A Sensor Network Approach for Intelligent Transportation Systems

Hemjit Sawant, Jindong Tan
Electrical and Computer Engineering
Michigan Technological Univ.
Houghton, Michigan, USA
jitan@mtu.edu

Qingyan Yang
System Division
Iteris Inc.
Madison Heights, MI, USA
kyang98578@yahoo.com

ABSTRACT

This paper presents a novel approach to increase the safety of road travel using the concept of wireless sensor networks for intelligent transportation systems (ITS). Safety of road travel can be increased if vehicles can be made to form groups for mutual interaction with each other. With the number of sensors available on vehicles increasing, a need has arisen to make collaborative use of the information collected by individual vehicles to form an enhanced data set to improve the inter-vehicle safety features. We discuss how a group of vehicles can form a mobile ad hoc sensor network and exchange data sensed by the on-board sensors. The fusion of these data could give a better understanding of the surrounding traffic conditions. An inter-vehicle communication (IVC) protocol which decides the manner of data exchange among vehicles based on the data contained in the messages is utilized for communication among vehicles. These messages are divided into two main types, namely, periodic and alert messages. Periodic messages can be generated by a sensor based control system on the vehicle and are transmitted at regular intervals to inform other vehicles. Alert messages are generated by the vehicle in an emergency situation, like, after an air-bag deployment. This differentiation is needed since periodic and alert messages are used to convey different types of data under different situations. This work also discusses exchange of alert messages between vehicles and fixed roadside gateways. This type of vehicle to vehicle and vehicle infrastructure integration (VII) raises the safety of road travel. Results of simulations in network simulator (*ns-2*), MATLAB and hardware experiments with mobile sensor nodes prove the effectiveness of the proposed IVC protocol for providing safety-related services to vehicles.

I. INTRODUCTION

Vehicle crashes in the U.S.A. account for more than a staggering 40,000 deaths, 3,000,000 injuries, and $150 billion in financial losses annually [36]. Traveling safety is always the most important issue in transportation systems. In general, there are several factors that cause road accidents, such as, human errors, mechanical failures of the vehicle, inclement weather conditions, and roadway limitations (e.g. pavement, lane geometry, etc.). Accident analysis results indicate that misjudgment made by the driver was the leading cause of accidents in the U.S.A [36]. Many accidents are caused when drivers lack a better understanding of the surrounding traffic conditions. This is because traditionally while driving, the driver not only needs to control his vehicle but also needs to pay attention to the movements of the vehicles around him. A driver cannot be fully focused on the road continuously due to many factors, such as, distractions or fatigue.

According to a survey done by the United States Department of Transportation [33], major vehicle crash types in USA are intersection, road departure, and rear end. In 1996, NHTSA convened a Collision Avoidance

System (CAS) Benefits Working Group that estimated the number of crashes that could be avoided in the United States with full deployment of rear end, road departure, and lane change and merge collision avoidance systems. It is concluded that more than 1 million or about 40% of the total crashes could be avoided if some safety measures, like an automated collision avoidance system or adaptive cruise control system, are implemented on vehicles. These could be further enhanced if inter-vehicle communication is used for transmission of alert messages among traffic. For examples, studies have shown that more than half of rear-end vehicle crashes could have been prevented if the driver was alerted about the impeding dangerous situation one-half second before the collision [15].

The automobile industries are working hard to enhance the vehicles' safety features by taking advantage of on-board sensor technologies. Drivers will be able to purchase vehicles with certain advanced safety features such as, collision avoidance, obstacle detection, range detection [12], reversing sensors, automatic braking [13], intelligent headlights [1], etc. to assist them to drive safely. The concept of these driver-aid systems is that, by using the information collected by the sensors on the vehicle, potential unsafe situations could be detected rapidly and automatically; and these captured data could alert the driver or help the driver with appropriate actions.

Safety of road travel can be increased if vehicles can be made to form groups for mutual interaction with each other. With the number of sensors available on vehicles increasing, a need has arisen to make collaborative use of the information collected by individual vehicles to form an enhanced data set to improve the inter-vehicle safety features. This work discusses how vehicles can form mobile ad-hoc networks and exchange data sensed by the on-board sensors. The fusion of these data could give a better understanding of the surrounding traffic conditions. The feasibility of using Bluetooth and IEEE 802.11 for data exchange among vehicles is evaluated. Coverage area and probability of detection for isotropic and non-isotropic sensors are analyzed to study the sensor network approach to avoid potential dangerous situations in traffic. Vehicle infrastructure integration (VII) is studied as a basis for data exchange among roadside gateways and vehicles on the road. Hardware experiments were performed to test the effectiveness of VII for communicating alert messages among vehicles. As the simulation results show, inter-vehicle communication (IVC) and sensor networks can be used collaboratively to increase the safety of road travel.

II. Analysis of Traffic Scenarios for a Sensor Network Approach

In the following sub-sections, several typical traffic scenarios are discussed which may lead to potential accidents and then it is shown how the potential accidents can be avoided, if the vehicles involved in these situations are equipped with sensors and have communicating capabilities to exchange data with other vehicles in the inter-vehicle network.

A. Rural area with single lane traffic

The common intelligent transportation System (ITS) infrastructure may not exist in rural areas, which may make the inter-vehicle cooperative safety features especially valuable. Considering the typical traffic situation depicted in figure 1, four vehicles A, B, C and D are shown on the road. Initially, assume that the vehicles are not equipped with any sensors and are not part of any sensor network. Vehicle A and vehicle C cannot see each other. If vehicle A tries to overtake vehicles B and D, it may collide with the approaching vehicle C. These types of accidents can be avoided with the help of sensors and intelligent sensor networks. Now, consider that vehicles A, B and C are equipped with front-collision avoidance sensors using millimeter-wave radar or scanning laser [11]. They also have communication capability using an inter-vehicle communication protocol like Bluetooth or IEEE 802.11 protocols [18], [30] so that they can exchange sensors' data among themselves. Vehicle D does not have such a system on it and hence is not part of the network.

Vehicles B and C can sense each other and so can vehicles A and B. So vehicle A knows that there is a vehicle approaching i.e. vehicle C and it will not overtake. We can see that this scheme works even if there is a vehicle in between two networked vehicles which is not part of the network, in this case vehicle

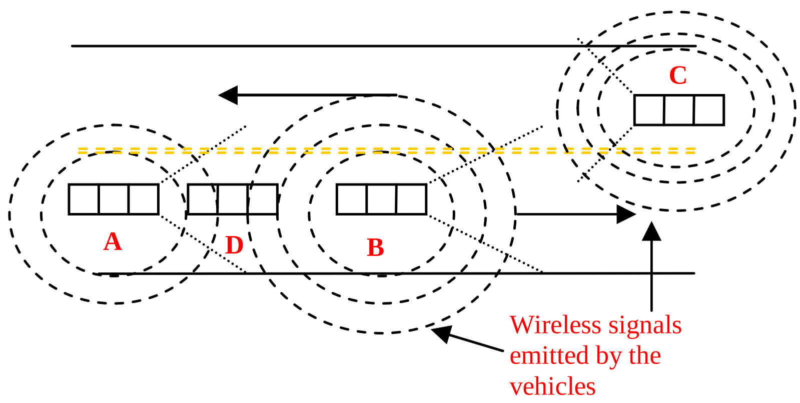


Fig. 1. Traffic on a bridge or in a rural area

D. The difficulty of forming an ad hoc network for this case lies in establishing communication between vehicles traveling along opposite directions. Results obtained in [25] show that Bluetooth devices have low device discovery time. This is encouraging, since for vehicles traveling in opposite directions the time for interactive communication is less. Also, as stated in [25], this time is independent of the type of Bluetooth device used. This can give consistent performance independent of the manufacturer of the Bluetooth device. Besides this, exchanging data among vehicles traveling in opposite directions can be used for many other applications. Consider that there has been an accident due to which traffic flow has been altered which may lead to a traffic jam. With vehicles having the ability to communicate with each other, the vehicles that pass this site can relay data about the accident to other vehicles approaching the site. These vehicles can then avoid this route and prevent a possible traffic jam.

