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Challenges and opportunities in immersive vehicular sensing: Lessons from urban deployments

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ABSTRACT

Vehicles provide an ideal platforms for a plethora of emerging applications such as networked gaming, multimedia content delivery and urban sensing. Cars have no power constraints and they can be instrumented with high end computational units and graphic devices. The deployment at scale of urban vehicular systems, however, requires a careful design able to consider challenges across several domains. Vehicular systems are arguably a prominent example of cyber-physical systems. The development of such systems requires a truly multidisciplinary approach and a close integration between the application, communication, and physical domains. Hardware and software mounted on vehicles will face a harsh physical and communication environment that will greatly affect all the system components. In this paper we report on the challenges and opportunities for multimedia vehicular urban sensing systems based on our field experiences in Macao (China) and Los Angels (USA). We designed and built the components for a pollution monitoring system able to support closed-loop optimization between pollution and traffic management. Our initial set of prototype vehicles are now running in the city of Macao and they are measuring the air parameters as well as the urban traffic. The paper aims at exposing some of the issues encountered, outlining the problems of a city wide deployment, and augmenting our in-field experience with the results from large scale simulation studies.

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1. Introduction and background

The 1900s were marked by unpredictably changes of our planet temperature and sea levels. Between early 1900 and 2011 the sea levels rose 10 cm and the average temperature of the earth surface has risen by 0.74 °C. The data indicates a sudden acceleration of those phenomena and scientists expect an additional 2–4 °C temperature increase and a further major raise in sea levels by 2100.[1] Climate changes of this amplitude are closely related to major disruptions in the food chain and can potentially cause the extinction of several plants and animal species [1].

The last 150 years of industrialization are to be blamed for the dramatic changes in our environment. Burning massive and ever increasing quantities of oil, gasoline, and coal, a continuous quest for land at forests' expenses, and the practice of certain intense farming methods all contribute to endanger the health of earth's ecosystem. These activities carry the principal responsibility for the enormous amount of "greenhouse gases" in the atmosphere, especially carbon dioxide, methane, and nitrous oxide [2,3].

In western countries the road transportation sector accounts for a large share of the Greenhouse Gas (GHG) emissions thus there is an urgency for its redesign. In the United States, for instance, road-transportation contributes

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[1] Some sources estimate an additional increase in the sea levels between 18 cm and 59 cm.

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for 28% of the total emissions. In particular, 35% of road-transportation emissions is due to passenger cars, 30% is due to light duty trucks, SUVs, pickup trucks and minivans, 20% from freight trucks, 6% is produced by commercial aircraft, and 9% comes from other sources such as buses, railways, ships, motorcycles, etc. [4]. The United Nations Framework Convention on Climate Change found similar ratios for most of the industrialized countries [3]. A major shift in the transportation sector emissions will happen with the advent of fully electric vehicles that are expected to hit the mass-market in about two decades; thus a natural question is what we can do now?

We believe the road-transportation system as it is known today is obsolete and offers numerous improvement opportunities. In particular, smart vehicles can closely cooperate with an intelligent road infrastructure to reduce pollution emissions and, in general, to monitor the city environmental health. We foresee cooperative urban sensing at the heart of the intelligent city traffic management with the aim of reducing pollution, fuel consumption and traffic delays. We envision vehicles as building blocks for a multimedia distributed sensor system able to track down pollution hot-spots and take an active role in enhancing the urban environment for the next generations. The key components of the envisaged green transport city system will be a combination of pervasive mobile-sensing performed by vehicles and infrastructure-based sensing and control utilizing the infrastructure sensor mesh that includes intelligent traffic lights. The interaction between the intelligent traffic light, the physical components on the vehicle (such as vehicle ignition system, chemical sensors for pollution detection, and car navigator) and the city traffic control center (typically a distributed system in a modern metropolis) will ensure greener, less-polluting traffic in the city. The enabling technology is already available and largely deployed in our cars such as in-vehicle WiFi[2] and IEEE 802.11p [5] devices are becoming increasingly more popular and set the stage for a large scale deployment of vehicular networks (VANETs). Cars are expected to operate both in Ad Hoc mode and in infrastructure mode to provide a broad range of services including mobile navigation [6–8], intelligent transportation (ITS) [9,10], mobile marketing [11,12], mobile multimedia [13], mobile social networks [14], participatory sensing [15–17], and mobile hot spots [18]. This vision is supported by market studies showing that in western Europe already 40% of the population owns a Wi-Fi PDA [19,20].

