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Towards On Demand Road Condition Monitoring Using Mobile Phone Sensing as a Service

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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 energy consumption of mobile devices and overhead in terms of communications and processing. We have previously proposed the concept of Mobile Sensing as a Service (MSaaS), in which mobile owners can offer the sensing capabilities of their phones as services to other users. 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. In this paper, we adapt the concept of MSaaS to the area of transportation, and present an on-demand vehicular sensing framework. This framework enables a data consumer to send a sensing trigger request to a vehicular sensing platform, which matches it with the most suitable set of data collectors that would perform the sensing task, and return the data to the platform for validation and processing. The collected data is then used to infer intelligence about the city and send the required traffic information to the data consumer, in a timely manner. The proposed model and architecture were validated using a combination of prototyping and traffic simulation traces, and the obtained results are very promising.

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Keywords: Sensing as a service; Intelligent transportation systems; traffic estimation; road condition monitoring

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

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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 – the mobile phone sensing[1] era. 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].

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 cameras 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 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)[4]. 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[5] and Microsoft Research's Nericell[6]. 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 backend server. 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).

We have previously proposed the concept of Mobile Sensing as a Service (MSaaS) as well as a business model enabling its realization[7]. In this concept, we perceive mobile devices as data collectors and mobile device users as willingly participating in the sensing process and offering their phones' sensory data collection capabilities as services to other users. In this work, we adpat the concept of MSaaS into the area of transportation and propose a vehicular sensing framework enabling on-demand road condition monitoring in efficient and flexible manner. In the proposed model, traffic related data sensing about any region of interest would occur on demand, when triggered by a sensing request. The set of targeted users acting as data collectors will be determined by the sensing platform based on their presence in the region of interest, phones' sensing capabilities, and availability to participate in the sensing activity. Furthermore, the data collector has the possibility to accept or reject the sensing request. The elaborated approach provides reduced energy consumption and communication overhead between the mobile phones and the server since only the required data will be sent to the sever when needed, and the ability of users to control sensing activities thus having control on the sharing of their personal information.

The rest of the paper is organized as follows: In Section II, we present some illustrative scenarios. Section III discusses the related work. Section IV details the proposed vehicular sensing framework. This is followed by the system validation and experimental results in Section IV. We end the paper with our conclusions.

2. Vehicular Sensing Illustrative Scenarios

Many interesting scenarios could be enabled by the concept of on-demand sensing as a service. In the sequel, we provide two participatory and opportunistic transportation related scenarios:

- ***On-Demand Accident Scene Intelligence Gathering:*** When an accident occurs, it takes the police some time to arrive to the accident site. In order to collect information about the accident before arrival to the site, the police force could send an on-demand sensing request that would be conveyed by the sensing platform to a select group of cars in the accident area. The car drivers who accept this request would then take pictures/videos of the accident as well as collect additional contextual information using their phones and push them back to the platform. The platform would then process this data and produce a summary report containing information such as the number of stationary cars, number of casualties/people laying on the floor, and the temperature/smoke levels within the accident scene. This summary report along with pictures and videos footage collected would be returned by the platform to the police force for fast situation assessment and decision-making.

- ***On-Demand Road Condition Monitoring:*** Drivers on the road could serve as source of information for traffic and road conditions, by using their phones to collect contextual information such as snow removal conditions, potholes in streets, fog or bad weather conditions, accidents, extreme traffic, and road redirection. This information could be requested in real time by drivers heading in a certain direction and wishing to learn about the roads' conditions in order to either continue on a specific road or find an alternative one. In this case, a driver would send an on-demand road condition-sensing request to the sensing platform. This last would forward the request to a set of targeted cars located in the specified destination, would get the required data as their responses and then process it and send the response back to the requester. This way, the data consumer would be able to gather useful real-time information about roads' conditions, and thus reach his/her destination within a short trip time. Such scenario applies to both participatory and opportunistic sensing paradigms.

