A Platform for Heterogeneous Vehicular Communications and Applications

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ABSTRACT

In this paper, we present our approach to designing, building, and deploying a hybrid inter-car communication system. The system aims at supporting various applications such as real-time road-traffic based navigation, emergency signaling, mobile environment-sensing, and mobile content-delivery. Supporting such applications requires novel networking paradigms that operate over highly dynamic, hierarchically structured, sparsely connected, location aware networks, and using highly diverse communication rates. We propose an architecture for heterogeneous vehicular communication to support the required communication services needed by future vehicular communication. We present a hardware platform to implement the proposed architecture and provide preliminary results of the performance that can be achieved by this architecture based on analysis and measurements. We also propose a novel smooth deployment vision for a vehicular communication system that relies on an initial deployment over taxicabs in a city like Boston, Massachusetts.

Keywords

Vehicular networks, taxicabs, heterogeneous networking, connectivity, architecture, demonstrator.

1. INTRODUCTION

Vehicular Communication Networks are usually viewed as a subclass of Mobile Ad hoc NETworks (MANET). However, they have favorable characteristics, which make them particularly interesting and more realistic to be operational in the near future than traditional MANETs:

- Vehicular nodes can be powered by the vehicle's energy source. Therefore, they are virtually unconstrained when the vehicle's engine is turned on. When the vehicle is off, they still have significantly more energy than traditional MANET nodes. They can also transmit, if necessary, at (multiple) higher power level thus they are capable of a larger communication range and suffer less from connectivity issues. However there is trade-off between transmission power increase enabling long range and a decrease of collision probability. These aspects must be studied carefully.

- Vehicular nodes are not limited by the small form factor of a mobile node carried by a human. Therefore, they can integrate more computation and memory capability. The form factor flexibility has an impact on the antenna size. Larger antennas allow for a higher gain and can even be directional/sectored. Directionality has the potential of reducing interference therefore providing better scalability of the network capacity. However they increase the probability of occurrence of hidden nodes.

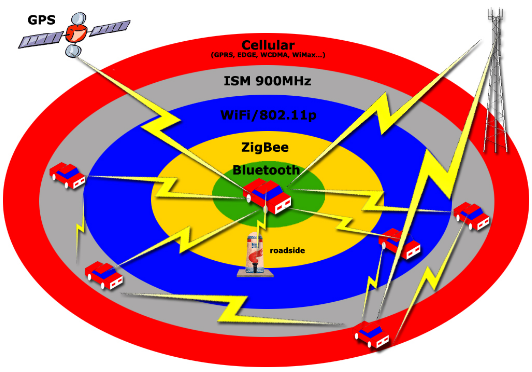

Figure 1: Heterogeneous Air-Interfaces for Vehicular Communications and Applications.

- Advances in wireless communication and manufacturing of computer systems will make such nodes a cheap commodity that will probably be integrated in most vehicles. Many cars are already equipped with GPS and Bluetooth devices. Given the car density, in most urban areas, it is reasonable to expect that ultimately we will have a highly dense and connected network of cars.

- Since some car owners will probably have GPRS / EDGE / 3G / WiMAX cellular connectivity, and given that in some countries (e.g., USA) flat rate plans exist for cellular data communication, moving nodes will have an additional lower/medium data rate interface that can be used to maintain connectivity.

- Vehicular nodes usually move at higher speed than traditional MANET nodes. However, this does not necessarily have a dramatic impact, since these nodes' communication range can be substantially larger. However the Doppler shift is higher and the amount of time during which nodes can communicate can be very short, even too short to establish communication. In consequence, communication technologies used have to enable fast signal detection, gain adaptation and synchronization.