As the role of vehicles has been rapidly expanding to become pervasive sensor platforms as well as nodes of the future Internet [21,22], the research community is investing considerable time and resources in the design of new protocols and applications that meet customer demands, endure highly dynamic topology changes and run efficiently on hardware limited on-board processors [23]. In this paper, we draw from our experience in building the prototypes of an urban vehicular sensing system in Macao and Los Angeles to explore the challenges and research opportunities to transform today's basic transportation infrastructure into a sophisticated multimedia dynamic cyber-physical system. We expand our hands-on knowledge acquired building the first few vehicular sensing prototypes with the results from a number of large scale studies performed on the city of Portland and based on very accurate mobility traces [23,24] provided by the Los Alamos National Labs. The reminder of the paper is organized as follows: in Section 2 we describe a shift in the methodology to perform urban sensing driven by recent atmospheric research and that calls for pervasive mobile sensing systems while in Section 3 we detail the functional blocks for the proposed system. Section 4 focuses on the design of large scale urban VANETs and argues for a hybrid solution that includes both Ad Hoc and Infrastructure characters. In Section 5 we outline the problems and solutions we encounter while building our system prototype in the city of Macao S.A.R. Section 6 reports our final remarks, summarizes the lesson learnt and concludes the paper.

2. New applications and system paradigms

Modern metropolis presents a number of challenges for urban planners and health authorities. Large population, high vehicular densities, massive motorways, and a large number of diversified human activities are sources of pollution and traffic congestion. The current best practices in managing pollution and traffic rely on few bulky and very expensive air quality stations and on very limited congestion control techniques such as dynamic road signs, dynamic traffic lights and rate-limited freeway access [25,26]. Recent studies [27–30] support this view as they have shown air pollution diffusion in urban areas behaves similarly to microclimate. Winds and urban artifacts (i.e. buildings, urban canyons, etc.) play a substantial role in determining the concentration levels that can change even within just one or two blocks thus few and very expensive fixed stations do not accurately represent the reality [31–35]. We argue for a radical paradigm shift in our transportation and pollution management systems. The core idea is to create a closed-loop control system that leverages on the data sourced from a plethora of inexpensive air quality sensors mounted on public service vehicles to discover optimal routes for the end user and optimize the intelligent traffic lights behavior in accordance. The United Nations Framework Convention on Climate Change [1] estimates that between 5% and 20% reduction in the transportation sector emission can come from traffic management alone.

3. System model

Fig. 1 shows a high level view of the proposed system. Data flows from a plethora of in-vehicle and fixed sensors forming a shared traffic and pollution knowledge that evolves in real time and can be used by advanced intelligent navigation systems to suggest ideal routes

[2] Most modern smartphones and navigators are equipped with WiFi.