3. Related Work

Several traffic estimation approaches have been proposed in the literature, some relying on specialized sensing devices while others leveraging mobile phones as sensing devices. In[8], the authors proposed the use of GPS and accelerometer data for the detection of traffic conditions, abnormalities, and potholes on roads. This approach consists of five components: smartphones, a local database (for temporary storage of data), open wireless networks, a server hosting a central database, and open street maps. The sensed data is sent to a heuristic algorithm that analyzes it and produces roads' traffic status. Herring et al.[9] proposed a solution that targets traffic conditions on highways. In this approach, data is collected using mobile phones on specific trajectories called virtual trip lines. This data is sent to a server that aggregates it and sends it to the Ensemble Kalman Filtering based traffic estimation algorithm.

In [10], Thiagarajan et al. proposed an approach to overcome energy consumption and inaccurate position sampling challenges by using a Hidden Markov Model (HMM) to model a vehicle trajectory over a block level map of the area. They performed map matching, which associates each position sample with the most likely point on the road map, and produces travel time estimates for each traversed road segment. In [6], Mohan et al. proposed a solution called NeriCell. This solution consists of a system of rich monitoring of road and traffic conditions that piggybacks on smartphones and calculates roads' traffic status using vehicles' acceleration data. Herreraa et al. proposed two data gathering techniques (spatial and temporal) in [11]. Spatial sampling implies that equipped vehicles report their information (position, velocity, etc..) at specific time intervals T regardless of their positions, while temporal sampling implies that the vehicles report their information as they cross some spatially defined sampling points. Recently, the authors in [12] proposed a distributed peer-to-peer approach to traffic estimation. In this approach, a car uses V2V communication to collect position and velocity related data from nearby cars. The data collected is sparse data in the form of floating car data snapshots and the Underwood traffic-engineering model based on density is used for traffic condition estimation. All these approaches suffer from the problems related to continuous sensing, i.e. high-energy consumption on mobile devices and overhead in terms of communication and processing. To the best of our knowledge, none of the approaches in the literature have addressed on-demand sensing in the context of ITS and traffic estimation.

4. Vehicular Sensing Framework

Figure 1 depicts the high-level architecture of the vehicular sensing system we are proposing. Our system encompasses three main roles: Data consumers interested in the acquisition of sensed data related to a particular area of interest within the city (e.g. provide me with traffic conditions or snow clearance conditions on road X); data collectors offering their phones' data collection/sensing capabilities as services to other users; and the vehicular sensing platform acting as intermediary and data broker between consumers and collectors. The vehicular sensing platform receives sensing requests from data consumers and matches those requests with the most suitable data collectors (based on some matching criteria). Afterwards, the platform sends the sensing request to the chosen data collectors, who can either accept or reject it. Those who accept the request would perform the sensing task required and send the sensed data to the vehicular sensing platform that is responsible of validating it, aggregating and processing it, then sending the reply to the requestor. The communication between the different roles can occur either using mobile communication infrastructures (e.g. 3G/4G mobile networks) or over public WiFi hotspots if available (e.g. in smart cities). Moreover, a group of data collectors may use peer-to-peer communication to collaborate for the collection of a certain types of required data.

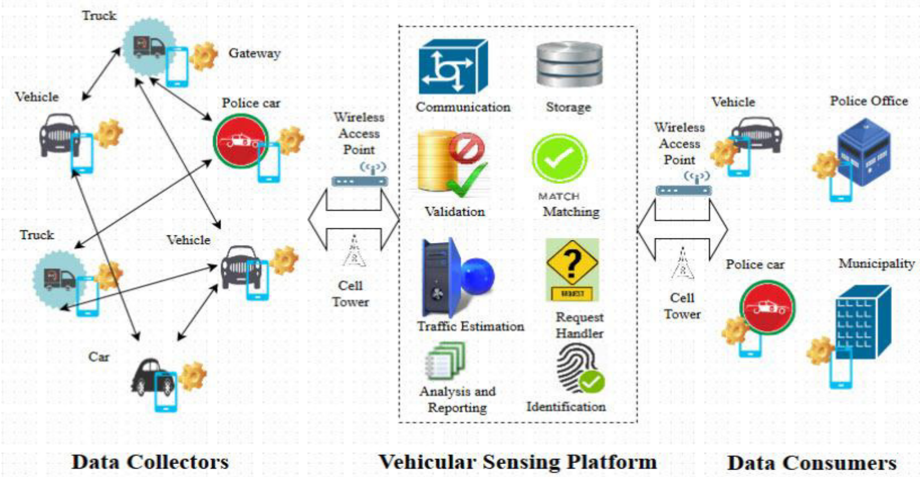

Fig. 1. High Level Vehicular Sensing System Architecture

4.1. Functional Entities' Description

We now describe the functions performed by our system's entities in more detail:

- **Data Consumer:** The data consumer is a user who is interested in sensing services. To access those services, the data consumer interacts with the vehicular sensing platform to discover the sensing communities available. Once subscribed to a sensing community, the data consumer can discover and subscribe to (all or some of) its associated services. An example of a sensing community could be "New York city drivers" and examples of sensing services are "Traffic condition monitoring service" and "Snow clearance notification service". After subscription to sensing services, a data consumer can send a sensing trigger to the vehicular sensing platform, specifying the data type requested, the sensing mode (i.e. sense once, event-based sensing, or continuous sensing), as well as the geographical area of interest.
- **Data Collector:** A data collector is a user equipped with a sensor-enabled mobile device, and who is willing to offer its data collection capabilities as services to other users. The mobile device should host a sensing gateway application enabling the interaction with the vehicular sensing platform. To offer sensing services, a data collector must first subscribe to become part of a sensing community. After subscription, the data collector can periodically publish his/her availability to the sensing platform (e.g. available, busy, and away) to indicate willingness to participate in sensing activities. The data collector's sensing gateway application should support a number of functionalities, including: handling sensing trigger requests from the platform; allowing the user to initiate sensing without trigger (i.e. offer-based sensing) and send the captured data to the sensing platform; ability to collect requested data from embedded sensors; supporting some information processing and formatting capabilities; providing Geo-temporal tagging of the sensed information; scheduling of sensing tasks and management of sensing sessions based on received requests.
- **Vehicular Sensing Platform:** The vehicular sensing platform constitutes the key entity in our architecture. It acts as intermediary between data consumers and data collectors by matching sensing requests (in real time) with the

most suitable data sources, and offers information management and data brokerage capabilities. To achieve that role, the vehicular sensing platform consists of a number of modules, namely: *communication, request handling, storage, validation, matching, identification, traffic estimation, analysis and reporting, and community membership modules*. The *communication module* is responsible of creating the communication messages (requests and responses) exchanged between the platform and the users. The *request handler* is responsible of identifying the type of message received and forwarding it to the appropriate module for further processing. The *storage module* is responsible for storing sensing activities related information. The *validation module* is responsible of the pre-processing of the collected information to detect inconsistencies and calibrate data. The *matching module* is a key module implementing a matching algorithm that relies on certain criteria (e.g. location and availability of data collector, data collection capabilities, data accuracy, available battery level, and user's reputation) to match sensing requests with the most suitable set of data collectors. The *identification module* is responsible of assigning unique IDs to the sensed entities, the sensing services offered, as well as users' roles in the system. The *traffic estimation module* processes the raw sensed data and produced traffic status information using a traffic estimation algorithm. The *analysis and reporting module* is used in some scenarios to generate advanced reports from collected data (e.g. accident scene summary reports). Finally, the *community membership module* keeps track of sensing communities, their related sensing services, as well as their subscribed users.

4.2. Traffic Analysis and Estimation Model

We focus in this model on the scenario where a data consumer sends a sensing trigger request to the sensing platform, with the following parameters: *Data type = traffic condition*; *sensing mode = sense once*; *Area of interest = name of street on which sensing is required*. The platform will then match the request with a set of targeted cars in the desired area, and will forward them the request for data collection. Once the sensed data is received by the platform, a traffic estimation algorithm is used to estimate the speed on the specified road, from which the traffic condition is inferred (e.g. free flowing, moderately congested, congested, highly congested) and sent back to the data consumer. We are using two different traffic estimation techniques and comparing their results. The first technique is a statistical analysis technique that calculates vehicles' mean speed at a time instance t_k according to equation (1)[12]. Although this approach is widely used for traffic speed estimation, it should be noted that it works under the assumption that vehicles' speeds are constant, which is not a realistic assumption.

