BikeTrack: Tracking Stolen Bikes through Everyday Mobile Phones and Participatory Sensing

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ABSTRACT
Bicycle theft has been a well-known issue for many years. This study presents Biketrack, a participatory sensing system that uses everyday smartphones and low-cost Bluetooth devices to help people recover their bicycles. In BikeTrack, a customized Bluetooth tag mounted on a participant's bicycle broadcasts a beacon ID for bicycle identification. To detect the presence and location of a bicycle, BikeTrack participants use Bluetooth and GPS enabled smartphones to upload data to a remote server. Users can also check their bicycle's last seen location. To evaluate the feasibility of BikeTrack, a two-week user study with eleven participants was conducted at a school campus. Preliminary user-study results show that the bicycle and its location was detected 5.1 times per day on average and mostly locate within campus boundary. The results also show that user smart phones detect other bikes at different times of the day, suggesting that potential battery reduction can be applied based on user behavior.

1. INTRODUCTION
Due to their low cost and convenience, bicycles are a common means of transportation in many countries. Bicycles have recently gained in popularity as an environmentally-friendly and healthy alternative to vehicles. Some governments even operate bicycle rental services to encourage people to save energy through cycling [6].

Based on the increasing number of bicycles, cyclists face the problem of not being able to find their bikes and having their bikes stolen. Many places are plagued by rising bicycle theft rates, and have deployed several measures to solve this problem. Examples include Copenhagen's previous bicycle anti-theft project [9], which was based on RFID tags and readers. However, these projects involve high deployment costs, such as RFID readers and dedicated personnel to scan bikes. This also requires extensive coordination between authorities, manufactures, retailers, and users. Another option bike owners can adopt is to install a commercial asset tracking system on their bike, such as Lojack [1]. These systems use GPS to determine the location of property and report that location to users. This approach requires less infrastructure support, but is more expensive than RFID tags and requires the user to frequently recharge power-hungry GPS devices.

Table 1. A survey of bicycle experience from 208 National Taiwan University students who use or have used a bicycle

Questions	Avg. Answer
What is the total period that you ride a bike in campus?	2.38 years
How many bikes have you lost?	0.55 per person
How many bikes have you successfully found?	0.27 per stolen bike
Continued from the previous question, where did you find your stolen bike?	Mostly on campus, the school metro stop, or towed by school

Similar bike theft anecdotes are prevalent on the campus of National Taiwan University, with thousands of registered bikes on campus according to school databases. To verify this, we conducted a survey with 208 students (see Table 1) from National Taiwan University to understand the bike theft problem users face on campus. This data indicates that most recovered bicycles that were stolen, forgotten, or towed, are actually found on campus. Given the limitations of existing solutions, the research question this work tries to answer is "Can we build a low cost tracking system with a long lifetime (up to months)?"

To address this research question, this paper presents BikeTrack, a participatory sensing system that uses everyday smartphones and low-cost Bluetooth tags to track bikes. The goal of BikeTrack is to create a participatory platform that allows bicycle-tracking jobs to be crowdsourced to a community. Each bicycle is equipped with a customized Bluetooth tag that actively sends beacons. To discover the bicycle with a Bluetooth tag, participants use their mobile phones to scan Bluetooth tags through a BikeTrack client application and report the location of bicycle to the BikeTrack centralized server so that bike owners can find stolen bicycles.

This paper makes the following contributions:

- It describes the design and implementation of BikeTrack, a participant sensing system based on Android 2.x and customized a low-cost Bluetooth tag for bicycle identification.
- It presents the results of a two-week user study with eleven participants to demonstrate the feasibility of BikeTrack. Preliminary results show that participants successfully located other bicycles 5.1 times per day on average. Results further show that detection of other bicycles occurs within campus boundaries so BikeTrack can be useful for recovering lost bicycles on campus, which is the most common case from the survey in Table 1.

