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Requirements for the Physical Layer of the NOTICE System for Vehicular Communications

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***Abstract*—In this paper we investigate physical layer requirements for the NOTICE system proposed for notification of traffic incidents. The system uses short-range wireless communication between vehicles and sensor belts embedded in the roadway which impose constraints on time available for connection and data exchange, and we study the probabilities of establishing the wireless link and of successfully exchanging information between a sensor belt and a vehicle passing over it. We derive analytical expressions for these probabilities as functions of several parameters such as the time available for handshaking/information exchange, average speed of the vehicle, data rate and amount of information to be exchanged between vehicle and belt, and we evaluate their values for specific parameters corresponding to practical scenarios. Our numerical results indicate that inexpensive short-range wireless systems such as ZigBee radios are good candidates for the physical layer of the NOTICE system.**

I. INTRODUCTION

According to estimates by the United States Department of Transportation (US-DOT) congestion events on major roads and highways due to traffic incidents result in huge losses in worker productivity and billions of gallons of fuels wasted [1]. The US-DOT also notes [1] that over half of the congestion events are caused by highway incidents rather than by rush hour traffic in densely populated areas. With sufficient advance notification of traffic congestion drivers could make educated decisions about taking alternate, less congested routes, which would improve the overall traffic fluency and reduce the severity of congestions.

Current technology used for traffic monitoring and incident detection based on Inductive Loop Detectors (ILDs) is expensive and not very accurate and reliable, and the Intelligent Transportation Systems (ITS) community is looking for less expensive and more reliable methods for traffic monitoring and incident detection. Vehicular Ad-hoc Networks (VANETs) employing latest wireless sensor and networking technologies [2] have received increasing attention in the ITS community lately. They employ a combination of Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) wireless communication and are envisioned to integrate the driving experience into a ubiquitous and pervasive network that will enable novel solutions for traffic monitoring and incident detection [3], [4].

Recently, a secure and privacy aware architecture dubbed NOTICE was proposed for implementing a new system for notification of traffic incidents [5]. NOTICE is a V2I system whose architecture enables concrete security and privacy mechanisms by employing short-range secure radio communication operating at low power which prevents entities that are not actual traffic participants to gain access to the system and does not disclose any identifying information for vehicles in traffic. A related approach based on using a different type of infrastructure was proposed in [6].

However, the use of short range wireless communications imposes strict constraints for the NOTICE system as vehicles on the road have a limited time to establish connection with the roadway infrastructure and to successfully exchange traffic related information. We note that the actual speed of a given vehicle determines the time that the vehicle has available for communication and information exchange with the road infrastructure and this should be closely correlated with the specifications of the wireless technology employed. In this paper we introduce formal requirements for the physical layer of the NOTICE system and investigate the probability of establishing a wireless link as well as the probability of successful data transfer between vehicles and the roadway infrastructure.

The paper is organized as follows: in Section II we give a brief review of the NOTICE system followed by an analysis of the wireless communication process between vehicles and the roadway infrastructure in Section III. We present numerical results in Section IV and final remarks and conclusions in Section V.

II. A BRIEF REVIEW OF NOTICE

According to [5] the NOTICE architecture assumes that vehicles are equipped with a tamper-resistant Event Data Recorder (EDR) designed to store basic information about the vehicle's movement such as lane changes, speed, acceleration, position, as well as any additional information that may be input by the driver related to actual road conditions. The EDR works in conjunction with two short-range radios installed in the vehicle that operate at low power to communicate with wireless sensor belts embedded in the roadway at some given distances designed to collect the traffic information and provide driver notification in case of incidents. This is different than the approach in [6] where magnetic sensors are deployed

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along both sides of the road for information collection and dissemination.

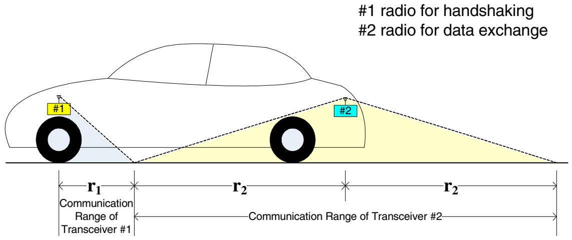

Fig. 1. Vehicle equipped with EDR and two short-range radios for the NOTICE system.

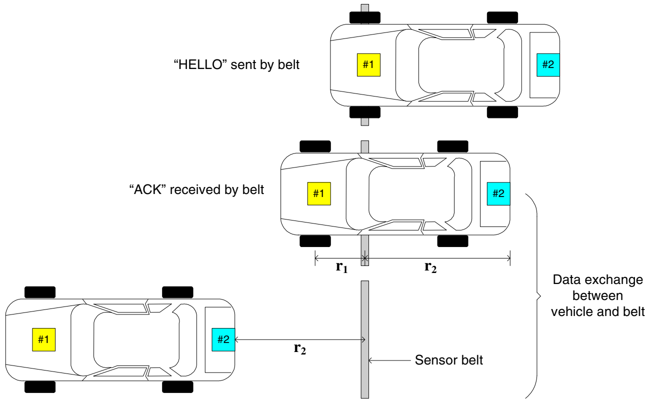

Fig. 2. Sketch of communication between a vehicle and a sensor belt in NOTICE.

The two radios inside the vehicle are placed as shown in Fig. 1 with one radio mounted close to the front axle of the vehicle and the second one installed at the rear of the vehicle. The corresponding communication ranges of the two radios are also shown in Fig. 1 and 2, and we assume that r_1 and r_2 shown in these figures are the same for all vehicles. We note that this is a reasonable assumption if one considers that similar wireless technology implied by some given standard is used by all vehicles in the NOTICE system.

The communication process between a belt and a vehicle is sketched in Fig. 2 and is as follows: when the wireless sensor in the belt determines that a vehicle has arrived (using for example pressure sensing activated by the front wheels of the vehicle) a radio transceiver on the belt will attempt to establish communication with #1 transceiver in the vehicle by sending a short range "HELLO" message with low transmit power. While the sensor belt is within the range r_1 of transceiver #1 in the vehicle this has limited time t_h available to respond with an acknowledgment message "ACK" to the "HELLO" message from the belt in order to complete the handshaking stage of the communication between vehicle and sensor belt. If the belt does not get the acknowledgment from the vehicle it will not attempt further communication with that vehicle.

Upon successful handshaking between belt and vehicle a wireless radio link is established with #2 transceiver in the vehicle and information/data will be exchanged securely by using symmetric key encryption technique as discussed in [5]. The transmission power available for the information/data exchange will be higher than that used in handshaking. Consequently, as shown in Fig. 1–2, the range $2r_2$ of transceiver #2 in the vehicle is larger than r_1 and, assuming constant vehicle speed, a longer time interval t_d is available for data exchange than the time t_h available for handshaking as shown in the timing diagram of Fig. 3.

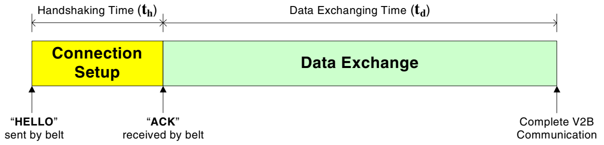

Fig. 3. Sketch of the timing diagram for car-to-belt communication in NOTICE.

Unlike other systems proposed for notification of traffic incidents where traffic participants alert each other directly of incidents [7], in the NOTICE system a given sensor belt first confirms that a traffic incident has actually occurred by aggregating information successfully received from multiple vehicles and then sends alert messages to traffic participants. Belts in the same driving direction may communicate with each other indirectly through passing vehicles that carry information from a given belt to the next belt: a passing vehicle uploads information received from previous belt to the current belt and also downloads information from the current for the next belt. Sub-belts on opposite sides of the road are linked together and communicate directly when a given belt needs to send notification about incidents to other belts in the backward direction.

The incident detection time, which is the time needed by a sensor belt to determine that a traffic incident has occurred, is influenced by various parameters such as the spatial density of the vehicles in traffic, the spacing of the sensor belts, how conservative the belt inference mechanism is, and the number of vehicles that are able to exchange information with the sensor belts [5]. We note that an acceptable value for the incident detection time of around 1 minute can be achieved even when only a fraction $\eta = 0.8$ of the vehicles that pass over a given belt exchange traffic-related information with the belt [8].

In the following section we present an analysis of the requirements associated with the actual communication between a passing vehicle and a sensor belt, and we derive an expression for the probability of successful information exchange between vehicles and sensor belts.

III. TIMING REQUIREMENTS FOR VEHICLE-TO-BELT COMMUNICATION

To investigate the timing requirements of the vehicle-to-belt communication in the NOTICE system we first convert the range parameters r_1 and r_2 of the two radios mounted in the vehicle to available time values as follows:

$$r_1 = T_{ah} \cdot k_1 \tag{1}$$

$$2r_2 = T_{ad} \cdot k_2 \tag{2}$$

where T_{ah} is the maximum time available for handshaking, T_{ad} is the maximum time available for data exchange, and k_1, k_2, are conversion factors with units of measure of speed. We note that the values of T_{ah} and T_{ad} depend on the wireless technology and standard used in conjunction with NOTICE as follows: T_{ah} is limited by the actual time required for handshaking and connection setup by the wireless protocol, while T_{ad} is limited by the amount of information to be transmitted and by the actual data rate supported by the wireless standard. We also note that this conversion is necessary since vehicles travel at different speeds v which are randomly distributed around some mean value μ, and as a consequence the same distances r_1 and $2r_2$ will be covered by distinct vehicles in different time as follows: t_{ah} is the actual time available for handshaking for a vehicle traveling at speed v and represents the time in which it covers the radio range r_1 of transceiver#1, while t_{ad} is the actual time available for data exchange and for a vehicle traveling at speed v represents the time in which the vehicle covers the radio range r_2 of transceiver #2 (see Figures 1 and 2). Their values are given by

$$t_{ah} = \frac{r_1}{v} = \frac{k_1 T_{ah}}{v} \tag{3}$$

respectively

$$t_{ad} = \frac{2r_2}{v} = \frac{k_2 T_{ad}}{v} \tag{4}$$

In order for a vehicle in traffic to exchange information with the wireless sensor associated with a given belt both stages of the communication process between vehicle and belt – handshaking and data exchange – must be completed successfully. We note that since these two stages are performed by two distinct radios mounted in opposite parts of the vehicle it is reasonable to assume that they are independent events with probabilities P_{sh} for successful handshaking, respectively P_{sd} for successful data exchange. Thus, the probability of successful information exchange P_s between a vehicle and a sensor belt is given by

$$P_s = P_{sh} \cdot P_{sd} \tag{5}$$

Successful handshking is defined by the condition

$$t_h \leq t_{ah} \tag{6}$$

where t_h denotes the actual time required by a belt and a vehicle passing over it to complete the handshaking stage and t_{ah} is the time available handshaking given in equation (3). We note that no actual data is exchanged by the belt and vehicle during handshaking and the time t_h is essentially the hardware setup time required for setting up the physical radio link between belt and vehicle.

Thus, the probability of successful handshaking is expressed as

$$P_{sh} = \text{Prob}\{t_h \leq t_{ah}\} = \text{Prob}\left\{v \leq \frac{k_1 T_{ah}}{t_h}\right\} \tag{7}$$

and is given by the cumulative distribution function (CDF) $F_v(\cdot)$ of the vehicle speed v. Considering that v is a Gaussian distributed random variable [9], [10] with average speed value μ and variance σ^2 equation (7) becomes

$$P_{sh} = 1 - Q\left(\frac{\frac{k_1 T_{ah}}{t_h} - \mu}{\sigma}\right) \tag{8}$$

where $Q(\cdot)$ is the standard normal complementary CDF [11, p. 141].

Once the handshaking stage has completed, the data exchange stage is successful if the amount of information I to be exchanged between vehicle and belt is transferred while the vehicle is within the range $2r_2$ of transceiver #2. We note that I is not the same for all vehicles since distinct vehicles may have different information to exchange with the belt. Nevertheless, as noted in [5], this amount is upper bounded, and in order to consider worst case scenario in our analysis we assume that I is the maximum amount of information that a given vehicle may exchange with the belt.

The actual amount of data d that can be transferred between between vehicle and belt while they are within the communication range $2r_2$ is given by

$$d = D \cdot t_{ad} \tag{9}$$

where D is the data rate corresponding to transceiver #2 expressed in [bits/s] and t_{ad} is the time available for data exchange given in equation (4). Thus, the probability of successful data exchange is expressed as

$$P_{sd} = \text{Prob}\{d \geq I\} = \text{Prob}\left\{v \leq \frac{D k_2 T_{ad}}{I}\right\} \tag{10}$$

and is also given by the cumulative distribution function (CDF) $F_v(\cdot)$ of the vehicle speed v. With v having a Gaussian distribution with mean value μ and variance σ^2 equation (10) becomes

$$P_{sd} = 1 - Q\left(\frac{\frac{D \cdot k_2 \cdot T_{ad}}{I} - \mu}{\sigma}\right) \tag{11}$$

Summarizing our results we have that the probability of successful information exchange P_s between a vehicle and a sensor belt is given by

$$P_s = \left[1 - Q\left(\frac{\frac{k_1 T_{ah}}{t_h} - \mu}{\sigma}\right)\right] \cdot \left[1 - Q\left(\frac{\frac{D \cdot k_2 \cdot T_{ad}}{I} - \mu}{\sigma}\right)\right] \tag{12}$$

This value implies that, out of the total number of vehicles that pass over a given belt, only a fraction $\eta = P_s$ will successfully exchange traffic-related information with the belt that can be aggregated and used for deciding whether a traffic incident has occurred.

IV. NUMERICAL RESULTS AND DISCUSSIONS

In order to evaluate the physical layer requirements for the NOTICE system we note that a value of $P_s \geq 0.8$ implies that the fraction of vehicles that pass over a sensor belt and successfully exchange traffic-related information with it is $\eta \geq 0.8$ and implies an incident detection time of about 1 minute or less as discussed in [8]. This value for

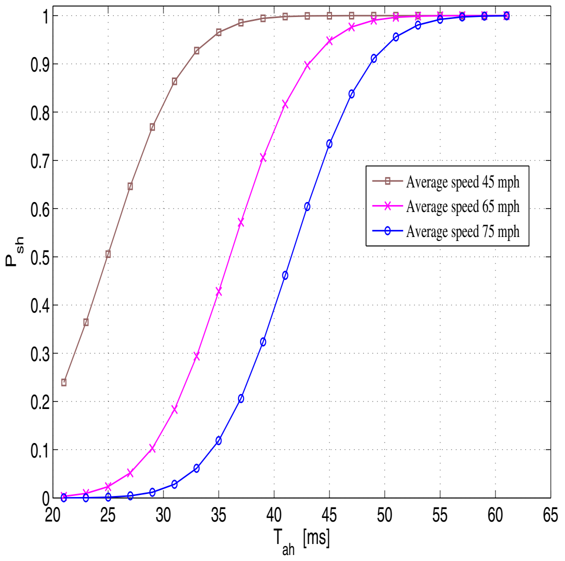

Fig. 4. Probability of successful handshaking P_{sh} as a function of the time available for handshaking T_{ah} for fixed connection setup time $t_h = 36$ ms and average vehicle speed equal to 45 mph, 65 mph, and 75 mph.

