beginning of the study (as described under Task 4 below), this helper positioned himself at a bus stop, located two stops away from the stop where the blind participant would board the bus. The helper was notified (by cell phone) once the participant arrived at the designed (instrumented) bus stop; he then turned on the router, boarded the first arriving bus, and found a seat towards the front of the bus. In this way, the project team could be certain that the first bus arriving at the instrumented bus stop (where the participant was waiting) would be instrumented. This simple strategy worked well, and faithfully emulated a real world situation in which all bus vehicles are instrumented.

A second hurdle the project team had to overcome was the lack of access to the current bus vehicle location, which was necessary for the system to announce upcoming stops. Although the METRO vehicles are equipped with GPS, the GPS data was not made available to the project team's system. For the prototype, the team decided to couple the TP-LINK router with an external GPS-equipped device (a dedicated Android smartphone). The two systems (TP-LINK and smartphone) communicated via Wi-Fi. The GPS locations of all bus stops were stored in a file in the smartphone. The smartphone sent a properly formatted message to the TP-LINK as soon as the bus reached a distance of approximately 50 meters to the next bus stop; this was then relayed by the TP-LINK router to the application on the tablet. Clearly, in a real-world application, the in-bus would have to have access to location data from the bus's own GPS.


**FIGURE 4 Top: Science Hill—East (left) and Science Hill—West (right) bus stops. Bottom: East Remote Parking—West bus stop.**

**TASK 4: USER STUDIES**

Before starting the formal user studies with blind participants, the project team thoroughly tested the system in multiple conditions, and was extremely pleased with its performance. On the basis of these results, the team concluded that, while Task 4 originally called for testing the system with 10 sighted participants in addition to the four blind participants, tests with multiple sighted participants would contribute no relevant information. Indeed, sighted users of the system can perform all operations (such as recognizing the correct bus or recognizing the destination stop) just using visual input, making use of this system irrelevant. Instead, the project team decided to concentrate on thorough studies with the visually impaired participants. These tests took a substantial amount of time to prepare and complete, and, in the team's opinion, produced very interesting results. The team realizes that the sample size considered (four blind participants) is very small, and that experiments with more participants will be needed to reach definitive conclusions about the usability and benefits of this prototype.

The project team started by preparing a detailed Human Subject Protocol that was approved by the UCSC Independent Review Board (IRB). The participants were recruited from the network of acquaintances maintained by the PI. Two participants reside in Santa Cruz; one participant resides in Monterey and one in Saratoga (both about one hour away by car from Santa Cruz). Studies were conducted individually on February 14 and 15 and on March 14 and 15 of 2015. Participants were either driven to UCSC by the PI, or reached UCSC using private transportation. They were then accompanied to the PI's office in the Engineering 2 building, where they were read the IRB-approved Consent Form. Upon signing their consent, they were provided with an accurate description of the system and of the experiment. The project team purposely decided not to perform a "dry run" training exercise, in order to evaluate whether the user interface was simple enough that could be used without prior training. Participants were offered the option to use earphones during the tests, rather than having to listen to the tablet's speaker. After a participant had a chance to answer questions about the system and the experiment, he or she was accompanied by the PI and the graduate student in charge of the project (Mr. German Flores) to the Science Hill – East bus stop, located about 150 meters away from the Engineering 2 building. This instrumented bus stop is visible in the top left of Figure 3, marked by a pink circle (a picture of this bus stop is shown in Figure 4). Note that a user located at that bus stop could connect to both the Science Hill—East AP and the Science Hill—West AP, which is just across the street. The app was then started and the tablet handed to the participant, who was instructed to select the Science Hill—East AP for connection, and then to select East Remote Parking—East as final destination (shown by a pink circle in the bottom right of Figure 3—see also Figure 4), using the tap and swipe interface described under Task 2. While waiting for the bus, participants were encouraged to occasionally interrogate the system, to ask for the waiting time till bus arrival. Once the bus arrived and the participant received confirmation that this was indeed the desired bus, the participant was accompanied inside the bus, where he or she took a seat in one of the seats reserved for people with disabilities. During the trip, the participant was informed about each upcoming bus stop by the system. Note that the same information was also announced by the speakers in the bus; however, the participants were able to hear the announcement multiple times, if desired, from the tablet. The participant was asked to pull the cord to call the final stop when he or she determined that the stop was approaching. Once arrived at destination, the participant was accompanied outside the bus, where he or she waited until the system announced that it had disconnected from the bus AP and would go into standby mode. The participant was then accompanied to the instrumented bus stop “Science Hill—East,” located across the street (see Figures 3 and 4), and asked to wake up the application again (by a tap-and-hold gesture). The whole process was then started again, with the only difference that the final destination to be selected was Science Hill—West. This leg of the route is shown by a pale blue thick line in Figure 3. The whole test (including waiting for the busses to arrive and traversing the route eastward and westward) took between one and two hours. Pictures and videos were taken while the participants interacted with the system. At the end of the test, each participant was accompanied back to the PI’s office, where he or she underwent a semi-structured interview conducted by the PI and audio recorded. Questions ranged over the regular use of public transportation by the participant, the perceived accessibility problems of public transit systems, the strategies used by the participant while traveling by bus, the perceived benefits and shortcomings of the system that was just tested, and suggestions for improvement.