2. Design and prototype of BikeTrack

This section describes the design of the BikeTrack, including the following design principles and choices:

- *Easy to deploy:* Compared to pilot projects with large budgets and expensive anti-theft devices, BikeTrack is affordable and easy to deploy. The system relies on smart phone users to download the application from a mobile app download center (currently only at Android Market) and purchase affordable Bluetooth tags. Users must also voluntarily scan for the bikes. The system does not require the cooperation of authorities or vendors.
- *Accurate*: the most important design goal is for the location reported to be useful when bike users cannot find their bikes. We face two decisions (1) radio communication ranges and (2) data reporting frequency. This study chose Bluetooth because it offers a 10-20 meter range, which is sufficient to help users find their bikes. As for data reporting frequency, BikeTrack reports frequently enough (at least twice a day) to ensure good coverage. This reporting frequency is based on the mobility model of bike owners. For example, students often use their bikes to commute between classes held in several large teaching buildings on campus.
- *Minimal user overhead*: To encourage users to participate, BikeTrack has a very low user overhead. For example, (1) the tags for bike owners do not require care or battery recharge for 3–4 months (e.g. a semester period), and (2) the client application has minimal power consumption, CPU utilization, and network bandwidth to avoid interfering with other applications.

2.1 BikeTrack Overview

Figure 1 provides an overview of BikeTrack system. The three main components are (1) a bicycle equipped with a *customized Bluetooth tag* that actively broadcasts a unique beacon ID, (2) mobile phones that run a *BikeTrack client app* to scan the Bluetooth beacon from the bicycles, and (3) *BikeTrack centralized server*. When a beacon is found, the phone logs the location, beacon ID, and timestamp and reports the information to the server. Note that we do not ask users to locate the bicycles at a specific area. Instead, users find their bicycles through their daily activities. The *BikeTrack centralized server* logs user data to a SQL server and provides a web interface that allows users to inquire their bicycle locations on Google map. The following sections describe each component in detail.

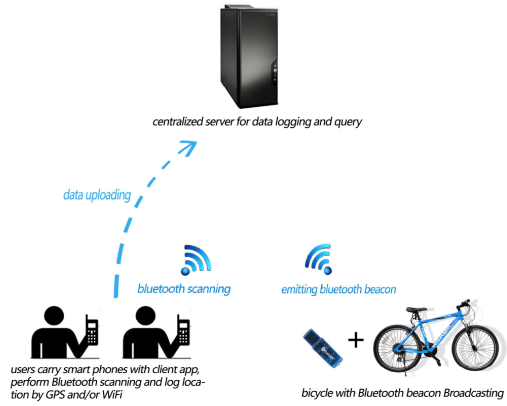

Figure 1. BikeTrack System Overview.

(a) (b)

Figure 2 (a) the Bluetooth device (b) mounted to a bicycle. We used a keychain and double-sided tape to lock the tag underneath the Bike

2.2 Customized Bluetooth device on bicycle

Many types of radio channels, including RFID, Wi-Fi, Zigbee, or Bluetooth, can potentially be deployed in BikeTrack system. This study chooses Bluetooth because (1) almost all mobile phones have a built-in Bluetooth technology, (2) the radio range is up to 10-20 meters, and (3) the power consumption is low when it operates only in discoverable mode[1].

[1] Discoverable mode in Bluetooth means that the device will send information such as its device name and MAC ID to other devices.

Figure 2 (a) shows the actual class 2 Bluetooth device customized for this study by a vendor [10] at $16 US dollar per unit. The main customization to this Bluetooth device is that it runs solely in discoverable mode. In other words, the device does not allow any pairing and continually broadcasts its device name and MAC address after it is turned on. With its current consumption measured at 1mA and battery size of 800mA, the device has a 40 to 50-day lifetime on average.

Figure 2 (b) shows how the device can be mounted on the bicycle. We chose to mount it under the bicycle seat to prevent it from getting wet and being seen. Similar to other anti-theft systems that removing the tag may render tracking ineffective, one way to address this issue is to hide the tag better or increase the trouble of removing the tag, such as welding or integrate the tag into a bike lock.

