Research Statement

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There has been an exponential growth of smartphone usage and its computational capability in the past several years. The widespread usage of smartphones provides a unique opportunity for large-scale monitoring of urban and suburban environments. For example, aggregated and anonymous *localization* and *tracking* of smartphones of a subset of people in a particular area enable several applications such as monitoring street traffic flow and crowd movement. With the increasing computational and sensing capability of smartphones, it is now possible to build compute-intensive applications such as high-accuracy localization of a smartphone by video analysis, which can be very useful for navigation by visually impaired. However, there are many challenges for building these applications effectively, such as low-level and domain-specific computation methods, accuracy, resource cost, and efficient system and network architecture. In my research, I am addressing some of these fundamental challenges to enable applications that can have a real-world impact. My approach to research is to collect real-world data, analyze them to infer the underlying dynamics, solve fundamental problems, and evaluate the prototype applications through real-world deployment. Below, I present a brief overview of my research and my future directions.

Localization and tracking of smartphones using Wi-Fi: All smartphones come with Wi-Fi, and to detect the availability of Wi-Fi networks these smartphones periodically transmit probe messages. By deploying Wi-Fi monitors in an area of interest, it is possible to detect these transmissions, providing a coarse-grained location trace for each phone. Inspired by these observations, I developed WiFlow [1, 2, 3] to track unmodified smartphones, which enables applications such as monitoring street traffic flow and crowd movement. However, some major challenges for passive smartphone tracking are *sparse packet transmissions*, *received signal strength variation*, and *a variable number of received packets*. To address these challenges I used a *hidden-Markov-model*-based solution, using *map topology* to impose restrictions on movement and *signal strength* characteristics. Furthermore, to obtain additional packets from a passing smartphone for improved tracking accuracy, I used low-level Wi-Fi protocol features involving *association process* and *management frames* that increased the number of received packets by up to 5 times. Based on my experimental evaluation from one 9-month deployment and several single-day deployments, passive Wi-Fi tracking detects a large fraction of passing smartphones and produces high-accuracy trajectory estimates. Specifically, in one 12-hour trial using 7 monitors across 2.8 kilometers of arterial road, I observed over 23,000 unique phones. Combined with the probabilistic trajectory estimation method, this resulted in mean error across the entire trajectory of 67 meters compared to GPS ground-truth. This work received significant attention from academia, transportation institutes, and several companies. I also collaborated with some of them for further technical guidance and advised them with their specific implementation.

Performance and cost optimization for online GPS tracking: GPS tracking applications are widespread today. These include freight logistics, asset monitoring, public transit arrival time prediction, and widely popular smartphone apps for ride-sharing (e.g., Uber, Lyft) and navigation (e.g., Google Maps, Waze). The primary characteristic of all these applications is that the GPS clients need to transmit the GPS coordinates to a central server over a cellular network. For online GPS tracking, optimizing *cellular data usage* with a controllable *error bound* is an important problem. To investigate real world deployment of such applications, I studied a dataset consisting of 1.6 billion GPS points obtained from Nokia Research and found that 90% are sent using a naive periodic policy (1-300 second period). Through experiments, I also found that every packet sent incurs significant overhead. Additionally, in online tracking, a fundamental *three-way trade-off* exists among *delay* in location reporting, the *accuracy* of server-side location, and *data usage*. With these observations in mind, I designed a *thrifty tracking* system [4, 5] that allows the user to specify desired targets for any two of timeliness, accuracy, and cost; and optimizes the third. I also provided the *first unified view* of the three-way trade-off with a closed-form characterization equation. In my experiments, this system outperformed the status quo by over 80% without any delay in location reporting, and over 90% with as little as 8 seconds delay.

High accuracy localization beyond GPS: Smartphone GPS receivers typically encounter an error of 10-15 meters under the open sky, and over 100 meters in challenging places (e.g., urban canyons), making applications such as navigation for the visually impaired essentially impossible. Currently, I am working on a video-based localization solution with *sub-meter* accuracy using a smartphone's camera. Here, I am addressing three key challenges. (a) 3D model construction using standard techniques is not robust to the varieties of smartphone video, (b) due to resource constraints, 3D model size must be kept to a minimum, and (c) feature extraction, particularly for accurate image features, remains computationally very costly. Based on an extensive set of both indoor and outdoor videos, meticulously annotated with location ground truth, I demonstrated that the proposed techniques for reducing 3D points and 2D features produce accurate models despite challenging video conditions and substantially reduce model size without sacrificing accuracy. I also demonstrated an *optical-flow* based method to reduce the feature extraction effort required for accurate localization. Additionally, to make this system widely available and useful for the visually impaired, real-world landmarks (e.g., bus stops, shops, etc.) need to be tagged. I will release a smartphone app that sighted people can use to provide imagery data by walking in an area of interest while simultaneously tagging landmarks using voice narration. Using the app, a visually-impaired person can localize herself with high accuracy, and identify landmarks from the audio narration.