B. Freeway: Entry and Exit ramps

Ramps, being the entries and exits of freeway systems, usually are places where many high velocity accidents take place because of the merging traffic and variation of the vehicle speed. Consider the case shown in figure 2. It shows an entry ramp onto a freeway. Vehicle A and vehicle C cannot see each other and this may lead to a collision since vehicle A wants to enter the lane. But if the vehicles can exchange data among them, then this can be avoided. As soon as vehicle A nears the ramp it becomes part of the ad hoc network and joins vehicle B and C. So now vehicle C knows that there is a vehicle entering from the ramp and it can adjust its speed to let vehicle A merge in between itself and vehicle B.

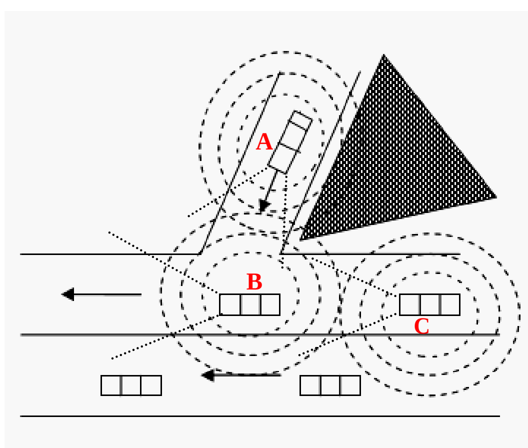


Fig. 2. Typical situation at an entry ramp

C. Street Corners

The traffic patterns at street corners are unpredictable and can often lead to dangerous situations. In figure 3, vehicle A wants to overtake vehicle B. Vehicle A cannot see vehicle C. If vehicle A changes the lane to overtake vehicle B it may collide with the approaching vehicle C. This could be avoided if the vehicles can exchange data. If vehicle B is equipped with vision sensors, it can sense vehicle C and send a signal to vehicle A that vehicle C is approaching. So vehicle A will not overtake and the collision will be avoided. The data flow from vehicle C to vehicle A has to pass through vehicle B. This can be achieved by the rapid formation of scatternets among the existing piconets. This will require the application of routing algorithms which can be used in such multi-hop ad hoc networks to route data among the vehicles.

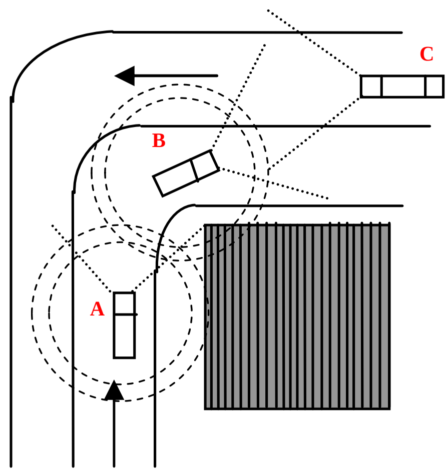


Fig. 3. Corners like these host many accidents due to driver misjudgment around the blind turn

D. Intersections

Even though the common ITS infrastructure based safety system may exist at certain intersections, still, a networked approach for communication among vehicles can increase the level of safety as we discuss below. Accidents at highway intersections can account for almost thirty percent of all the road accidents in the USA [33]. In Fig 4, a traffic scenario at a road intersection is shown. Assume that the signal for the horizontal lanes has been turned green and consequently the signal for the vertical lanes is red. Vehicle B wants to make a right turn while vehicle A wants to proceed straight from left to right. Neither of the vehicles can see each other due to vehicle C.

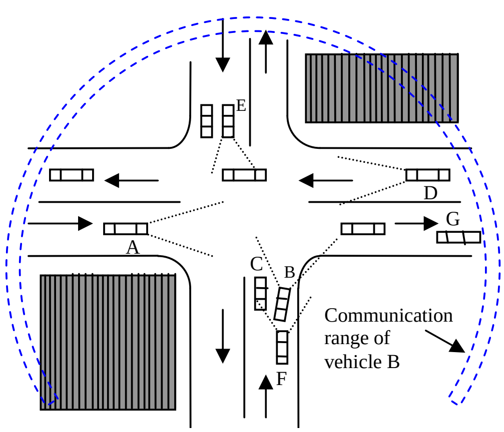


Fig. 4. Vehicles at an intersection

If the vehicles are able to communicate with each other, then vehicles A, B, D, E and F could form a sensor network and could communicate with each other. We show in chapter 3, section III-D how vehicles A and B can use their sensed data and data from other vehicles to avoid a collision even though vehicle C is blocking the direct line-of-sight view between them. Based on the scheme discussed in chapter 3, section III-D, each vehicle would know the position and the velocity of the other vehicle using area coverage techniques and would take appropriate measures to avoid the accident and cross the intersection safely. We can see in figure 4 that the communication range of vehicle B can cover all the vehicles at the intersection. The major challenges in such cases are that, there being many vehicles in its communication range, vehicle B should be able to obtain only those data which are useful while neglecting data from other vehicles. In figure 4, vehicle G has already turned right, so its information is not useful for vehicle B and hence should be neglected. Another challenge maybe that at intersections in urban areas, the wireless radio signals may experience some interference due to any buildings surrounding the intersection. This may affect the communication among the vehicles. Overall, our scheme proposes a method to exchange data among vehicles in real-time situations while traveling on the road. These data are obtained by various sensors mounted on the vehicles. Every vehicle contains the data gathered by different sensors on it. It is proposed that the IEEE 802.11 [18] or the Bluetooth technology should be the major data exchanging media protocol among vehicles. These data can be fused with data sensed by other vehicles and the driver can have a better knowledge of the surroundings.

III. Area Coverage For Inter-vehicle Communication and Coordination

The sensing and communication range for a vehicle are different. Generally, the sensing range is smaller than the communication range, and it is generally non-isotropic. By exchanging sensed data, via the wireless network, the area of coverage of each vehicle will be enlarged. The area of coverage is a measurement of the quality of service of a sensor network [14]. Coverage can be used to find weak/strong points in the sensor field, which could be used in future deployment schemes to improve quality of service. The sensor network coverage is also one of the metrics for energy preserving, node scheduling and self-organization of sensor networks. In this paper, the coverage of a vehicle in the traffic is discussed. In the area covered by the sensors, we use the probability of detection over the area to describe the performance of the inter-vehicle sensing.

A. Collision Avoidance Sensors and Their Area Coverage

Sensors are progressively being used on vehicles for the purpose of obstacle detection and collision avoidance. Currently, a variety of sensors ranging from temperature sensors to visual sensors are available on board. These sensors collect important data related to the vehicle [12], the driver [13], the passengers [8], as well as the vehicle's surroundings [14].