2.3 Implementation of client app on mobile phone

The phone program in this study was implemented on Android 2.x. The phone models used in this study include HTC Hero, HTC Desire, HTC Legend, and Samsung Nexus 1. When the user launches our program, it scans Bluetooth devices every 20 seconds in the background. The client application only logs customized Bluetooth tag by comparing the MAC ID. If it finds a Bluetooth device, it logs the location (longitude and latitude), timestamp, Bluetooth device name, MAC ID, and the user ID. The client app also logs phone battery level and Bluetooth RSSI (receive signal strength indication) values for future improvement of battery consumption reduction and location accuracy. The client application automatically uploads data to a remote site when a network connection is available.

We measure the battery lifetime to be 22 hours for a client application that scans for Bluetooth tags every 20 seconds on an HTC Desire HD. This period is fine in our current implementation as we assume users charge their phone daily. However, we plan to decrease the scan frequency to increase the battery life time as future work.

2.4 Centralized Server

The server runs an Apache HTTP server and MySQL database on a Linux machine. This allows users to upload and store data. It also provides a simple web interface for users to sign in to the webpage and find their bicycle location on Google Maps. Users can only view their own bicycle location data for privacy reasons.

3. System Evaluation and Initial Results

Our preliminary evaluation answers the following questions:

- How well does participatory sensing track bikes?
- How can we reduce battery consumption based on user behaviors?

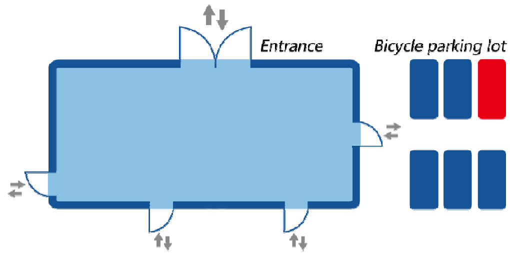

Figure 3. Department layout and bicycle parking lot area on the right. Users were asked to park in the red zone if possible. The capacity of the whole parking lot is approximately 300 bicycles.

- Is BikeTrack effective for recovering a stolen bike?

To evaluate the feasibility of BikeTrack, we conducted a two-week user study (not including holidays) with 11 students (3 undergrads, 7 grads, and 1 lab admin) from our CS department at National Taiwan University. All 11 students regularly rode bicycles on campus. We distributed Android phones with a BikeTrack client app installed to each user. Figure 3 shows the layout of the department building and its entrances. The bicycle parking lot is on the east side of the building. Since the number of users is limited, we asked the users to park their bicycles in the red area if possible. The dataset includes 3763 data entries with Bluetooth detections.

Effectiveness of participatory sensing for tracking bikes
Figure 4 shows the results of average Bluetooth detection per user. The x-axis represents a different user id and the y-axis represents the average number of Bluetooth detections per day over two weeks. Bluetooth detection can be categorized as detection of others and detection by others. *Detection of others* means that the user detects other users' Bluetooth tags. The more a user detects Bluetooth devices of others, the more data he contributes to the system. Results show that most users' phone can detect others' Bluetooth tags, except for user 6 who did not detect any. *Detection by others* means that the user's bicycle is detected by another user's phone. If a user's bike is stolen, other users may help locate the stolen bicycle. In our user study, all users' Bluetooth tags were detected and reported. The average detected rate is 5.1 time per day.

Battery reduction opportunities based on user behavior
Figure 5 shows the average number of detections per day indexed by hours. For example, any detection occurring between 10:00:00am to 10:59:59am is considered as 10am. Note that the detection only counts detection of others as in Figure 4 and only three users are chosen for illustration purpose. This figure shows that most detections happen during noon time, dinner time, or at the end of the day. These results match the general thought that people usually