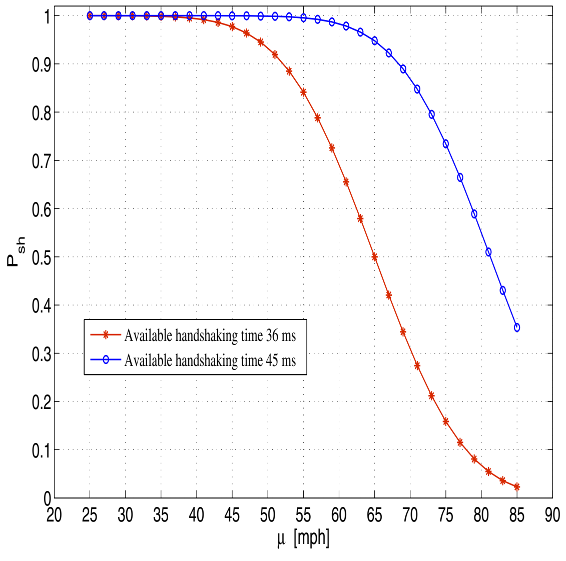

Fig. 5. Probability of successful handshaking P_{sh} versus average vehicle speed μ for fixed connection setup time $t_h = 36$ ms and available handshaking time $T_{ah} = 36$ and 45 ms.

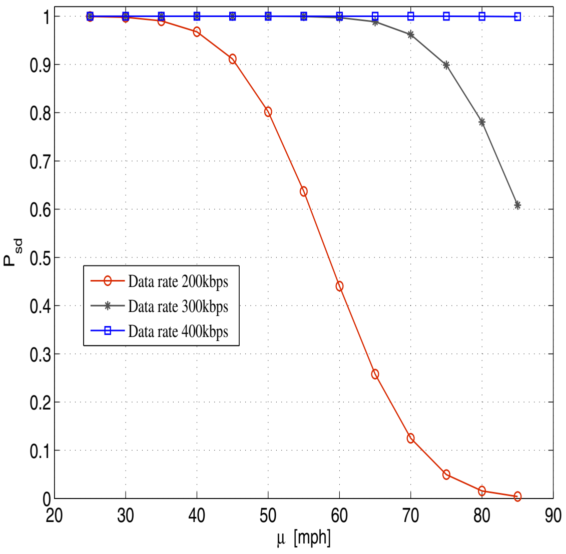

Fig. 6. Probability of successful data exchange P_{sd} versus average vehicle speed μ for fixed available data exchange time $T_{ad} = 216$ ms and data rate equal to $D = 200$, 300, and 400 kbps.

P_s can be achieved when both $P_{sh} \geq 0.9$ and $P_{sd} \geq 0.9$, and in this section we investigate scenarios which imply that these values are achieved. We take the two conversion factors $k_1 = k_2 = 65$ mph which is a common speed limit of most highways in the United States. For data exchange stage we assume that the maximum amount of information I to be exchanged between vehicle and belt is 6 kbytes which is about 8 times more than the value suggested in [5].

We first plot P_{sh} versus T_{ah} for fixed $t_h = 36$ ms and average vehicle speed equal to 45 mph, 65 mph, and 75 mph in Fig. 4 from where we note that for a given value of the available handshaking time T_{ah} the probability of successful handshaking P_{sh} decreases as the average speed of the vehicles increases. In order to achieve $P_{sh} = 0.9$ we need $T_{ah} \simeq 43$ ms for average speed value $\mu = 65$ mph, $T_{ah} \simeq 32$ ms for $\mu = 45$ mph, and $T_{ah} \simeq 47$ ms for $\mu = 75$ mph. We also note that according to equation (1) an available handshaking time of 43 ms implies that the effective handshaking range is about 1.25 m.

Next we plot P_{sh} versus average vehicle speed μ for fixed available handshaking time $T_{ah} = 36$ and 45 ms in Fig. 5 from where we note that, as expected, for a given value of the average vehicle speed the probability of successful handshaking decreases as the available handshaking time T_{ah} decreases. We also note that in order to achieve $P_{sh} = 0.9$ the average vehicle speed is $\mu \simeq 52$ mph for $T_{ah} = 36$ ms and $\mu \simeq 68$ mph for $T_{ah} = 45$ ms.

For the data exchange stage, we plot P_{sd} versus average vehicle speed μ for fixed available data exchange time $T_{ad} = 216$ ms and data rate equal to $D = 200$, 300, and 400 kbps, in Fig. 6 from where we note that for a given value of the average vehicle speed μ the probability of successful data exchange decreases as the data rate decreases (an obvious fact). In order to achieve $P_{sd} = 0.9$ with $T_{ad} = 216$ ms the average vehicle speed value must be below $\mu \simeq 45$ mph for data rate $D = 200$ kbps, respectively $\mu \simeq 75$ mph for data rate $D = 300$ kbps, while for data rate $D = 400$ kbps the data exchange is successful for any reasonable average speed of the vehicle[1]. We also note that according to equation (2) an available data exchange time of 216 ms implies that $r_2 = 3$ m and the effective range for data exchange is about 6 m which is consistent with the initial estimates in [5].

We also plot P_{sd} versus T_{ad} for fixed average vehicle speed equal to 65 mph, data rate equal to $D = 200$, 300, and

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[1] Speeds in excess of 75 mph are illegal on most highways in the United States.

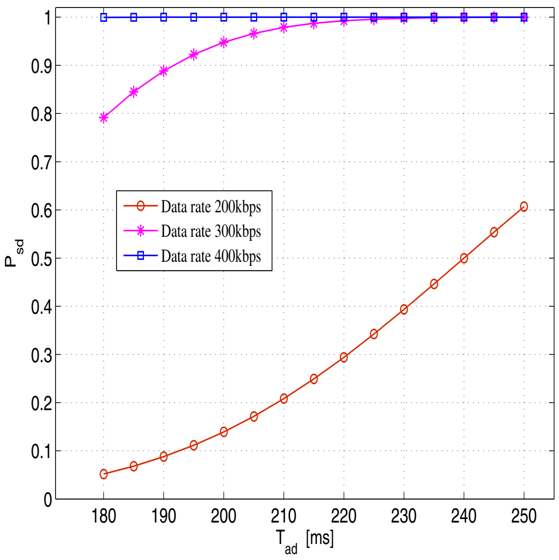

Fig. 7. Probability of successful data exchange P_{sd} versus available data exchange time T_{ad} for fixed average vehicle speed equal to 65 mph, data rate equal to $D = 200$, 300, and 400 kbps.

400 kbps in Fig. 7 from where we note that for data rate equal to 300 kbps and average vehicle speed $\mu = 65$ mph the probability of successful data exchange $P_{sd} = 0.9$ for $T_{ad} \simeq 193$ ms. We also note that for average vehicle speed $\mu = 65$ mph and data rate of 400 kbps the data exchange is successful for a wide range of values for the available data exchange time values while for the same average speed but data rate of 200 kbps the data exchange stage is essentially unsuccessful (with a probability around 0.5 or below).

V. CONCLUSIONS

We present an analysis of physical layer requirements for the NOTICE system proposed for notification of traffic incidents in vehicular communication networks [5]. The NOTICE system uses short-range wireless communication between vehicles and sensor belts embedded in the roadway in order to collect traffic information and to provide driver notification in case of traffic incidents. The limited transmission ranges of the radios involved in the wireless communication process in NOTICE impose constraints on time available for connection and data exchange, and we study the probabilities of establishing the wireless link and of successfully exchanging information between a sensor belt and a vehicle passing over it.

We derive expressions for the probability of successful connection setup (handshaking) and for successful information exchange as functions of several parameters such as the time available for handshaking/information exchange, average speed of the vehicle, data rate and amount of information to be exchanged between vehicle and belt, and we evaluate their values for specific parameters corresponding to practical scenarios. Our numerical results show that for average vehicle speed of 65 mph (which is the legal speed limit on most highways in the US) a given vehicle and sensor belt can achieve a probability of successful connection and information exchange around 0.8 with radio transceivers that require approximately 40 ms (or less) for connection and operate at 300 kbps (or higher) data rates. These results indicate that inexpensive short-range wireless systems such as ZigBee [12]–[14] are good candidates for the physical layer of the NOTICE system. In future work we plan to study in more detail the relationship between the parameters of various wireless standards and the requirements of the NOTICE system identified in this paper in order to establish clearly which standards are suited best for this type of application.

ACKNOWLEDGMENT

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An Integrated Framework for Vehicular and Urban Sensing

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***Abstract* -** In this work, we examine the integration of vehicular sensing and urban sensing to assess the operation, performance and environmental impact of vehicles in urban settings. We have designed an integrated framework for vehicular and urban sensing. A prototype implementation of this framework has been developed by building a testbed based on campus shuttle buses. We discuss the design and implementation of this system, focusing on its hardware platform and software architecture.

I. INTRODUCTION

In recent years, we have seen rapid development in many aspects of wireless sensor network technologies. These innovations have enabled many exciting applications [1], [2] to be developed. The technology advancement has helped to greatly reduce the cost of sensors, embedded processors and communication chips, as well as the size and power consumption of the integrated nodes. Therefore, building large-scale wireless sensor networks has become feasible for applications in areas such as environmental monitoring, security and homeland defense, intelligent transportation, structural monitoring, etc.

Wireless sensor networks are very useful for monitoring the interaction between human activities and the surrounding environment. For example, several recent research studies have examined the consumption of resources (such as electricity, water, fuel, etc) by people and associated the consumption to specific activities [16]. This may be an innovative way of motivating efficient resource usage and facilitating the management of the resource. Such resource monitoring and management can take place in an urban setting, for example within a university campus area.

Vehicles and transportation systems are closely involved in our daily lives. These systems have many kinds of sensors and are considered a rich information source. Vehicular sensing technologies have been implemented in many applications such as vehicle tracking systems [18] and commercial fleet management systems [19].

Urban sensing is a new paradigm on collecting information about systems and the environment which are closely related to and affected by human activities. Most prior work on sensor networks is based on collecting and processing environmental data using a static topology and an application-aware infrastructure. Urban sensing, on the other hand, involves collecting, storing, processing and fusing large amounts of data related to everyday environmental changes resulting from human activities, vehicles and other agents. This form of sensing is performed in a highly dynamic and mobile environment.

Urban sensing applications are emerging in several areas. A good example of human centric urban sensing is Active Map [17]. It is built on top of a geographical map, and collects and exchanges information about human activities such as the location and other details. Therefore it provides a platform for people interaction and also serves as an interface for registering context-aware event triggers. An important application area within urban sensing is the urban information system. A common design approach is to build a publish-and-subscribe mechanism and provide differentiated services to meet individual user's interests. Therefore, real-time, context-aware and online information management systems of urban sensing applications are highly encouraged.

In this paper, we present our work on the integration of vehicular and urban sensing. We describe the development of a prototype implementation of the framework based on the university campus shuttle bus transportation system. The hardware platform and software architecture of the prototype system are described.

II. BACKGROUND AND MOTIVATION

A. Vehicular Sensing

There are many existing examples of vehicular sensing systems. On-Board Diagnostic (OBD) systems are now used in most vehicles. The OBD-II [14] interface is a standard that provides almost complete engine control and also monitors parts of the chassis, body and accessory devices, as well as the diagnostic control network of the vehicle. OBD-II systems provide real-time data streams, including data from a host of sensors such as sensors for oxygen, coolant, pressure, temperature, airflow, vehicle speed, steering angle etc. This information can be used for fine-tuning the vehicle performance.

Vehicle tracking systems [17] can now be found in most vehicles. Automatic vehicle location (AVL) [11] systems allow for easy localization of the vehicle. The research interest has now grown from just tracking vehicles to obtaining information regarding traffic patterns, environmental conditions and other hazards by sharing information between neighboring vehicles [6]. Thus, inter-vehicular communication is emerging as a hot research topic in urban sensing [12], [13]. MobEyes [22], [23] aims to exploit vehicular mobility to opportunistically diffuse concise summaries describing the sensed data.

Singapore was one of the first countries to charge motorists for road usage during peak hours. The Singapore Electronic Road Pricing (ERP) system [10] uses a dedicated short-range

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radio communication system to deduct ERP charges from Cash Card. The smart card has to be inserted in the In-vehicle Units (IUs) before each journey. Each time vehicles pass through a gantry the ERP charges will be automatically deducted. Another successful commercial example of vehicular sensing is the car park gantry systems [15] for collecting parking charges.

One of the major environmental concerns today is air pollution. It has been shown that mobile devices equipped with environmental sensors on cars and public buses not only provide location of the vehicles but also information about the next approaching bus and detect the presence of high concentration of exhaust gases. Solution offered in [9] relies on a device that can be installed on cars and buses to warn people about high pollution levels through web-enabled mobile phones, PDAs and laptops. It is worth noting that these systems only provide continuous, passive sensing of pollution. They lack human interaction and feedback aspects that common to human-centric urban sensing systems.

B. Urban Sensing

The development of sensing systems for urban deployments is still in its early years. Urban sensing has been attracting researchers worldwide, with several systems and applications being proposed to utilize users' mobile devices to collectively measure environmental data [4], [5]. In [6], [7], [8] mobile sensor computing systems are proposed, which are designed to collect, process, deliver and visualize data from sensors embedded in mobile units such as automobiles, bikes and even skiers. Modern mobile phones are already equipped with many sensors that can be used for sensing [7].

In these systems, applications can task mobile nodes (such as a user's sensor-equipped mobile phone or vehicle) in a target region to report context information from their vicinity. In participatory sensing, individual mobile nodes opt to participate in meeting an application request. Whereas in opportunistic sensing [5], the mobile nodes may not be aware of the applications and nodes that choose to participate report their sensor data through opportunistic network connections (such as third-party access points encountered).

Applications of opportunistic sensing include collecting traffic reports or pollution readings from a particular street or part of a university campus [3], finding parking slots etc. In the context of human-centric urban sensing, sensed data is typically used to provide feedback to the users and to aid future sensing decisions.

C. Integrated Framework: Vehicular Urban Sensing

Our aim is to go a step further in integrating vehicular and urban sensing by providing the collected information to the public/users, allowing them to make informed decisions for a better quality of life. This can also help the public understand the impact of their daily activities, such as driving patterns, on the environment. This can be used as an innovative approach to solving today's environmental problems. Such participatory or "human-in-the-loop" sensing systems involve people in many sensing decisions based on the collected information.

For example, in the case of vehicles, the human 'driver' is an important part of the system. It is the driver's decision on when to sense/collect environmental data based on a number of factors like imminent environmental hazards, pollution, vehicle health, available fuel, speed of the vehicle etc.

In this paper, we present a system that allows us to measure and transmit information regarding the presence and amount of various pollutant gases along with the geographical location in real-time. In the proposed system, information from OBD-II [14] and the environmental sensors along with the GPS location information will be provided to the driver in real time. This information will also be transmitted using GPRS/3G/Wi-Fi and made available on the web for the public/users. Based on this information the driver can decide on which data to sense and any actions that need to be taken such as servicing the vehicle. This data will also be used to create pollution maps for urban environments containing details such as the type of cars, amount of pollutant emitted and fuel used etc. On-board emissions diagnostic indicator to warn the driver can also be implemented.

III. VEHICULAR URBAN SENSING FRAMEWORK

In this section, we present an integrated framework for vehicular and human-centric urban sensing. The proposed framework is illustrated in Figure 1. A traditional four-tiered architecture is proposed for vehicular sensing. Its tight integration with human-centric urban sensing is achieved through decision, control and feedback mechanisms involving humans.

