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A novel on-demand vehicular sensing framework for traffic condition monitoring

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ABSTRACT

With the increased need for mobility and the overcrowding of cities, the area of Intelligent Transportation aims at improving the efficiency, safety, and productivity of transportation systems by relying on communication and sensing technologies. One of the main challenges faced in Intelligent Transportation Systems (ITS) pertains to the real time collection of traffic and road related data, in a cost effective, efficient, and scalable manner. The current approaches still suffer from problems related to the mobile devices energy consumption and overhead in terms of communications and processing. To tackle the aforementioned challenges, we propose in this paper a novel infrastructure-less on-demand vehicular sensing framework that provides accurate road condition monitoring, while reducing the number of participating vehicles, energy consumption, and communication overhead. Our approach is adopting the concept of Mobile Sensing as a Service (MSaaS), in which mobile owners participate in the data collection activities and decide to offer the sensing capabilities of their phones as services to other users. Unlike existing approaches that rely on opportunistic continuous sensing from all available cars, this ability to offer sensory data to consumers on demand can bring significant benefits to ITS and can constitute an efficient and flexible solution to the problem of real-time traffic/road data collection. A combination of prototyping and traffic simulation traces are used to realize the system, and a variety of test cases are used to evaluate its performance. When compared to the traditional continuous sensing, our proposed on-demand sensing approach provides comparable high traffic estimation accuracy while significantly reducing the resource consumption. Based on the obtained results, using the on-demand sensing approach with 30% of cars as participants in the sensing activity, and a six-criteria matching approach yields a reduction of 73.8% in terms of network load and a reduction of 60.3% in terms of response time (when compared to the continuous sensing approach), while achieving a traffic estimation accuracy of 81.71%.

1. Introduction

With the rapid widespread of smartphones that come embedded with a variety of sensors (e.g. gyroscope, GPS, and accelerometer), users now hold in the palms of their hands powerful devices that can be used as personal sensing platforms enabling the collection of a wealth of contextual information. This integration of sensing technology in mobile devices opens the door for a new sensing approach and era [1]. Mobile devices can act as super sensors that are readily deployed and can be used to dynamically collect intelligence about cities. There are two main mobile phone sensing paradigms: Participatory sensing in which the user actively participates in the data collection and sensing activity; and opportunistic sensing that occurs in a transparent automated manner without any user involvement [1]. Furthermore, different sensing modes can be adopted, namely: Sense-once, Event-based sensing, Time-based sensing with expiry duration, and continuous sensing. Sensing technologies constitute one of the key enablers of Intelligent Transportation Systems (ITS). In fact, ITS rely on communication and sensory technologies along with data processing and analysis techniques to improve the safety, efficiency, and productivity of transportation systems [2]. Typical ITS applications include traffic management, road safety applications, and route planning applications. The collection of real time traffic and road conditions constitutes an important challenge in such applications. Conventional methods for the collection of such information typically relied on infrastructure sensors such as surveillance cam-

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eras and inductive loops, which may not be always available and involve high deployment and maintenance costs [3]. Recently, the idea of using mobile crowdsensing for the collection of traffic and road related information [4] has attracted attention in academic and industrial forums. In this approach, regular users equipped with sensor-enabled phones collaborate to sense data related to phenomena of interest (e.g. traffic conditions and accidents' occurrence) [5]. The reliance on the drivers carrying sensor-embedded phones for the collection of traffic related information brings important benefits. The first benefit pertains to the easy on-demand deployment of a large-scale network of sensors, since millions of mobile phones are carried everyday by vehicle drivers. Moreover, this approach leads to important time saving and costs reduction with respect to traditionally deployed specialized sensing infrastructures. Examples of mobile crowdsensing systems used in the area of intelligent transportations include MIT's CarTel [6] and Microsoft Research's NeriCell [7]. These systems mainly adopt a continuous sensing approach in which data is continuously sampled from all cars on all street segments (without the explicit involvement of users), and then processed offline on the back-end server. However, this imposes high energy-requirements on mobile devices, entails significant overhead on the mobile communication infrastructure, and results in large amounts of data requiring processing on the server. Furthermore, the opportunistic automated data collection strategy adopted by such systems gives rise to privacy concerns by mobile users, which may not wish to share sensory data that reveals sensitive information about themselves (e.g. their geographic location).