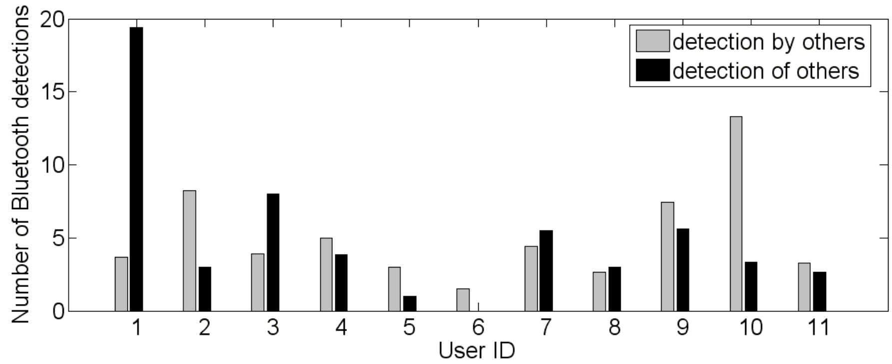

Figure 4. Number of average Bluetooth tags scanned per day by each user and detected by all other users

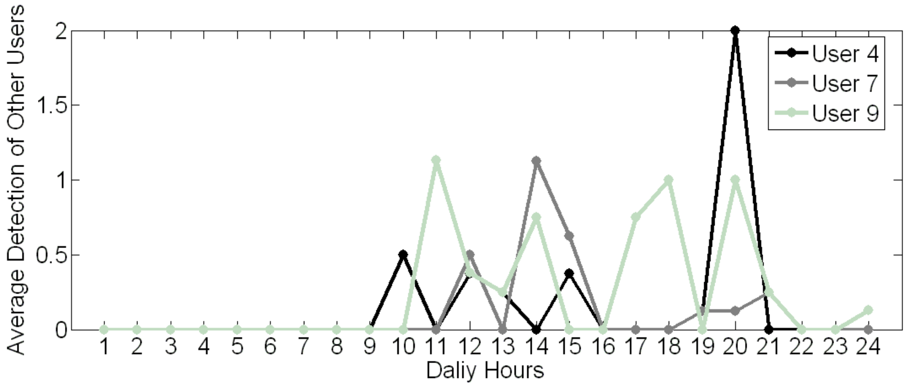

Figure 5. Average Bluetooth detection pattern during a day

come in the morning, leave after work, and go out for lunch/dinner, at which times their phones are more likely to detect the Bluetooth beacons. In addition, Figure 5 shows that user detection patterns are quite different: user 7 detects between 2pm and 3pm, user 4's detection mostly around 11am and 8pm, and user 9 sometimes detects around midnight. This gives us a very good chance to optimize the Bluetooth sampling rate in the future. Ideally, the client app should only perform Bluetooth scanning when the user is nearby bicycles.

BikeTrack effectiveness for recovering stolen bikes on campus Figure 6 shows the bicycle location distribution on a Google map over two-week based on our dataset. In addition to detection of other user's Bluetooth tag and location, this dataset also includes detection of the owner's tag and her bicycle location. The blue line represents the campus boundary, and the green line represents the CS department boundary. Most users rode their bicycles between the dorm and the CS department building or between the metro station and the CS department. This figure shows that bicycles are used on campus a lot. If the stolen bike is located on campus, the system is likely to detect its Bluetooth tag and report its last seen location. Note that the Figure 6 shows fewer location detections on the bottom of map, this is because none of our users live on the southern side of campus.

4. Related Work

Related research generally falls into the following categories.

Wildlife sensing and tracking: Previous methods on tracking wild animals, such as ZebraNet [4], deploy wireless sensor nodes to sense and transmit data on the same device. This work tracks bikes, which are mobile, but uses simple passive Blueooth tags instead of active sensor nodes.

Anti-theft sensing system: AutoWitness [3] demonstrates how to reconstruct the path of a stolen item with low-powered inertial sensors. It shows very promising results in path reconstruction. However, it assumes the stolen items follow paths on Google Map, while BikeTrack does not assume any road structure and focuses on last seen location of the stolen item.