A. Vehicular Sensing Architecture

1) Sensed events or objects: The underlying purpose of vehicular sensing is similar to that of traditional wireless sensor networks, i.e. to sense various events and objects. In the vehicular sensing context, objects include vehicles and other mobile objects along with their surrounding environment. We would like to sense the geographic location of vehicles, amount of pollution emitted by vehicles, speed, acceleration and other parameters of the vehicles' operation. Events could refer to a high traffic zone, an uphill road, a road with pot holes or any other event or feature of interest which we would like to sense.

2) Sensors: The second tier of the architecture consists of the sensors used to sense the various physical parameters and events. In an urban space, sensors can be classified as mobile and stationary sensors or as active and passive sensors. Mobile sensors are typically embedded in vehicles or other mobile devices while stationary sensors are embedded in the surrounding environment or are part of the infrastructure such as buildings, lamp posts etc. Mobile sensors improve spatial coverage of the sensing tasks. On the other hand, passive sensors are used for continuous sensing or sensing at periodic intervals. Active sensors are activated only when a specific event or threshold or criterion is met, or when activated by a human operator. Active sensors can sometimes support sensing at higher resolutions while meeting the same energy constraints as passive sensors operating at lower resolutions.

3) Sensor data acquisition and management: This tier deals with acquiring, processing and managing the sensed data. This involves communicating the data from the sensing unit(s) to a central location or data server. The data communication could be achieved directly using long range radios or 3G/cellular networks, or using a short range technology from the sensing unit to a gateway node and then on to the data server. After the data reaches the server it is recorded in a database for further processing and stored for archiving purposes.

4) Services: After the sensed data has been processed, a number of provided services enable better visualization of the data. These services can be categorized as administrative services and user services. Admin services allow the administrative team to infer the health of the different system components, and to manage and control the system more efficiently. User services allow the system users (and community members) to visualize the sensed data and infer about various events or features of interest.

B. Human-Centric Urban Sensing

The term *human-centric urban sensing* has typically been used in the context of human-in-the-loop sampling scenarios where human involvement is mainly in the sampling or the sensing process (through handheld mobile devices etc.). We propose to redefine or extend the definition of human-centric urban sensing. In the proposed framework, human-centric urban sensing refers to human involvement in the data assimilation, processing, inference as well as decision, control and feedback processes. The proposed framework, through a number of mechanisms for human involvement in these processes, tightly integrates vehicular sensing and human-centric urban sensing.

1) Human: The human element refers to human activities and behavior, and their affect on the surrounding environment. These are the features of interest in a human-centric urban sensing context. The integration with vehicular sensing would result in monitoring activities or events such as driving pattern, traffic hot-spots, pollution level.

2) Human Perception: Human-centric urban sensing introduces human perception as an additional sensing modality which will augment the measurements obtained from the various sensors. Human perception can be in form of visual (eyes), aural (ears), smell (nose) senses etc. These senses can be used to corroborate or augment the sensor measurements. In addition, these senses can be involved in the sensing decision to activate certain sensors or sensing modalities when an event of interest is perceived as imminent. For example, in an application gathering data on road condition, the sensing unit can be activated when a road is perceived to have pot-holes or needs maintenance.

3) Data Assimilation: Traditionally, data management involves storing the data in a database and then querying the database via the request-reply paradigm. The data returned by the query is used for further processing and visualization. However, data is a dynamic entity, which changes rapidly and is updated by many processes in a distributed environment. Thus in addition to the request-reply paradigm, an event-driven model is needed where applications are notified when events of interest are generated in the data fabric. Such a model is accommodated through a combination of ad-hoc querying (request-reply) and continuous querying (event-driven). In the continuous query model, human users (or applications) can register queries or events representing complex patterns of interest. The queries, instead of being executed on resident data, are continuously evaluated by a query engine that is aware of the interest expressed by various distributed client processes.

In addition, human-aided data analysis is an important part of data assimilation processes. Visualization and analysis of the sensed data through human intervention could point to events which hitherto were not identified. For example, it is well known that pollutant emission increases with the acceleration of the vehicle. Correlating pollution levels and terrain features (such as altitude or gradient) can reveal new patterns of interest.

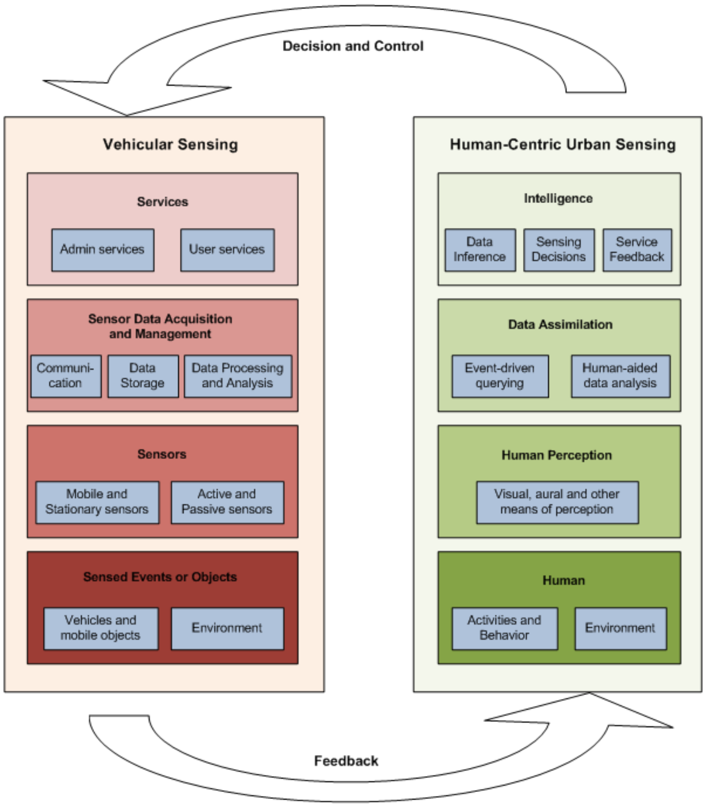

Figure 1. Integrated Framework for Vehicular and Human-Centric Urban Sensing

4) Intelligence: The data assimilation processes described above enable us to identify various events and recognize new patterns. These allow us to make inferences about the sensed events and their impact on the surrounding environment. For example, driving patterns resulting in lower pollution levels can be inferred and used in formulating new driving guidelines and pollution standards. Based on the data gathered decisions can be made about when, where and which sensing modes should be activated. These decisions could also be based on various data quality metrics such as relevancy, coverage, timeliness etc. In addition, users' experiences with the various services will enable them to provide feedback and suggest improvements to existing services, request new services etc.

IV. SYSTEM DESIGN AND IMPLEMENTATION

A. System Architecture

BusSense consists of three major components: in-vehicle unit (IVU), data hub, and service hub. BusSense general framework is designed to connect and control the three components through software and hardware.

The in-vehicle unit consists of the sensing module and the associated embedded software. It gathers information from all the available sensors. In our current implementation, the available information includes environmental pollution data from gas sensors and data from the GPS receiver, such as the UTC time stamp, location coordinates and vehicle speed. The in-vehicle unit, being an embedded device, is limited in terms of computational and energy resources. Thus, only minimal pre-processing of the data is done on-board before it is transmitted to the fusion centre. The need for real-time data streams, including location information, prevents us from buffering the data in the in-vehicle unit. The in-vehicle unit currently uses GPRS to transmit data to the fusion centre and for receiving administrative commands and software updates. GPRS provides a reliable communication channel with data transmission rates of 56-114 kbps over the GSM network, which satisfies our current system requirements.

Data hub acts as the centralized data server to handle the incoming data packets from all the active in-vehicle units. In the BusSense general framework, data hub includes two major components. In the lower layer, MySQL is implemented as the sole database management system. It manages the collected vehicular sensing data and responds to queries passed from the service hub. On top of the database management system is the BusSense Management Service. This acts as a data processing service for refining raw data received from the sensing modules. This service accepts raw data and performs decoding, refining, recomposing before inserting the data at its appropriate position in the MySQL database.

Service hub is a mixed structure which includes the central apache web server supported services and other more dynamic client services. There are three types of client services: the Management Control Service, the Web Client Service and the Mobile Client Service. These client services have been built independent of each other and serve different purposes and user groups. Management Control Service is the administrative tool provided for the BusSense management team. It consists of the web-based administration panel which provides functions such as database management, in-vehicle unit management and historic data query. It also includes back-end scripts which support queries to MySQL database and direct communication to the sensing modules. Web Client Service is the main web interface to the normal users who use BusSense through a web browser to track real-time locations of the campus shuttle buses on a map. Meanwhile, the Mobile Client Service provides a more convenient and friendly channel for the end users - the passengers - a lightweight and intuitive method to access the service through their mobile phones. Details of the described BusSense general framework are shown in Figure 2.

B. Hardware Platform

The hardware platform in the BusSense general framework refers mainly to the in-vehicle unit. As shown in Figure 3, the sensing module consists of three parts connected together to form the hardware platform. The Gumstix embedded computer [20] is used to control data acquisition from the exhaust gas sensors. It also provides connection to the GPS and the communication module. In our BusSense implementation, we have chosen Telit GM-862-GPS [24] as an integrated solution for both the GPS receiver and the GPRS communication module. It is equipped with a 20 channel SIRF GPS receiver

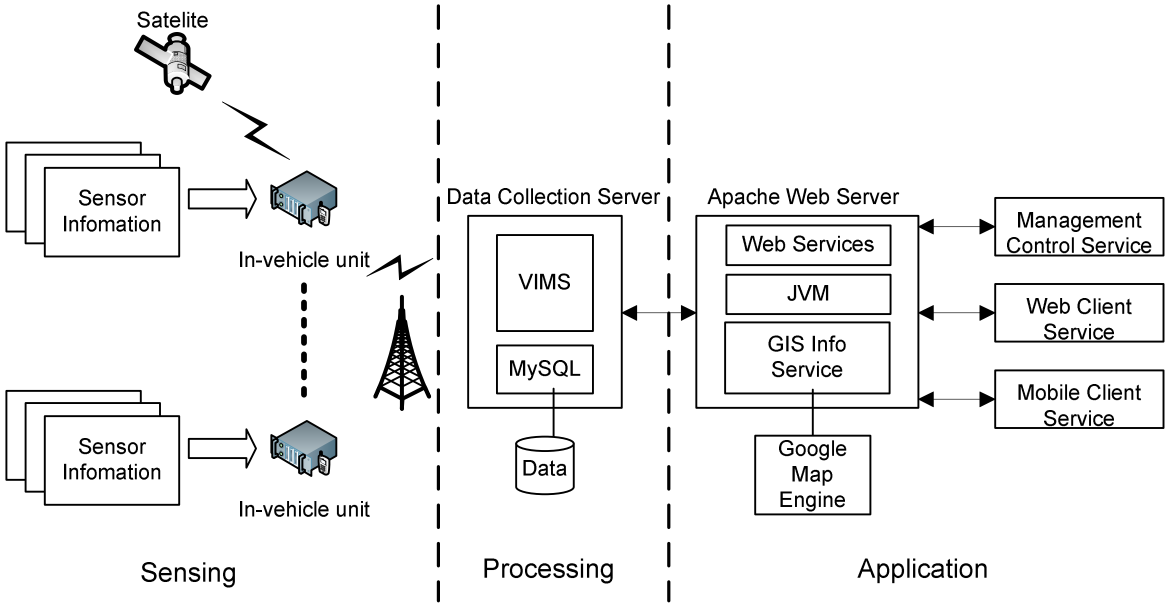

Figure 2. BusSense System Architecture

which provides quick start and high accuracy location coordinates.

In our current BusSense implementation, the following gas sensors, manufactured by Figaro [21], are installed. TGS 2201 sensor is used for detection of gasoline and diesel exhaust gases. The major components of diesel and gasoline exhaust are nitrogen oxide, carbon monoxide, hydrogen and incombustible hydrocarbons. TGS 2442 sensor is used to detect carbon monoxide as it is necessary to detect this poisonous gas separately. TGS 2600 sensor is used to detect air contaminants such as hydrogen and carbon monoxide present in cigarette smoke. TGS 2600 was chosen due to its sensitivity to hydrogen, which is a good indicator of air pollution. These sensors are miniature in size, consume low power and have a long life.

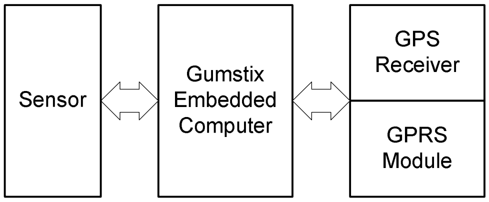

Figure 3. The In-Vehicle Unit (IVU)

C. Software Architecture

BusSense software architecture consists of two sections. First is the embedded software system on the in-vehicle unit. The other section is the server side software supporting the data hub and the service hub along with all the supported services.

The design of on-board embedded software for the in-vehicle unit is fairly straight forward. The embedded Linux core controls the data acquisition from the gas sensors. GPS data acquisition and the GPRS data transmission are managed by a Perl script.

Server side software is responsible for handling both the incoming sensed data from the in-vehicle units and the various client requests from the service hub. We have built a middle layer to cover the lower MySQL database management system and the data storage. In Figure 4, it is shown as Database Operation API. These APIs provide the frequently used database operation functions, such as the creation of data table and manipulation of each data record. Database Operation API processes requests from two components: the Data Hub Interface (DHI) and the Service Hub Interface (SHI), as shown in Figure 4. DHI contains functions for raw data processing while SHI is responsible for handling requests coming from the end users.

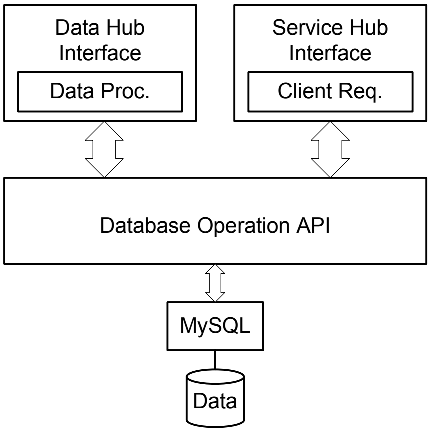

Figure 4. Software Architecture

D. System Implementation

We have developed a prototype system, BusSense, based on a tight integration of human centric urban sensing and vehicular sensing, to understand the environmental impact of vehicles. The system is being implemented for the university campus shuttle bus service. The prototype BusSense is based on an embedded mobile sensing platform making it a low-cost and easily deployable solution. It allows us to monitor the campus shuttle transportation system and the surrounding environment through geographical location information, environmental sensing data and OBD-II information.

The in-vehicle unit collects the vehicle's real-time information including its geographical location, speed, altitude, pollution data and other OBD-II information. This data is transferred back to the central data service, where it is stored and analyzed.

We use the Google Map Engine for displaying the real-time geographic locations of the vehicles (or the sensing modules). It provides multiple options for the map viewing mode and convenient map control. It also provides high resolution maps with detailed street views. JVM is used to support the development of various web services such as the interfaces for various client services, and the administrative panel. . A snapshot of the BusSense campus shuttle bus tracking web portal is shown in Figure 5.

V. CONCLUSION

Human activities and its interaction and impact on the surrounding environment are of major importance. We have presented an integrated framework for vehicular and urban sensing, which enables us to study the impact of human usage of vehicles on the environment. The design of BusSense, a prototype campus vehicle information system based on campus buses, has been described. Details of the hardware platform and software architecture of the system were presented.