The extra capabilities of vehicular nodes make the creation of networks realistic. Many countries have already allocated dedicated frequency bands for Vehicle-To-Vehicle and Vehicle-To-Roadside communication (e.g., in the US a 75 MHz frequency band was allocated by the FCC). At the same time many applications can make use of such networks. Examples are Approaching Vehicle Emergency Warning, Platooning, Road Condition Data Collection, Traffic Congestion Data Collection, Fleet Management, and Data / Multimedia Transfer. Most current academic and industrial research efforts, like FleetNet in Germany [11], are focused on short-range car-to-car communication and car-to-roadside communication, the key technologies being DSRC / WAVE / 802.11p, operating in the 5.8 / 5.9GHz band. Applications mainly include dissemination of emergency information, road state information and road traffic information. To make a network with such short range communication operational, the penetration rate of communication systems needs to be very high. This will require a long transition phase. To solve this problem, we propose a hybrid communication architecture for vehicular communication (with DSRC as one element of it) that can support a larger set of applications, network-wide applications (meshed with the Internet) and that can be smoothly deployed as discussed in Section 4. Long-range communication interfaces provide connectivity over a large scale while high-speed short range communication allows efficient local communication. A smooth deployment by first targeting taxicabs can guarantee the bootstrapping of the system. Comparing to normal cars, taxicabs will have the advantage to be circulating 24 hours a day, 7 days a week, and this mainly in city areas, enabling particularly dense network conditions from the start. Other research initiatives include CarTel at MIT[14], VSN at UCLA[15].

Previously proposed mechanisms for operating MANETs such as routing (e.g., AODV[8], DSR[9]) have been shown to be inadequate for vehicular networks [4] mainly due to the high mobility of vehicles. Embedded GPS receivers enable position-based routing techniques which drastically improve routing performances [4]. However, most existing mechanisms focus on a single type of wireless interface resulting in limited data rates or very low connectivity. Therefore, we are interested in a flexible heterogeneous system that can provide resiliency and support a wide variety of applications and services.

In Section 2, we outline the proposed architecture. Section 3 presents our current hardware and software platform that can support the proposed architecture. In Section 4, we provide our deployment vision and preliminary analysis in terms of connectivity characteristics, if such as system is deployed over Boston, Massachusetts. Finally we conclude and provide directions for future research.

2. ARCHITECTURE

2.1 Objectives

The system aims at supporting a wide variety of applications with different networking requirements. Here we only describe some of the potential applications:

- *Mobile Content Delivery Network (MCDN):* given the large data storage available at each of the nodes, significant media content can be locally stored and forwarded at a high data rate whenever two vehicles are within WiFi (IEEE802.11g) range. Mechanisms such as store-carry-forward can be used. When deployed over taxis one can have fixed access points with large storage and high speed wired connections located at taxi stands.
- *Mobile Environment Sensing:* placing sensors on some of the vehicles that circulate over a city (e.g., taxis) provides a high coverage mobile sensor network. Such mobile sensor network can be supplemented with a small number of fixed sensor nodes that can be located at strategic locations without having to be directly interconnected. The moving vehicles can gather the sensor nodes data, carry it, and deliver it or disseminate it. Typical information to be sensed is temperature, humidity, luminosity, roads states (from shock sensors embedded in cars).
- *Emergency Signaling:* these applications include car-to-car emergency signals, road-to-car signaling, but also larger signaling for global coordinated evacuation of one or multiple area in case natural or man-made disasters. The first types of application will probably be covered by DSRC but the later one requires that few coordination units can reach all cars to guarantee a quick evacuation.
- *Navigation Assistance based on real-time car traffic:* efficient navigation in urban areas requires knowledge of car-traffic conditions and congestion levels of roads. Mobile vehicles are capable of determining the congestion level at their location based on engine status and current speed (e.g., acquired through the OBD-II interface). Combined with location obtained from a GPS or CellID with RSSI-triangulation it is possible to build a distributed navigation-assistance system. Vehicles can gather traffic conditions from neighboring cars but only need limited accuracy for remote areas. This allows to implement efficient data-gathering techniques such the fish-eye mechanism.

2.2 The Network

To support the above mentioned applications, the car network needs to be carefully designed and provide non - traditional communication capabilities.

2.2.1 *Heterogeneous Hierarchical Structures*

The proposed network is heterogeneous with various communication air-interfaces that can be hierarchically structured with lower rates for high coverage links and time changing disconnected islands of high data rates clusters. We plan to have periodic wake-ups in cars that are parked on the roadside, so that they can be used as relays and increase the network connectivity.

- Low-rate high-range: provides connectivity and can carry high-priority traffic such as emergency signaling and control traffic of the network.
- High-rate low-coverage: results in islands of connected nodes. Such interfaces allow transferring large amounts of data when nodes are within proximity of each other. Complete delivery of packets relies on a delayed mobility based routing.

2.2.2 Routing

Previously proposed routing protocols for MANETs such as AODV and DSR are not adequate for our system. They do not account for the high-probability of disconnection of a vehicular communication system. They are not designed to efficiently benefit from the hierarchical, partially connected, with variable rates, nature of the proposed system.

