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SensTrack: A Versatile Energy-Efficient Location TrackingWithSmartphone Sensors

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***Abstract*—Nowadays, as smartphones are becoming more and more powerful, applications providing location based services have been increasingly popular. Many, if not all, smartphones are equipped with a powerful sensor set (GPS, Wi-Fi, the acceleration sensor, the orientation sensor, etc.), which makes them capable of accomplishing complicated tasks. Unfortunately, as the core enabler of most location tracking applications on smartphones, GPS incurs an unacceptable energy cost that can cause the complete battery drain within a few hours. Although GPS is often preferred over its alternatives, the coverage areas of GPS are still limited (GPS typically cannot function indoors). To this end, our goal is to improve the energy-efficiency of traditional location tracking service as well as to expand its coverage areas. We introduce SensTrack, a location tracking service that leverages the sensor hints on the smartphone to reduce the usage of GPS. SensTrack selectively executes a GPS sampling using the information from the acceleration and orientation sensors and switches to the alternate location sensing method based on Wi-Fi when users move indoors. A technique is employed to reconstruct the trajectory from the recorded location samples. We implement a prototype on an Android smartphone that can sample the related sensors during the user's movement and collect the sensor data. Evaluation on traces from real users demonstrates that SensTrack can significantly reduce the usage of GPS and still achieve a high tracking accuracy.**

***IndexTerms*— Location tracking, smartphone, sensor.**

I. Introduction

UNDERSTANDING human mobility in daily life is a fundamental resource for broad-domain applications, especially for the applications that provide location based services. With the increasing pervasiveness of smartphones over the past few years, many emerging location based applications are adopted by mobile users. Consumer and advertiser expenditure on location based services is expected to approach $ 10 billion by 2016.

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The reason that location based applications become so popular is two-fold. First, location based services rely on the knowledge about the user's geographical location to obtain relevant information on the spot, and thus offer the user a plethora of options to satisfy his/her needs under that particular context. Second, a typical modern mobile device usually has the ability to locate or estimate its current position. The localization technologies used today mainly based on Global Positioning System (GPS), other technologies also obtain assistance from WiFi and GSM, each of which can vary widely in energy consumption and localization accuracy. As it is known to be more accurate, GPS is often preferred on mobile platforms over its alternatives such as GSM/WiFi based positioning systems.

Although smartphones today are capable to accomplish complicated tasks such as localization, we still face problems. The demand of computing and storage capability on mobile devices is rapidly increasing in recent years; whereas the battery manufacturing industry moves forward slowly (battery capacity grows by only 5% annually). In spite ofthe increase in processing power, feature-set, and sensing capabilities, the smartphones continue to suffer from limited battery life. Unfortunately, it is also well-known that GPS, the core enabler of many location-based applications, is power-hungry. The aggressive usage of GPS can cause the battery to completely drain within a few hours Location based applications still cannot assume continuous and ubiquitous location access in their design because of the high energy expense for localization. Even within the limited hours of being activated, GPS may not function well all the time, especially when the mobile user is under the shelter of buildings due to the signal loss under indoor environment. When GPS is unavailable, alternate location sensing techniques must be used to obtain the approximated location. The variability in accuracy provided by various location sensing technologies and the limits on their cover age areas pose additional challenges for application developers. Using multiple location sensors simultaneously to make up for this variability in accuracy would further increase energy cost.

We present the design of SensTrack, a location tracking service that provides user's moving trajectory while reducing its impact on the device's battery life. By applying different localization technologies, we expand the coverage area compared to the traditional approach that only uses GPS. In addition, the sensor hints from the smartphone itself can help us make decisions about adaptive sampling. SensTrack smartly selects the location sensing methods between Wi-Fiand GPS, and reduces the sampling rate by utilizing the information from acceleration sensor and orientation sensor, two of the most common sensors found on smartphones today.