In future, we plan to enhance the functionalities of the BusSense system, and to carry out extensive experiments to assess the impact of human driving patterns on the environment, such as environmental pollution.

Select Route

Route C

More Info

Bus No. 99 >>> Route C

Next Stop: -- Hall 6

Arrive In: -- 0'10"

☑ ETA to All Stops

Bus No. 90 >>> Route B

Status: -- Off-Service

☐ Time Schedule

More Info

Hall 7 near EEE	7'40"
opp. S1	9'10"
opp. School of BME	10'40"
opp. Block N2	11'40"
opp. Canteen A	13'40"
Hall 3	15'40"
opp. Hall 13	16'40"
opp. Hall 14-15	17'40"
opp. Grad Hall	20'10"
opp. Hall 11	21'40"
Nanyang Heights	23'40"
opp. Canteen 2	25'10"
Hall 6	0'10"
opp. Hall 1	1'10"
opp. Hall 4	2'40"
opp. Innovation Center	4'40"
School of math. & Phy.	6'40"

Figure 5. Sreenshot of the BusSense web portal

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RAMC: A RSU-Assisted Multi-channel Coordination MAC Protocol for VANET

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***Abstract*—This paper proposes a RSU Assisted Multi-channel Coordination MAC (RAMC) protocol that fully utilizes all DSRC channels to provide simultaneous safety and non-safety communications. Within the radio range of a roadside unit (RSU), vehicles are free to tune to any service channels. The RSU monitors all the safety messages being transmitted in both the control and service channels. Periodically, the RSU broadcasts a consolidated traffic view report to all neighboring vehicles in all channels. Therefore, a vehicle can operate in a service channel as long as it needs to achieve high throughput for non-safety applications, while maintaining adequate and timely safety awareness. Our simulation results show that the proposed RAMC protocol consistently provides high throughput for non-safety applications, while maintaining high safety message delivery ratios in various traffic density conditions.**

I. INTRODUCTION

VehiculAr Inter-NETworking (VANET) mainly works on developing efficient and reliable Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) communication technology for future transportation systems. There are two types of applications: safety applications (such as collision warning and traffic coordination), which assists driver to avoid accidents or mitigate the impact, and non-safety applications (such as mobile infotainment and congestion advisories), which improve passenger comfort and traffic efficiency [1], [2].

In order to provide sufficient Quality of Service (QoS) support for both safety and non-safety applications, the U.S Federal Communication Commission (FCC) allocated 75 MHz of spectrum in 5.9 GHz band as Dedicated Short Range Communication (DSRC) in 1999. The DSRC spectrum is divided into 7 independent 10MHz channels. The Channel 178 is designated as the Control Channel (CCH), which is exclusively for safety communications and some brief control messages, while the other channels called Service Channels (SCHs) are available for both safety and non-safety usage. Vehicles will be equipped with the GPS and a DSRC transceiver, called *On Board Unit* (OBU). The roadway infrastructure would have to be equipped with DSRC transceivers, called *Roadside Units* (RSUs). Due to the high cost of the duplex radios and the cross-channel interference problem [3], an OBU will likely have a single 802.11 radio.

Safety messages are typically targeted for all neighboring vehicles. Since a single radio vehicle can receive messages from one channel at a time, this multi-channel operational model creates a great challenge. For example, when an emergency warning message (e.g. reporting a traffic accident) is sent on the control channel, if some neighboring vehicles are using non-safety services on the service channels, the warning will be missed. This will reduce the effectiveness of the safety applications.

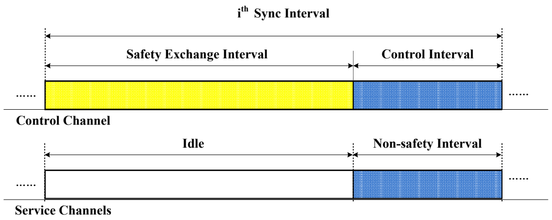

Fig. 1. DSRC channel synchronization scheme

Several approaches [4], [5], [6] have been proposed to address the multi-channel coordination problems. They are all based on some synchronization-oriented schemes, as shown in Fig. 1. In each sync interval, all vehicles must first tune their radios to the CCH until a full safety exchange among all neighboring vehicles is complete. During the safety exchange interval, all service channels are completely idle. Vehicles can only departure for non-safety services in the SCHs after the safety exchange is complete. This leads to the cyclic transmission phenomenon where safety activities on CCH are followed by non-safety activities on SCHs in a repetitive fashion. Such schemes give up substantial channel bandwidth. Furthermore, it often starves out non-safety applications when it needs the whole sync interval for the safety exchange under the high density traffic conditions [7].

The fundamental problem with these schemes is that vehicles attempt to listen to all safety messages. Adequate safety awareness does not require vehicles receive all the detailed safety messages. In normal driving conditions, it is sufficient

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for vehicles to periodically (e.g. every 100ms) receive a consolidated traffic view report. In the vicinity of a RSU, the traffic view report can be generated and then broadcasted to all nearby vehicles by the RSU.

In this paper, we propose a RSU Assisted Multi-channel Coordination MAC protocol (RAMC) for VANET. RAMC protocol is an improvement of the DCAP scheme [6]. RAMC supports simultaneous safety and non-safety communications, which relies on a multi-radio RSU to coordinate the CCH and SCHs communications. Within the radio range of a RSU, vehicles are not required to listen to all safety messages. Instead, the multi-radio RSU monitors all the safety communications in CCH and SCHs. Periodically, the RSU broadcasts a consolidated traffic view report to all vehicles in both CCH and SCHs. Furthermore, if there are any emergency warning messages, the RSU will immediately rebroadcast them to all vehicles in both CCH and SCHs. Therefore, a vehicle can operate in a service channel as long as it needs to achieve high throughput for non-safety applications, while maintaining adequate and timely safety awareness. Our experiments confirm that the RAMC can fully utilize all communication channels and thus achieve high throughput for non-safety applications, while maintaining high delivery ratio for safety messages.

The rest of the paper is organized as follows. Section II reviews current multi-channel coordination schemes for VANET. The proposed RSU-Assisted Multi-Channel Coordination MAC (RAMC) protocol is described in section III, while the performance evaluation of the proposed scheme is discussed in Section IV. Finally, Section V concludes the paper and presents our plans for future work.

II. CURRENT MULTI-CHANNEL COORDINATION SCHEMES FOR VANET

There exist several multi-channel coordination schemes for VANET. These schemes can be classified into two categories: distributed ad-hoc coordination and centralized coordination.

A. Distributed Ad-hoc Multi-Channel Coordination Schemes

Zang et al. in [5] discusses Vehicular MESH Network (VMESH) protocol based on a distributed beaconing scheme. VMESH divides the CCH interval into the Beacon Period (BP) and the Safety Period (SP). Each node has to transmit a beacon packet in every BP which contains channel negotiation information for making dynamic resource reservation on SCHs. It enables the contention free channel access on SCHs, and thus improves the throughput of non-safety applications.There is one main drawback in this scheme. In VANET, the most critical performance of DSRC communications is to ensure reliability of safety applications. Using the 802.11 DCF[8] as the channel access mechanism, a broadcast message from a vehicle often suffers frequent collisions from neighbors accessing the channel at the same time. Although the above distributed scheme provides enough support for safety applications by dynamically adjusting the CCH interval based on vehicle density, the available share for non-safety applications is strictly limited by the long CCH interval. Jiang et al. in [9] presents the Peercast protocol. Each node proactively echoes a received safety message from its nearby neighbors. If a vehicle hears no safety packet or echo packet on the CCH, it may return back to the SCHs for non-safety data communications. Due to the existence of the echo packets for safety messages, a node can have high probability to detect the safety messages, even if it spends little time on the CCH. Thus, Peercast results in a general performance improvement for non-safety applications. However, this scheme cannot guarantee that the emergency warning messages can always be received, when a vehicle is operating in a SCH.

B. Centralized Multi-Channel Coordination Schemes

Considering non-safety applications are typically provided by a RSU, Mak et al. [6] proposed a centralized MAC scheme, called the Dedicated Coordinating Access Point (DCAP). DCAP contains a Coordinating Access Point (CAP) and one or more Service Access Points (SAP) that provide non-safety services in the service region. DCAP divides each sync interval in the CCH into two distinct time periods: contention free period (CFP) and contention period (CP). During a CFP, DCAP sends broadcast packets to gain the control of medium and polls each node individually. The other nodes that are not polled in the CFP, will contend the channel in the following CP. Moreover, DCAP partitions the communication range of CCH radio into multiple circular regions centered at the CAP with different radius to avoid potential interference during the CFP. All vehicles must tune to the CCH for a full safety exchange during the CFP, and then they are allowed to departure for non-safety services in the SCHs during the CP. DCAP achieved good performance under interference free scenario. However, in the presence of a more realistic vehicular channel model such as in [10], the performance would be degraded. Its ability of synchronously supporting the reliability of safety applications and high throughput of non-safety applications under high vehicle density conditions is still questionable.

III. SYSTEM DESIGN

Our proposed RAMC protocol is an improvement of the DCAP scheme. The RAMC relies on a multi-radio RSU to coordinate CCH and SCHs communications. One of the radios is dedicated to safety applications in the CCH, and the remaining radios are used to provide commercial services in the SCHs. In the radio range of a RSU, vehicles are free to tune to any service channel.

A. Simultaneous Safety and Non-Safety Communications

As shown in Fig. 2, vehicles and RSUs operate in CCH and SCHs in parallel instead of sequentially. Time is partitioned into periodical period, called the sync interval. The length of the period is determined by the maximum tolerable latency of safety messages. In each sync interval, a vehicle is required to send at least one safety message in either CCH or SCH.

In the CCH, each period is divided into two sub-periods: a contention-free safety exchange period (CFP) and a contention-based control period (CP). During the safety

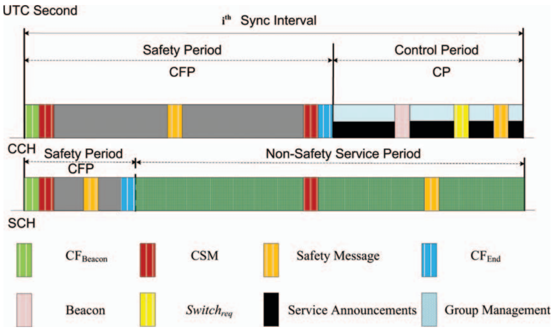

Fig. 2. RAMC Protocol

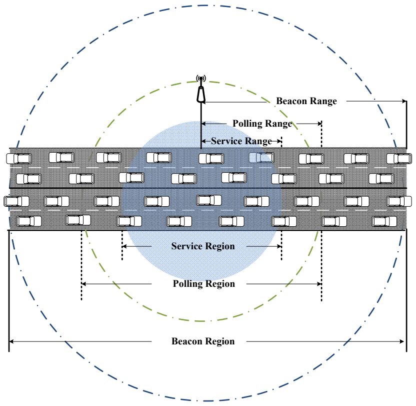

Fig. 3. Spatial Division

exchange period, each vehicle is individually polled. When polled, a vehicle can transmit its safety message while others must remain silent. This coordinated scheme minimizes interference, and thus greatly improves the reception rate of safety messages. This process is similar to the point coordination function (PCF). During the CP, brief private service announcements, other control messages, and additional safety messages are sent using the distributed coordination function (DCF). In each service channel, each period is also divided into two sub-periods: a contention-free safety exchange period and a non-safety service period. The safety exchange operates in SCHs in the same way as it does in the CCH. However, the safety exchange period in a SCH is much shorter because only a small number of vehicles operate in a SCH at the same time. The non-safety service period is for commercial services. During the non-safety service period, the RSU can interrupt the ongoing commercial services to broadcast high priority safety messages, such as emergency warning messages.

A RSU is responsible for safety information gathering, distribution, and aggregation. It will continuously analyze the aggregated information to look out for potential dangerous conditions. In each sync interval, a RSU performs the following activities:

- Monitor all the safety messages in both CCH and SCHs.
- Aggregate and analyze the information received to check for potential hazardous conditions.
  ◦ Broadcast a consolidated safety message (CSM) to all vehicles in each channel in the area.
  ◦ Warn all the related vehicles, if there is a potential hazardous condition.
- Rebroadcast the aggregated emergency warning messages (EWMs) to all vehicles in each channel in the area, if any.

Within a service region, a vehicle is free to operate in any service channel or the control channel. In each sync interval, a vehicle needs to do the following:

- Broadcast a status safety message in its current channel, when polled.
- Return to the control channel at any time if requested by a safety application.

B. Spatial Division

As shown in Figure 3, we propose to divide the surrounding area of a RSU into three regions: service, polling, and beacon regions. The main purpose of the spatial division is to ensure that safety message transmissions during the contention-free period in the service area are not interfered by nearby vehicles.

- The service region is the area in which non-safety services are provided. Vehicles within the service region can operate in either CCH or SCH. During a sync interval, vehicles are free to switch channels after they send their safety messages.
- Vehicles within the polling region but outside the service region operate only in CCH. Thus, they can also exchange safety messages with nearby vehicles in the beacon region but outside the polling region. Vehicles entering the polling region will be added to a RSU poll list. They will be polled to transmit their safety messages during the contention-free period (CFP).
- Vehicles within the beacon region but outside the polling region must keep quiet during the CFP. They send their safety and control messages during the CP. Thus, they won't interfere with the reception of polled safety messages during the CFP.

C. Status Safety Message Aggregation

Under the normal driving conditions, the RSU periodically aggregates the status safety messages (SSM) received in the CCH and SCHs as a *consolidated safety message* (CSM). The consolidated safety message includes the location of the RSU, the number of vehicles in the service region, median speed of vehicles, the relative location and speed of each vehicle. In each sync interval, the RSU updates and broadcasts the consolidated safety message twice, one at the beginning of the sync interval and one at the end of safety exchange period. This provides adequate safety awareness to all vehicles in the polling region. When the RSU performs consolidation, the location and speed of each vehicle relative to its service area is represented in a vehicle status record (VSR). Note, for each broadcast, we recalculate the relative location of each vehicle

TABLE I
THE LIST OF SAFETY MESSAGE TYPES

Type	Channel	Range	Functional Description
SSM	CCH,SCH	polling range	used by vehicles to send periodical status safety messages
EWM	CCH,SCH	polling range	used by vehicles to send emergency warning messages
EWM_Echo	CCH,SCH	polling range	used by RSU to echo emergency warning messages
CSM	CCH,SCH	polling range	used by RSU to broadcast consolidated safety messages
WARN	CCH,SCH	polling range	used by RSU to broadcast safety warning when an unsafe situation is detected

TABLE II
THE LIST OF CONTROL MESSAGE TYPES

Type	Channel	Range	Functional Description
Beacon	CCH	beacon range	used to announce the location of the RSU and poll and service range
CF_Beacon	CCH,SCH	beacon range	used to notify the beginning of the CFP and polling schedule
CF_End	CCH,SCH	beacon range	used to notify the end of the CFP
Safety_Poll	CCH,SCH	polling range	used to notify a vehicle for the right to transmit a safety message
Service_Adv	CCH	polling range	used by service providers to advertise their services on the control channel
Assoc_Req	CCH	polling range	used by vehicles to request to be added to the poll list
Assoc_Resp	CCH	polling range	used by RSU to respond to the add request
Switch_Req	CCH,SCH	service range	used by vehicles to request to switch channels
Switch_Conf	CCH,SCH	service range	used by RSU to confirm the switch request
De-Assoc_Req	CCH	polling range	used by vehicles to request to be removed from the poll list
De-Assoc_Resp	CCH	polling range	used by RSU to respond to the remove request

based on its last reported location, acceleration, speed, and the elapsed time since the reporting.