There is a need for novel routing mechanisms: higher layers carry priority traffic such as emergency signaling and routing control traffic (e.g., where are the cars located to assist a position based routing occurring at the lower layer?)

We identify at least two major routing schemes

- **Delay Sensitive Routing:** All air-interfaces should be used, in an efficient way, to deliver a packet to its destination with minimal delay. This can be implemented by extending some of the position-based routing schemes to account for heterogeneous links and also the existence of a wired back-bone.
- **Delay Tolerant Routing:** Here, techniques such store-carry-forward can be extended to account for the system characteristics [7, 10]. Such schemes can be used to transfer large amounts of data (e.g., multimedia) in a bandwidth and energy efficient way.

2.2.3 Services

To support the targeted applications, several services need to be provided by the network in addition to unicast routing of packets. Examples are GeoCasting in an area, diffusion with gradually degrading accuracy, and summarization.

3. PLATFORM

3.1 Board/System

Here we present our platform which will implement the proposed architecture. The car environment requires the platform to be of reasonable size, still providing enough resources and performance for the planned applications. Our current system is based on a VIA EPIA board (Mini-ITX) with a x86 compatible 1 GHz processor. 30 GB of disk space allow to store large amounts of data for CDN and flood-delayed delivery of data. Car environment requires a special automotive power supply enabling automatic graceful shutdown of the system when the car is turned off, automatic boot up when the car is turned on and possible periodic wake-ups when the car is turned off. A battery voltmeter system prevents a deep discharge of the car battery.

3.2 OS/Software

The operating system is a Debian GNU/Linux with a 2.6.17 kernel. The application software we are currently developing is based on a Java SE/ME platform. It enables to send and receive data over all the wireless interfaces with different data rates and power levels. Given the position of the two communication parties, we will adapt the transmission power in order to reduce interferences on the network. This technique linearly increases the throughput of the overall network [13].

3.3 Communication Technology

Our system should enable the car to communicate with the network in different situations and scenarios, each with different range and data rate requirements. A layered approach with high data rate technologies for short range communications and low data rate for high range communications is the central idea here. The following multiple air-interface system fulfills these expectations.

- *Cellular communications* (GPRS, EDGE, WCDMA, HSDPA, 1xEv-DO, WiMAX under 2W) will allow to communicate at medium or low data rate with a centralized server when a node has no connectivity to the car network in an ad hoc fashion.
- *900MHz ISM band* transceivers (Maxstream Xtend), with transmit power up to 1W, enable car-to-car communication over a few hundred meters with rates up to 115.2Kbps. This technology will be used in an ad hoc mode, when WiFi is out of reach. It is planned to be the main communication interface in the case of a smooth deployment of the system over taxicabs. We did extensive noise floor measurements in a downtown area, and the results have shown that this particular frequency band has relatively low noise comparing to other bands.
- *WiFi* (later 802.11p, WAVE) enables various high data rates of short range communication and will be used in an ad hoc fashion between cars and possibly also with fixed base stations spread all over the city.
- *Bluetooth* is a medium data rate, very short range communication technology, that will be used mainly to control and use the system via a cellphone or PDA application for drivers or passengers in the back seats.
- *Low-Power ISM*, e.g. ZigBee, or proprietary XEMICS, is a short range medium data rate communication technology. It will be used as an interface to the roadside, as this technology does not require long discovery periods to enable communication.

3.4 Localization

In a vision with position based routing, precise positioning is a key element of the system. An embedded GPS receiver with a high gain (16dB) active antenna has been chosen (Garmin 15-L, GA 27C). In urban areas, WAAS or DGPS signal reception is rare, so that the precision often relies on traditional GPS. At the moment, we do not expect to require more precision. However, we might deploy our own DGPS base station in a downtown area if the application