*Participant Description and Experience with the System*

In the following the project team introduces each participant, describes his or her relevant characteristics and travel-related habits, reports observations from the user studies, and summarizes each participant’s comments and suggestions about the prototype system. To preserve their anonymity, participants were assigned fictional names in this report: Albert, Bill, Candace, and Donald (see Figure 5).

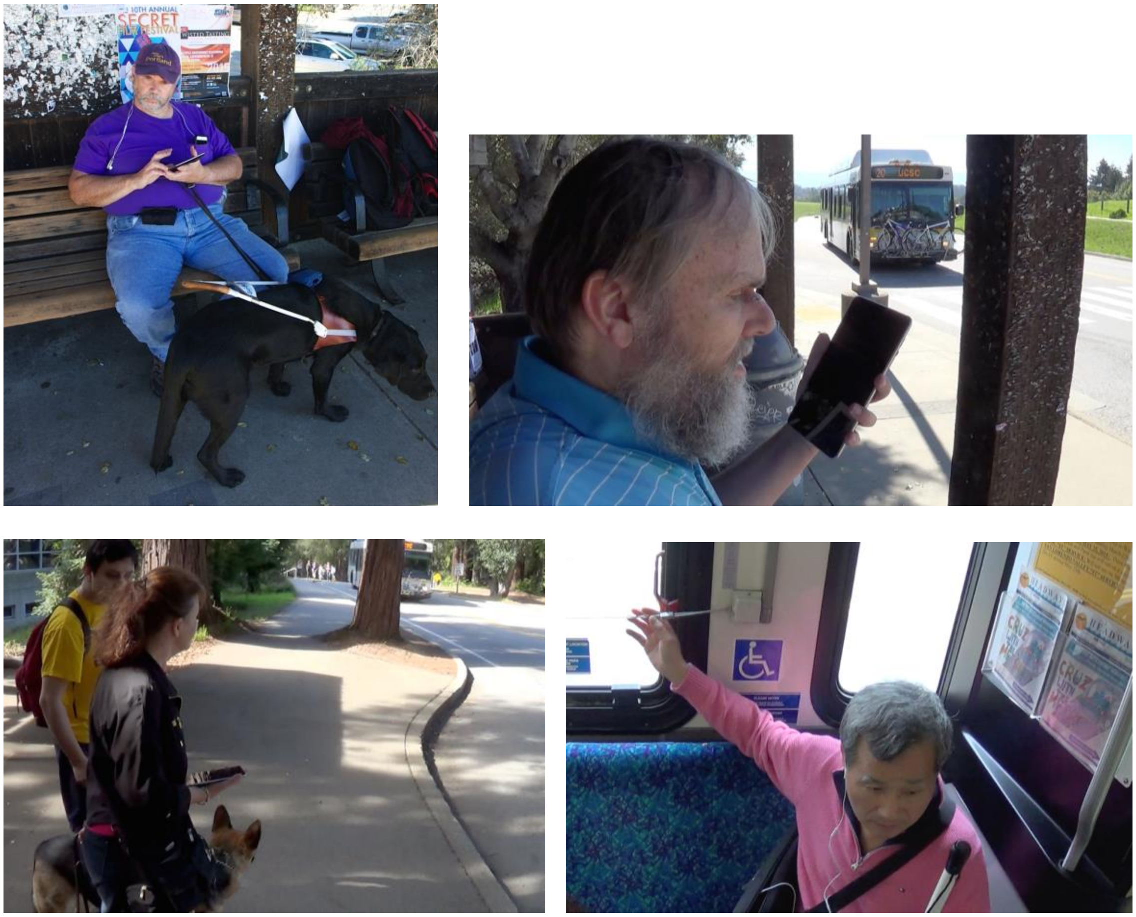


**FIGURE 5 Blind participants during user studies. In clockwise order starting from top left: Albert interacting with the application on the tablet; Bill being informed by the system that the 20 bus has arrived; Donald pulling the cord to call the stop; Candace waiting to hear from the system whether the arriving bus is the correct one. (Note: the participants' names are fictional to preserve anonymity.)**

*Participant 1: Albert*

Prior Travel Experience and Public Transportation Usage

Albert is a 55-year-old man, who is blind except for some residual light perception from one eye, and has regular hearing. He has outstanding mobility skills, and normally walks with his dog guide. He is an experienced iPhone user; in fact, he regularly tests new assistive technology devices and apps. He is very familiar with the local bus system and uses public transportation on a regular basis (although he prefers to walk to places when they are not too far away). In a typical week, Albert completes 4–5 round trips by bus. He very rarely uses the Paratransit system, as he finds it costly ($5 per ride). Given his familiarity with the area, only rarely (perhaps once every two months) does Albert find himself taking a bus to an unfamiliar destination. To make sure that he exits the bus at the right stop, Albert asks the driver to alert him when his destination is approaching, and listens to the stops being announced by the speakers in the bus. To reduce the risk that the driver may forget to warn him when the bus reaches the desired stop (something that happens occasionally), he normally tries to find a seat where he is visible by the driver. Still, at times he misses his destination stop. He sometimes checks the timetable before leaving the house, or, during a trip, calls the METRO service to figure out arrival times (even though he finds that obtaining