The millimeter-wave radar [29] can be used for detecting the distance of obstacles or other vehicles. Figure 5 shows vehicles equipped with a millimeter-wave radar traveling on the road. The millimeter-wave radar is based on the FM-CW (Frequency Modulated-Continuous Wave) radar system, and can detect targets even during stormy conditions. It can simultaneously measure both the target's distance and its relative velocity. It can, hence, be used in driving conditions with poor visibility, such as driving in a fog. In addition, a visual sensor or a camera can also be mounted on board for classification of sensed objects. It has been approved that cameras mounted on vehicles [27] could assist the driver to drive the vehicle more safely. If more than one type of sensors is used in a vehicle, it is necessary and possible to combine or fuse the data sensed by each sensor to facilitate processing and communication among vehicles [28].

The millimeter wave radar or the scanning laser sensors have been used on vehicles for the purpose of collision avoidance, obstacle detection, adaptive cruise control applications, etc. [11], [29]. They are non-isotropic sensors whose sensor detection model can be described as $p(d) = \frac{K}{d^{\mathbf{k}}}$, where K is the energy emitted, $\mathbf{k}$ is the decay coefficient, and d is the distance between the sensor and the object. The sensing

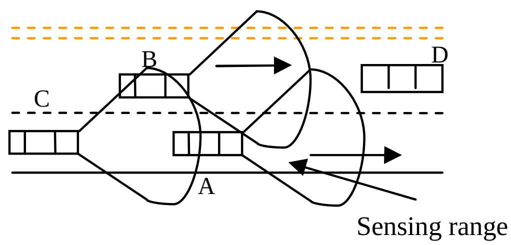


Fig. 5. Vehicles with MMW radar on the road

power of such sensors can be expressed as a normally distributed function as shown in equation 1. The sensing model follows a Gaussian distribution with mean μ and variance σ.

$$p(d|\,\mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(d-\mu)^2}{2\sigma^2}} \tag{1}$$

B. Sensor Network Model for Inter-Vehicle Communication

A vehicle may be equipped with different sensors. A sensor based control system (SBCS) can be put on vehicles to monitor the vehicle at regular periods and inform the driver about any possible malfunction. The detection models are different for different sensors. For example, the pedestrian detection sensor uses the energy emitted by the object. The signal from the target decays as a polynomial of the distance. The sensor intensity of a network of sensors can be defined based on the detection model [19]. Vehicles can also be equipped with ranging sensors such as millimeter-wave radar. The sensing area of the millimeter wave radar resembles a sector of a circle. Each vehicle equipped with such a sensor can detect objects or other vehicles in this area. However, radar has a certain field of view, from 150^0 to 270^0 and is generally non-isotropic. The sensing range of a sensor is the area in which it can sense the data. The communication range of a sensor defines the area in which it can interact with other devices which are often sensors.

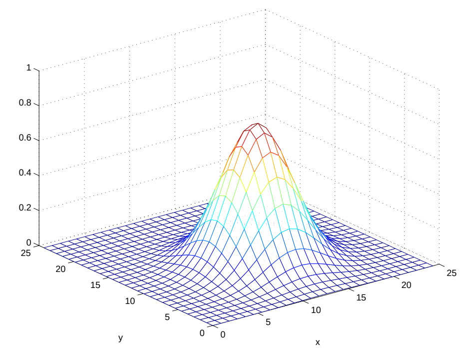
The SBCS should be able to generate messages based on the different vehicular sensor readings. It should also be able to recognize potential dangerous situations, like an air bag deployment, and generate and transmit the appropriate alert messages. The SBCS should be able to correctly interpret received messages in real time. It should generate different messages depending on the conditions of the vehicle and the surrounding traffic. Hence, the IVC protocol, like the one discussed in chapter 5, should be designed to differentiate between the various types of messages generated or received by the vehicle. The manner of exchange of these messages should also be different for each type of message.

Figure 6(a) shows the sensing model plot for an isotropic sensor while figure 6(b) shows the same for a non-isotropic sensor. An isotropic sensor can sense data all around itself i.e. it has a complete 360^0 of sensing ability. Whereas, non-isotropic sensors, like the millimeter wave radar or scanning laser, can sense data around it in a direction ranging from 150^0 to 270^0. Figures 6(c) and 6(d) show the sensing model plots for three isotropic and three non-isotropic sensors respectively. We can see considerable overlap among the sensing models of the three sensors.

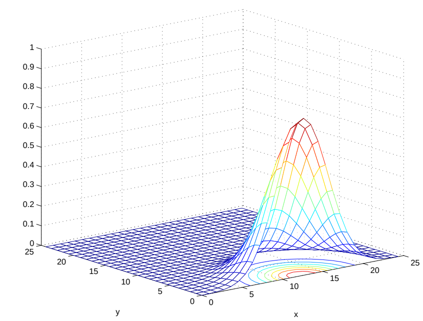
When the sensing ranges of vehicles overlap, as is seen in Fig. 6(c) and 6(d), the sensing strength in the overall area around the vehicles also increases. This in turn increases the probability of detection of any other sensors or obstacles or other vehicles without sensors which may enter that area. Hence, this leads to the overall increase of sensing ability of the sensors in that area. This can be effectively used for the collaborative exchange of data among the vehicles.

$$p = 1 - (1 - p_1)(1 - p_2)(1 - p_3) \tag{2}$$

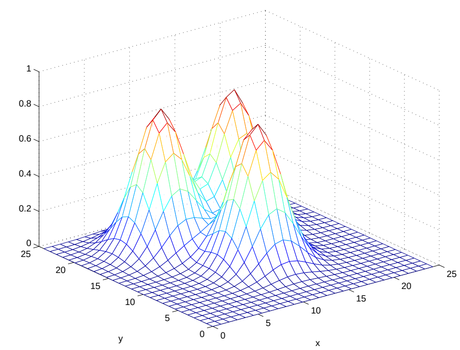
The probability of detection at the overlap area is defined by equation 2; where p is the total probability of detection and p_1, p_2 and p_3 are the probabilities of detection of individual sensors. It means that the



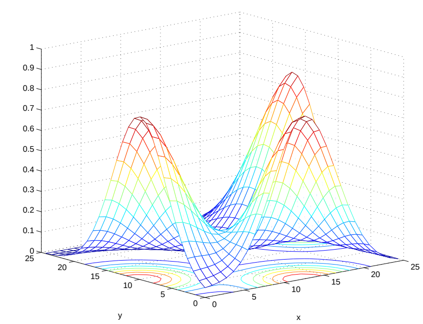
(a) Single isometric sensor



(b) Single non-isometric sensors



(c) Three isometric sensor



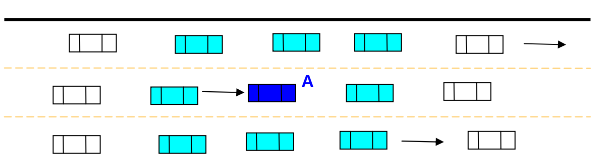
(d) Three non-isometric sensors

Fig. 6. Sensing models for isometric and non-isometric sensors

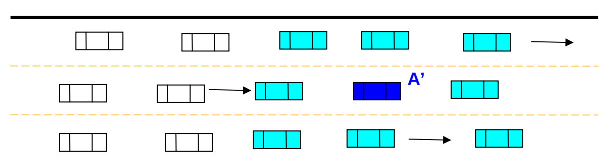
vehicles can effectively use data from other vehicles to gain a wider perspective of their surroundings. In the above detection fusion scheme, the distance between two sensors/vehicles is very important. For this purpose, sensor localization can be used. Sensor localization is a mechanism for discovering spatial relationships among sensor nodes. To localize itself, a sensor node first calculates its distance from its immediate neighbors which is called ranging and then it estimates its location using the ranging data and beacon node data. Ranging, finding the distance between two sensor nodes, can be done using the millimeter-wave radar which measures the distance between the nodes using the signal strength of the received signal.