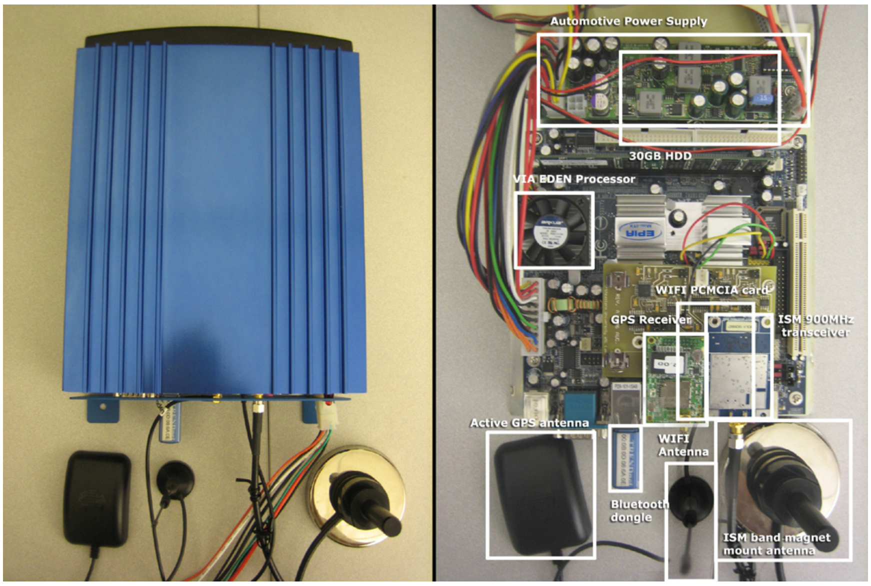

Figure 2: Car Unit.

requires this additional signal correction. For area based location information, CellID from cellphone base stations or ISM base stations IDs can be used.

3.5 Sensing

The vision to have a mobile, city-wide sensor network seems a promising idea. The following sensorial information are relevant:

- Traffic fluidity: derived from car speed, accelerometers measurements, GPS data
- Road state: car shocks (vertical accelerometers)
- External environment sensing: humidity, temperature, visibility sensors

To acquire engine state, speed, temperature data and emergency warnings we are using a OBD-II adapter (Scantool Elmscan) which acquires most of the interesting data from the current embedded car sensors. Currently, even if the OBD-II is a standard, underlying protocols vary from one car manufacturer to the other, though most cars use the ISO9141-2 and ISO14230-4 protocols. For the remaining sensor data, we plan to use external sensors. An additional fixed sensor network, together with our mobile sensor network, is also planned.

4. DEPLOYMENT VISION AND ANALYSIS

4.1 Vision

One of the factors that limited previously proposed ad hoc networks from being deployed is that they require to start with a connected network and therefore there is a need for a large number of nodes. Convincing many people to participate in an ad hoc network at once is very difficult.

Our vision relies on a smooth deployment starting by deploying the communication units on taxis over a city, then extending the system to other cars. As the number of enabled vehicles increases the connectivity increases and the need for low-rate high-range interfaces decreases. In the end only the taxis would need a 3G/WiMax connectivity.

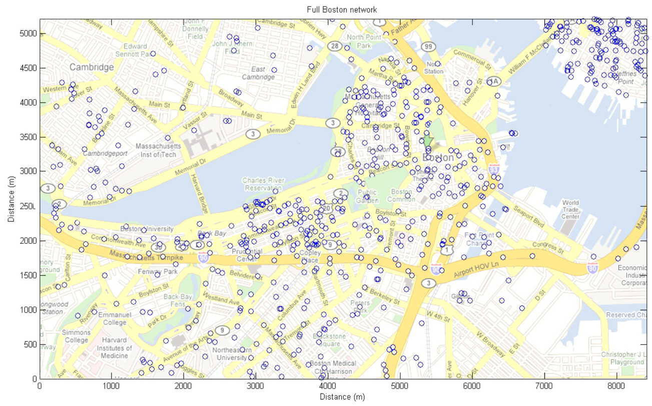

Figure 3: The taxicabs network of Boston (after extrapolation).

4.2 Preliminary Analysis for the City of Boston

4.2.1 *Introduction*

Today, Boston city represents a network of 1825 taxicabs, distributed among 6 taxi companies. The Boston land area (not including rivers, sea) is 125.5km2 which corresponds to a density of 1 taxicab in every 0.068km2 and an average distance of about 260m between taxicabs. However this oversimplified model does not reflect real conditions, as the presence of taxicabs is limited to roads. In total, the Boston road network has a length of 1300km, which corresponds to a distance of 712m between each taxicab. This result is also not meaningful, as taxicabs mainly drive on major road segments and most minor roads are only rarely used. The

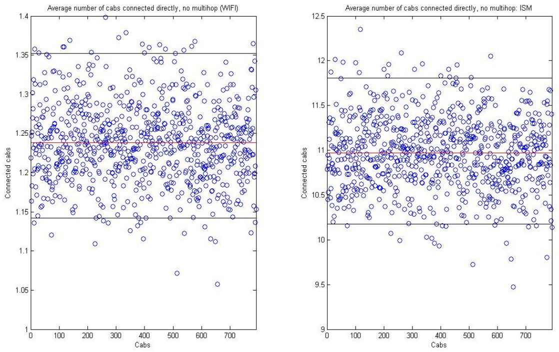

Figure 4: Nodes within range.

only way to get a reasonable model for the network is by monitoring taxicabs with GPS.