the correct information is not always easy). He is not aware of any other accessible ways to find out which busses go through a certain stop. When waiting for a bus at a stop, once a bus vehicle arrives, Albert asks the driver for the bus destination. He also uses a simple device to indicate which bus line he wants to take: he carries a set of cards with numbers written on them, and inserts the two cards forming the number of the desired bus line inside the clear inserts of a vinyl wallet, in such a way that, holding the wallet open, the number is visible by the driver of the upcoming bus. Even so, he remarked that sometime drivers fail to pull over at the bus stop. When that happens, he makes sure to report this incident to METRO. In terms of physical accessibility, Albert noted that sometimes bus vehicles cannot pull close enough to the curb, which complicates the process of exiting the bus (he needs to step into the street before stepping onto the curb). He also laments a general lack of education by the drivers about giving informative directions in a way that is useful to a blind person. Another accessibility issue is represented by the fact that bus stops are not easy to locate: Albert said that he may not be certain that he has reached a bus stop until he accidentally hits a bench or a shelter. When asked about the audio announcements in the bus, Albert points out that the audio quality is usually pretty good, but sometimes the driver for various reasons shuts the speaker system off.

### Observations from the Study

When Albert tested the system, the app was started when he was still quite far from the Science Hill stops (perhaps 70 meters away). As a result, the system could sense the APs, but was unable to establish a communication (it was in the "actual range" of the AP, as shown in Figure 1b). From the user's perspective, this should be considered a system failure, and has the effect of decreasing confidence in the system. The project team will look at ways to mitigate it; for example, the system could refrain from announcing to the user that Access Points have been detected until a reliable communication channel has been established. This was the only time that this situation happened; the other three participants started the applications when they were already within "effective" communication range (Figure 1b).