We implement a prototype that collects the data from the sensor and records the location samples from GPS and WiFi.The collected data is further analyzed and filtered. Performance evaluation on the real data sets shows that SensTrack only needs 7% GPS samples of the naive approach and saves nearly 90% GPS activated time. Meanwhile, SensTrack reconstructs the user's trajectory with high accuracy and better coverage.

The main contributions of this paper are listed as follows:

- We identify the problems of traditional location tracking service including limited availability of GPS and unnecessary GPS samplings. The opportunities of energy-efficiency improvements by utilizing the assistance from sensors on smartphones are discussed.
- We present the detailed design of an energy-efficient location tracking system, SensTrack. Mechanisms for making smart adaptive sampling decisions are also discussed.
- We implement a prototype of SensTrack, and evaluate the proposed system through real-world experiments.

II. Related Work

To track the user's locations, many energy-efficient sensingapproaches with adaptive sensing policies have been proposedto minimize the energy consumption. Withthe objective of minimizing the location error for a given energy budget, EnLoc, an energy-efficient localizationframework, includes a heuristic with a local mobility treeto predict the next sensing time by utilizing the dynamicprogramming technique. Jigsaw uses the informationobtained from the acceleration sensor and the microphoneto continuously monitor human activities and environmentalcontext. According to the user's mobility patterns, adiscrete-time Markov Decision Process is employed to learnthe optimal GPS duty cycle schedule with a given energybudget.

Smartphone's energy consumption has been a major concern in research for a long time, and a number of studies have been done to improve the energy efficiency of mobile devices. In order to understand where and how the energy is used, A. Carroll et al. measured the power consumption of a modern mobile device (the Openmoko Neo Freerunner mobile phone), broken down to the devices major subsystems (CPU, memory, touchscreen, graphics hardware, audio, storage, andvarious networking interfaces), under a wide range of realistic usage scenarios. M. Ra et al. proposed the Stable and adaptive link selection algorithm (SALSA), an optimal online algorithm for energy-delay tradeoff based on the Lyapunov optimization framework. SALSA defers the transmissions of delay-tolerant applications until a less energy-consuming WiFi connection becomes available.

Inspired by many existing studies, we takeefforts to achieve high energy efficiency by reducing thesampling rate of sensing users' locations. However, our work uses a novel approach by utilizing the sensors on smartphones to capture thegeometric features of users' moving trajectories.

III. Challenges and Opportunities

In this section, we start by describing the defects of typicallocation-based applications that utilize GPS, including limitedavailability and unnecessary samples. We then discuss theopportunities for making improvements.

A. Limited Availability of GPS Versus Multiple Location Sensing Methods

It should be noted that traditional GPS cannot work properly under the indoor environment. The standard GPS receiver requires signals from at least 4 satellites simultaneouslyto calculate and output 3-dimensional locations and velocity information. Therefore, the mobile devicesneed to be in line-of-sight contact with the GPS a satellite, which significantly limits the usage of typical location basedapplications.