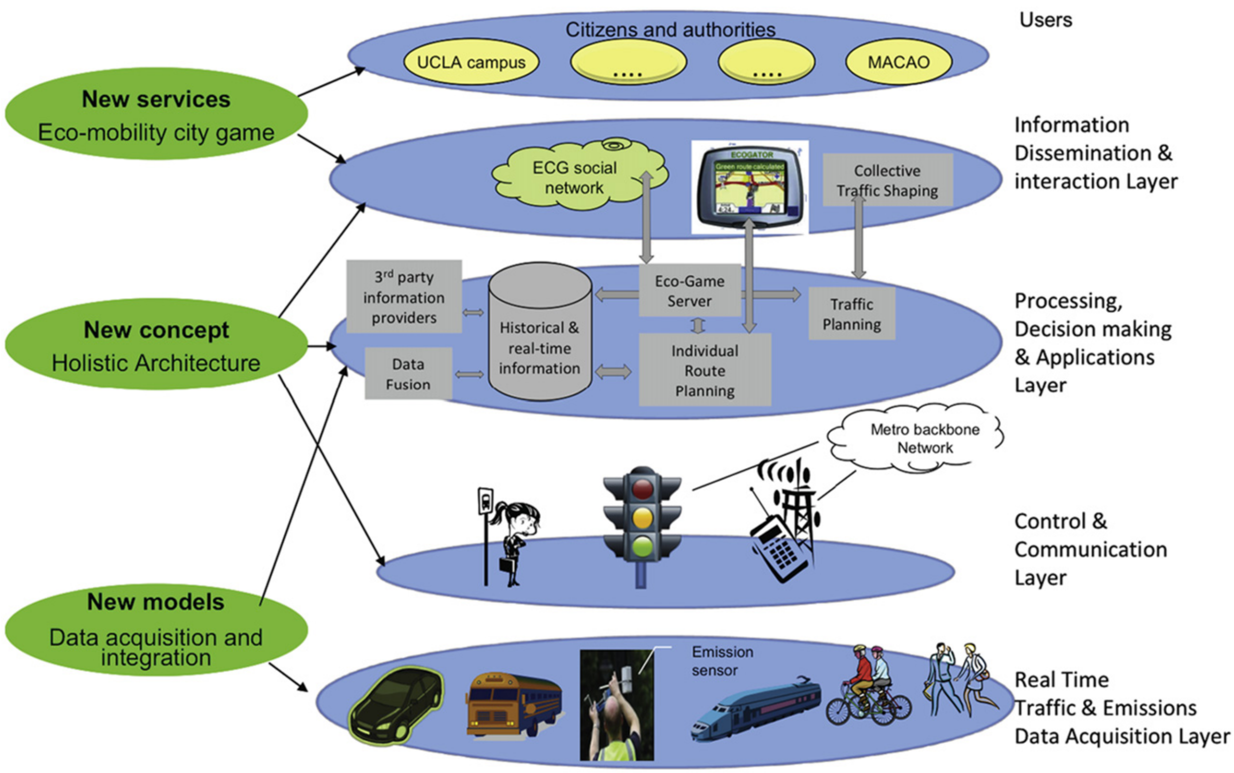

Fig. 1. High level system view.

according to the user needs and city constraints. We envision future navigation systems will be mainly built as smartphones and tablet applications thus offering the ideal platform for an advanced info-mobility platform integrated with the city infrastructure.

There are several technical and social challenges to overcome to achieve our vision. The system design needs to support high-mobility scenarios, dynamic network partitions, hybrid communication technology, and must scale up to several million nodes and very large geographical areas such as, for example, Los Angeles in California, with its 17.8 million inhabitants and 10 million cars on the road every day.[3] The system architecture needs to be highly distributed and to be able to exploit any locality in mobility patterns and communications. Finally, a proper set of incentives and policies needs to be in place for users to adopt and accept the systems. We identified the following functional blocks key for the system architecture:

- *In-vehicle sensing*: Pollution sensing can be performed by using a small number of public service vehicles equipped with computing units, wireless communication devices, and a plethora of sensors including CO_2, NO_x, particle sensors, cameras, etc. Traffic sensing can be performed via crowdsourcing the information from the user base as well as from a number of other players such as the city authority, and active roadside sensors.
- *Communication infrastructure*: The communication infrastructure needs to support dynamically partitioning topology, sparse connectivity and some degree of disruption-tolerant communications. The city environments feature a very diversified communication environment that includes cellular, WiFi, and Ad Hoc networks resulting in complex multi-homed architecture.
- *Roadside sensors*: Traffic lights offer an ideal opportunity to install a number of traffic and pollution sensors. In particular, traffic lights are located at the intersections of several roads, they are connected to the power grid and often to a high-speed network. The co-location of traffic lights with high data rate sensors such as cameras is ideal to reduce the complexity on power and communications.
- *Intelligent traffic lights*: Recent advances in traffic engineering allow transport authorities to remotely control the traffic lights to improve traffic flow and reduce congestion; however to the best of our knowledge today's light management is based on historical data, or highly contingent situations. We argue for traffic light control system able to take advantage from the traffic and pollution data sensed on the field by the probe vehicles.
- *In-vehicle bi-directional navigators*: The next generation of in-vehicle navigation system will connect to the network and feature a bi-directional communication

[3] Data from the 2010 US Census.

Fig. 2. Network characteristics. (a) CDF distance from the intersection, (b) 25 m range from the intersection center, (c) network stretch vs. penetration rate. The network is fully connected with a penetration of 12.5% however the average network stretch is over 10 hops.

capabilities thus paving the road for advanced navigation algorithms designed to support a smarter and greener mobility [36].

In this work we focus on two major issues: (i) Network Design in a city wide naturally sparse and dynamic partitioning topology; and (ii) Design and implementation of an unmanned reliable, and resilient in-vehicle prototype.

4. VANETs: challenges and opportunities in urban scenarios

Our vision is to have a potentially very large number of vehicles acting as traffic probes through their GPS sensors, and a smaller set of vehicles acting as probes for the pollution levels. The GPS data can be potentially crowd-sourced from any smart-phone augmented vehicle on the road while the pollution sensors, particularly those to measure deadly nano-particles, are still too expensive for a massive deployment and a different deployment strategy needs to be adopted such as for example the use of public service vehicles (i.e. taxi cab, parking enforcement, etc.). The Green City communication infrastructure, however, needs to support both applications and furthermore needs to be able to convey updated information to the in-vehicle smart navigation systems.

At the best of our knowledge there is no city-scale deployment of wireless networks that offers data for analysis, and there is no real fine-grain vehicular mobility traces available for a city wide deployment hence it is very hard to study the constraints and forecast the performance of a city wide communication infrastructure. However we are able to leverage on the work done by Rowstron et al. [23] using a high resolution mobility traces for the city of Portland, OR made available to us by the Los Alamos National Laboratory (LANL). The trace was originally created for homeland security reasons, and considerable effort went into ensuring the trace was realistic. It was generated using both macro- and micro-simulations. To increase the accuracy of the simulations, LANL incorporate activity flows, generated from census and other survey information gathered explicitly for the trace, over a period of a year. From this information it is possible to infer schedules for vehicles, such as a car leaving a house at a particular time and traveling to an office.

We used the Portland trace to study how vehicular mobility affects communication between vehicles and with the city infrastructure. In particular, the Portland trace spans from 8 am to 8.15 am on a working day in Portland, Oregon; they cover an area of 3×7 km that includes downtown and two major freeways the I405 and the I5 next to the Willamette River. The trace includes 16,528 unique vehicles, e.g. cars, trucks and buses, and is 900 s long. We used the Corner [37,38] propagation model to study the communication characteristics and draw some indications on the design space for a city wide wireless vehicular network. The Corner model in contrast with previous literature considers the presence of buildings therefore provides a more detailed estimation of the path loss and various propagation effects.