D. Reliable Delivery of Emergency Warning Messages

We propose a two-step approach for reliable delivery of Emergency Warning Messages (EWMs) to all vehicles. First, after an emergency warning message is broadcasted, the RSU will immediately rebroadcast the message in both CCH and SCHs, while piggybacking acknowledgement (ACK) to the sender. If the sender does not receive an ACK after a reasonable amount of time, then it retransmits the message. This way, we can guarantee the reception of emergency warning messages by the RSU and increase the reception of the messages by other vehicles. Second, the RSU filters the redundant messages for the same event, broadcasts an aggregated warning message multiple times, resulting in significant improvement in its reception among all vehicles.

E. Data Model

In our design, vehicles can broadcast their safety messages in their current channels no matter which channel they are tuned in. Each channel maintains a separate poll list. The various safety messages and control messages are shown in Table 1 and Table 2, respectively. The RSU dynamically adjusts its transmission power to cover a certain range.

- **Safety Exchange Period at CCH and SCHs**

As shown in Fig. 2, in both CCH and SCHs, each sync interval starts with a CFP for exchanging safety messages. The CFP begins with a CF_Beacon frame followed by a *consolidated safety messages* (CSM), proceeds to a safety exchange interval, and ends with another CSM followed by a CF_End frame. The CF_Beacon frame notifies the polling schedule and duration of the CFP to all vehicles. All vehicles add the CFP duration to their network allocation vector (NAV). They must keep quiet unless polled by the RSU. The CSMs contain the summarized the safety messages received in the last intervals. The safety exchange interval is used by vehicles in the polling region to send their safety messages. The RSU polls each vehicle on its poll list. When polled, a vehicle sends its safety message. The CF_End frame is sent to identify the end of the contention period, which occurs when all vehicles on the poll list have been polled.

- **Non-Safety Service Period at SCHs**

In each SCH, the end of safety exchange period is immediately followed by a non-safety service period. During the non-safety interval, the RSU can interrupt the ongoing services to broadcast the high-priority consolidated safety messages and emergency safety messages.

- **Control Period at CCH**

In the CCH, the contention-based control period (CP) follows the safety exchange period. During the CP, vehicles in the beacon region have their turns to send safety messages. Vehicles in the polling region send any newly generated emergency warning messages due to the abnormal driving conditions. The RSU sends beacons to inform newly arriving vehicles, performs group and channel switching management functions, advertises commercial services in SCHs, and rebroadcasts any newly received emergency warning messages.

IV. PERFORMANCE EVALUATION

A. Simulation Setup

Simulation is performed in a 2km stretch of freeway with a total of four lanes where vehicles pass along the road in one way at an average speed of 55 mph, under ns-2.33. We simulate five different traffic density scenarios (from high to low), by varying the average vehicle spacing in the same lane from 20 meters to 40 meters. An RSU is placed at the center of the road, with two radios. Each radio is pre-assigned a non-overlapping 20MHz channel. One radio is for the control

TABLE III
SYSTEM PARAMETERS

Category	Parameter	Value
PHY	Frequency	5.9 GHz
	Channel Bandwidth	20 MHz
	Power monitor threshold	-102 dBm
	Noise floor	-99 dBm
	Carrier sense threshold	-85 dBm
	SINR preamble capture	4 dB
	SINR data capture	10 dB
	Antenna gain	2.512 dB
MAC	Slottime	$13\mu s$
	SIFStime	$32\mu s$
	Preamble length	$32\mu s$
	PLCP header length	$13\mu s$
	CWmin	15
	CWmax	1023
Scenario	Safety Message Range	150 meters
	Service Range	80 meters
	Polling Range	230 meters
	Beacon Range	530 meters
	Sync Interval	100 ms
	Safty Message Rate	10 pkts/s
	Inter-Vehicle Spacing	20-40 meters
	Simulation time	12,000 seconds

channel, and the other one is for the service channel. The data rate of the control channel is set to 6Mbps, while that of the service channel is 54Mbps. Instead of the two-ray ground channel model used in DCAP, we use the more realistic Nakagami m=3 radio propagation model as suggested in [11], [12]. Furthermore, a vehicle transmits one safety message in each sync interval. We vary the percentage of EWMs message of the total safety messages from 0 percent to 40 percent, representing from the accident free normal traffic conditions to the extremely unsafe driving conditions. The size of EWMs message and SSM message are set to 150 bytes, and the size of consolidated safety message that includes aggregated safety information is 400 bytes. As for non-safety application data, each packet size is set to 512 bytes. The parameters of the simulation are summarized in Table 3.

B. Simulation Results

One of our key goals is to achieve high delivery ratio and low delay for safety messages. We define the delivery ratio of a safety message as the ratio of the number of vehicles that receive the message in its useful time (100 ms) to the number of all vehicles within the vehicle safety range. Similar to DCAP, we set the vehicle safety range to 150 meters and define the delay of a safety message as the elapsed time between the time in which the MAC layer of the sender receives the message to send, and the time in which the receiver correctly receives the message for the first time. Because RAMC utilizes the RSU to aggregate the original safety messages received and rebroadcast them as a CSM message, we consider that a vehicle receiving a CSM message as receiving the safety messages inside it with the same safety information.

Fig.4 and Fig. 5, respectively, show the average delivery ratios of safety messages in the polling region in different vehicle densities and different occurrence probability of EWMs message. On average, our proposed schemes achieve 98.9 percent delivery ratio for EWMs and 94.5 percent delivery ratio for SSMs message. Furthermore, the delivery ratios of safety messages are almost not affected, when the vehicle density increases and the occurrence probability of emergency warning message increases. One of the reasons is that each safety message in the polling region is broadcasted in a contention-free way; therefore, the probability of packet collisions does not increase with the increase of the number of safety messages. Moreover, multiple rebroadcasts of safety messages result in dramatic improvements of their receptions.

Fig. 6 and Fig. 7 show the effect that varying the vehicle density and the occurrence probability of emergency warning message has on the average delay of safety messages. We can observe that the delay of emergency warning messages is much less than that of status safety messages, average 0.64 milliseconds vs. 7.0 milliseconds. This is because after the RSU receives an emergency warning message, it must immediately rebroadcast the message in both CCH and SCHs. On the other hand, after the RSU receives a SSM message, it only aggregates the SSM message into a CSM message and the RSU then waits until it gets a chance to send the CSM message (twice in each sync interval). This waiting increases the delay of status safety messages.

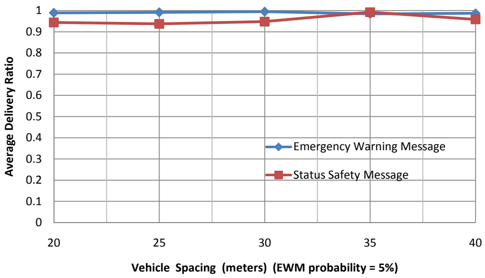

Fig. 4. Safety message delivery ratio as a function of traffic density

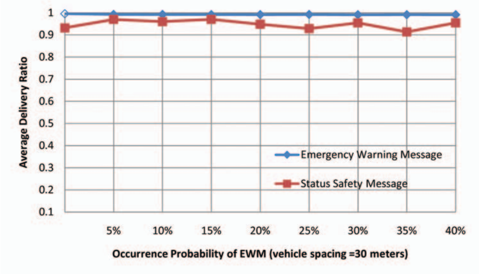

Fig. 5. Safety message delivery ratio as a function of EWM percentage

Furthermore, we evaluate the performance of non-safety applications in terms of the share for non-safety usage in each sync interval. As expected, our experiments show that the share of non-safety usage is more than 82 percent, even when the traffic density is very high. As shown in Fig. 8, the share of non-safety usage is 92 percent for the low traffic density condition with the inter-vehicle spacing 40 meters, while it is 82 percent for the high traffic density condition with inter-spacing 20 meters. In addition, Fig. 9 shows that

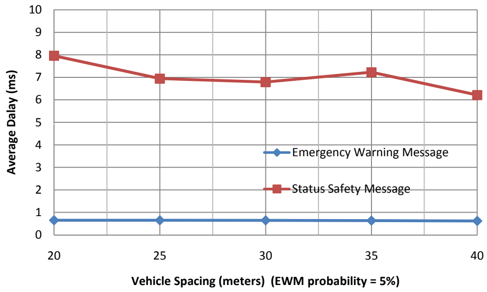

Fig. 6. Safety message delay (millisecond) as a function of traffic density

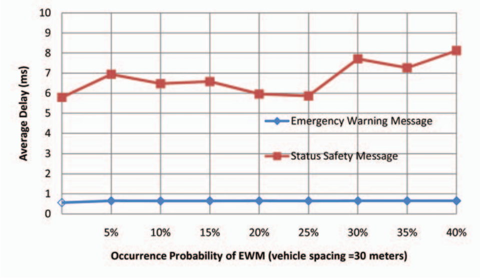

Fig. 7. Safety message delay (millisecond) as a function of EWM percentage

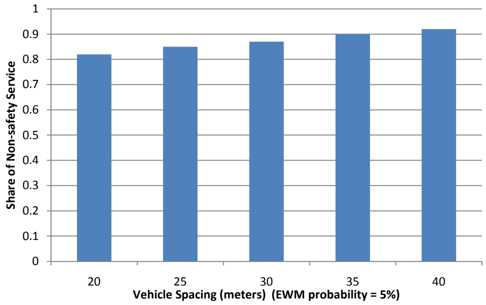

Fig. 8. Share of non-safety applications for different traffic densities

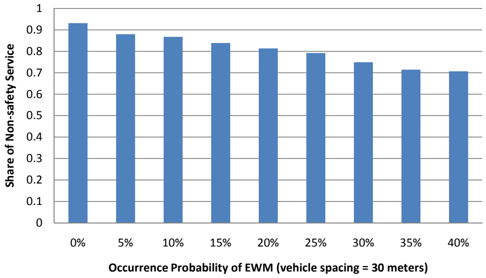

Fig. 9. Share of non-safety applications for different EWM percentages

when the percentage of emergency warning safety messages increases, the share of non-safety usage is reduced accordingly. This is because the vehicles staying on the SCH have to spend more time on handling the emergency warning safety messages forwarded by the RSU, so that the share of the non-safety usage is compromised. However, we find that the proportion of non-safety service time remains at over 70 percent, even though when the occurrence probability of emergency warning safety messages is 40 percent (an extremely unsafe situation).

V. CONCLUSIONS

In this paper, we present the RSU-Assisted Multi-channel Coordination MAC protocol (RAMC) that efficiently utilizes multiple channels to support simultaneous safety and non-safety communications in vehicular networks. With the assistance of a multi-radio RSU, vehicles do not need to periodically monitor the control channel for safety messages transmitted by the neighboring vehicles. Instead, the multi-radio RSU monitor all the safety messages and broadcast a summarized traffic view report to all vehicles in both the control channel and service channels. Thus, a vehicle can stay on the service channel all the time to achieve high throughput for non-safety applications without missing any important safety messages. Moreover, simulation results show that RAMC outperforms the existing multi-channel coordination schemes, especially in high density traffic conditions.

ACKNOWLEDGMENT

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Vehicle-To-Vehicle Channels: Are We Done Yet?

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Abstract- **In this paper, we review the state of the field on measurements, models, and analysis for the vehicle-to-vehicle (V2V) channel. We first provide a survey of existing work on V2V models, including analytical and empirical models, and note main features and findings. Remaining work to be done in V2V modeling is then described, beginning with the logical next steps, then addressing less obvious areas of V2V channel research. We also provide some new results on statistically non-stationary models, specifically in terms of non-stationary Markov chains for modeling multipath component persistence. We show that in terms of delay dispersion measures, stationary 2nd-order Markov models perform as well as non-stationary models. The paper concludes with a summary.**

I. INTRODUCTION

Vehicle-to-vehicle (V2V) communication research has been growing steadily over the past several years [1]. Multiple papers, workshops, conference sessions and conferences attest to this. Applications range from the most important—road safety improvement—to useful and energy-saving improvements in vehicular traffic efficiency and density, to so-called "comfort" or "infotainment" applications [2]. For example, traffic warning systems may broadcast information on road obstacles, accidents, work zones, weather, etc. These broadcast applications would employ local transceivers at roadsides, and would constitute vehicle-to-roadside (V2R) or vehicle-to-infrastructure (V2I) communication. Similarly, V2V networking using multiple V2V links (hops) could be used to relay such information [3]. Much of the work on these technologies and applications lies in the area of Intelligent Transportation Systems (ITS) [1]. Mobile ad hoc networking is also a part of V2V communications, and military vehicular ad-hoc networks (VANETs) are of interest. Literature on V2V/V2R communications is burgeoning [4] so our review here is selective.

The importance of accurate channel models in optimizing communication system performance is well known [5]. Channel models are used in analysis, computer simulations, and hardware testing [6], all of which are key steps in actual system design and deployment. To cite just a few examples, channel knowledge is used for selection of equalizer length and adaptation algorithms, specification of subcarrier bandwidth, specification of pilot symbol period and pilot frequency separation, selection of cyclic extension duration, and selection of synchronization algorithms. If we broaden the discussion to include multiple antenna systems, channel knowledge is also critical in array design and processing.

Environments for V2V communication are roadways in urban, suburban, and rural areas, but significant differences from traditional cellular communication exist[1]. In V2V cases, both transmitter (Tx) and receiver (Rx) may be mobile, and both may have multiple scattering/reflecting vehicles nearby, which are also mobile. Scattering geometry will very often be non-isotropic and time-varying, yielding time varying Doppler spectra. When both Tx and Rx are mobile, fading rates can be twice as fast as in cellular. With low elevations for both Tx and Rx antennas (on vehicle roofs, or inside vehicles), obstruction of line of sight (LOS) paths will be more frequent, even when link distances are short. With obstacles around both Tx and Rx, the phenomenon of multiple scattering can arise, and this yields more severe fading than in cellular channels. These are two key differences from cellular: V2V channels can incur fading that is more severe [7], and V2V channels will be statistically stationary for shorter durations.

The frequency band of operation for V2V communications is likely to be in the 5 GHz range. In the US, 75 MHz of spectrum is available in the 5.85-5.925 GHz band. Work has also been done in the 5.1-5.2 GHz band [8], [9]. Thus, although some channel measurements have been made in other bands, such as the 2.1-2.4 GHz band [10], [11], and 900 MHz band [12], and analysis in other bands such as 60 GHz [13], most near-term V2V systems are likely to be deployed in the 5 GHz band, so that is our focus here. In addition, since most V2V systems are planned to be operated over short ranges (from a few m up to 1 km), propagation path loss is not difficult to overcome with moderate transmit power levels. Thus we concentrate on small (and medium, or "meso") scale channel fading effects.