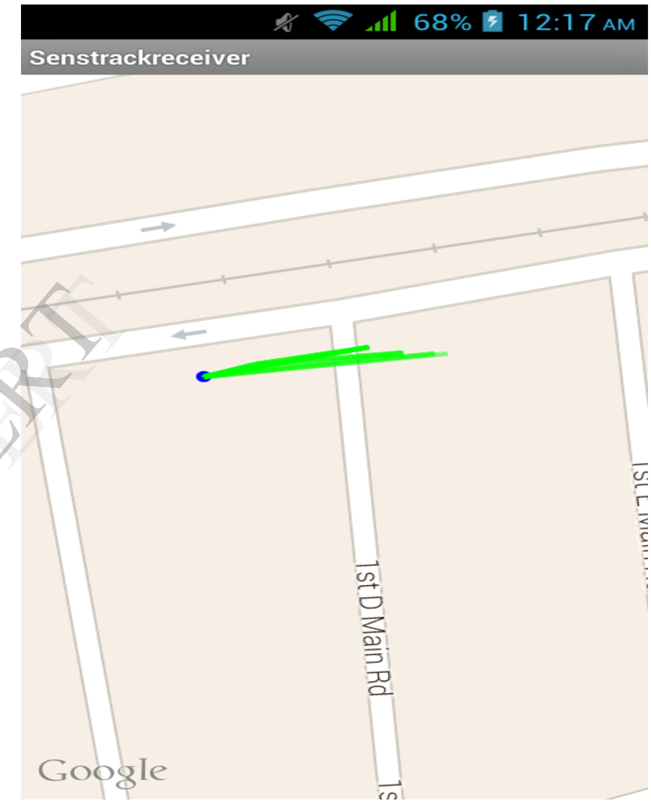

Fig. 1. Tracked results

Figure 1 shows one track that we took using GPS on amobile device. The trackends once it entered the building, which indicates the performance of GPSlargely depends on the working condition. The signals fromGPS satellites can be blocked not only by buildings but alsoby canyon walls, trees, and even thick clouds. When theuser walks through buildings, GPS equipped by a normalsmartphone cannot function since the lack of satellite signals.Even worse, GPS units may consume more energy than thenormal situation when there is no satellite signals.

Besides GPS, there also exists alternate location sensing technologies. For example, Android OS provides a networkbasedlocalization mechanism, which exploits GSM footprintsfrom cell towers and WiFi signals to obtain an approximatelocation. Although the network-based location sensing is notas accurate as GPS, it provides the possibility to keep tracking inside a building since it mainly relies on the WiFi connection,in which case GPS units can be deactivated to save battery.For the scenarios like university campus, hotels or hospitals,we can always assume persistent wireless local networkaccess, which implies that other location sensing methods mayprovide us valid options when GPS is out of use.

Whentheuser is inside a building, WiFi signal is usually relativelystrong. Therefore, the network-based localization can be avalid choice under the indoor environment where GPS is nolonger available. The idea is to use the GPS satellite signal andthe wireless network connection as indicators for switchingbetween GPS and the network-based location sensing method.

B. Unnecessary GPS Samplings Versus Adaptive Sampling

The GPS sensor can sample the user's location at a relativelyhigh rate. However, it is not ideal to record every locationupdate since the error for each location sample varies. To makethe path more smooth and fit the real trajectory, a typicallocation based application usually updates the user's locationonly if the distance to the last valid location sample is larger than a certain threshold. Therefore, with a fixed andfrequent GPS location sampling policy, it probably introducesa significant amount of unnecessary GPS samples.

C. Assistance From Other Sensors

Nowadays smartphones become more and more powerful in terms of hardware, which usually contains various sensors. As an example, iPhone 4 is equipped with several environmental sensors, including an ambient light sensor, a magnetic compass, a proximity sensor, an accelerometer, and a three-axis gyroscope. Android 4.4 (API Level 19) also supports up to 13 kinds of sensors, even though the sensors availability varies from device to device.

To reduce unnecessary GPS samples, adaptive sampling is proposed in many existing works. Usually we need additional information to make adaptive sampling decisions, which may include the location history, the speed history, the distance information, remaining battery power, the accuracy requirement, etc. Based on these useful information, we are able to make smart adaptive sampling decisions. The detailed design is described in the following section.

IV. SENSTRACK: DESIGN DETAIL

A. Overview

To reduce the frequency of location sensing, SensTrack periodically collects data from the sensors. The high energy efficiency of this approach is supported by the fact that the GPS sensor consumes more energy than network-based techniques. When the network-based location sensing method is not available or when the WiFi connection is inactive, SensTrack switches to GPS satellite signal sensing method to obtain raw coordinates. The last step of SensTrack is to update the coordinates of sampled location to a smartphone which acts as the receiver end to reconstruct a smooth and accurate trajectory.