Albert was accompanied by his dog guide during the tests. He decided not to use the earphones, and held the tablet in his left hand during the whole test. He was able to perform all tasks correctly, but had problems with the "tap-and-hold" gesture. It is not fully clear to the team what the nature of the problem was; perhaps he was not able to hold the finger on the screen without moving it after tapping, or he may have been touching the screen with another finger. Each time he wanted to activate a menu via tap-and-hold, Albert needed to repeat the gesture three or four times before the system recognized it.

### Comments and Feedback

Albert said that he would certainly use the proposed system if it were universally available. Indeed, he claimed that this was the most useful prototype he had tested in years. He particularly liked the warning given by the system at the stop before the final destination ("this alone is worth the price of the app"), because it removes the need to memorize a whole list of bus stops to be traversed. When asked to comment on the system functionality that allows for spoken information to be repeated, he said that he found this to be an important feature, especially when, due to loud noise, the information was not heard the first time around. The project team asked Albert whether he thought that the system should provide information about the number of stops till the final destination; he remarked that he would like the system to announce the distance (e.g., 2 miles) till the destination, rather than the number of stops. Albert also thought that, when waiting for a bus at a stop, it would be useful to know whether there may be an express bus going to the same destination following the next arriving bus—the user may decide to wait for the express bus, rather than taking the next, slower one. According to Albert, blind users at a bus stop need to figure out the distance between their location while waiting for the bus and the exact place where the bus can be boarded. For example, the Science Hill—East stop has a shelter with a bench that is located almost ten meters away from the edge of the curb where the bus will stop. This information is important for a blind person who needs to plan when to get up when the bus arrives and where to move. In general, accessing the detailed layout of a bus stop would be helpful for a blind traveler. Albert commented negatively on the malfunctioning of the system, when, as described above, it "sensed" the presence of the bus stop AP but could not connect to it. He also commented that it would be very useful to know the transmission range of the bus stop AP, as this would help one to understand the distance to the stop. Albert also was unhappy with the "tap and hold" interface mechanism that simply did not work for him. He did like the swipe gesture though. Another comment concerned the need for using both hands while interacting with the tablet. A blind person rarely has both hands available, as one hand is normally used to hold the long cane or the dog guide. However, Albert conceded that this is not much of an issue since interaction with the tablet is required only occasionally. He also commented that this system should be recommended only for experienced and independent travelers—a blind person must have already developed good mobility skills for this system to be useful.

*Participant 2: Bill*

Prior Travel Experience and Public Transportation Usage

Bill is a 58-year-old blind man with no residual sight and good hearing. He uses a long cane for mobility. Bill is technologically savvy and likes to try new accessible apps on his iPhone. He lived in Santa Cruz for more than thirty years, during which time he acquired good knowledge of the area and of the local transit systems. He likes walking to places if his destination is within a couple of miles away and it is not raining, otherwise he takes the bus (on average, 3 to 4 times per week). He never takes Paratransit. The majority of places he goes to are well known to him, although occasionally (perhaps once or twice a month) he needs to go to an area he is not familiar with. When going to a new place, he normally already knows the bus route to the place, and he may just call METRO to know the schedule; sometimes, he may try to use the METRO web site (which has some accessibility issues of its own). If he has reasons to believe that a route has changed, he would call METRO to ascertain the actual route. He would not trust Google maps for this information. Bill lamented the lack of ready online access to routing information in Santa Cruz. Timing information is available through automated phone system, but without clear knowledge of the route of each bus, this is difficult to use.

When a bus arrives at the stop, Bill listens to the acoustic announcement that is generally given when the bus pulls over and the door opens. This is a not always easy in certain stops, where multiple busses may pull in at the same time. In this situation, it may also happen that the driver of the bus leaves before the passenger manages to reach the bus. Once in a bus, Bill listens to the stops being announced. In the case of routes he is very familiar with, he is able to track the progress of the bus along the route. Bill also noted that, while in Santa Cruz all stops are announced, the same is not true for other bus systems, for example in nearby San Jose, where only the major stops are announced. In these situations, he would make sure to let the driver know at which stops he wants to exit.

Observations from the Study

Bill chose not to user the earphone and listened to the tablet's speaker instead. He had no problems interacting with the system, and quickly learnt to select his destination and browse through the menus. He used his long cane during the test. This caused some difficulties when he entered the bus, as he had both hands occupied (holding the cane and the tablet).

Comments and Feedback

When asked whether he would purchase an app that provides similar functionalities to the system he had just tested, Bill said that he would. He recognized, though, that this is still an early stage prototype. For example, he said that it would be desirable to know in advance when the bus is arriving (e.g., when the bus is 5 minutes away). He liked the one stop-away warning, as this gives one time to "tie up loose ends," especially if one was in the bus for a little while or on an unknown route. Bill said that he often finds himself in a situation in which the stop is announced and he suddenly needs to exit the vehicle. Bill also found the ability to select the destination bus stop very useful. He appreciated being able to input this information while at the bus stop, rather than inside the bus, where the noise level is higher and it may be more difficult to operate the tablet. Bill mentioned that finding the exact location of a bus stop is extremely challenging for a blind person: it would be very useful if this system could give some precise directions to the bus stop location. The project team asked Bill if he would find it useful to have the ability to access detailed information of the layout of the bus stop, and he confirmed that this was the case. For example, some bus stops have a bench and some do not; having this information would be important, as this would save one from spending time searching for a bench that is not there.

Bill commented that most users of Android applications with TalkBack (an Android accessibility service) are more used to double-tap gestures than to tap-and-hold (although tap-and-hold is common enough). He liked the right-swipe gesture, as he found it easy to perform. Also, he noted that expert users of the system would probably quickly right-swipe through whole lists of options, to select a specific item (e.g., a destination bus stop); the system needs to be able to support this behavior. Another suggestion was to use a vibrational interface for those who do not want to have to listen to the speech from the tablet. Bill noted that accessing the list of bus lines through a certain stop would be very useful (this is something that the system can certainly do, but was not implemented in the prototype since there was only one instrumented bus.) He also thought that being able to query the system to know how many stops there are before one's destination could be useful. Bill also suggested enhancing the system so that a bus driver could be informed that a blind passenger is waiting at a certain stop, to make sure that the driver pays special attention to this passenger.

*Participant 3: Candace*

Prior Travel Experience and Public Transportation Usage

Candace is a 64-year-old woman who has been blind for most of her life, with only some light perception left, and no hearing problems. She uses a dog guide when she moves around. She does not own a smartphone and is generally not too interested in technology. Candace does not often go to unfamiliar places at this point in her life, although she did in the past. She used to take public transportation; now she prefers to take taxicabs and, occasionally, Paratransit. She currently uses public transportation only 2–3 times a year; hence, her answers to the project team's questions about public transit accessibility refer for the most part to the time (perhaps 30 years ago, before the ADA was enacted) when she used public transportation more frequently. She used to obtain information about bus schedule either from someone who would read the schedule for her, or by calling the transit service. When visiting a new location (e.g., a store she had not visited before), she would either call the store to ask about the closest bus stop and how to reach the store from that stop, or alternatively, she would consult with an Orientation & Mobility (O&M) professional about the best way to get there. At a bus stop, once a bus arrived, she would stand up and ask the driver about the bus number, to make sure this was the right bus. Occasionally, a bus would not stop; however, she would have no way to understand why it did not stop. To make sure that she would exit at the right stop, she would ask the driver to tell her when the bus reached that stop. This was not a foolproof strategy, as sometime the driver would forget; one time, she almost missed a flight for this reason. When asked about perceived issues with physical accessibility of busses, Candace said that she could not think of any major problems—except perhaps that sometimes she would almost sit on somebody's lap. In terms of information accessibility, she noted that now (thanks to the ADA-mandate announcement system), things are much better than they used to be. Still, she thought that the prototype device provided a superior experience in terms of information access.

Observations from the Study

Candace used her dog guide during the test. She chose to use earphones, which allowed her to put the tablet in her purse when not interacting with it. She was instructed that, before putting the tablet in her purse, she was supposed to press the external button to put the system to sleep (and avoid accidental undesired interactions). Although she had some initial difficulties with operating this button, she quickly learnt the correct way to use it.