C. Dynamic Cluster Formation for Inter-Vehicle Networks

Theoretically, the relevance of the data exchanged in inter-vehicle networks depends on the time the data exchange took place and also the position of the vehicles at the time of data exchange. This characteristic property can be referred to as spatiotemporal dependency of data [19].



(a) Vehicle A and its immediate neighbors in a cluster



(b) Vehicle A has moved ahead in its lane and so has the cluster associated with it

Fig. 7. Scenarios depicting formation of a dynamic inter-vehicle network

Normally, vehicles will keep on changing their positions while traveling along the road. A vehicle needs to periodically exchange data with its neighbors so that they are aware of any changes to the surrounding vehicles. Such dynamic change is a major characteristic of inter-vehicle networks. The establishment of inter-vehicle network is illustrated in two diagrams of figure 7(a) and figure 7 (b). Figure 7(a) shows vehicle

A and its immediate neighbors with one hop that are depicted as shaded vehicles. It can be seen that vehicle A and its immediate neighbors form a cluster with vehicle A at the center. Vehicles could periodically exchange data with other vehicles in the same cluster. It is possible that the transmission range of vehicle A covers more vehicles than its immediate neighbors, for example, the non-shaded vehicles. If those vehicles receive packets from vehicle A then the packets are considered as redundant because those vehicles are not the immediate neighbor of vehicle A. In figure 7(b), vehicle A has moved ahead in its lane to position A', possibly, after overtaking its preceding vehicle. The immediate neighbors of vehicle A have also changed. Consequently, the cluster associated with vehicle A has changed and can be said to have moved forward along with vehicle A.

The sensors need to be aware of their neighboring sensor nodes to decide about which data are relevant to them and which is to be discarded. For this purpose they need to make use of a global positioning model based on the other sensors in the network. Voronoi diagram and Delaunay triangulation are used to establish relationship among neighboring sensor nodes [6], [9], [31], [32]. Figure 8 shows a Delaunay triangulation for a group of vehicles traveling in the network. A Voronoi diagram is the dual graph of a Delaunay Triangulation. Each point in the Voronoi cell around a vehicle is closer to that vehicle than any other vehicles in the group. The Voronoi diagram thus gives us an idea of the coverage of each sensor in the network. Each point in the Voronoi cell around a vehicle is closer to that vehicle than any other vehicles in the group. The Voronoi diagram thus gives us an idea of the coverage of each sensor in the network. There is a link between any two immediate neighboring vehicles in the network having sensors. This link represents the flow of data between two vehicles.

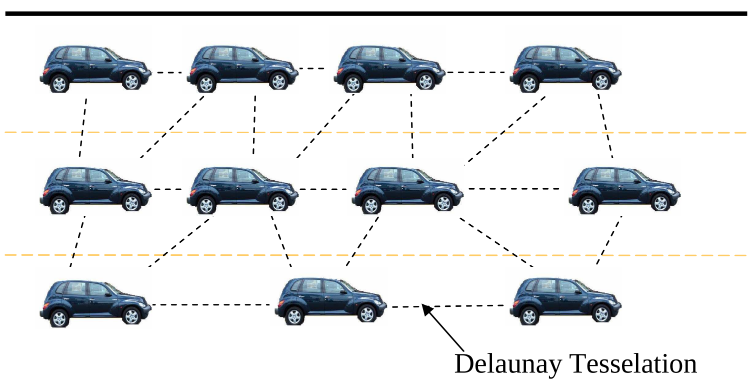


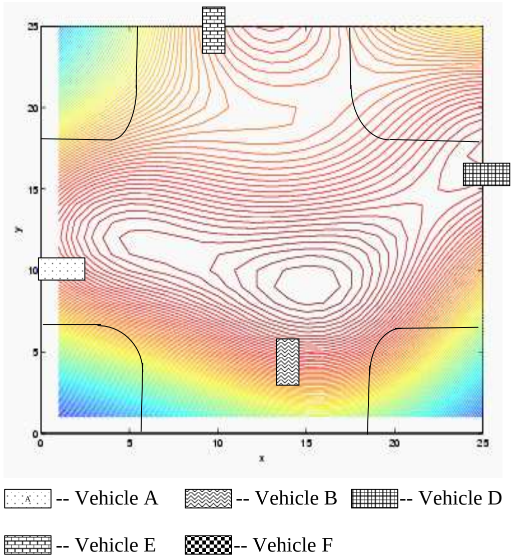
Fig. 8. Delaunay tessellation for a group of vehicles traveling on the road.

These sensor nodes can be considered as vehicles, $V = V_1, V_2, \ldots, V_n$ equipped with scanning laser sensors. Each vehicle can sense a certain region Ω. The sub region for a vehicle V_i is defined as $R_i = (x \,\epsilon\, \Omega \,|\, |x - p_i| < |x - p_j|) \quad j = 1, 2, ., n;\; j \neq i$. The vehicle, V_i, is called the generator of the diagram. R_i is the region of the convex polygon which the vehicle covers. Distributed algorithms can be used to define this Voronoi region for a group of vehicles traveling in the network [32].

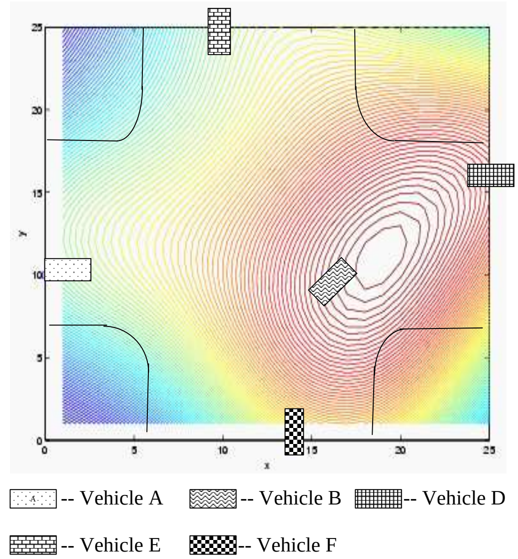
D. Example Traffic Scenario — Intersection

In this section, we apply our coverage based sensor network principles to the intersection scenario which was shown in figure 4 in chapter 1. The sensor area coverage plot for vehicle B at the intersection is as shown in figure 9 (a). As compared to the area coverage plot for a single sensor we can see that more area is covered when more sensors are used. This is because of the significant overlap in the coverage areas. But, not all the data that can be obtained at the intersection are relevant to vehicle B. Hence, for this plot, we have considered the sensed data only from vehicles A, D and E along with the data of vehicle B.