$$V_{mean}(t_k) = \sum_{v \in o_{i(t_k)}} \left(\frac{l_i^v}{\sum_{v \in o_{i(t_k)}}} \times v \right) \tag{1}$$

The second traffic estimation approach we are using is a density-speed approach based on the Underwood macroscopic traffic engineering model[14]. This approach relies mainly on cars' density on the road for speed estimation and is found to be more accurate than the mean speed model. The reason is that the variance of cars' speeds can be significant over a time period, while the cars' density represents a more stable metric that can better reflect the traffic conditions. The density-based estimated traffic speed is calculated using equation (2)[15], where v_{free} is the free flow speed on the road, and $\bar{X}$ is the average distance between adjacent cars per lane that is calculated using equation (3). In equation (3), n is the number of cars on the road segment and the X_i is the distance between each car i and its adjacent car i+1. $\bar{X}$ is inversely proportional to the cars' density.

$$v_{dens=}\ v_{free}.\, e^{-\frac{(v_{free}+10)}{\bar{X}}} \tag{2}$$

$$\bar{X} = \frac{\sum_{i=0}^{i<n-1} X_i}{(n-1)} \tag{3}$$

Finally, to determine the accuracy of the obtained results, we calculate the estimation error using equation (4). Typically, the ground truth (v_{gt}) is calculated using video surveillance of real traffic. In our case, since we used simulated traffic, we used visual observation of the traffic simulation to determine a set of cars C_i (t_k) that enter the road segment within a certain time window (t1, t2) $\subseteq$ ($t_k - \tau$, $t_k + \tau$), where t_k is the chosen moment in time to calculate the ground truth and τ is a predefined constant. For those set of cars, we calculated the time it takes each of them (Δt_c) to traverse the road segment of length l, and we used equation (5) [15] to calculate the ground truth for the road, which is a statistical measure that describes the entire traffic flow.

$$\bar{E} = \left| v_{est} - v_{gt} \right| \tag{4}$$

$$v_{GT}(t_k) = \frac{l_i}{\frac{1}{|C_i(t_k)|} \cdot \sum_{c \in C_i(t_k)} \Delta t_c} \tag{5}$$

5. Solution Validation

As a first step towards the validation of our proposed solution, we combined prototyping with simulation traces generated using VanetMobiSim. VanetMobiSim is a widely used traffic simulator that generates realistic vehicular movement traces, based on macroscopic and microscopic mobility models[13]. Instead of using real sensory data collected using phones, we opted for simulation traces as it allows the generation of a large set of data for our experiments and enables the control of different parameters (e.g. roads' topology, the number of cars used, their mobility model, and the speed limits on the road). In our experiments, we used a macroscopic mobility model.

5.1. Prototype software architecture

Figure 2 illustrates our prototype's software architecture. The prototype, which was implemented in JAVA, consists of four main components: a data consumer node generating sensing trigger requests; a vehicular sensing platform node matching requests with collectors and managing the sensed data; a data collector nodes' generator emulating the operation of multiple data collectors; and a database containing the traffic simulation traces generated using VanetMobiSim. Communication between the different components is achieved using local function calls.