4.1. Portland trace characteristics

We analyzed the Portland trace to extract a statistical description of the mobility in the city. We discovered a key role for the intersections in the city mobility structure [39]. In particular, Fig. 2a shows the CDF of the distance between each vehicle and the closest intersection across the duration of the trace. Sixty percent of the vehicles are within 25 m from the intersections thus the intersections will be a key part in the communication design (see Fig. 2b for a visualization). Furthermore, we investigated how the penetration rate, i.e. the number of vehicles equipped with a WiFi, impacts the network connectivity and topology, in particular we noticed that the network becomes connected when the 12.5% of the vehicles are equipped with a wireless interface however the average network stretch would be 10 hops and the 99th percentile path would be over 25 hops long as detailed in Fig. 2c.[4] It is worth noting that even at considering the scenario of a 50% penetration rate the average network stretch and the

[4] Note that the stretch at lower penetration rates reflects the fact that the network is actually disconnected and the number of reachable nodes is very low.

99th percentile stretch of 8- and 20-hops respectively hint that a pure Ad Hoc Vehicle to Vehicle communication is not a viable choice for city wide deployments; a hybrid approach able to dynamically and seamlessly operate in both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication paradigms is more suitable for the system constraints [39]. As the sole use of the cellular infrastructure would require unlikely massive investments from the cellular operators we predict vehicular networks will route packets across few Ad Hoc hops before entering in the network through a roadside access point.

4.2. Network infrastructure: design principles

The deployment of WiFi access points will be required to enable city wide multimedia vehicular communications. We explored the design space focusing on the requirements imposed by VANETS and taking advantage of the important role played by the intersections. For the city of Portland we estimated via simulation the number of access points needed to support hybrid vehicular communications operating according to the Vehicle-to-Vehicle-to-Infrastructure (V2V2I) communication model. We explored the design space estimating the number of Access Points per square Kilometer needed to bound the path stretch for the Ad Hoc section in the network topology. In other words we decided a priori how many hops the Ad Hoc part of the path could extend and then estimated the access points density needed to meet the hop-count constraint. Leveraging the results from the trace analysis in Section 4.1 we placed the access points *Always* on the intersections as they are the best place for maximum coverage. We evaluated several access point deployment strategies such as for example by importance (i.e. intersection with highest traffic first), randomly on the intersections, or as a GRID. For the sake of space we here report results only for the GRID case which outperformed the other deployment algorithms. In particular, the access point deployment strategy is depicted in Fig. 3a. Furthermore, we simulated only the scenario with a penetration rate of 100%, i.e. each vehicle is WiFi enabled thus we expect the results to be precise for the best case and optimistic in other scenarios. Fig. 3b, shows the results for 1, 2, 3, 4, and 5 Ad Hoc hops. In particular, given a number of V2V hops, the chart describes the portion of network reachable in relation to the number of Access Points per square Kilometer (AP/KM^2) using a GRID strategy. The results shown require few considerations. It is economically unsustainable to build a WiFi infrastructure able to guarantee connectivity for vehicles with no Ad Hoc routing in the path (i.e. 1 hop = direct link to AP); we run our simulations up to 100 Access Points per square Kilometer and yet only 20% of the network was covered. In the case of 2 hops to reach the AP the situation improves dramatically as 10 AP/KM^2 cover 91% of the network however 75 AP/KM^2 are needed to provide a 99% coverage therefore a two hop solution appears to be quite expensive. Relaxing the hop constraint to 3 and 5 hops the results show that 4.5 AP/KM^2 are sufficient to guarantee a 97.6% coverage in the 3-hops scenario and 99.4% coverage in the 5-hop scenario. Restricting the focus to the sole 5-hops case 1 AP/KM^2 is sufficient to cover the 96.3% of the network, furthermore 0.48 AP/KM^2 is enough to support the connectivity to 90.2% of the network. In essence, allowing 5-hops the start-up costs dramatically decrease to the point that the network becomes economically viable; in some cases, where the WiFi network is already provided by the municipality the vehicular network can be deployed at virtually zero costs. Planning for a hybrid V2V/V2I network topology impacts the design of applications and protocols that need to cope with temporary connectivity disruptions lasting from a fraction of a second to about 1 min. The current TCP/IP network architecture is no longer fit for such dynamically partitioning environment and a clean-slate protocol design able to support mobility and intermittent connectivity is required.