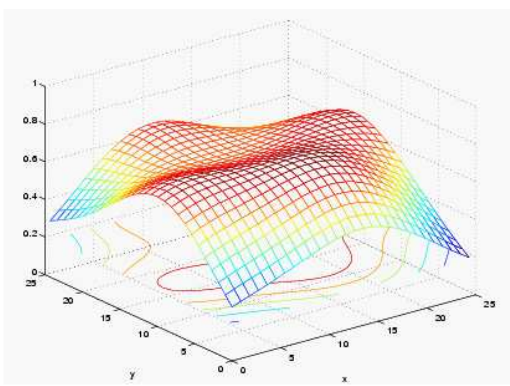
Figure 9(c) shows the plot for the probability of detection for vehicle B. For this plot too, we have considered the data from vehicles A, D and E along with the data of vehicle B. As is seen in 9(c), the



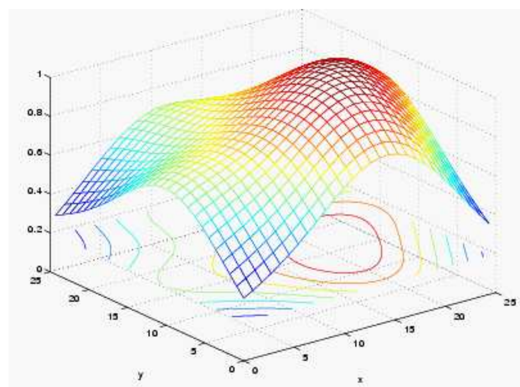
(a) Vehicle B and its immediate neighbors in a cluster



(b) Vehicle B has moved ahead in its lane and so has the cluster associated with it



(c) Plot of probability of detection for vehicle B



(d) The changed plot of probability of detection after vehicle B turns right

Fig. 9. Coverage area map and probability of detection at an intersection

probability of detection becomes more uniform than when a single sensor is used as in Fig 6(b). This means that the probability of detection of data (i.e. in this case another vehicle) increases due to the overlap in the sensor signals of the four vehicles.

To detect the changes in these plots we consider that vehicle B turns right while the other vehicles remain at their original positions. Figure 9 (b) depicts the area coverage map for this case after vehicle B has turned right. Figure 9(d) shows the probability of detection plot after vehicle B has turned right. We can see that the peak probability areas shift towards the right. This is because the sensed data of vehicle B now gets added with the data of vehicle D.

Based on our scheme, each of these vehicles can exchange its area coverage map with the other vehicles at the intersection that are part of the network. Using these maps vehicles A and B can predict that their paths will cross each other and can take appropriate action to avoid any collision. Thus, vehicle sensor systems can be programmed to recognize changes in coverage area and probability of detection plots and can use this sensed data to decide whether the path of the vehicle is safe.

IV. IVC Communication Protocols

A. Messages Analysis

Technically, the IVC communication protocol should provide a basis for data exchange among the vehicles. The inter-vehicle networks do have certain unique characteristics, such as, the anonymity of highly mobile hosts, highly changing speeds, which distinguish them from other mobile ad-hoc networks [3]. Due to this highly dynamic nature, sometimes it is difficult to establish relationships among vehicles based on their relative positions. It also makes the network routing protocol difficult. Therefore, the common communication protocol, which usually based on the exchange of request and reply packets among the hosts, is unsuitable.

1) Need for Periodic Messages: As mentioned above, vehicles that are equipped with an SBCS can generate messages at regular periods about the vehicle's information, such as, position, velocity, turn indication, etc. These messages are called periodic or regular messages. In figure 7, vehicle A is assumed to broadcast such periodic messages. Other vehicles in a single hop obviously can get the messages. These vehicles are referred to as immediate neighbors of vehicle A. Only these vehicles are needed to be aware of vehicle A's regular data since they are highly relevant. This reasoning is based on the principle that as long as there are no abrupt or emergency changes to the regular attributes of vehicle A, these changes will not directly affect the non-shaded vehicles or the non-neighbors of vehicle A. Therefore, the relevance of periodic messages will decrease if the messages are transmitted beyond a single hop. In figure 7, we also make the assumption that the communication range of vehicle A can only cover its immediate neighbors. In the real world, it may extend to vehicles that are further away from vehicle A. Since the data from vehicle A received by these non-neighborhood vehicles are not highly relevant to them, these vehicles could just ignore these messages. As it is later shown from our simulation results, this could help to reduce the exponential rise of the communications packets, which is being used in flooding protocols.

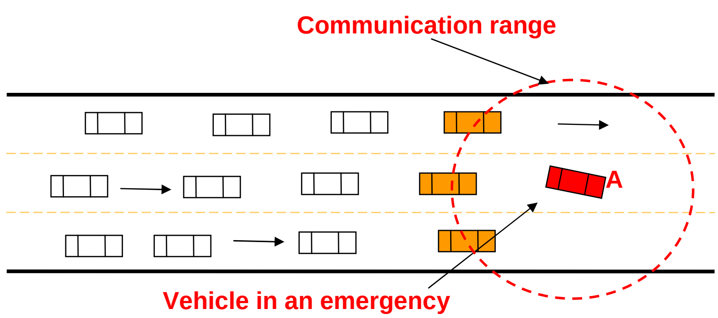


Fig. 10. Vehicle in an emergency emitting alert messages

2) Need for Alert Messages: Instead, broadcasting is usually used as the method of transmitting messages. This kind of data exchange may take place in the form of data packets that are transmitted over a shared radio channel. For example, the 2.4 GHz industrial, scientific and medical (ISM) band has been used to perform experimental studies involving IVC [4]. Meanwhile, the IVC protocol, like the one discussed in this paper, should be designed to be flexible enough to incorporate different message types in association with different application scenarios.

Figure 10 depicts an emergency scenario in which vehicle A has suddenly stopped in its lane, possibly due to a malfunction, accident or congestion. Vehicle A starts broadcasting alert messages. In such a situation, it is obvious that all the vehicles, including the non-neighbors of vehicle A, which are approaching this emergency site, need to be alerted. This can be achieved by using multi-hop transmission, in which vehicles keep forwarding the alert messages received from another vehicle [13]. In this way, even those vehicles that are not in the transmission range of vehicle A will be alerted. This may raise another question that a vehicle may receive the same alert message repeatedly, which will lead to an exponential increase in the message count. In order to avoid this problem, we have used an alert message count in our communication protocol to limit the communication redundancy. In addition, the chances of broadcasting alert messages should be significantly less than the chances of broadcasting periodic messages, but it should have higher priority level. According to the FCC rules, safety applications should always have priority, if there ever be a conflict, safety applications will always be able to have the ability to interrupt or override other low level priority applications.

In summary, as a vehicle traveling on the road, there need at least two types of data exchanging among vehicles for safety purpose. One is the regular periodical message generated by the SBCS to reflect the dynamic change status of each vehicle. These data are only exchanged among immediate neighbors with one hop. The other one is the alert message, which is only generated during an emergency situation. This type of message should be forwarded to the downstream vehicles as much as possible.

B. IVC Communication Protocol

Figure 1 shows the pseudo-code depicting the proposed inter-vehicle communication protocol. For periodical messages, the broadcast uses flooding protocol, in which every vehicle broadcasts periodic messages at regular intervals. Flooding was used for communication among mobile hosts in [21]. Our protocol requires that the medium access control (MAC) layer is able to support the transmission of different sizes of messages with different priorities. The IEEE 802.11e protocol [18] provides such functionality through its enhanced distributed coordinated function (EDCF), which is highly suitable for the exchange of alert messages and periodic messages over the same radio channel within inter-vehicle networks. The alert message count can be set to a pre-defined value (say N, as shown in the pseudo-code). A high alert message count indicates that more alert messages will be broadcasted. This ensures that more vehicles will be alerted. This is necessary, especially, for the vehicles traveling in opposite directions with less interaction time. Meanwhile, this protocol gives preference to the transmission of alert messages over periodic messages. This protocol also assumes that a vehicle's own emergency should be given a preference over the emergency of other vehicles.