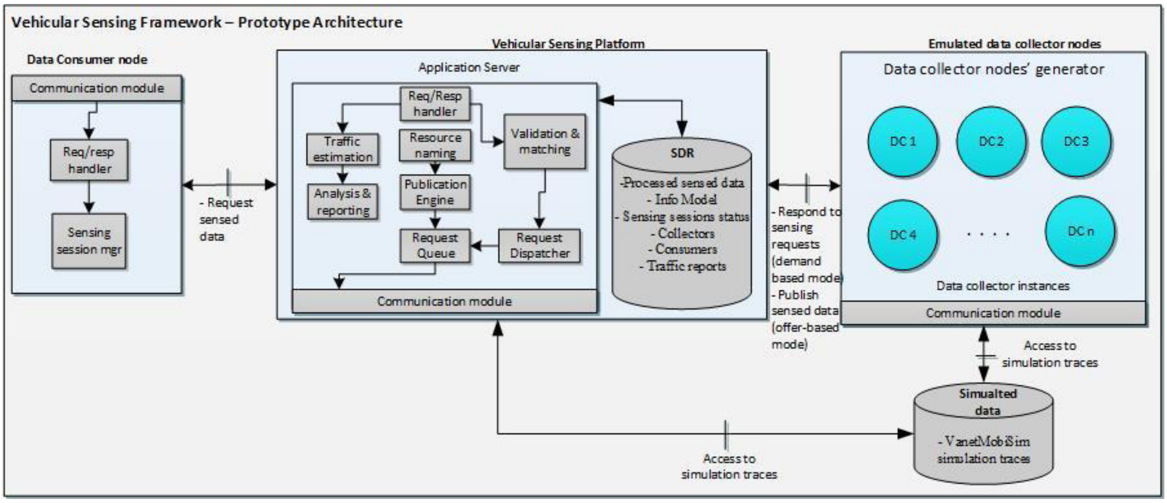

Fig. 2. The prototype components

As shown in the figure, the data consumer node is a simple node consisting of a request/response handling module responsible of the generation of sensing requests and the handling of responses, and a sensing session manager node responsible of the tracking of the sensing sessions and their status. The vehicular sensing platform is the main node in our prototype. It consists of the following modules: a request/response handler responsible of the processing of received requests and responses; a validation and matching module implementing the matching algorithm and validating the data received; a request dispatcher and request queue responsible of queuing and dispatching requests to selected data collectors; a resource naming module responsible of assigning IDs to sensed entities, sensing services, and users; a publication engine handling voluntary data publications from data collectors; a traffic estimation module implementing the traffic estimation algorithm used; an analysis and reporting module responsible of the generation of advanced traffic reports from the collected data; and a sensing data repository (SDR) storing the sensed data, the generated traffic reports, the sensing sessions' status as well as information about data collectors and consumers. Instead of having real mobile devices collecting sensory data, we emulated those nodes by developing a data collector nodes' generator that generates the number of data collectors needed. Those data collectors communicate with the simulated data DB to acquire traffic traces' simulated data (such as vehicles velocity at certain time instances) and return this information as response to sensing requests, to the sensing platform. Furthermore, a data collector is also able to publish sensed data voluntarily to the sensing platform, without any solicitation or trigger (offer-based mode). It should be noted that the sensing platform also interacts with the VanetMobiSim simulation traces DB to get the cars' IDs and positions.

5.2. Testbed Setup and Experimental Results

We conducted two set of experiments on a congested and an uncongested road, using traffic traces generated using VanetMobiSim. In each experiment, a data consumer triggers the sensing activity by sending a sense request to the vehicular sensing platform, which selects a set of targeted cars to collect the traffic data, and then returns the traffic status as response to the requestor. In our experiments, the number of targeted cars was varied from 100% of the cars (i.e. all cars on the road) to 11% of the cars, in order to evaluate the impact of the number of targeted cars (i.e the size of the data set) on the accuracy of the results obtained. Two traffic estimation methods were used and their results compared with the ground truth: the mean speed method[15] and the density-based speed methods[12]. Figures 3a and 3b show the results obtained for a congested road and an uncongested road, respectively.