Intelligent Bikes: There has been a wealth of research about adding sensing and computing functions to bicycles. BikeNet [5] is one of the earliest methods of applying sensor technology to improve biker fitness. The Cyber-Physical Bike [8] uses computer vision technology to alert bikers when a car is approaching from behind to ensure biker safety. Biketastic [7] provides a platform for bikers to share their route experience. In contrast to three previous projects, this study focuses on bicycle theft recovery. The Copenhagen Wheel [7] is a successful commercial project

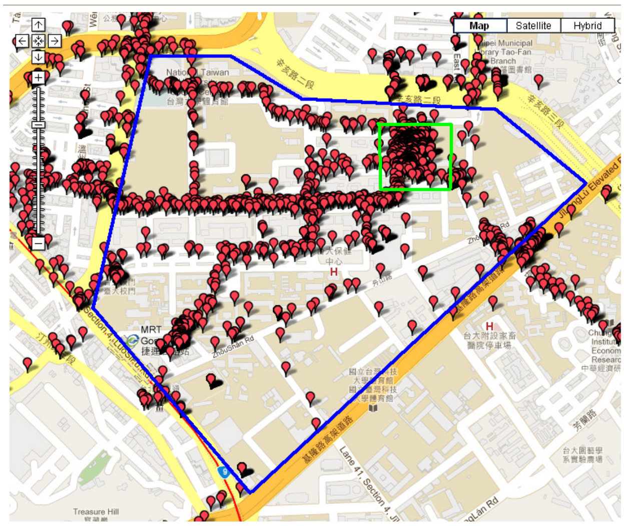

Figure 6. Location distribution of participants in NTU campus. Most Bluetooth detection occurred on campus (within blue line), and particularly near the CS department (within green line).

that adds sensing and power-assist technology to encourage people to use bikes more. It also leverages the power of participatory sensing in that all Copenhagen Wheel users collect environmental data for the government. Although Copenhagen Wheel also provides anti-theft mechanism, it requires accelerometers, a microcontroller, GPS, a GPRS modem, and a battery. The system is packed into a customized hub on wheel, which is too expensive for entry-level bikes. On the other hand, BikeTrack only requires a simple Bluetooth tag on the bicycle and crowdsources the job of finding bike to users.

5. Future Work

We plan to make a larger-scale deployment on campus during then school year when more students can participate. In addition, we are currently working on the following improvements:

Energy and CPU Optimization on Phone: As Fig. 5 shows, Bluetooth detection occurs more often in certain periods. This suggests that a power reduction scheme, in which the phone only scans for Bluetooth devices when the user is nearby the bicycles, would be beneficial. We plan to incorporate a Hidden Markov Model to our system to adapt the Bluetooth sampling rate to each user's daily behavior based on historical data. To reduce the localization energy consumption from GPS, we plan to use a Wi-Fi radio map at National Taiwan University for localization instead.

Better Bluetooth Tag: The current tags can operate for 40-50 days. We are exploring a few options to increase the tag lifetime so that no battery recharge is required during the deployment period. One option is to increase the battery size from 800mA to 3000mA. This would increase the lifetime from approximately 40 days to 150 days. Other options include adjusting the Bluetooth duty cycle, or harvesting energy from a small solar plane or the motion of bike pedals. Bluetooth 4.0 technology, which features Bluetooth Low Energy (BLE) [2], is also a promising option. The goal of BLE is to achieve much lower power consumption (a button cell battery can operate more than one year) and provide even longer radio transmission range (up to 50m to 100m) than the current Bluetooth 2.0 standard. Thus, BLE technology will be a better replacement of the Bluetooth 2.0 that BikeTrack is currently using.

Formulating Deployment Strategy: Our current deployment gives initial evidence that crowdsourcing can be effective in detecting bikes, but we still lack a systematic way to help plan future deployment. We plan to use BikeTrack and our campus as the example to explore the general problem of mobile sensors deployment in a crowdsourcing environment to understand the relationship between density and distribution of mobile sensors to the quality of sensor data collected.

6. Conclusion

This paper presents BikeTrack, a participatory sensing system that uses everyday mobile phones and simple Bluetooth tags to locate bicycles. The results from a preliminary user study confirm that BikeTrack can locate bicycles on the street with users carrying their smart phone running a Bluetooth scanning application. The promising results of this small-scale deployment suggest that ongoing improvements can further improve the system for future deployment at the campus of National Taiwan University.

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