Performance Evaluation of IEEE 802.11a MAC Protocol for Vehicle Intersection Collision Avoidance System

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***Abstract*—Vehicle-to-vehicle (V2V) communications network is a subclass of mobile ad hoc networks (MANET). With the new dedicated short range communications (DSRC) at 5.9 GHz, vehicles equipped with DSRC devices will communicate and collaborate to broadcast their safety-critical information to each other. DSRC is to be used in a wide range of advanced vehicle safety applications such as intersection collision avoidance system. The DSRC specification is based on the physical (PHY) and medium access control (MAC) layers of the IEEE 802.11a. The MAC mechanism for the IEEE 802.11a is the distributed coordination function (DCF), which is based on carrier sense multiple access with collision avoidance (CSMA/CA). Mobile nodes contend for the channel using a DCF random backoff timer. A random backoff algorithm chooses a *Contention Window (CW)* value between *aCWmin* and *aCWmax.* The random number, *CW*, is the number of time slots the mobile node has to sense the channel idle before it may transmit. In this paper, we developed an intersection traffic simulator to evaluate the settings of IEEE 802.11a DCF *aCWmax* on the available bandwidth per vehicle and on the required communication range. Our simulation results show that it is sufficient to set the *aCWmax* to 200 and the communication range to 200*m* for the intersection collision avoidance system enabled by DSRC.**

I. INTRODUCTION

Recent reports from the National Center for Statistics and Analysis (NCSA) of the National Highway Traffic Safety Administration (NHTSA) show that motor vehicle accidents are the leading cause of death in the United States for ages 4 to 34 [1]. There are 38,253 fatal crashes, 1,862,000 injuries, and 4,281,000 in property damages [2]. For more than fifteen years, the Intelligent Transportation Society of America (ITSA) [3] and the United States Department of Transportation [4] have been working on promoting the development and deployment of Intelligent Transportation Systems (ITS) technologies to provide a safer traffic and to reduce deaths, injuries and economic losses from motor vehicle crashes. