FinderX: A Bluetooth Beacon Based System for Designing Sustainable Green Smart Cities

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***Abstract*—Cities offer extensive facilities to enrich the quality of life by utilizing smart devices and sensors. The Internet of Things and smart sensors connect various city services with the inhabitants. The services should be convenient and accessible to all, especially pedestrians and people with visual impairment. However, the lack of information about service locations often limits their availability and use. To this end, we developed *FinderX*, a Bluetooth beacon-based system to search for the nearest services and amenities. *FinderX* identifies the locations of nearby amenities in real-time using the signal from attached beacons. The system does not require Internet or other communication infrastructure and can function where the GPS signal is inaccessible. To demonstrate the feasibility of *FinderX*, we set up a testbed and evaluated the system in an urban environment. We show that *FinderX* has adequate usability and feasibility and it reduces the time to find the amenities by 18.98% on average. We also demonstrate that Bluetooth beacons have lower horizontal error compared to GPS in micro-positioning (where semi-indoor or surrounding infrastructure limits signal accessibility), which motivates the use of Bluetooth beacons for such applications.**

I. Introduction

Cities are home to more than half of the world's population and are expected to add another 2.5 billion new residents by 2050. In the United States, 775 cities have more than 50000 people, and 127 million people live in these cities collectively [1]. As a result, cities are facing increasing environmental pressures and infrastructural needs as well as growing demands from residents to deliver a better quality of life. However, a city is not just about infrastructure development but also about the extent to which it helps achieve sustainable goals and ensure the quality of life using information and communication technologies (ICTs) [2]. The city planners boost the efficiency of municipal services and increase benefits that add convenience for the inhabitants [3]. They are deploying the Internet of Things (IoT) and smart sensors in various infrastructures, such as safety management, traffic management, waste management, environment monitoring, pedestrian safety, etc. [4]. For example, in the United States, major cities such as Boston and Baltimore have deployed smart trash bins that relay how full they are and determine the most efficient pick-up routes. Cities are embedding smart devices to reduce fatalities (e.g., homicide, road traffic, fires, etc.) and accelerate law-enforcement response.

In recent years, people have become accustomed to using smartphones for various purposes besides talking and texting. This includes entertainment, navigation, safety systems, monitoring device, etc. Statistics show that more than three billion people in the world currently use smartphones [5]. The use of smartphones is increasing, and in the near future, this device will continue to be an integral part of our daily lives. Moreover, smart cities are providing more services that are accessible to the smartphone. The manufacturers are adding smart technologies and functions to the phone to make them compatible with those services. For example, many cities provide information on traffic congestion, weather condition, block by block air quality, nearby amenities, etc. [6], [7]. However, location accessibility and the Internet are required for most of these services. The Global Positioning System (GPS) is a widely used technology for navigation, localization, tourism, and engineering. The accuracy of GPS depends on a strong signal between the receiver device and the navigational satellite. The lack of GPS signals in the indoor environment and the horizontal error of accuracy in outdoor environments often limit its uses. Von et

Fig. 1. FinderX System at the urban landscape can locate nearby amenities and services such as restrooms and trash bins.

al.'s early study found the average location accuracy of GPS enabled devices (i.e., iPhone, iPod, iPad, etc.) is between 108 and 655 meters [8]. Mok et al. [9] found the accuracy is around 20 meters in a study using GPS-enabled devices. More recently, a study found that the smartphone's GPS accuracy is between 6-13 meters [10]. However, this level of accuracy is often influenced by the characteristics of the landscape of the city. Consequently, the quality of GPS data collected using smartphones is not comparable with a dedicated stand-alone GPS receiver. In addition, there is a trade-off between accuracy and battery consumption of smartphones for positioning using location service.

Cities provide various amenities to the residents in multiple locations, including restrooms facility, trash collector bin, food truck, public parking, pedestrian-only streets, etc. In addition, numerous events occur in the city each day, such as open-air concerts, dramas, political rallies, etc. It is often difficult for people to find the nearest amenities, trash bins, information centers, restrooms in the crowd, especially those who have a physical inability or visually impaired people and those who are not familiar with the neighborhood. The dependency on the Global Positioning System (GPS) to search for anything in the city is often limited by the inaccessibility of signals. GPS signal accuracy is low in indoor, semi-indoor, and outdoor urban areas, such as malls, stations, skylines buildings, etc. To solve this, we need a system that does not require other infrastructure for positioning, and which is inexpensive and easy-to-deploy at inaccessible locations.

To this end, we developed *FinderX*, a Bluetooth Low Energy (BLE) beacon-assisted system to find amenities in the city using smartphones. Figure 1 illustrates the *FinderX* System. We used BLE beacons for identifying amenity locations. The *FinderX* smartphone app can receive signals from the beacons within a 100-meter radius. *FinderX* provides distance and direction to the users by triangulating signal strengths. It successfully locates amenity locations both indoors and outdoors without requiring Internet access. *FinderX* has advantages over solutions using Geo-fencing and fixed positioning with latitude-longitudes – such solutions do not work for portable facilities and amenities. Also, we demonstrate that *FinderX* overcomes the lack of accuracy and signal availability of GPS-based systems.

II. BLE Beacon in Smart City

Bluetooth Low Energy (BLE) beacons, or simply beacons, are small pieces of hardware that broadcast wireless signals in short range. BLE beacons operate using Bluetooth 4.0 and upper versions [11], which has some advantages over classic Bluetooth. For example, BLE requires low energy and is low-cost compared to the classic Bluetooth for similar communication range. BLE beacons broadcast the signal spherically and have a specific signal transmission range. Beacons are one-way transmitters; they do not receive any signal from other devices and can not connect to nearby receivers.

BLE beacon technology can track people and assets in indoor and outdoor. After the release in 2013, renowned chain stores worldwide installed beacons to provide customers in-store notifications about items, product reviews, and deals. The Wayfindr mobile application provides direction to the visually impaired at Underground in London using beacons [12]. It uses a headphone to provide the potential obstacles information. There are more than 8.2 billion Bluetooth-equipped devices in the world and that number does not include just tablets and smartphones but over 90% of cars released after 2016 have the technology [13]. By 2025, the BLE beacon market size is expected to reach USD 56 billion [14].

III. GPS vs BLE Beacon

Millions of people are now using the Global Positioning System (GPS)-enabled devices for daily activities. However, the horizontal position errors of GPS are not negligible in many cases. GPS based systems suffer from signal unavailability or limited signal in the GPS denied environment, in large and crowded structures around the users, during the environmental disaster, etc. This often affects the accuracy of GPS for ordinary users. To compare the GPS and BLE beacons, we measure the accuracy of the horizontal position. We collected the signals from three different locations called P1, P2, and P3. The structural conditions are different in these locations. P1 is situated between the two buildings; one is eight-storied, the other is twelve-storied. P2 is a traffic intersection, in which three sides have three buildings(four to five-storied), and another side is a park. P3 is near a roadside, in which one side is empty (trees and open space), the opposite side (another side of the road) is a four-storied building. Overall, the testing site in an urban landscape with all buildings is between 4–15 storied (in 100-meter radius). Figure 2 shows the location of P1, P2, and P3.

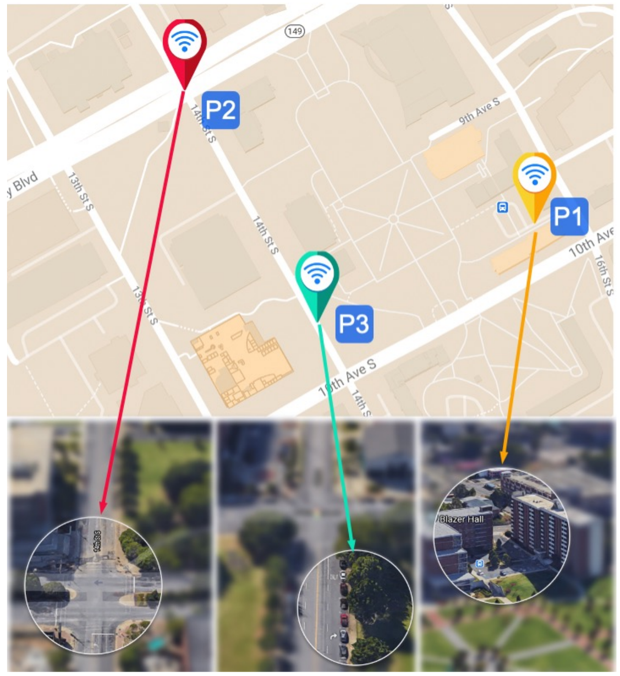

Fig. 2. The location of P1, P2, and P3 at the testbed.

After manually collecting the GPS position without WiFi at different times and days, we installed the beacons at the same location. Again we collected the position and distance with mobile applications (in Immediate and Near radius). Then we manually measured the length with a distance measuring tape. We got the estimated error after subtracting these lengths with the mean value of GPS values and beacon values. However, the error is not the same among the locations (P1, P2, P3). Table I shows the average horizontal error between GPS and BLE beacon at our testing sites.

TABLE I
HORIZONTAL ERROR BETWEEN GPS AND BLE BEACONS

Position	**Horizontal Error (m)**	
	GPS	**BLE Beacons**
P1	6 - 10	1 - 8
P2	6 - 9	2 - 7
P3	3 - 8	3 - 4

The result shows that BLE beacon-based system provides less error than GPS for micro-positioning. For example, in location P1, horizontal error are 6-10 meters; in contrast, the error in beacon positioning are within 1–8 meters.

The user has to enable the location service or Bluetooth service in their receiver device to get data for GPS or BLE beacons, respectively. However, power consumption is a major issue when smart devices use these services. For that, we measured the power consumption in the smartphone for both services. We actively used these services in the testing sites for 45 minutes to 2 hours a couple of times. During that time, the user device gets data from the beacons and GPS position. The time is measured individually, and we calculate the average values at the end of the study. During the experiment, all phones were in standard settings. Figure 3 shows the detailed results of battery consumption. The result shows the location service consumes more than 32% battery. In contrast, the Bluetooth service consumes 23% battery on Android and 15% battery on iOS during that time. Furthermore, we have tested the power consumption between Android and iPhone and concluded that Android operated phone consumes more battery than the iPhone. For example, during the location service, the iPhone consumes on average 32% battery, where Android phones are responsible for on average 38% battery. We used the same numbers of smartphones for Android and iOS to measures the battery consumption for GPS, Bluetooth, and the *FinderX* application. To eliminate the battery-capacity differences due to manufactures and models, we counted the percentage values.

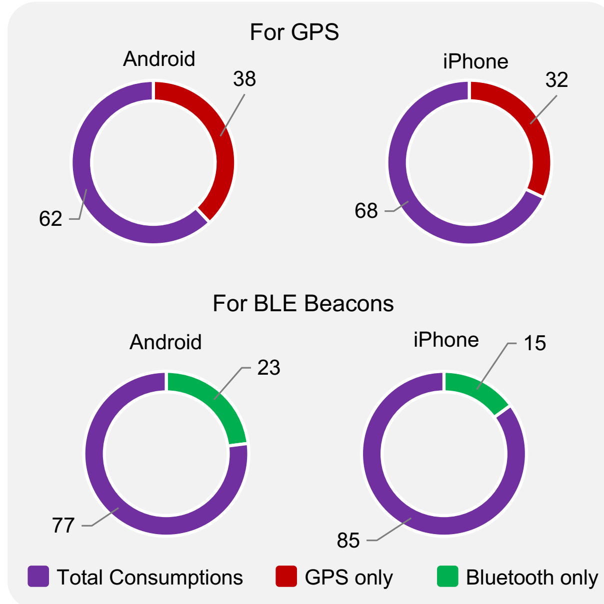

Fig. 3. Comparison of battery consumption between location and Bluetooth service.

IV. System Design

There are three components in the *FinderX* system – pre-configured beacons, a mobile application, and a backend server. We configured the beacons based on their purpose (e.g., indicator beacons, helper beacons, etc.). The mobile application runs on the receiver devices (e.g., smartphone, smartwatch, etc.) as a background service and responsible for all types of calculations. The server is not required for the basic operation, but it helps update and modify the beacon list in real-time.

A. Mobile Application

The mobile application helps to build an interface between users and beacons. To receive the BLE signal and calculate the distance, we developed the *FinderX* mobile application for Android and iOS platforms. Only some benign permission is needed for positioning, and the application use required services in an on-demand fashion to reduce battery consumption. *FinderX* is compatible with Android 6.0 and iOS 12.1 or a newer version. The pre-configured beacon information comes up with the installation package. However, there is a provision to update the list of beacons and their responsibility in real-time. Though the application shows only the nearest distance from multiple beacons, it periodically stores all available signal data for future calculations. Figure 4 show FinderX application interface for nearest amenities.

B. Distance Calculation

We calculate the distance between user and beacon position by Received Signal Strength Indicator (RSSI). The RSSI and distance are inversely proportional; if the signal strength increases, the distance decrease and vice-versa. The mathematical formula to distance calculation from RSSI is:

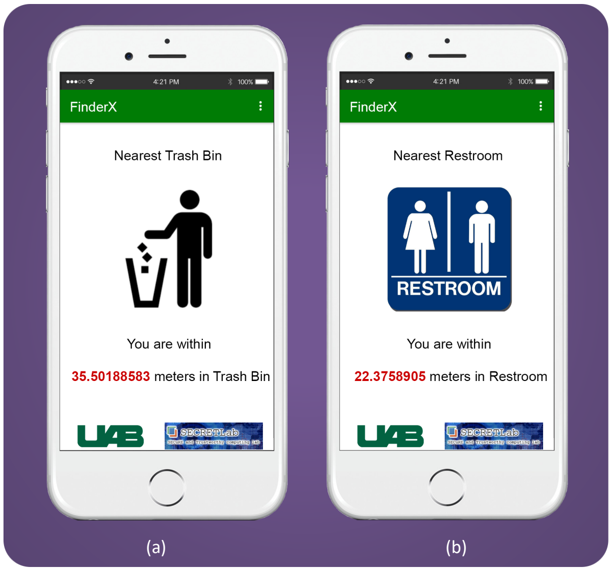

Fig. 4. FinderX mobile application with an approximate distance. (a) nearest trash bin with distance in meters. (b) nearest restroom with distance.

$$RSSI = -(10n)log_{10}(d) + A \tag{1}$$

Here, A = transmission power; d = distance; and n = signal propagation constant [15]. Modern beacons come up with manufacturer-specific SDK that also provides the distance. The receiver must uniquely identify the beacons with multiple values (e.g., UUID, Major, Minor, etc.) to calculate the distance. We can regulate how frequently the receiver application will get signals and perform the calculation. The frequent distance calculation provides a more accurate reading but drains the smartphone battery. *FinderX* application receives a signal and calculates the distance once in every second. Theoretically, the receiver gets a BLE signal immediately within a beacon radius. However, we found that it takes up to two seconds to get the signal at the study site (in the outdoor environment).

C. Direction Toward Beacon

Beacons broadcast signals spherically and do not have any indication for directions. The *FinderX* application calculates direction using the distance-over-time approach. If the distance decreases over time, it indicates that the user is going toward the beacons. The distance increases if the user goes in the opposite direction. The application keeps track of the user's movements and gives a warning if the user goes in the opposite direction. We assumed the average human walking speed is 1-1.50 meters per second to identify the user activity.

V. Test Deployment of FinderX

We set up a testbed in the urban university campus to test the feasibility of the *FinderX* system. We define the trash bins and restrooms as the amenities and installed two types of pre-configured beacons. Usually, one beacon is sufficient for one location. However, we installed multiple helper beacons to reach the amenities situated in the far distance. There were eight beacons for the trash bins and three for the restrooms. Figure 5 shows installed beacons at the testing site.

We faced several challenges while setting up a testbed in the outdoor environment. Here, we discuss the challenges and how we resolved them in an actual setup.

A. Height of the Installed Beacons

The height of the installed beacons is a crucial factor in getting an accurate signal. The signal strength decreases if we install it on or near the ground within 0 - 0.2 meters. We found the optimal height would be at least .6 meter (2 feet) from the ground by trial and error. Another indication we found during distance calculation is that the user carries their phone at that height. We did not try more than 3 meters of height (15 feet) in our study. As the Bluetooth signal strength decreases over distance and some points were not at the same distance, we have installed two supporting beacons. These beacons do not provide a direct location but give the direction toward a point.

B. Power Consumption

The battery issue is one of the main concerns of beacon technology. Consumption depends on multiple factors, such as the manufacturer settings, broadcasting power, advertising interval, etc. Modern beacons broadcast signals for up to five years without any replacement of power cells. We set the broadcasting power as +4 dBm and the advertising interval as 100 ms, sufficient for the testing sites. There was an automatic battery health

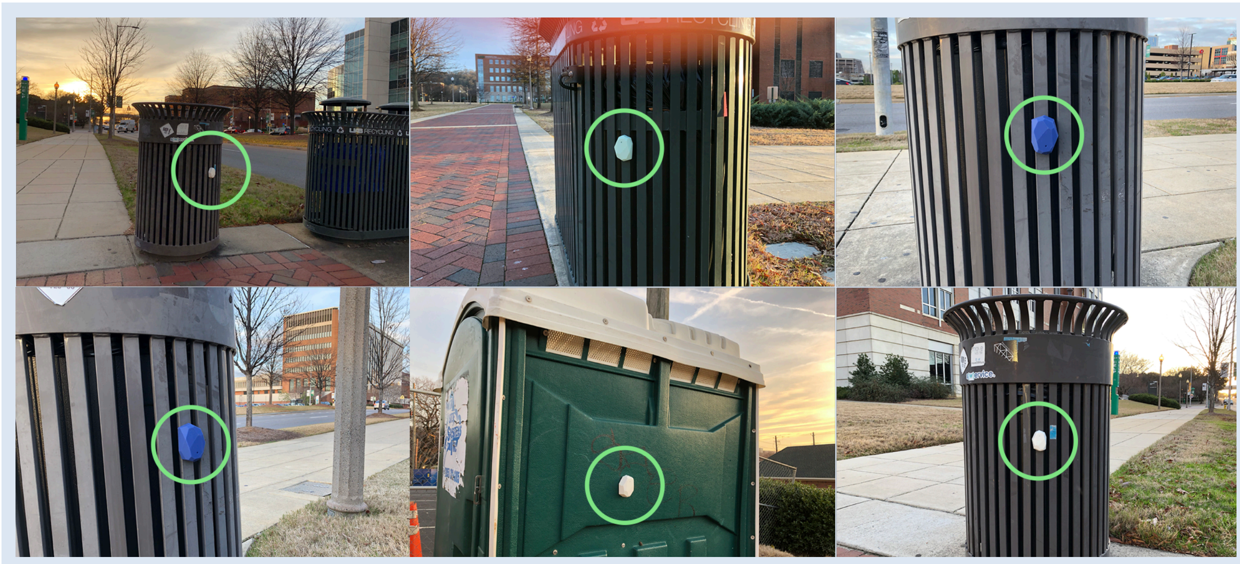

Fig. 5. Some samples of the installed beacons are at the study sites. The beacons in the circle are installed on the targeted amenities surface to localize them.

checking portal to identify the consumption in the *FinderX* system. However, we did not need to charge the battery during the study. On the mobile application, we need to turn on the Bluetooth service to get the BLE signal. Besides, *FinderX* uses some other services to get the user movement data (e.g., accelerometer, light sensor, etc.). Continuous use of these services causes battery drainage. *FinderX* only turns on the services when the application is in the foreground; it automatically turns off all services after it goes to the background.

VI. Experimental Findings

To test the feasibility and accuracy of *FinderX*, we set up a testbed at an urban university campus. First, we pre-configured sets of beacons for different amenities. For the experiment, we chose to set beacons on trash bins and mobile/portable restrooms. There were 16 participants in the study who voluntarily tested the *FinderX* application. There were two portions of this experiment; first, we give some dummy trash to the participants and ask them to dump it to their nearest trash bins. We calculate the time and distance to search and dump the trash. Second, we ask participants to install the *FinderX* application on their smartphones. We explain how the application works for the participants. Meantime, we relocate the trash bin to a new location but at an identical distance, which is already discovered by the participant. We ask them to dump the trash again with the help of *FinderX*. Each participant conducts this experiment two times at different locations. We calculated the distance and time and recorded the average values. Figure 6 illustrates the experimental findings.