Comments and Feedback

Candace commented that the tablet would be too big for regular use, but understood that the system could be implemented on a regular smartphone. She liked that the buttons (used to put the system to sleep and to wake it up) were easy to find, although she was surprised that they were so sensitive. She found the quality of synthesized speech to be very clear. Talking about the tap and swipe interface, she said that "this is as much as I can handle." She found the interface mechanism easy and logical to follow. Candace particularly liked the fact that the system announces the bus stop before the last one. When asked about the system functionality that announces the bus arrival shortly before the bus pulls over at the stop (as soon as the client application connects to the in-bus AP), she said that the announcement is given too late—or better, that it would be desirable to be warned about the bus arrival with more advance (perhaps 10 seconds), and then again once it has arrived. Even if early warning were not possible, though, she thought that the current functionality is still valuable. Asked about the tap-and-hold interface, Candace said that she would prefer a triple tap gesture. Regarding use of the earphones, she thought that earphones worked well—they did not bother her, as she was still able to hear ambient sound. Candace suggested that, once arrived at destination, the system should give some information about the nearby streets and intersections—enough to help one situate oneself upon exiting the bus. Perhaps the system could also announce the name of the roads traversed by the bus on his route.

*Participant 4: Donald*

Prior Travel Experience and Public Transportation Usage

Donald is a 67-year-old man who lost his sight as a teenager. He has some level of hearing impairment, especially in his left ear. He is fairly proficient with technology, and loves his iPhone. Donald is highly mobile and used to travel around the world for business. He uses a long cane as a mobility device. In recent years, he has only used private transportation (or taken public transportation while accompanied by his wife), so his answers to the project team's questions related to public transportation usage refer to the time when he did use public transportation independently. During his college years (in Japan), Donald would take the bus every day. Sometimes, when visiting a friend, he would take a bus to an unfamiliar location. His friend would give him directions about what bus to take and where to exit. He would then try to create a mental map of the area. As for the bus schedule, he would call the bus company. Before boarding a bus, Donald would ask the driver to tell him the bus number; sometimes, the bus number was announced upon bus arrival. Donald also pointed out that in Japan, as soon as a bus vehicle leaves a stop, it promptly announces the next stop; then, the announcement is repeated as the bus approaches the next stop. He found this system to be very valuable; still, he would sometimes miss his stop. In this case, he had to find a way to go back to the desired destination, which at times could be very challenging. Sometimes, he was able to get back to the desired stop by remaining in the same bus vehicle while it completed its loop. In terms of accessibility, Donald found that the biggest problem was when the desired stop was not announced, or the announcement was too low in volume, or could not be heard because of ambient noise. Another undesirable situation occurs when a passenger waits for the bus sitting on a bench, and, unaware that the desired bus has arrived, does not stand up. In this situation, the bus may simply not stop. Donald also noted that sometimes it is difficult for a blind person to find the poles or overhead straps one can hang on to for balance inside the bus vehicle.

Observations from the Study

Donald used his long cane during the tests. He chose to use earphones, and thus was able to keep the tablet in his pocket when not interacting with it (while still hearing announcements produced by the system through the earphones). He carefully tested all functionalities of the system, pushing it to its limit. For example, while at the bus stop and after selecting a destination, he selected the “start all over” option soon shortly before the bus arrived, thankfully without causing any disruption. He also tried moving quickly through the items in the menu list by a rapid succession of right-swipe gestures. At some point, the system appeared to have hung, but in fact it worked again after a little while. The project team will need to look carefully at this less than perfect system behavior. He sometime had problems with the tap-and-hold gesture, and needed to repeat it multiple times before the gesture was recognized by the system.