Moreover, in similar context, the connected vehicles technology [8] has emerged recently, which enables the communication between vehicles (i.e. Vehicle to vehicle) as well as between vehicles and the roads' infrastructure (i.e. vehicle to infrastructure), using dedicated short range communications (DSRC) [9]. In [10], a traffic estimation for highway was estimated using connected cars with and without being equipped with Adaptive Cruise Control. However, despite the merits of the connected vehicles technology [11] and its potential use for safety and congestion management applications, this technology presents certain limitations when compared to the mobile crowdsensing technology. The first limitation pertains to the smaller market penetration rate of connected vehicles (fore casted to reach 152 million connected vehicles sold by 2020 [12]), when compared to the massive and pervasive market penetration of smart-phones that have passed the 2 billion device mark in 2016 and are expected to reach 2.87 billion in 2020 [13]. In fact, the effectiveness of ITS relying on sensory technology depends on the sufficient penetration of the technology in streets, a fact that cannot be currently guaranteed with connected vehicles, but can be easily achieved with smart-phones. Furthermore, smart vehicles [14] currently face limitations in terms of their communication and sensing capabilities, under adverse weather conditions.

Recently, the Mobile Sensing as a Service (MSaaS) approach has been emerged [15,16], in which mobile devices and users willingly participate in the sensing process and offer their phones' sensory data collection capabilities as services to other users. This approach is very promising to address the aforementioned issues, and to the best of our knowledge, none of the previous related works consider it in ITS solutions. In this work, we propose a novel vehicular sensing framework enabling on-demand road condition monitoring in efficient and flexible manner. Unlike existing solutions that rely on opportunistic continuous sensing from all cars available, we advocate participatory on-demand sensing from a selected number of cars that can offer a high quality of sensed information. In the proposed framework, status and traffic data sensed about any region of interest would occur on demand, when triggered by a sensing request. Once the sensing request is received by the sensing platform from a data consumer, the set of targeted users acting as data collectors will be determined by the platform based on a proposed multi-criteria matching algorithm that takes into account the collectors' presence in the region of interest, their phones' sensing capabilities, the users' willingness to participate in the sensing activity, the users' reputation, the phones' battery level, and the accuracy of the data they provide. Once the sensed data is received from the targeted data collectors, the sensing platform relies on a traffic estimation algorithm to estimate the traffic condition, which is sent in the form of a traffic report to the user who sent the original sensing trigger request. More interesting scenarios could be enabled by the concept of on-demand vehicular sensing as a service such as "On-Demand Accident Scene Intelligence Gathering" and "On-Demand Road Condition Monitoring". Accident scene such as stationary cars, injuries and Road status such as traffic level, snow removal conditions, potholes in streets, fog or bad weather conditions, road redirection can be collected on demand by the sensing platform, analyzed and then provided as a report to the user triggering the sensing request. It should be noted that the messages exchanged between the platform and the users (acting as data collectors and data consumers) is conducted using RESTful web services communication interfaces which we defined for our framework.

In order to study the performance of our vehicular platform and compare the on-demand sensing approach to the traditional continuous sensing approach, we combined prototyping and simulated traffic traces to build a proof-of-concept prototype of the system. Furthermore, we conducted extensive experiments in which different parameters were varied, such as: the traffic conditions on the road, the matching criteria used for participants' selection, the number of sensing requests received by the platform/hour, the frequency of voluntary data publication requests, and the percentage of cars participating in the sensing activities. Four main performance metrics were measured using various test cases, namely: The traffic estimation accuracy, the participants' selection accuracy, the system's response time, and the system's network load. This comparative performance analysis gives interesting insights on the contributions and benefits of an-demand participatory sensing approach, and the trade-offs that can be achieved between the data collection frequency, the percentage of cars participating in the data collection activity, the traffic estimation accuracy, and the system's performance.

In summary, the main contributions of our participatory on-demand sensing framework are five folds:

- **High traffic estimation accuracy**: Our proposed approach is able to successfully infer the traffic status in all the tested scenarios. The experimental results show that the estimation error % decreases from 17.82% for 10 sensing requests received/hour to 2.9% for 10000 sensing requests received/hour in the on-demand approach. Such results are comparable to the standard continuous approach, in which the estimation error decreases from 17.7% for data voluntarily published each 10 minutes to 5.9% for data published each 30 s.
- **Reduced resource consumption**: Due to the fact that the number of cars involved in on-demand sensing is reduced to a selected set of cars present in the area of interest, chosen based on several selection criteria, and approached on need basis only (instead of continuously publishing their information), important reductions in the amount of generated network load, energy consumption on mobile devices, and amount of data requiring processing on the server can be achieved. Moreover, our proposed approach strikes a balance between traffic estimation accuracy and resource consumption. This is achieved by using contextual information and a multi-criteria participants' selection approach to select the smallest number of data collectors that can provide the best quality

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