5. A concept proof prototype

In Macao and Los Angeles, we are building a concept-proof system designed to gather the data needed for extensive traffic and pollution modeling and optimization

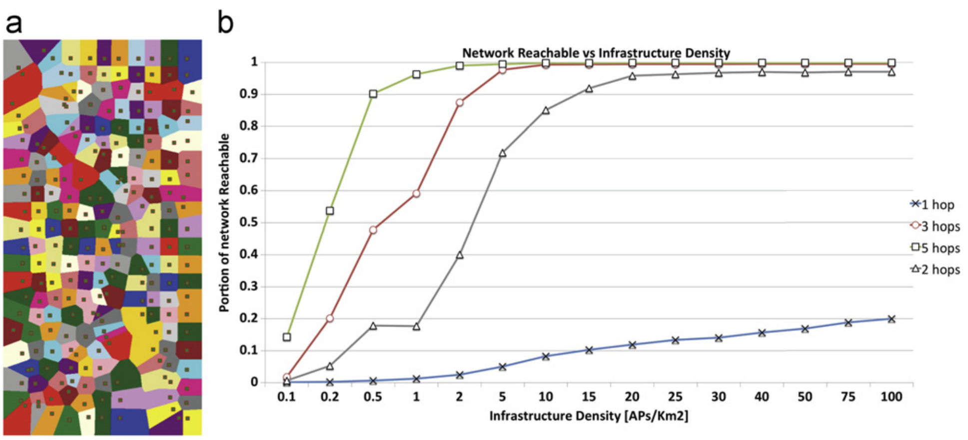

Fig. 3. WiFi deployment analysis. (a) AP positioned at the intersections in GRID, (b) portion of network reachable vs. AP density AP/KM^2. 100% penetration rate; GRID placement algorithm.

that ultimately leads to new routes delivered through the user smartphones or bi-directional navigation systems. In this section we describe the Macao prototype that started first and, at the time of writing operational with two probing vehicles and 10 APs. We plan to expand the fleet to 3 Pollution probes and 50 GPS probes (thanks to the local cab company); in addition several vehicles will be equipped with 3G capability for telemetry purpose and to operate as last resort mobile access points.

At the UCLA-MPI joint research center on ubiquitous computing we designed and built the first two in-vehicle immersive sensing prototypes. We used two vehicles from the Macao Polytechnic Institute (MPI) fleet and equipped them with GPS and pollution sensors. The data gathered is reported to a central server in a disruption-tolerant fashion. The vehicles are dispatched daily according to the institution's needs. They are driven for several hours a day in the city of Macao. The foremost requirements for the in-vehicle sensing platform are reliability and resilience. Once the platform is in place we have limited access to the system, furthermore the system must not interfere in any way with the regular vehicle activities. We took a system level approach to designing in-vehicle sensing platform by focusing on the system quality as a whole to achieve very high reliability levels and prevent any interference with the regular vehicle activities.

The system is based on an Intel Core II duo industrial PC customized to operate in the vehicle. The software architecture is based on Linux. The hardware setup required a careful design and engineering of the storage (we used SSD) and the power management subsystems. In particular, we designed and built a power-system connected to the car alternator that provides support to the computing unit and the sensors. The power subsystem detects if the vehicle engine is on or off and triggers an Advanced Configuration and Power Interface (ACPI) signal that is trapped by the PC Bios and results in graceful start-ups and shutdowns of the unit according to the vehicle duty cycles. The power-supply system, shown in Fig. 4a, consists in a PLC-based power regulator and a small 7Ah battery which supplies energy during the transient phases allowing graceful power-cycles for the computer. In addition the battery guarantees a complete voltage stability at 13.8 V protecting the instruments from the fluctuations of the Alternator's power. The system WiFi interfaces (two per node) are placed on the vehicle roof and connected with a low-loss SMA-N cable that has been waterproofed and professionally installed. The connection to the air measurement instruments is performed through an IP67 rated high resistance waterproof USB cable that is also used to hold the sensors housing as shown in Fig. 4b. Finally, the sensor housing has been designed to stand in a monsoon-prone weather and provide sufficient protection from rain but yet allow a sufficient air intake for the pollution measuring instruments and sufficient view for the micro-cameras; the sensor housing bottom is a metal griddle while the top is a heavy duty plexiglass semi-sphere as shown in Fig. 4c.