In consequence, our performance analysis is based on data obtained by a taxicab company in Boston (Metro Cab), which is equipped with a fleet management tool. Given the position information provided, we could extrapolate to the complete taxi network in Boston including the 5 other associations and perform simulations to obtain statistical connectivity predictions.

In the following part we give some other interesting information obtained by the taxi company.

The network has approximately the same number of nodes during daytime and nighttime. However the density tends to be higher in downtown area at night, as taxi drivers tend to avoid some parts of the city due to insecurity concerns.

Taxicabs drive between 250km and 320km in a 12 hour shift. In consequence, the average speed of taxis is about 25km/h alternating between periods with fixed position (waiting for customer, traffic lights...) and periods of motion (on duty)

Figure 3 represents a sample of the full network at 11:51am after extrapolation.

4.2.2 Simulations parameters

Simulations have been performed in MATLAB with our own developed network model. It considers the VANET composed of taxicabs without any infrastructure. Two communication layers are included in the simulation:

- WiFi: 100m range
- ISM 900MHz: 300m range

These average range data have been chosen based on our extensive experiments in the city environment. However observed ranges are by far not constant in practice. Communication range does depend on the distance between taxicabs. However other aspects have to be considered carefully [1, 14]. Interference from other devices (cordless phones, medical equipment) may have a major impact on the signal to noise ratio (SNR). Even the SNR is not a very precise indicator whether a packet arrives properly or not (and testing the RSSI is not suitable for precise performance evaluation). Doppler effect, due to high mobility of cars, can degrade the signal and cause a frequency shift of 120kHz for 900Mhz operation when cars are driving at 72km/h (45mph) in opposite direction. Multi-path fading due to reflections on the surrounding buildings, trees, and cars may have a major impact on the range, both positively and negatively depending on whether the interference is constructive or destructive. Another key aspect are the RF line-of-sight (RF LOS) conditions between taxicabs. RF LOS is different from visual LOS as it requires an American football shaped area (called Fresnel zone) between both antennas to be free of obstructions [2]. For a communication over 300m, antennas must be placed at least 2.45m over the road to have RF LOS, given that there is no obstruction between both nodes [2]. These conditions are very rarely met in practice. In conclusion, the results of the simulations must be considered carefully.

Simulations have been performed for a total duration of 8 hours. Each cab chooses random destinations. The distribution of potential destinations is based on data obtained from the taxi company to keep densities of taxicabs relatively constant throughout the simulation in each city districts. Speed values are updated every 2 seconds, respect the average speed observed and are based on a realistic speed model based on data obtained by the taxi company.

4.2.3 Simulation results

Nodes within range: the first result (figure 4) shows the average number of taxicabs that are within communication range. Each dot represents the average value for each taxicab. These results do not include nodes reachable via multihop routing. The central horizontal line represents the mean value and the two boundary lines represent the prediction interval with 95% probability for the mean. For WiFi, in average, we have 1.24 cabs within range. For ISM, in average, we have 10.2 cabs within range. We can see that using the second communication layer drastically improves the connectivity of the network.

Connectivity probability: on figure 5, we can see that the probability of having at least one one-hop neighbor within range or the percentage of time with connectivity for WiFi is 64%, as for ISM it is about 94%. These results are very promising for our project.

Average delay before one node within communication range: given that a message has to be sent at a random moment t, the average delay before having a neighbor within communication range is 3.192s for WiFi and 0.27174s for ISM 900MHz.