SensTrack's system architecture consist of two stages: the first is to collect the location samples; and the second is to reconstruct the original trajectory. SensTrack switches between network-based and the GPS-based localization using the WiFi or GPS sensors, respectively.

B. Switching Location Sensing Methods

As mentioned, it is well-known that GPS cannot function properly indoors. To expand the coverage areas, SensTrack switches between GPS and network-based localization through the wireless connection. Basically we want to use GPS outdoors and the network-based localization indoors, and thus it is important to decide when to switch. Initially, SensTrack starts in the network-based mode and periodically executes a WiFi scan. When it detects the network loss as well as an inactive wireless network connection, SensTrack turns into the GPS mode. If network becomes available again, and the phone loses GPS connection significantly, SensTrack switches back to network mode. In some cases, both of the two methods are available when the user passing by some buildings. According to our rules, we should not change SensTrack's working mode, since in these situations the wireless connection tends to the unstable and short. In other cases, none of the two methods are available if we simply lose the GPS satellite signal outdoors. Our rules can also avoid the unnecessary switching in these cases.

V. EVALUATION

A.Methodology

In SensTrack, the phone is equipped with an integrated GPS sensor, and WiFi sensor. We implement SensTrack prototype on Android 4.4.2 (API level 17). When the network-based signal is available, a location listener is registered to request location from network periodically. Meanwhile, the prototype always tries to initiate and maintain a GPS connection, which can be used to record the location samples from GPS sensor when the network fails. We further analyze the data collected by the smartphone and filter the GPS and WiFi location samples.

We also compare SensTrack with the naïve approach, in which GPS is the only way to obtain location information and the GPS sensor is kept to be activated during the whole tracking period. Unlike SensTrack, which samples the GPS location actively, the naïve approach is a passive method that records all the valid location updates from GPS. Without significantly losing the accuracy of tracking, SensTrack effectively reduces the number of GPS samples and the time that the GPS sensor needs to be turned on.

B. Accuracy

When the user enters the building, since the signals from GPS satellites are blocked by the building, which indicates the performance of GPS largely depends on the working condition. Compare to the naïve approach, SensTrack demonstrates a reasonably better performance. SensTrack as a similar outdoor part, meanwhile it has the indoor part that the original one does not have. Although the indoor part of the trajectory may be not that accurate given the limitation of WiFi localization technology, it is still good to have an approximate trajectory.

(GPS can achieve an accuracy of 5 meters in good signal conditions). It should be noted that even GPS trace may not be the real path that the user has taken, because the performance of GPS depends on a number of factors such as the user's position, time, surroundings, weather, etc.

C. Energy Efficiency

In modern mobile devices, the GPS receiver usually consumes much more power than network-based sensors. For example, smartphones equipped with an integrated GPS receiver, with the battery supply (3.7 volt), the power consumption (in terms of current) of the GPS receiver is 80 mA. SensTrack can significantly reduce the number of needed GPS samples and the time that the GPS sensor needs to be activated. We do not measure the actual energy of SensTrack, since we thought it is unnecessary. For different hardware the power consumption varies and thus the energy consumption of SensTrack on a specific hardware model only provides limited information. Therefore, it is sufficient to show the relative energy efficiency of the SensTrack to the naïve approach by comparing the number of required sampling and the activated time of the GPS receiver.

The naïve approach updates the user's location every second, and the GPS sensor has to be kept active even when the user enters the building and loses the GPS satellite signals. SensTrack on the contrary selectively activates the GPS sensor at some locations, and turns off the GPS sensor once the device loses the satellite signals and have an active WiFi connection.

VI. CONCLUSION

We propose a versatile location tracking system, SensTrack. We first discussed the limitations of the traditional GPS-based approach and opportunities of improvements. Next the detailed design of SensTrack is presented including the rules of switching between two location sensing methods. We then evaluate the performance of SensTrack, which shows that SensTrack can significantly reduce the usage of GPS and generate accurate tracking results.

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