Algorithm 1 IVC Communication Protocol: Pseudo-code of proposed communication protocol

```
while 1 ≠ 0 do
  transmit periodic message
  if alert message is generated then
    set alert message count as zero
  end if
  if alert message count < N then
    transmit alert message
    increment alert message count
  end if
  if alert message is received then
    transmit alert message
  end if
end while
```

Table I shows the contents of a typical periodic data packet and an alert message packet. The size in bits of the various packet fields has been assumed to be similar to that used in [10]. The packet header contains the cyclic redundancy check (CRC) of the packet data. It serves as a check to ensure that the packet has been correctly received. The table I also shows the contents of an alert message broadcast by a vehicle and by a roadside gateway, respectively. The alert type could be encoded to reflect different emergency situation, such as, emergency braking, air-bag deployment, and congestion etc. Alert messages have a hop count field, which is incremented each time the packet has been transmitted by a vehicle. It indicates how many hops the packet has traveled from the vehicle that generated it. There may be some typical drivers who, in order to preserve their secrecy, would not want to share their vehicle's information among other vehicles. They

TABLE I

PACKET FIELDS AND SIZE OF MESSAGES

Periodic message

Data Field	Size (bits)
Packet Header (includes CRC)	8
Vehicle position (GPS)	48
Velocity	12
Bearing	12
Turn Indication	12
Other data	33
Total	125

Alert message generated by vehicles

Data Field	Size (bits)
Packet Header (includes CRC)	8
Packet hop count	3
Vehicle position (GPS)	48
Alert data	32
Total	91

Alert message generated by road-side sensors

Data Field	Size (bits)
Packet Header (includes CRC)	8
Alert data	32
Total	40

may turn off the vehicle's communication radio. Hence, we have proposed the use of scanning laser on all vehicles so that at least an adaptive cruise control system can function and safety is not compromised to a great extent.

V. SIMULATIONS AND EXPERIMENTS

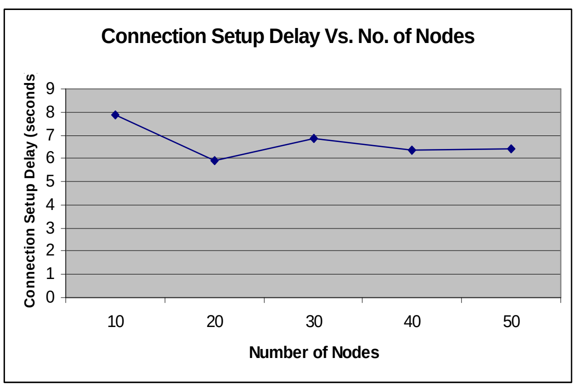
A. *Wireless Network Protocols for IVC*

A number of wireless network protocols, such as IEEE 802.11, Bluetooth, IEEE 802.16 and IEEE 802.15.4 can be used for communication among vehicles. This study chooses BlueTooth and IEEE 802.11 for simulation since the hardware is available. Bluetooth is an open specification for short-range communications of data and voice between both mobile and stationary devices [30]. Bluetooth has a raw bandwidth of 1 Mbps. It also provides three levels of security. A Bluetooth device can discover other Bluetooth devices in its communication range by the process of inquiry. During inquiry, the listening and the sending nodes hop using the same sequence. A sender can inquire more than one listener and collect data about them, such as, their clock offsets. In the paging procedure, messages are unicast by the sender to a specific listener. On receiving an acknowledgment message, the sender becomes the master while the listener becomes the slave. In this way, Bluetooth devices can form piconets and communicate among themselves. A piconet can contain up to seven active slaves and one master. If a master device has more than seven slaves then some of the slaves have to be parked. Hence, to communicate with a parked slave a master has to unpark it first, consequently, parking some other active slave. Two or more piconets can be joined together to form a scatternet. The Bluetooth standard allows a device to have multiple roles. It can be master in one piconet while it can be a slave in one or more other piconets. But, a device can be active only in one piconet. To become a member of another piconet, a device has to switch to the hopping frequency sequence of the other piconet. Communication among slave devices has to be performed through the master. Using such piconets and scatternets, vehicles can communicate their sensed data with other vehicles in the network and can travel safely along the road aware of the surrounding traffic movements.

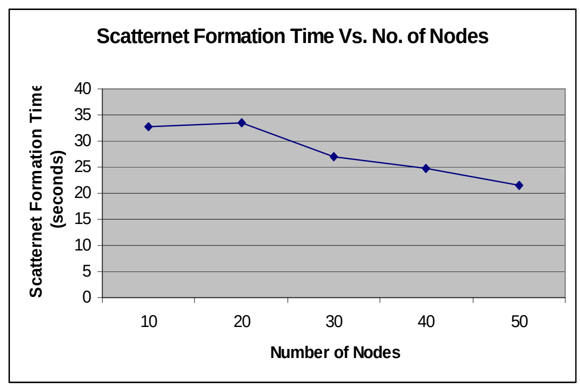
To achieve the "cooperative" concept of VII, the key issue is to find a way to establish the wireless communication links between vehicle and ITS infrastructures, as well as between vehicle-to-vehicle. The Dedicated Short Range Communication (DRSC) has been identified as the potential solution for vehicle to roadside communication media. And the 5.9 GHz DSRC standard has been approved by the Federal Communications Commission (FCC) for ITS applications [7]. For instance through DSRC, in VII traffic safety scenarios, the data from road-side gateways [24] can be transmitted to moving vehicles to alert them about any emergency situations like road blocks, traffic jams, ice-accumulation, etc. IEEE 802.16 is a potential solution for IVC and VII. IEEE 802.16 supports point-to-multipoint architecture in the 10-66 GHz range, transmitting at data rates up to 120Mbps. The 802.16 medium access control (MAC) layer (define) supports many different physical layer specifications. IEEE 802.16 task group is working on adding portability and mobility to the standard. This group will address many different mobility issues, including providing connectivity to moving vehicles within a base station's sector.

B. Bluetooth Simulations

To evaluate the performance of the Bluetooth protocol we used the Blueware simulator [2]. The Bluetooth devices that can be simulated using the Blueware simulator are equipped with different modules which implement many aspects of the Bluetooth protocol. In inter-vehicle networks, vehicles equipped with Bluetooth radios need to discover other such vehicles in their communication range to establish communication with them. The simulated environment was 25m by 25m. The Blueware simulator places the specified number of Bluetooth nodes in the simulated environment randomly. Each node has a communication range of 10 meters.



(a) Average connection setup delay for different number of Bluetooth nodes



(b) Scatternet formation time for different number of Bluetooth nodes

Fig. 11. Evaluation of Bluetooth protocol

Figure 11(a) shows the plot of connection setup delay against the number of Bluetooth devices. The connection setup delay is the time taken for a Bluetooth device to establish its first communication link with another Bluetooth device. It indicates the time taken for a Bluetooth node to discover other Bluetooth devices in its communication range. As can be observed from figure 11(a), the connection setup delay is fairly constant when the number of nodes is increased from 10 to 50. This indicates that Bluetooth devices can be used for communication in inter-vehicle networks to provide fairly consistent performance even when the number of vehicles is not constant or is changing; as is inherent in vehicle traffic networks.

Figure 11(b) shows the plot for the time taken for the formation of a connected scatternet consisting of all the simulated Bluetooth devices against the number of Bluetooth devices. It can be seen that a slight decrease is observed in the scatternet formation time with the increase in the number of nodes. As the number of nodes increase, there is more overlap in their communication ranges since the simulated area is kept constant.