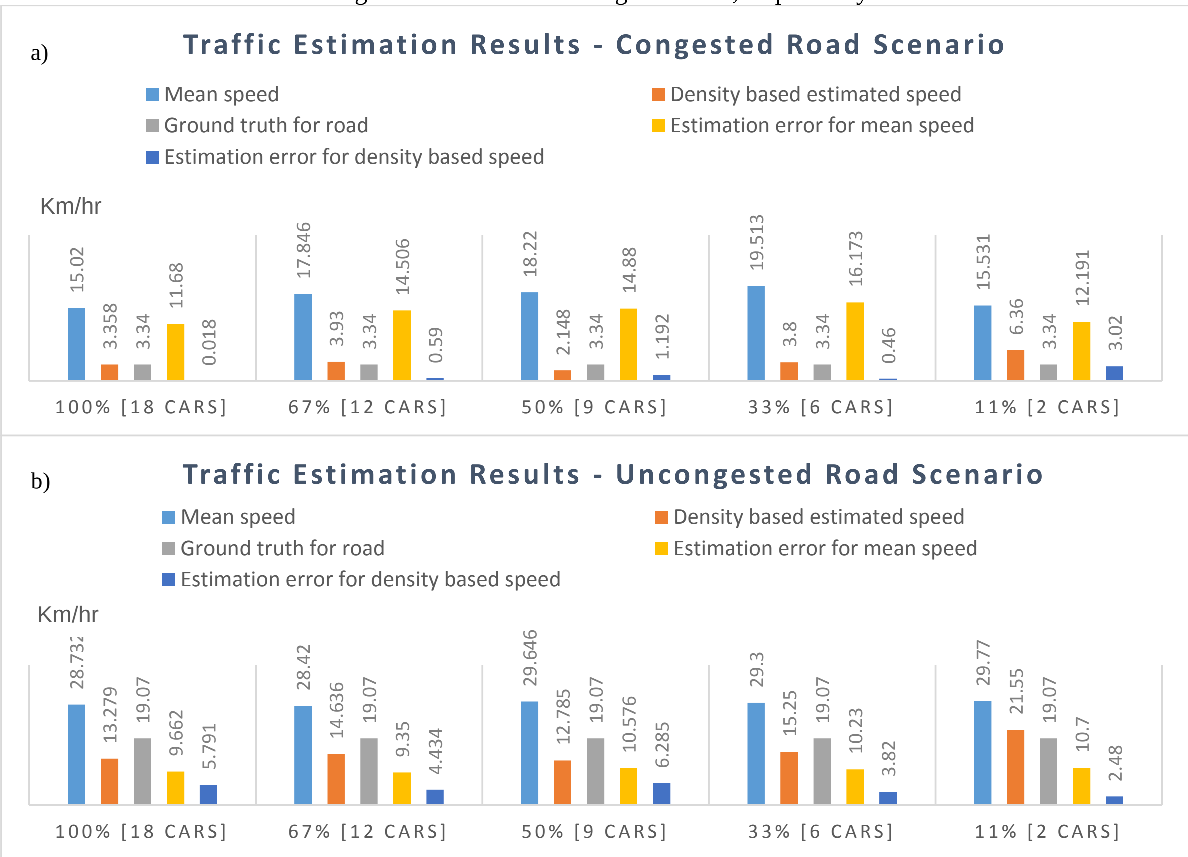

Fig. 3. (a) Traffic estimation results on a congested road; (b) Traffic estimation results on an uncongested road.

Analyzing the results, we notice that for the congested road scenario, the density-based speed estimation method yields more accurate results that are closer to the ground truth, when compared to the mean speed estimation method. The estimation error for the density based speed method varied between 0.018 km/hr. to 3.02 km/hr., while the mean speed estimation error varied between 11.68 and 16.173 km/hr., which is a significant error. Moreover, we notice that the decrease in the % of targeted cars (acting as data collectors) does not have a significant impact on the traffic status determination result, since we are more interested in the traffic status (e.g. free flowing or congested) rather than the actual speed on the road. In fact, with only 6 cars (i.e. 33% of total cars in this scenario) as data collectors, the traffic status inferred is the accurate one (i.e. free flowing in this case). As for the uncongested road scenario, the results obtained show that the density based traffic estimation approach yields less accurate results than in the congested scenario. The density-based speed estimation error varied between 2.48 km/hr. and 6.285 km/hr., while remaining lower than the mean speed estimation error (varying between 9.35 km/hr. and 10.7 km/hr.). It should be noted that the mean speed estimation method resulted in speed over-estimation in both congested and uncongested conditions.

6. Conclusions

The concept of sensing as a service implies the ability to offer sensory data to consumers, on demand, following a utility-based model. In this paper, we applied this concept to the area of intelligent transportation and have proposed a vehicular sensing framework enabling the on-demand sensing of traffic conditions, about any area of interest, by relying on a selected set of mobile phone owners acting as data collectors. The proposed framework was implemented using a combination of prototyping and traffic simulation traces generated using VanetMobiSim. The results obtained using two traffic estimation techniques show the feasibility of our proposed approach and that the selection of a small % of targeted cars acting as data collectors does not have a negative impact on the accuracy of the results.

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