In Section II, we summarize the "state of the field" in V2V channel modeling. In addition to recent work, we include citation of key work from the past for context. Section III covers logical next steps in the field. In Section IV we list some areas of V2V channel modeling that are uncovered, and which may see research in the future. We conclude with a summary in Section V. Due to page limitations and the need to balance subject coverage with reference citations, our reference list is necessarily incomplete. We refer the reader to [14] for a set of complementary references, which together with the references here provide a comprehensive V2V

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[1] Although it is almost certain that V2V communications will be used in "off-road" conditions in the future (as they are now in ad hoc fashion), we do not address that environment in this paper.

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channel reference list. In addition to coverage of some similar topics, this paper differs from [14] by more treatment of non-stationarity and comparisons of measured results.

II. STATE OF THE FIELD

As with other types of channels, including cellular, indoor, etc., models come in various types. There are multiple ways one may classify such models, such as deterministic vs. statistical, analytical vs. empirical, "physical," or combinations of these. Within each type of model usually lie multiple classes, for example, the urban/suburban/rural classes for cellular. In addition, we may also classify according to frequency band, by number of antennas, V2V vs. V2R, etc. Our taxonomy here is but one possible, and classes are not perfectly disjoint; we discuss in terms of analytical, simulation, empirical, and MIMO.

A. Analytical Models

By analytical, we mean models based upon theory. An example is that of [15], arguably one of the earliest papers on V2V channels. This paper assumes rich scattering so that Central Limit Theorem (CLT) arguments yield classical Rayleigh fading, but with potentially twice the fading rate—the spaced-time autocorrelation function of the received envelope is a generalization of the classic form derived in [16]. The associated V2V Doppler spectrum was also derived. The same author extended this work in [17] to derive corresponding analytical results for level crossing rate, average fade duration, and random FM. These models are narrowband in that they do not expressly model delay dispersion, and naturally are functions of mobile velocities.

Shortly after the publication of [17], the authors of [18] extended the derivation of Doppler spectra and autocorrelations in [15] to three dimensions. These functions contain integrals that in general must be evaluated numerically, but the expressions are quite generic, allowing for arbitrary antenna gain patterns and angle-of-arrival probability density functions (pdfs). As with [15], simplifying assumptions include rich enough scattering to invoke the CLT for Gaussianity, and wide-sense stationarity (WSS).

A general-purpose analytical model for angle of arrival (AoA) and angle of departure (AoD) pdfs that allows for non-isotropic scattering is presented in [19]. This model employs the von Mises pdf, and via this density, the time-autocorrelation function of the received envelope is obtained in closed form as a product of modified Bessel functions, dependent upon Tx and Rx Doppler frequencies f_{di}, angular spreads κ_i, and mean AoD and AoA μ_i:

$$R(\Delta t)=\prod_{i=1}^{2}\frac{I_0\left(\sqrt{\kappa_i^2-4\pi^2 f_{di}^2\Delta t^2+j4\pi\kappa_i f_{di}\Delta t\cos(\mu_i)}\right)}{I_0(\kappa_i)} \quad (1)$$

The Doppler spectrum associated with this autocorrelation must be found numerically. Sum of sinusoids (SoS) simulations in [19] employing the non-isotropic pdfs showed the ability to replicate theoretical predictions fairly well—assuming stationarity—but with a generally large number of sinusoids (e.g., 100 or more).

More recently, in [20], a detailed analytical model was presented. This model could also be classified in our next class—simulation models—since due to the extraordinary level of detail, any use of the model requires a computer. We discuss it as an analytical model because it is in principle based upon plane wave (ray) theory and geometry (so called geometric stochastic channel models, GSCM). Indeed, this could also be classed as a geometric model, as it assumes two cylindrical "rings" of scattering objects surrounding the Tx and Rx. The authors develop a so-called "reference model" that assumes rich scattering and CLT applicability, and implement this via the SoS approach. This model also incorporates multiple-input/multiple output (MIMO) modeling with antenna arrays at both Tx and Rx vehicles. Numerous (1-2 dozen) geometric parameters must be specified, and values for some of these are drawn from random distributions that are user-selectable. The authors validate their SoS implementation against the theoretical (WSS) autocorrelations and Doppler spectra. Once configured, this complicated model has the ability to replicate a range of scattering conditions.

B. Simulation Models

We classify as simulation models those that use established theoretical principles, but because of complexity of evaluation, closed form expressions are not available. Some of these simulations take the form of Monte Carlo simulations, i.e., repeated trials of a probabilistic experiment in which the parameter distributions are selected a priori.

A good example of this type of model is that found in [21]: a ray tracing model for the V2V channel. In these simulations, local environment characteristics must be specified. In general, in addition to object dimensions, electrical parameters such as conductivity and permittivity must also be included, so these simulations require large numbers of inputs. Many software packages are available with built-in databases for common materials, e.g., [22], thus simplifying this task somewhat. In [21], the authors construct a model for V2V channels in which other vehicles and roadside obstacles are modeled stochastically: basic properties are specified (e.g., building shape, vehicle size), and then the simulation runs by first placing these objects according to the appropriate distributions, and then running the ray-tracing program to compute the channel characteristics. The program can compute either narrowband (~amplitude) characteristics or wideband characteristics, with the latter requiring more computation. The model in [21] was an updated version of that in [23], in which the simulation of propagation was only a single part of a larger, system-level simulation. The authors continued their work in [24], in which they simulate the performance of an IEEE 802.11a system in the V2V channel.

A perhaps more traditional simulation is that described in [25]. In this paper, the authors presume Rayleigh fading a priori, and develop a simulation to efficiently emulate fading that agrees with the reference model of [15]. The SoS approach is used, and the authors show that this narrowband model reproduces desired fading envelope correlation properties.

C. *Empirical Models*

These are models based on measurements, and are typically "physical" models for the channel impulse response (CIR). As with analytical or simulation models, these models can pertain to either narrowband (flat, or frequency non-selective) fading or wideband (dispersive, or frequency selective) fading. An example of the former is [26], in which the authors explored fading characteristics in the 5.9 GHz Dedicated Short Range Communication (DSRC) [27] band. The DSRC system is a modified version of the IEEE 802.11a wireless LAN standard [28], also known as WAVE for Wireless Access in Vehicular Environments [29]. The authors of [26] measured and modeled large scale path loss and flat fading in suburban Pittsburgh, and found some severe fading (worse than Rayleigh statistics). Fading was modeled using the Nakagami distribution [30], with shape parameter ("*m* factor") ranging from 0.5 to 4. In [31], these authors employed wideband measurements to help specify criteria for DSRC system parameters. In contrast to the commonly-used root-mean-square delay spread (RMS-DS), they used excess delay [32] to characterize delay dispersion (this excess delay is equivalent to the *delay interval* I_X, the duration of the power delay profile containing all energy equal to or above X dB below the power delay profile peak). They also provided results for 90% coherence bandwidth, 90% coherence time, and maximum Doppler spread. Explicit models were not provided.

In [33], the authors provide a measurement-based model for expressway V2V channels. The dispersive channel model takes the usual tapped delay line (TDL) form, and pertains to a 10 MHz bandwidth. The developed model was aimed at implementation on a commercial channel emulator, so flexibility was limited: fading had to be Rayleigh or Ricean, and Doppler spectra could take only a few basic shapes (or sums of these basic shapes). The authors measured time-varying Doppler spectra, indicating statistical non-stationarity.

The authors of [34] also did expressway measurements at 5.2 GHz. They developed a TDL model with Rayleigh/Ricean coefficients. This model has a significantly smaller RMS-DS than those in [6], [10]. Interestingly, delay spread values in [8] lie between those of [34] and [6], [10]. The authors of [8] developed TDL models for channel bandwidths of 5 MHz and 10 MHz (additional models for other bandwidths are provided in [35]). In [8], both severe fading and NS behavior were observed and modeled. Reference [36] provides additional measured results in terms of delay and Doppler spread. Table I summarizes some of the RMS-DS values discussed here.

TABLE I
REPRESENTATIVE ROOT-MEAN-SQUARE DELAY SPREAD VALUES σ_τ FOR V2V EXPRESSWAY SETTINGS

Reference	**Frequency Band (GHz)**	**σ_τ (nanosec)**	**Comments**
[6]	5.9	40.2 67.6	Oncoming Same direction, w/wall
[34]	5.2	15	Doppler > $2v/\lambda$ found
[8]	5.1	20 48	Median, low traffic density Median, high traffic density
[36]	5.7	40	Oncoming

Our last representative citation in this section is [37], in which the authors employ time-frequency analysis [38] to estimate "stationarity times" for V2V channels. For expressways, these times were as small as 23 millisec for vehicles driving in opposite directions and as large as 1.4 sec for vehicles traveling in the same direction.

D. *MIMO Models*

Multiple-input, multiple output, or MIMO channels and systems have seen enormous attention recently [39], and V2V applications are no exception. We have already cited several MIMO references in the previous section [34], [36], and [38]. Most measurements use between 2-4 antennas, typically roof-mounted. Two analytical MIMO models are [40], [41]. In [40], the authors employ the "2 ring" scattering model and, akin to previously cited analytical work, assuming the CLT and WSSUS apply, they derive correlation functions and Doppler spectra for a narrowband V2V channel. Similarly, [41] extends the work in [20] to the MIMO case. The "2-cylinder" geometric model is employed to assess correlations and Doppler spectra, and these are compared to measurement results. Agreement with measurements is reasonably good.

In [42] the authors used two diversity measures to assess achievable diversity orders via estimated MIMO correlation matrices for an expressway setting. As known from non-V2V MIMO studies, they found very high correlations among antennas for LOS cases. They also clearly show time-varying diversity order, reflecting the NS nature of the V2V channel.

III. THE LOGICAL REMAINING WORK

In this section, based on the findings in existing work described in the previous section, we discuss logical next steps. From the review of the literature, one can observe a clear trend from the fairly simple (assumed WSSUS and narrowband Rayleigh fading) in early works, to MIMO, NS, and severe fading in more recent results based on measurements.

A. *Additional Frequency Bands*

Although the 5 GHz band will be the band of interest for any commercial ITS applications, clearly V2V communications can be employed in other bands. Two primary candidates are two public safety bands in the US: 750 MHz and 4.9 GHz [43]. The 4.9 GHz band will have characteristics essentially the same as the 5 GHz bands, but the 700 MHz band (allocated from recently-vacated television bands) is largely unexplored for V2V applications. In addition, the public safety community is not in any way committed to 802.11p or WAVE; in fact, both in [43] and [44], the newer IEEE 802.16e standard [45] is noted as being the primary candidate technology for deployment. Other bands may also see use of V2V communications, such as dedicated military bands, aeronautical bands, at VHF and other frequencies.

B. *More on MIMO*

As noted, MIMO models come in both analytical and measured forms. The analytical work cited presents some clear guidelines for selection of antenna element separation and array type required for the best exploitation of rich scattering.

Yet rich scattering is not always present, particularly in expressway environments. In addition, both economic [46] and aesthetic considerations will likely limit antenna arrays to a few elements, with placement not always on vehicle roofs. Thus effects of the vehicle body on MIMO performance should be quantified when antenna elements are placed in a variety of locations (e.g., trunk, hood, interior, etc.). The use of dual polarizations also needs further exploration [56], as this can provide at least moderate link capacity gains.

C. Non-stationarity or Not?

Bello's framework [47] for modeling channels statistically has seen widespread use. The WSSUS assumptions are in fact so common that many simply tacitly assume these conditions apply. The growth of V2V measurements has forced researchers to re-evaluate the validity of the WSSUS conditions, and treat it as the special case it actually is [48].

As true for other channels, the V2V channel can be modeled as a linear time varying filter, hence the channel is completely described by the CIR. For simplicity of exposition, we discuss a SISO model, but this is easily generalized to MIMO cases. For durations within the stationarity time, the channel impulse response $h(\tau;t)$ is defined as the response of the channel at time t to an impulse input at time $t-\tau$,

$$h(\tau,t)=\sum_{k=0}^{L(t)-1} z_k(t)\alpha_k(t)e^{j\phi_k(t)}\delta[\tau-\tau_k(t)] \qquad (2)$$

where $\alpha_k(t)$ is the k^{th} resolved multipath amplitude at time t, and $\phi_k(t)=\omega_{Dk}(t-\tau_k)-\omega_c\tau_k$ is the k^{th} resolved multipath component (MPC) phase. The radian carrier frequency is ω_c and $\omega_{D,k}$ is the Doppler frequency shift associated with the k^{th} resolved MPC. The delta function is a Dirac delta and $\tau_k(t)$ is the time-varying delay of the k^{th} resolvable MPC.

The CIR representation in (2) differs from traditional ones [5] via a time-varying number of MPCs $L(t)$ and the MPC persistence process $z_k(t)$. The persistence process takes values in the set {0,1}, and was used in our models in [8] to account for finite "lifetimes" of MPCs. Fig. 1 shows example persistence processes of the 3rd and 5th taps for a segment of measurement data from a small city, from [49]. As can be seen the later (generally weaker) MPC of the 5th tap is present for a smaller fraction of time than the 3rd tap. Causes for this medium-scale or "mesoscale" [52] effect are hypothesized to be rapid obstruction from nearby vehicles, and delay "drift," where the MPC absolute delay changes over time so that MPCs move from one delay bin to another.

We showed in [50], [51] that if non-stationarity is *not* taken into account in modeling the channel, system performance results do indeed change. As noted in [14], this "birth-death" process introduces abrupt discontinuities in the fading samples, but this is easily remedied via interpolation if desired. We termed this persistence effect a "mesoscale" effect, which occurs at a rate slower than small scale multipath fading, but faster than large scale shadowing effects. In the V2V case, one example cause of this is blockage by another vehicle. The channel models in [53] provide multiple ways for modeling this "medium-scale" behavior, such as via 2D spatial filtering, turning entire clusters of multipath components ON/OFF, etc. Our binary persistence processes are modeled using Markov chains, as in [54] for a similar phenomenon in indoor environments, and we show next some new results.

In [49] we explored the use of higher-order Markov models for multipath persistence, and found that model order need not be larger than 2nd-order. We recently evaluated NS Markov chains, in which multiple 1st-order chains were used, sequentially, to represent different segments of measured data. The gains we observe in terms of agreement with measured data were marginal, thus indicating that our 2nd-order models are likely adequate to represent this phenomenon. Fig. 2 shows some histogram RMS-DS results for an urban V2V channel, in which it is clear that the use of persistence does make simulations better agree with measured data, but that NS Markov model improvements over stationary 2nd-order results are minimal. This is more apparent in Fig. 3, in which we plot similar histograms for delay interval I_{25} (the width of the PDP containing all multipath components within 25 dB of the peak). Logarithmic scales were used only for clarity.

D. Model Standardization

For widespread acceptance, V2V models must be standardized. Although results in [10] were used for the IEEE 802.11p (WAVE) standard, it is clear from Table I that even considering only delay dispersion on expressways, consensus has not yet been attained! Similar comments pertain to other modeling features (e.g., Doppler spectra) and other environments (e.g., urban). In addition, as far as we are aware, there are as yet no standardized MIMO V2V models.