The immersive in-vehicle sensing system software architecture is shown in Fig. 5. We adopt Linux as the operating system. Conceptually it is possible to identify three architecture layers. The Module Management layer behaves like a control manager and watchdog. It ensures the various sensor and communication managers are responsive and that the data flow is proceeding as expected. The specific sensor/communication logic is implemented at the Hardware Control layer. For instance the GPS hardware control-level acquires the information from the GPSD. The GPS data is stored locally and used to geo-tag the other sensor information. The Communication Control layer, polls for available communication opportunities in the intent of sending the data off to the server for post-processing. The Hardware layer consists of the low-level drivers for the various sensors and network interfaces. The application logic is implemented by the user and leverages on the software infrastructure to gather sensor data. The data acquired from many sources is then processed through data consolidation and sensor fusion directly in the vehicle.

The first prototype vehicle has been in operation in the city of Macao since June 2011. In the initial setting we collected GPS, CO_2 and camera data. The system has been set to poll the GPS and the CO_2 sensor every second while the camera has been set to take pictures when there are changes in the CO_2 concentration levels. The Macao Polytechnic Institute vehicles are run by the institute drivers and we do not control the mobility; however we are able to gather the mobility information along with the timing and the relevant sensor data. The dataset is initially stored locally and delivered to the server at the first opportunity in a disruption-tolerant fashion.

The data collected by the in-vehicle immersive sensing system can be useful for extensive long-term data analysis in many disciplines including environmental protection and public health (see Fig. 6 for a visual example). The information gathered at the road level can be integrated with other databases such as the ones provided by

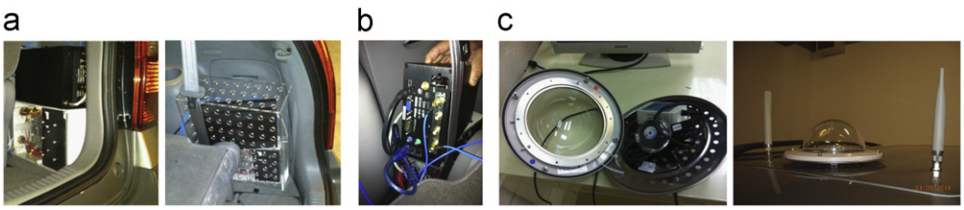

Fig. 4. UCLA-MPI—immersive sensing prototype hardware components. (a) Probing vehicle: the industrial PC lays on top and the power management system; final system enclosure is on the right side. (b) Wiring for sensors and WiFi interfaces. (c) Sensors housing components and final assembly on the vehicle.