Duration of isolation: in the case of emergency messages, a very short delay before having connectivity is essential. The average delay result are somewhat misleading, as we will see next. On figure 5, we can see that for WiFi, periods of complete isolation last about 20 seconds in average. They only last 11 seconds in average for the ISM band. These values are essential to consider when developing a delay-aware routing protocol. We have also to keep in mind that these packet delivery delays must be added for each additional

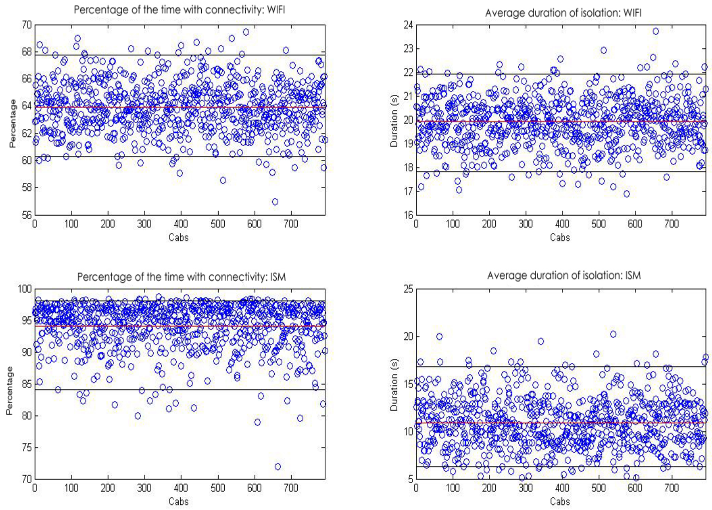

Figure 5: Connectivity probability and average duration of isolation.

Table 1: Duration of connectivity

	WiFi	ISM 900MHz
Shortest connectivity duration	1.4s	4.15s
Max raw data transmission	15.4Mbits	40.4/484.8Kbits

hop.

Duration of connectivity Supposing taxi drivers respect speed limits within a city (72km/h or 45mph in the United States), the worst case connectivity duration is obtained when two cars drive in opposite direction at maximal speed. For WiFi it corresponds to 1.4 seconds. During that time, given 802.11b 11Mbits/s raw over-the-air data rate, we can transmit 15.4Mbits. For the ISM case, we obtain worst case connectivity duration of 4.15 seconds and given 9600bps data rate we can transmit 40.4Kbits (or 484.8Kbits at 115.2Kbps).

Figure 6 shows connection duration and data transmission for different angles between two cars driving at the same speed (worst case, 72km/h). We see that for angles between 90 and 180 degrees, the connection duration is very similar. It grows exponentially as soon as cars start to drive in the same direction (angles below 90 degrees).

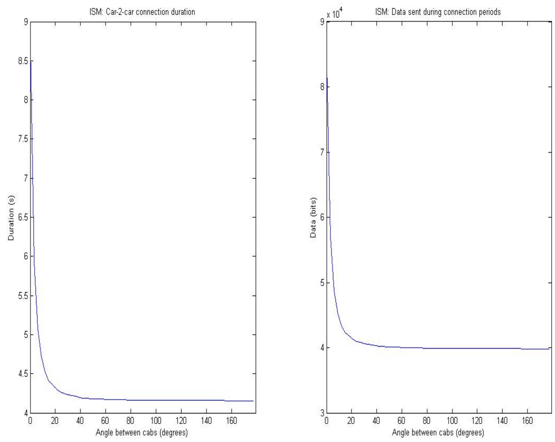

Figure 6: Connectivity duration and raw data transfer between two cars with different angles at 72km/h using 9600bps transmission rate.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we present a vision and architecture for a vehicular communication system that relies on heterogeneous communication interfaces (i.e., Long-Range ISM, WiFi, ZigBee, and Cellular). The architecture allows supporting a wide variety of services and applications from road navigation, emergency signaling, but also mobile content delivery, and mobile environment sensing. We propose a smooth deployment strategy for the system starting with taxis and extending to other vehicles. We described the current hardware and software platform over which our architecture is being implemented. Finally, based on real-world data obtained from a taxi company in Boston we analyzed the connectivity probability, duration, under a mobility that corresponds to this company's vehicles traffic. The preliminary results are very encouraging and indicate that mobility combined delayed forwarding can be a viable solution. In the near future, we plan to carry a more precise analysis of connectivity, end-to-end of packets transmission using a more accurate propagation model. To this end we will collect more precise Bit Error Rates for the various interfaces using our platform. We also plan to demonstrate the usefulness of the proposed architecture by implementing the mobile environment sensing application, and a road-navigation assistance using real-time congestion information.

6. ACKNOWLEDGEMENT

The authors of this paper would like to thank Metro Cab Association, Inc., for providing useful data about their taxicab fleet, data which were integrated in the simulation model.

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