Future direction: My long-term research goal is to understand *urban and suburban dynamics* (e.g., traffic flow, public transit operations, crowd movement) using *real-time* data obtained from active sensing, crowd-sourcing, and participatory sensing. Traditionally people relied on surveyed and historical data to infer these dynamics. While historical data provides some information, it cannot provide the detailed insight required for effective decision making in real-time. With the growth of smartphones, low-cost sensors, cameras, and ubiquitous networks, it is now feasible to collect data on urban and suburban dynamics in real-time and produce valuable information through careful analysis.

In the near future, I want to work on monitoring and measuring traffic flow and crowd movement in public spaces using camera-equipped *drones*. Cameras mounted on street poles offer some opportunity for monitoring the environment. However, they have very limited field-of-view, thus requiring hundreds of cameras to infer a wide area statistics. Compared to street cameras, drones have several advantages. A drone camera can cover a wide area because of its larger field-of-view at high altitude. Additionally, a drone can rapidly fly along a street or in an area of interest to record video. Drones can be also dynamically routed to obtain fine granular information based on some event such as congestion due to a traffic accident. However, drone-based monitoring has some research challenges. First, existing computer vision algorithms such as object detection and recognition, flow analysis are well studied for the case of still camera and moving objects, but not for the case where both camera and objects are moving. These algorithms are often too slow for real-time analysis. To address these challenges, I plan to adapt the existing algorithm and create new algorithms through real-world experimentation and evaluation. Second, combining video from multiple drones with potentially non-overlapping views to infer traffic model of a large area is an open problem. I will develop algorithms to solve this problem by combining video analysis and traffic flow constraints. Third, precise geo-location of drones is a major factor for analyzing traffic and people movement accurately. Real-Time Kinematics (RTK) GPS is a promising solution for this. An RTK GPS system can achieve sub-meter accuracy for mobile GPS receivers on drones along with a fixed base station GPS receiver. Finally, I plan to address the routing and coordination of multiple drones, their communication architecture, and flight optimization for coverage and battery life.

Besides drones, GPS trace data offers a big opportunity for monitoring urban and suburban environments. In future, I want to work on the analysis of GPS data to infer the urban and suburban dynamics. There has been some usage of GPS data for analyzing various demographics such as congested streets, safer routes for bicyclists, and neighborhood characteristics. These GPS datasets are typically limited in size and are obtained from taxi-cab and fleet companies. With the recent growth of smartphone apps for ride-sharing and navigation, people are generating a large volume of GPS data, which can be used to produce useful statistics in real-time. These applications include real-time traffic statistics, travel time prediction, re-routing city traffic, and controlling traffic signal timing. One major research challenge is to evaluate inference algorithms accurately with proper ground-truth. I plan to address this issue with multi-modal comparison methods such as evaluating inferences from GPS traces with video analytics.

Efficient *data and network architecture* is an important factor for large-scale sensor data collection and analysis. In a large system, thousands of smartphones, cameras, and sensors will upload data continuously. Such high data load is challenging for both network transfer and computation at a central cloud data-center. Hence I want to explore the system architecture with *edge computing* where computational nodes are placed on the edge of the network such as cellular base station or Wi-Fi access points for distributed computation and reduced network load. I want to adopt *data streaming* framework to work with continuous and real-time data generated by thousands of devices. I worked on some of these problems in the past in collaboration with IBM Research, where I developed a framework [6] for offloading computation to edge and cloud computing nodes. This framework distributes application computation across various processing nodes to achieve improved application performance and reduced latency. In future, I want to explore more in this direction and build sensing applications using these paradigms.

In summary, the continued growth of smartphones, cameras, and other sensors provide an opportunity to improve some existing sensing applications and to create many new applications. I worked on some of the key research challenges to create the primary *building blocks* for these applications. I collected sensing data through real-world deployment and evaluated the developed systems in the wild. Furthermore, I collaborated with industry on many occasions to apply these ideas at a larger scale. I plan to continue my research in this direction to address further challenges and develop real-world sensing applications in the coming years.

References

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