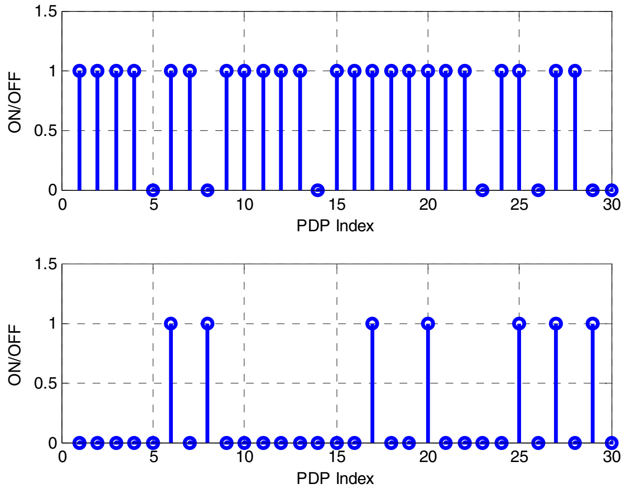

Fig. 1. Example persistence processes for taps 3 (top) and 5 (bottom) for segment of travel in small city, from [49].

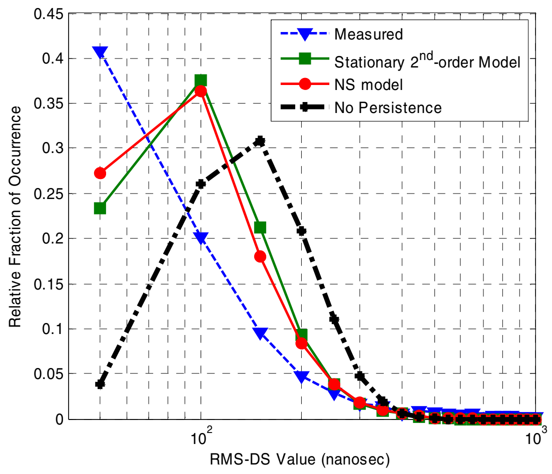

Fig. 2. Histograms for RMS-DS for measured data, and for various implementations of multipath persistence processes.

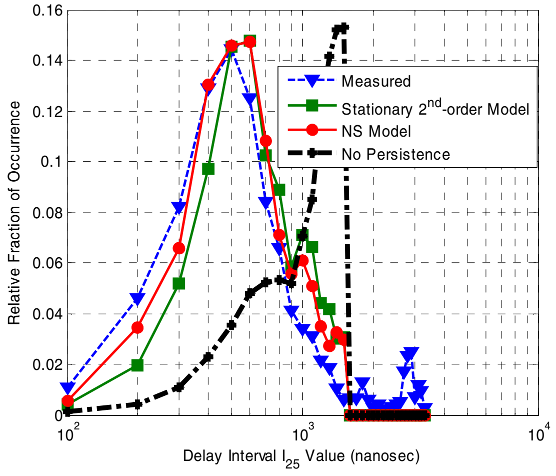

Fig. 3. Histograms for delay interval for measured data, and for various implementations of multipath persistence processes.

IV. ADDITIONAL REMAINING WORK

Beyond the areas already mentioned for future V2V channel work, we briefly note several others in this section. One area is the use of non-stationarity. For the greatest accuracy, NS effects must be modeled. The question—as noted in [48]—is "how much nonstationarity" is needed. The tradeoff here is the usual one between accuracy and complexity, hence more work on understanding the effect of NS on system performance (at the PHY and higher layers) is needed.

Although the geometric models (e.g., [41]) appear to be able to mimic actual environments, they obtain only reasonable agreement with measurements, and can not easily model diffuse scattering. These models require a substantial "set up" on the computer—in short, they are complex to use, and may not be easily tailored for standardized models.

A. *Traffic-Dependent Models*

In certain situations, such as when traffic density is high and links are short-range, multihop V2V communications may be prevalent. If accurate power control can be applied, simple short-range channel models may be of use. Similarly, for very low traffic densities, simple new models (simpler than the expressway models cited) may be of use.

B. *Outlier Terrain & Environments*

Certain types of terrain may induce channel characteristics not yet modeled. For example, in roadways that form "U" or "V" shapes, downhill then uphill, long-delay echoes may arise. Tunnels form another atypical environment; work in [55] is a good beginning. There may be other types of terrain and conditions such as mountainous areas or other off-road settings that should also be modeled, including three-dimensional highway models near expressway interchanges.

V. SUMMARY

In this paper we reviewed the state of the field in V2V channel modeling. We described various types of models for V2V channels, the obvious differences between V2V and cellular settings, and the ranges of some channel parameters found by multiple researchers. As do other researchers in this area, we believe that the statistical non-stationarity of the V2V channel should be modeled in some form, and that standardized models (incorporating MIMO), and models for additional frequency bands and V2V environments should be developed. In the conference presentation, we will provide more comparisons among existing models and additional coverage of recommended future work. In answer to the question posed in the title, our answer is, "no, not yet!"

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Information Hovering in Vehicular Ad-Hoc Networks

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***Abstract*—Information Hovering is a relatively new concept of information dissemination over a mobile set of peers. It naturally applies in many applications in Vehicular Ad-Hoc Networks, where useful information needs to be made available to all vehicles within a confined geographical area for a specific time interval. A straightforward approach, is to have all vehicles within the hovering area exchange messages with each other. However, this method does not guarantee that all vehicles within the hovering area will receive the message due to potential partitioning of the network in areas with low traffic density and/or low market penetration rate. In this work, we address the problem by applying probabilistic flooding schemes outside the hovering area. Informed vehicles outside the hovering area can serve as information bridges towards partitioned uninformed areas thus leading to high reachability. We consider a number of rebroadcast probability functions and we evaluate their performance using the microscopic simulation tool VISSIM. Our reference model represents a section of the road network in the cities of Bellevue and Redmond in Washington. The obtained results indicate that probabilistic flooding with a Gaussian like probability function outperforms other approaches by achieving high reachability values and a relatively small number of exchanged messages.**

I. INTRODUCTION

Vehicular Ad-Hoc Networks (VANETs) have recently attracted significant attention from the research community and the automotive industry as a tool to disseminate information among vehicles. Depending on the messages exchanged, VANETs can serve several purposes. They can greatly improve safety by informing drivers of imminent road hazards such as slippery roads [1], [2], [3], [4], they can improve comfort in driving by rerouting drivers to avoid traffic jams and they can serve as an entertainment tool by enabling on-the-road interactive games, file shearing and dissemination of advertisements to interested clients [5], [6], [7], [8].

Many applications in VANETs involve the exchange of information messages which are logically attached to a specific geographic area. For example, in case of an unexpected event such as a traffic accident it is important for all vehicles residing in the surrounding area to be notified of the hazard in order to take appropriate safety measures. In addition, the information must continue to lie in the area for a specific amount of time so that new vehicles entering the area are notified of the imminent danger. The same applies in the case of road works where warning messages can be issued to all vehicles in the area around the work zone to alert drivers of the irregular situation. Another example involves commercial enterprizes which wish to advertise their products to possible customers within the transportation network. These enterprizes can take advantage of the existing vehicular Ad-Hoc network to disseminate their advertisements in an area around their physical location.

In all the aforementioned situations, useful information must be broadcast to all vehicles in the specific geographical area and this information must be maintained in the area for a finite time interval dictated by the application, in order to notify new drivers entering the area of this useful information. The requirements as described above are closely related to the more general concept of information hovering.

The term ”Hovering Information”, introduced in [9], is a recent concept of information dissemination over a mobile set of peers, where the information itself is responsible for its own survivability. The main requirement of a single piece of hovering information is to keep itself attached at some specified location, which is called the *anchor location*, and to its vicinity area (*anchor area*), despite the unreliability of the device on which it is stored. In [10] the authors describe the concept in more detail and they outline the characteristics of a hovering piece of information. In [11] they present some usage examples of information hovering in a variety of applications of Mobile Ad-Hoc networks (MANETs). Finally, in [12] the authors formally define the concept of information hovering and they present simulation results for two algorithms whose objective is to ensure the availability of a piece of information at its anchor area.

As mentioned above, in VANETs there exists the need for Information Hovering protocols, which can facilitate the dissemination of useful messages in a specific geographical area and their maintenance in the area for a finite time period. Many solutions can be developed. However, the solution space can be refined by choosing solutions which make use of the available resources, as for example storage, power, bandwidth, etc., efficiently. In this work, our objective is to develop an information hovering protocol in VANETs, which achieves high message reachability to all vehicles lie and entering in the hovering area during the lifetime of the hovering information and at the same time minimizes the number of messages exchanged. Few number of exchanged messages imply fewer storage requirements, less power consumption and above all, low bandwidth use and low latency of information delivery.

The most common approach which can be adopted to achieve high reachability, is *blind flooding* i.e., all vehicles receiving the information message, broadcast the message to all neighboring vehicles. This method ensures the highest reachability possible at the expense, however, of an enormous number of exchange messages which, as mentioned above, is undesirable. In order to substantially reduce the number

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of exchanged messages, the obvious solution is to adopt blind flooding merely in the hovering area. However, this approach may also reduce the achieved reachability in the case of low traffic density. Low traffic density may cause the vehicular network to be intermittently connected. This implies that sections of the network which are partitioned from the information sources may never receive the messages; thus, the reachability achieved is low.

In this work, we address this problem by applying *probabilistic flooding* outside the hovering area. The reasoning behind this approach is that informed vehicles outside the hovering area can serve as information bridges towards partitioned uninformed areas, thus increasing message reachability. In addition, since blind flooding outside the hovering area is avoided, the number of exchanged messages is reduced. The use of location aware probabilistic flooding with the dual objective of reducing redundant messages and increasing the connectivity in case of low traffic densities in a specific area, has not been addressed in the literature. In addition, the models utilized in this study account for the special characteristics of VANETs which differentiate them from traditional MANETs such as, high mobility, confined and predictable movement. This has not been done in other studies pertinent to probabilistic flooding.

Probabilistic flooding works as follows: a vehicle, upon receiving a useful message retransmits the message with a probability p, which is calculated based on a probability function f. Our objective has been to investigate which probability function performs better by achieving high reachability and low number of exchanged messages. We focus on functions whose input variable is the distance of the receiving vehicle from the hovering area. Our performance evaluation method has been simulative. The reference model used represents a section of the road network in the cities of Bellevue and Redmond in Washington. We conduct all the simulation experiments using VISSIM [14], a microscopic simulation tool. The simulation scenarios involve different probability functions, different hovering areas and different market penetration rates. We infer that a Gaussian function with tuned parameters exhibits superior performance by achieving high reachability and relatively low number of exchanged messages.

The rest of the paper is organized as follows. In section II we provide a formal definition of the Information Hovering problem in VANETS and we describe in detail the considered information dissemination protocols. In section III we evaluate their performance using simulations and finally, in section IV we offer our conclusions and future research directions.

II. INFORMATION HOVERING PROTOCOLS

In this section we provide a formal definition of the Information Hovering problem in VANETS and we present the methodology and approach adopted to develop and evaluate an effective solution.

We consider a bounded geographical area which we refer to as the hovering area in which there exists at least one node which stores or generates information messages useful to all vehicles in the area. We refer to such vehicles as information sources. All equipped vehicles employ wireless communication to form a vehicular Ad-Hoc network which may also communicate with fixed infrastructure present in the region. The main objective is then for the information sources to utilize the vehicular Ad-Hoc network to persistently disseminate the useful messages to all vehicles in the hovering area. Persistent dissemination implies that the property of all vehicles receiving the message is not instantaneously achieved, but holds for an arbitrary time interval during which vehicles dynamically enter and leave the hovering area. The problem can thus be defined as follows:

Problem Definition:

Given a road map area which we refer to as the Hovering Area and a single message information data, it is required to find an Information Dissemination Protocol in VANETs so that when applied, a high percentage of Vehicles that exist in the area receive the message, with a small number of messages exchanged.

Our approach in this work has been to investigate through simulations the relative performance of a number of information dissemination schemes in order to infer which protocol satisfies, to the greatest extent, the objectives posed in the problem formulation. Below, we describe in detail and discuss the relative merits of the information dissemination protocols considered in the paper.

- **Blind flooding**: Blind flooding is a simple to implement and popular solution for many information dissemination problems. It involves each vehicle rebroadcasting the message whenever it identifies an uninformed neighbor. The main advantage of the protocol is that it guarantees the highest possible reachability as it unravels all possible routes to any given destination. However, this comes at the expense of a huge number of exchanged messages many of which are redundant.
- **Exchange messages if and only if both the sender and the receiver lie in the hovering area**: This method can be considered as a geographically confined blind flooding scheme. Its main advantage is that it drastically decreases the number of exchanged messages thus making more efficient use of the available resources. However, the protocol may lead to low percentage of informed vehicles. In cases of low traffic density, the network may become intermittently connected. When the partitioned areas of the network do not accommodate any of the information carriers, the vehicles within these areas cannot receive the useful information thus degrading performance in terms of the reachability achieved. In a worse case scenario, where all the information carriers lie on the boundary of the hovering area it is possible that they all move outside the hovering area thus endangering the survivability of the information. When this happens the system can only recover if an information carrier moves back to the hovering area.
- **Exchange messages if and only if the receiver is in the Hovering Area (Receiver in Area)**: This method attempts to alleviate the problem of low reachability in case of low traffic densities, by allowing vehicles which

lie within one transmission range from the hovering area to retransmit the received messages. Vehicles lying outside the hovering area can serve as information bridges between informed and uninformed areas thus increasing the percentage of informed vehicles. They can also help in improving the survivability of the information by providing an alternative way with which the information can return to the hovering area in case all information carriers move outside.

- **Probabilistic Flooding**: In a way similar to the previous protocol this scheme allows messages to be exchanged when the receiver lies within the hovering area. However, in order to further improve the achieved reachability, even in the case that the receiver lies outside the hovering area, the scheme offers the opportunity of retransmission by applying probabilistic flooding. Probabilistic flooding works as follows. When an informed vehicle identifies an uninformed neighbor and the neighbor lies outside the hovering area, the sender decides to transmit the message with probability p and decides not to retransmit the message with probability $1-p$. The probability p is calculated based on a probability function f. The function can have several input variables such as the distance from the hovering area, the traffic conditions, the priority of the message, etc., however, in this work we focus on a single input variable which is the distance from the hovering area. We consider strictly decreasing functions which cause the retransmission probability to decrease as the distance of the vehicle from the hovering area increases. The reasoning behind this design choice is that since the information is logically attached to a geographical area its usefulness decreases as the distance from the hovering area increases. We thus take advantage of this decrease in usefulness to decrease the number of exchanged messages by decreasing the retransmission probability. In this work we consider two probability functions: a strictly decreasing step function and a Gaussian like function. The step function is given by the following equation:

  $$p = \begin{cases} 0.80 & \text{if } d \le (r/4) \\ 0.60 & \text{if } (r/4) < d \le (r/2) \\ 0.40 & \text{if } (r/2) < d \le (r*3/4) \\ 0.20 & \text{if } (r*3/4) < d \le (r) \\ 0 & \text{if } d > (r) \end{cases} \tag{1}$$

  where d is the distance of the receiving vehicle from the hovering area and r is the vehicle's transmission range. We refer to the scheme utilizing this probability function as *Step probabilistic flooding*.

  The second function that we consider is a Gaussian like function given by the following equation:

  $$p = e^{-\frac{d^2}{2(2r)^2}} \tag{2}$$

  The above equation is obtained by considering a normal curve $p = \frac{1}{2r\sqrt{2\pi}} e^{-\frac{d^2}{2(2r)^2}}$ with mean 0 and standard deviation equal to twice the transmission range, which is then multiplied by a factor $2r\sqrt{2\pi}$. The latter multiplication is necessary to ensure that the transmission probability on the boundary of the hovering area is equal to 1. We refer to the scheme utilizing this probability function as *Guassian probabilistic flooding*.