The average time to find amenities without *FinderX* is 4.87 minutes and 4.55 minutes for the first time and second time (Figure 6(a)). In contrast, the average time to find amenities with *FinderX* is 3.29 minutes and 2.77 minutes, respectively. We infer that as the participants were new to find the amenities and the application, it takes more time in the beginning.

The average distance is also decreased with the use of *FinderX*. Though we measured an approximate distance, the distance amount was identical throughout the experiment. On average the participants traveled 187 meters to find a trash bin without *FinderX* (Figure 6(b)). However, they traveled 122 meters when using the app. We have configured the beacons to get the signal from 100 meters away. However, we received signals from a maximum of 80 meters away from a beacon in the study. A large number of concrete buildings reduced signal strength. *FinderX* consumes very low energy in user's smartphones. There are two versions of our

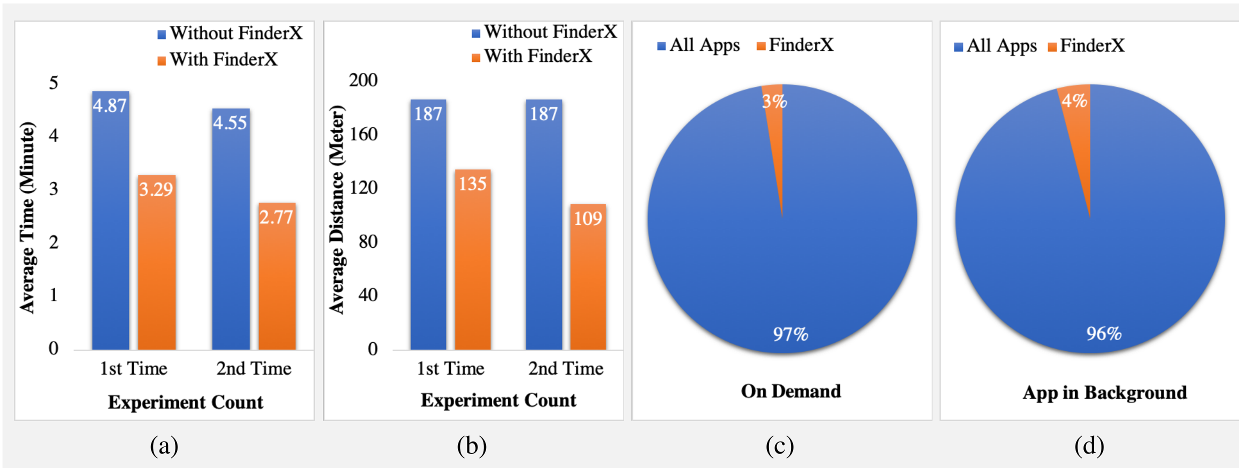

Fig. 6. Experimental findings. (a) reports average time to find nearest trash bin without FinderX and with FinderX. (b) Shows the average distance covered by the user to find the nearest trash bin. (c) and (d) illustrate the energy consumption of the user's phone. If FinderX runs all-time in the background, it consumes only 4% of total battery (d), if run in an on-demand fashion, it takes 3% (c).

app, on-demand application – user manually starts the application while needed and app-in-background – the application runs in the background all-time in the user phone. In both cases, *FinderX* takes less than 4% energy overall (Figure 6(c) and (d)).

VII. Conclusion

This paper reports the design, implementation, and evaluation of *FinderX* – a Bluetooth beacon-based amenities finding system in the urban city context. It also presents a comparison of micro-positioning error between GPS and Bluetooth beacons in the outdoor environment. *FinderX* provides the distance to the nearest trash bin and restroom to pedestrians within a beacon range. Our empirical testing demonstrates the effectiveness and feasibility. *FinderX* reduces the time to find a trash bin by 18.98% and the average distance by 34.7%.

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