The results obtained clearly indicate that Bluetooth can be efficiently used for inter-vehicle communication. But, these results will vary when such a Bluetooth based inter-vehicle network is actually implemented in the real world. Vehicle mobility will play an important part in inter-vehicle communication. The type of scatternet formation algorithm used will also affect the network formation time.

C. IEEE 802.11b Simulations

The network simulator (ns-2) [38] was used to simulate the inter-vehicle networks. The vehicles were modeled as wireless nodes capable of communication using the 802.11b medium access protocol provided in the simulator. The roadside gateways were also modeled in the same way, but, kept stationary. The simulated freeway length was 1000 m, with a width of 100 m and with 6 lanes in each direction. The transmission range of a vehicle was set as 80 meters. Each of the vehicles was equipped with an omni-directional antenna. It was assumed that each vehicle was equipped with a sensor based control system (SBCS) like the one discussed in chapter 3, section III-B. There were totally 80 simulated vehicles, 40 in one direction. The maximum relative speed for the vehicles was 40 mph i.e. the vehicle with the maximum speed was traveling at 75 mph while the vehicle with minimum speed was at 35 mph The periodic messages transmitted by vehicles were kept as 128 bits (instead of 125 bits) so that they could be encoded as 16 bytes. Similarly, the alert messages were kept as 96 bits (instead of 91 bits). The alert messages transmitted from roadside gateways were 40 bits (5 bytes) long. To simulate the delay caused due to packet queuing and channel contention in real time data transmission, a delay of two milliseconds was added to the wireless links.

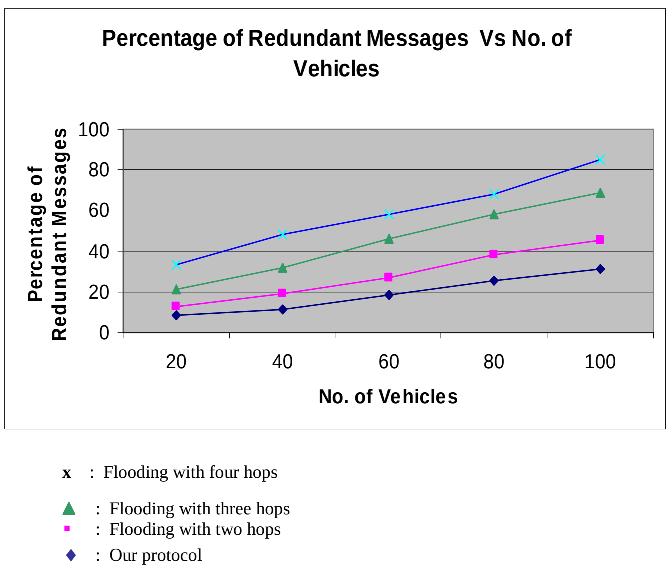
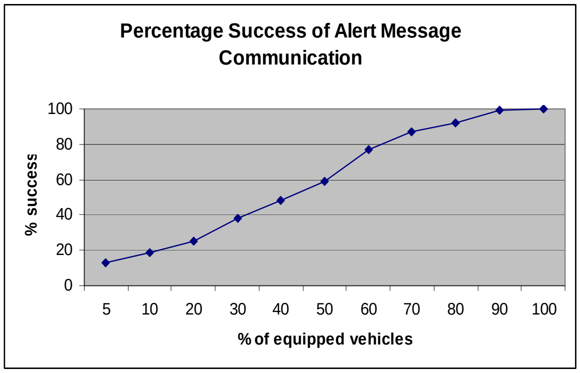


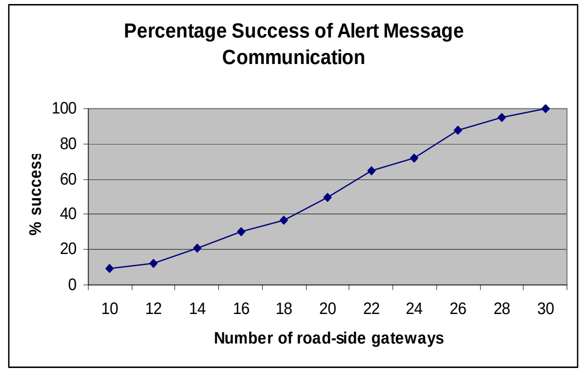
Fig. 12. Comparison of the performance of an ordinary flooding protocol (with two, three and four hops) with that of our protocol

D. Plot for Periodic Messages

A common flooding protocol suffers from the problem of exponential increase in the number of packets. Using such a flooding protocol for multi-hop inter-vehicle networks shall make this problem worse since vehicles will be re-broadcasting the periodic messages. This will lead to large number of redundant packets within the inter-vehicle networks. Hence, we proposed that broadcasting of the periodic messages should be limited to one hop. Figure 12 shows the plot of no. of redundant packets, as a percentage of the total number of packets broadcast, against the number of vehicles. Packets that were received by non-immediate neighbor vehicles were considered as redundant packets. We assumed that every vehicle was broadcasting a periodic message every one-second. As shown in figure 9, our proposed protocol has the least percentage of redundant messages given different number of vehicles.



(a) Percentage success rate for alert messages generated by a vehicle



(b) Percentage success rate for alert messages generated by road-side gateways

Fig. 13. Alert message transmission success rate

E. Plot for Alert Messages

Figure 13 shows the plot for the percentage of success of getting the alert messages against the percentage of equipped vehicles. For the plot in figure 13(a), the alert message was generated by a vehicle situated fairly in the center of the simulated environment while for figure 13(b) the alert message was generated by the road-side gateways. The maximum number of hops that an alert message could travel was kept as 4. For both the plots, the fact that a particular vehicle received an alert message was decided by reading its trace or .tr file. From figure 13(a), the percentage of successful reception of alert messages increases as the percentage of equipped vehicles increases for both the plots. This clearly states that more the number of equipped vehicles, more is the probability of retransmission of alert messages and more is the number of vehicles that will be alerted. In figure 13(b), the number of road-side gateways was increased from 10 to 30. The gateways were evenly spaced and distributed equally; half of them being on one side of the simulated freeway while the other half being on the other side. It was observed that as the number of road-side gateways was increased the percentage of success of the protocol rose. With just 30 road-side gateways, i.e. 15 on one side of freeway, a success rate of 100 percent was achieved. Thus, vehicle infrastructure integration (VII) was successfully simulated for the communication of alert messages.

F. Hardware Experiments

Figure 14 shows the CotsBots [5], commercial off-the-shelf mobile robots, which were used as the hardware platform for performing experiments involving the concepts of Vehicle Infrastructure Integration (VII). These mobile cars are equipped with the MICA2 [34] motes which have different types of sensors, that sense temperature, light intensity, etc. These motes are capable of wireless communication. MICA2 motes also have an accelerometer and a magnetometer to control the speed, turn direction, acceleration, bearing, etc. of the mobile cars using a motor board component. The motes are programmed using NesC [26] programming language in the TinyOS [34] operating system for embedded devices.