Comments and Feedback

Donald found the project team's system very useful overall. In particular, he appreciated the fact that he could pre-program it with the desired bus line, and that the system warned him when the bus was reaching the stop before the final destination. Donald, however, was not too happy with the fact that an arriving bus would be announced only a few seconds before it pulled over. He thought that this announcement should be made at least 30 or 40 seconds before the bus arrives, or perhaps when the bus leaves the previous bus stop. He also suggested that important announcements (the bus arriving, or the final destination approaching) should be communicated using a specific "alarm" sound, rather than just via speech. Another interesting suggestion was to add a "hot button" that would quickly trigger repetition of the last spoken announcement (currently, this is obtained by a tap-and-hold gesture followed by selection from a menu list, an operation that requires several seconds to complete). In addition, Donald recommended adding the possibility of canceling the last input from the user. This option is not currently enabled; instead, in the case of input error, the user needs to perform a tap-and-hold gesture, and select the "start all over again" option from the menu. He also noted that in the current system, while the user is selecting an item from a list (by listening to the listed items one by one and right-swiping to move to the next one), the sentence describing the selected item is fully spoken even after the user taps on the screen to confirm selection. Since the user is likely to have already learnt the various items in the list, there is no need to complete the sentence after screen tapping. In order to increase interaction speed, Donald also suggested that the system should support rapid sequences of right-swipes to quickly move through the listed items during selection. Concerning the type of information provided by the system, Donald recommended that the system be customized, for example, to announce when the traveler is five away from destination.

## PLANS FOR IMPLEMENTATION

The project team will consider two possible avenues for practical deployment of the proposed system. One possibility is to discuss with local transportation agencies (METRO Santa Cruz, SamTrans in San Mateo County, MUNI in San Francisco) the possibility of instrumenting bus stops and bus vehicles or urban light rail trains with the proposed Access Points. Note that many long-haul bus services already provide Internet access to passengers via Wi-Fi; this system could use the same Wi-Fi routers to also transmit specific trip-related information, which can then be customized by the client application at the users' smartphone as in the prototype. Equipping bus stops with Wi-Fi routers could also represent an effective way to provide Internet access to passengers waiting for a bus (assuming that Internet connection at the stop is available). Clearly, these solutions represent a substantial infrastructure investment, and transportation agencies will need to be convinced that this system is useful to relevant sectors of the population using public transit.

As an alternative solution, the project team could consider a scaled-down version of the system that uses the user's own smartphone for Internet access and localization via GPS, and does away with the Access Points. While this solution is suboptimal (for example, it would be difficult or impossible to ascertain that a bus arriving at a stop is the desired one), some of the functionalities could still be reproduced (e.g., warning the user when the bus is approaching the final destination).

## CONCLUSIONS

The project team has developed a system that provides customizable, accessible information access to users of public transportation who are visually impaired or have cognitive impairments. This system relies on Wi-Fi Access Points placed inside bus vehicles and at bus stops to relay transit-related information directly to the user's smartphone, where it can be accessed via synthetic speech and using a specific gestural interface. Thorough experiments with blind users have highlighted the benefits of the proposed system along with its shortcomings. In future work, the project team will address the following issues, which emerged from the user studies as well as from discussion with the team's review panel.

1. **Announcing bus arrival with more advance notice.** Several participants complained that an arriving bus was announced only a few seconds before it pulled over at the bus stop. In order to be notified about bus arrival when the user is outside the Wi-Fi range of the in-bus Access Point, a different mechanism needs to be used. In some situations, this information could be available through online services such as NextBus (www.NextBus.com), which have access to the GPS data of individual busses.
2. **Multiple busses arriving simultaneously at a stop**. When more than one bus pulls over at a stop at the same time, it is difficult or impossible for a blind person to identify the correct bus, even if he or she has received confirmation that the correct bus has arrived. The project team will consider several possibilities to address this problem, including use of iBeacons (short-range low energy Bluetooth transmitters) installed outside bus vehicles, and directional antennas for the in-bus Wi-Fi Access Points.
3. **One-handed gestures.** All gestures considered for interaction with this system require the use of two hands, one to hold the tablet or smartphone, and the other one for performing the actual gesture. Since blind users normally already use one hand for holding the long cane or the dog guide, these gestures may be difficult to complete at times. The project team will consider gestures that only require a single hand (such as shaking the phone or tilting it in a particular way) to simplify interaction in these situations.

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