III. PERFORMANCE EVALUATION

In this section we evaluate using simulations the performance of the information dissemination schemes presented in the previous section. We conduct our simulation experiments using the VISSIM microscopic simulation tool. The reference model used is drawn from a sample traffic setup of the simulator. It represents a section of the transportation network in the cities of Bellevue and Redmond in Washington.

We conduct each simulation experiment with a different seed number. The duration time of all simulations is set to 1000sec which is more than enough for the system to converge to its equilibrium state. The output of each simulation experiment is a text file which contains records for a number of fields such as the vehicle's id, the simulation step, the coordinates of each vehicle at every step, etc. The simulation step is set to 200ms and we consider data for 10 minutes.

In order to simulate the information hovering schemes presented in the previous section we have developed an application in C++ which processes the text files generated by the VISSIM simulator. The application takes a number of input parameters:

- *Vehicle Transmission Range*: Each vehicle selects its transmission range in a [min - max] interval according to a uniform distribution. The min and max values are the input parameters.
- *Hovering Area*: it can be defined as a circular area with input parameters the coordinates of the center and the radius of the circle.
- *Successful transmission probability*: In order to model problems in the communication channel which may lead to messages being lost, every transmission is characterized by a probability of successful delivery.
- *Market penetration rate of equipped vehicles (MPR)*: This parameter is defined as the percentage of appropriately equipped vehicles to participate in VANETs over all vehicles driving in the city.
- *Scanning Frequency*: This parameter sets the frequency with which each vehicle scans in its transmission range for any vehicles to exchange information with.

A. Simulation Results

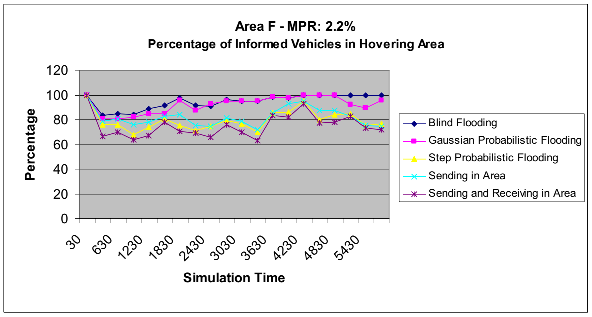
In this section we present the obtained simulation results. We consider a number of simulation scenarios reflecting different areas within the considered transportation network, with different traffic densities, and different market penetration rates. In all simulation experiments we consider the following parameter values: *Frequency of Scanning*: 1 second, *Transmission range*: 140-220m, *Successful Transmission Probability*: 0.8, *Hovering Area*: Circular Area with radius $R = 500m$. We also assume that the system has undergone an initialization procedure so that at its initial state, all vehicles within the hovering area possess the useful message.

In Fig. 1 we show a graphical representation of the simulation model generated on VISSIM. Within the considered geographical area we identify 7 hovering areas which we indicate on the diagram. We classify these areas in 3 categories based on their traffic conditions. Areas A and F report light traffic, areas C, D, E are classified as areas of medium traffic, whereas areas B and G are congested with heavy traffic reported within their boundaries. We use these areas to evaluate the performance of the considered hovering schemes in different traffic conditions.

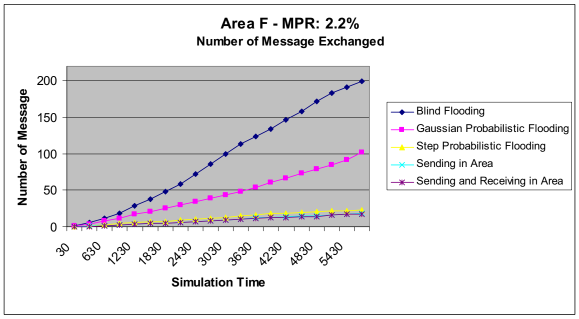
Fig. 1. Vissim model

Our first simulation scenario considers area F which, as mentioned above, represents an area of low traffic density. Initially, we consider a market penetration rate equal to 2.2%. In Fig.2(a) we show the time evolution of the percentage of informed vehicles within the hovering area whereas in Fig. 2(b) we show the time evolution of the number of messages exchanged for each of the considered hovering protocols. As mentioned above at the initial stage of the simulation all vehicles within the hovering area store the useful message. This is reflected in Fig. 2(a) as a 100% reachability value at time 0. As time increases, however, the reported reachability is shown to decrease. This reveals the problem of uninformed partitioned areas in the case of low traffic densities. As new cars enter the hovering area some of them are located at positions which are beyond the transmission range of the informed vehicles and can thus not be informed. This causes the percentage of informed vehicles to decrease. This behavior is common to all protocols. However, their subsequent behavior differs. Blind flooding, after some time, is successful in disseminating the useful message to almost all uninformed vehicles. This is highlighted in Fig.2(a) which shows that the percentage of informed vehicles, after some initial drop, gradually increases to values close to 100%. Similar behavior is exhibited by the Gaussian probabilistic flooding scheme. All the other protocols fail to recover from the original decrease, converging to reachability values close to 80%.

Fig. 2(b) reveals the main disadvantage of the blind flooding scheme. Blind flooding reports the greatest number of exchanged messages. Gaussian probabilistic flooding on the other hand, manages to achieve a significant decrease in the number of exchanged messages, almost by a factor of 2, while at the same time maintain reachability values comparable to the ones reported by blind flooding. The other protocols achieve a further decrease in the number of exchanged messages at the expense, however, of lower reachability values. Since our primary objective has been to achieve as high reachability as possible with the minimum amount of exchanged messages, our results indicate that Gaussian probabilistic flooding is the protocol of choice for the considered scenario.



(a) Reachability

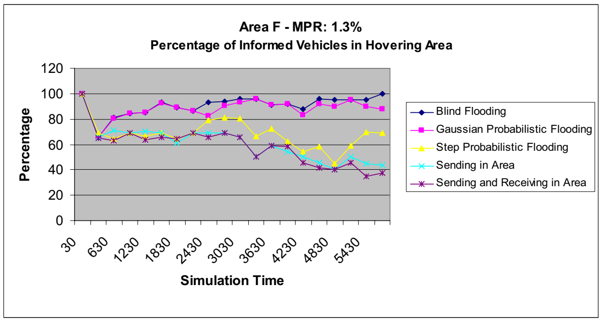


(b) Number of Exchanged Messages

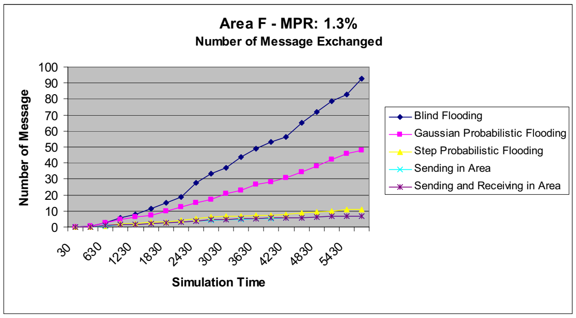
Fig. 2. Number of Exchanged Messages and Reachability in hovering area F with Market Penetration Rate equal to 2.2%

In order to investigate the performance of the considered protocols in the case of fewer vehicles being appropriately equipped to participate in VANETs, we repeat the same experiment with a market penetration rate equal to 1.3%. The results are shown in Fig. 3.

We observe that the system behavior is very similar to the one reported in the previous experiment. The major difference is that the protocols which were consistently reporting relatively low reachability, report even smaller values. The reason is that lower market penetration values imply less vehicles participating in the network thus creating a larger number of partitioned areas which exemplify the low reachability problem. Both blind flooding and Gaussian probabilistic flooding are shown to successfully alleviate the problem by converging to reachability values close to 100%. In addition, Gaussian probabilistic flooding is still the protocol of choice as it continues to reduce the number of exchanged messages by almost a factor of 2.

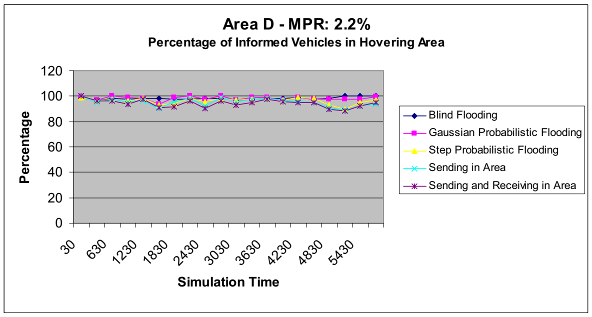


(a) Reachability

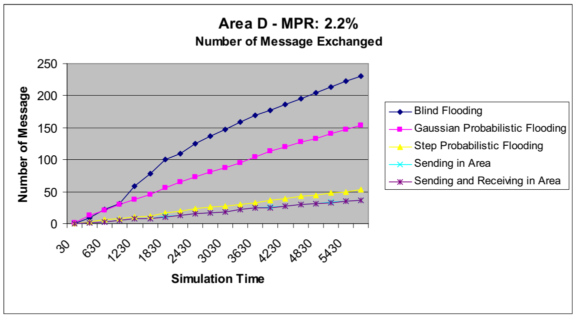


(b) Number of Exchanged Messages

Fig. 3. Number of Exchanged Messages and Reachability in hovering area F with Market Penetration Rate equal to 1.3%



(a) Reachability



(b) Number of Exchanged Messages

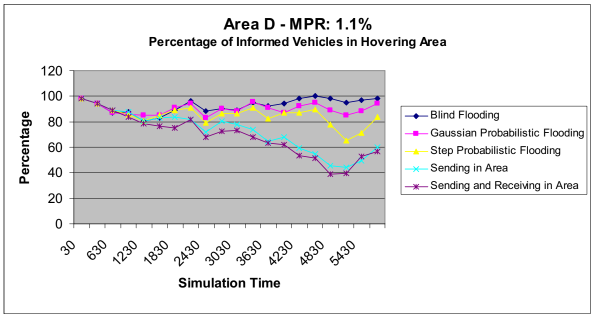
Fig. 4. Number of Exchanged Messages and Reachability in hovering area D with Market Penetration Rate equal to 2.2%

Our next set of experiments aim at investigating the performance of the considered protocols as the traffic density increases. We first consider area D, which represents an area of medium traffic, with a market penetration rate equal to 2.2%. In Fig.(4(a)) we show the time evolution of the percentage of informed vehicles within the hovering area whereas in Fig. 4(b) we show the time evolution of the number of messages exchanged for each of the considered hovering protocols.

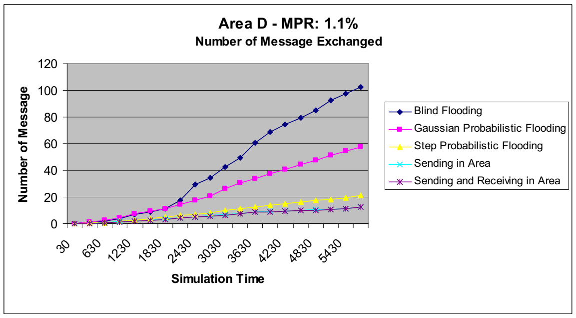
In this case, all protocols are shown to exhibit similar behavior in terms of the reachability achieved. They consistently report high reachability values close to 100%. The main reason for this behavior is that the medium traffic conditions combined with the relatively high values of the market penetration rate render the vehicular network to be almost fully connected. This means that by simply exchanging messages within the hovering area one can successfully disseminate the information to almost all vehicles within the area. Hovering methods which allow messages to be exchanged between vehicles outside the hovering area simply cause an increase in the number of exchanged messages without significantly improving the performance in terms of the reachability achieved. This is evident in Fig. 4 which shows that the Sending and Receiving in the Area scheme achieves high reachability values while at the same time reporting the smaller number of exchanged messages. This is the protocol of choice in this scenario. All the other protocols, with blind flooding being the extreme case, also report high reachability values at the expense, however, of a larger number of exchanged messages.

We repeat the same experiment after decreasing the market penetration rate to 1.1%. Since the number of vehicles participating in the Ad-Hoc network decreases, network connectivity also decreases, triggering reachability problems similar to the ones reported in area F. The results presented in Fig. 5 are thus in many ways similar to the ones presented in Fig. 2. The intermittently connected nature of the Ad-Hoc network causes the percentage of informed vehicles to experience a sudden drop at the initial stages of the simulation experiment. Blind flooding and Gaussian probabilistic flooding are then successful in alleviating the problem, by slowly increasing the reachability to values which are close to 100%. The rest of the protocols report much smaller values, with the Sending and Receiving in the Area scheme exhibiting the worse performance. Fig.5(b) then indicates that Gaussian probabilistic flooding does not only achieve high reachability values but also reduces to a significant extent the number of exchanged messages, making it the protocol of choice for this scenario.

Our final simulation experiment is carried out in area B which is characterized by heavy traffic. We consider a market penetration rate equal to 1.1%. The results obtained are shown in Fig. 6 and exhibit similar behavior to the ones obtained in previous experiments. Reachability initially decreases, due to the network being intermittently connected and Gaussian probabilistic flooding scheme solves the problem efficiently by reporting high reachability values with a small number of

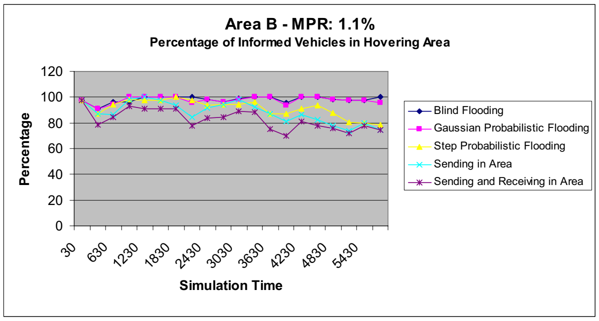


(a) Reachability

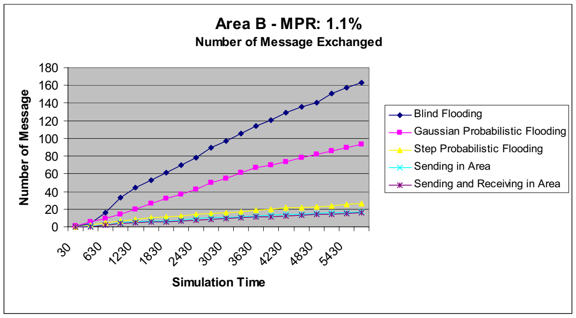


(b) Number of Exchanged Messages

Fig. 5. Number of Exchanged Messages and Reachability in hovering area D with Market Penetration Rate equal to 1.1%



(a) Reachability



(b) Number of Exchanged Messages

Fig. 6. Number of Exchanged Messages and Reachability in hovering area B with Market Penetration Rate equal to 1.1%

exchanged messages relative to blind flooding.

IV. CONCLUSIONS

In this paper we investigate the applicability of Information Hovering in VANETs. We consider a number of candidate solutions which we evaluate using simulations. Our results indicate that in case of an intermittently connected vehicular network, probabilistic flooding with a Gaussian like probability function outperforms other protocols. It achieves a high percentage of informed vehicles within the hovering area and at the same time guarantees a reduced number of exchanged messages thus ensuring efficient use of the available resources. In the future we aim at investigating the performance of a wider class of rebroadcast probability functions in a richer set traffic conditions and market penetration rates. We also aim at evaluating the performance of the proposed schemes using analysis.

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