Experiment 1: Scenario of Inter-vehicle Alert Message. Two mobile motes were used in this experiment. Both moved at different speeds with one car following the other, like usually happens on a freeway. The vehicles were in each other's transmission range, which is about 1000 feet. One mote was programmed to halt abruptly (i.e. its speed was reduced to zero) after a certain time (set using the Timer interface). As soon as this event occurred, this mote transmitted an alert message over the radio interface. When the other mobile mote got this message it reduced its speed to a pre-defined value. This experiment emulated an emergency situation, where a vehicle abruptly brakes and sends an alert message to warn other vehicles. These vehicles reduce their speeds on reception of such an alert message.

Experiment 2: Scenario of Speed Limit Alert. Vehicles need to follow certain speed limits depending on the type of road that they are traveling on. In this experiment, a fixed mote (road-side gateway) was

Fig. 14. A group of static sensors and mobile robots for the hardware experiments

used to alert vehicles about the permissible speed limit. One mote, which was fixed, was programmed to broadcast wireless messages (alert messages) containing the permissible speed limit. Other mobile motes were programmed with different speeds and were made to move in the transmission range of the fixed mote. In this way, the mobile robots emulated vehicles traveling on the road while the fixed sensors emulated roadside gateways. When the mobile motes received the messages sent by the fixed mote, the value in the received packet was compared with the current speed of these mobile motes. If the current speed was more (i.e. they were over-speeding) then an alert beep was sounded; otherwise, the packet was discarded.

VI. Related Work

Research based on inter-vehicle communication (IVC) has been actively performed in some countries such as he USA, Japan, Germany, Spain [16], [35]. It can be mainly divided into platoon and non-platoon based research. A platoon is a formation of vehicles traveling together as a group on specially designated highway lanes. The number of vehicles in a platoon and their corresponding identification are known. As the early demonstration of intelligent vehicle technologies, the California PATH program [17] focused on creating a complete Autonomous Highway System (AHS) in which vehicles travel together in platoons. The California PATH program discussed the operation of an automated highway system (AHS) where platoons of vehicles were controlled autonomously. However, it requires changes to the existing highway infrastructure to implement such a system, as discussed in [17]. The main drawback of platoons is that each platoon member should maintain its individual stability and also the stability of the entire platoon. Delays, possibly due to speed perturbations, may occur in the response of a vehicle to the dynamic changes of its preceding vehicle which may affect the stability of the entire platoon. The platoon solution is too realistic for the existing freeway system, and it requires separated special highway lanes for effective operation. Also, in the real world, the idea of forming platoons cannot be practically realized in everyday traffic which follows random patterns which vary depending on the type of vehicle and its driver. The platoon approach shall only be applicable to a certain category of vehicles (for e.g. truck fleets).

A study of safety and reliability of the AHS has been performed in [20]. This study focuses on the exchange of data between the AHS and the vehicles for providing forward obstacle collision avoidance. Again, this type of an approach shall require sensors and other data processing equipment to be located along highways that can communicate data with the vehicles. In contrast to this approach, we discuss the periodic exchange of vehicle data among vehicles. This will keep the vehicles informed about the movements of other vehicles around them which can efficiently help to avoid collisions.

A cooperative adaptive cruise control (CACC) system for vehicles traveling in a platoon has been discussed in [23]. It discusses the periodic exchange of vehicle data, like velocity and acceleration, between the preceding and the following vehicles in a platoon. This study assumes that at most only two vehicles can be involved in the CACC system. But, in real traffic scenarios with random movements of vehicles, the movements of a single vehicle can be affected by the movements of more than one vehicle. Also, this scheme suffers from all the inherent drawbacks of platoons. In our opinion, if vehicles exchange their periodic data with other vehicles, like we have proposed in our protocol, then such a type of a CACC is not required. This periodic exchange of messages will keep the vehicles informed about the velocity or acceleration changes of other vehicles around them and they can all travel in a safer manner.

Regular everyday traffic falls into the category of non-platoon driving. The vehicles change their positions randomly. This randomness creates certain inherent problems like, anonymity of hosts, or difficulty to implement a routing protocol. Hence, the success of any communication protocol for non-platoon traffic depends on the periodic exchange of vehicle data with other surrounding vehicles.

The DEMO 2000 [35] driving program discusses the implementation of an autonomous distributed communication system among vehicles. We follow this approach and assumes that vehicles can form ad-hoc networks among themselves for the exchange of data.

The Fleetnet project [16] has been designed to support IVC and vehicle to roadside-gateway communication. This project makes use of the UMTS Terrestrial Radio Access with Time Division Duplexing (UTRA-TDD), which has a communication range of more than 1 km. With such a large communication range, many redundant data messages will be exchanged among the vehicles especially, during high traffic density. This can lead to channel contention problems. Hence, in our protocol we have assumed the communication range less than 100 meters. This has two main benefits. Firstly, the cost of the radio devices will be reasonable. Secondly, the number of redundant messages will be lesser since a vehicle will be able to communicate with fewer number of surrounding vehicles which are its neighbors. Multi-hop transmission is used for spreading alert messages.

The R-ALOHA protocol based on data exchange among vehicles over a broadcast channel using time slots reserved for data transmission from each vehicle is discussed in [37]. This protocol does not incorporate communication among vehicles and road-side gateways. In our simulation results, we have shown that using slightly different data packets such communication, among fixed road-side gateways and vehicles, can be used efficiently for the transmission of emergency messages. Our protocol emphasizes the fact that it is important for the vehicles to recognize the different messages it receives and then decide the type of message which it should transmit next.

An approach to multicasting messages among highly mobile hosts in ad hoc networks is presented in [3]. It suggests a new definition of a role-based multicast that suits the special needs of inter-vehicle communication. A multicast group is defined implicitly by location, speed, driving direction and time. In this state, the resulting ad hoc network tends to be disconnected.

The formation of multi-hop networks among vehicles in an ad-hoc network is discussed in [22]. A simple multi-hop broadcast protocol is proposed. As each packet is hopped through the network the amount of data to be transferred decreases according to a predetermined cost function. The size of the retransmitted packet is reduced at every subsequent hop. This ensures that the nearby vehicles get the most data while the vehicles further away get less data. The protocol discussed in [22] assumes that vehicles are equipped with directed antennas and can communicate with only those vehicles that are in the antenna's angle of communication. In contrast, our approach assumes that vehicles are equipped with omni-directional antenna having a circular range of radio transmission (vehicles used in our simulations were equipped with such an antenna). An omni-directional antenna, unlike a directed antenna, can be used to provide communication between vehicles traveling in opposite directions, especially on single-lane two-way roads.

VII. CONCLUSION

This paper presented the approach of sensor networks and inter-vehicle communication (IVC) to increase the safety of road travel. Our scheme does not require additional changes to the existing highway infrastructure. We have shown, using various examples, that the exchange of sensed data among vehicles can be beneficially used to avoid accidents. Isotropic and non-isotropic sensors were studied with respect to the coverage area and the probability of detection. In our simulations, we considered a typical highway intersection and plotted the sensor coverage area and the probability of detection for various vehicles equipped with non-isotropic sensors. The simulation results of the proposed IVC protocol using *ns-2* were encouraging. The protocol was used to successfully broadcast both, periodic and alert messages. Hardware experiments with COTSBOTS vehicles were used to implement the concepts of IVC and vehicle infrastructure integration (VII).

As the first step study of this concept, this research does not consider several issues, which should be considered as the further research directions, such as, the potential communications overhead and its effect on the communication efficiency, the integration of the vehicle-based ad hoc wireless sensor networks with road side infrastructures, which will involve the vehicle-to-roadside sensor communications. The future challenges lie in designing effective sensor based systems which can interpret such changes and can take appropriate actions to avoid accidents.

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