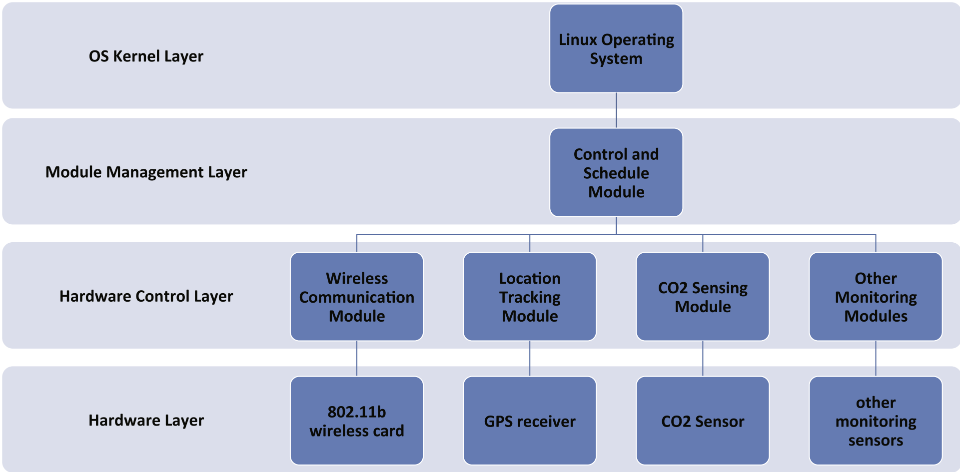

Fig. 5. UCLA-MPI—immersive sensing prototype software architecture.

Fig. 6. UCLA-MPI—immersive sensing examples of geo-tagged information. (a) Data mesh-up, the GPS data and the CO_2 data are used to geo-tag and timestamp the camera pictures. All three data types are sent to the server for processing and storage. (b) City of Macao: CO_2 concentration levels in parts per million (ppm): green $<$ 500 ppm; 500 $<$ yellow $<$ 650 ppm; 650 $<$ blue $<$ 750 ppm; red $>$ 750 ppm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the social network four square. For example from the Macao dataset we are in the process of extracting the information about the traffic flow in the city, the CO_2 levels and we are connecting this with the "foursquare" database to estimate the population exposure to certain levels of pollutants.

6. Final remarks

In this paper we discussed the challenges and opportunities underneath the design and implementation of an intelligent navigation system that closes the loop between the traffic optimization and pollution management leveraging on bi-directional navigation systems. We focused on the communication aspects and on the system implementation aspects for a permanent unmanned in-vehicle sensing system able to collect, store and upload a large number of telemetry data and multimedia information (i.e. pictures and movies of particularly congested/polluted areas).

From the study of a large scale mobility trace in the city of Portland, OR, it is possible to draw some general principles to guide the infrastructure design and deployment in the city. In particular:

- A large scale vehicular communications can be supported only via hybrid paradigms that opportunistically takes advantage of Ad Hoc, WiFi, and Cellular communications.
- Intersections play a key role in urban vehicular networks as statistically vehicles are likely to be within 25 m from the intersection center; hence, in an urban setting, intersections are clearly the best location to install Access Points.
- A full WiFi coverage of the city requires a very large number of access points and therefore may be financially not viable. The use of a hybrid paradigm that includes a relatively sparse access-point coverage complemented with multi-hop routing in Ad Hoc mode may be essential for actual deployments. In the case of Portland it is possible to bound the Ad Hoc routing to 5 hops and yet get 90% of the vehicles connected with just 1 AP/KM^2; and 2 AP/KM^2

are sufficient to achieve 90% connectivity with a bound of 3 hops in the Ad Hoc routing.

- Vehicular networks are naturally dynamically partitioning topologies. It is essential the design of disruption-tolerant applications and protocols able to cope with intermittent connectivity.

We also learnt a number of take-home lessons from the actual system implementation. Particular care is needed for the design of unmanned sensing system to be installed in a moving vehicle. From the hardware standpoint great attention should be paid to power management, vibrations, and other mechanical factor which are keys to avoid costly breakdowns and more importantly the end-users loss of confidence. Similarly, from software standpoint the architecture should support multiple failures and autonomous recovery. The system should try to operate unmanned as long as possible reporting errors and malfunctioning component but never interfering with the core-business of the vehicle.

In Macao we managed to build and operate the first few pieces of a permeant unmanned sensing fleet that integrates textual data (i.e. GPS and various air quality sensors) with multimedia sensing from a set of cameras placed on the vehicle thus giving a fully immersive sensing experience. Our prototype has been now operating for about six months without human intervention, the data is delivered to the collection center in an opportunistic disruption-tolerant fashion.

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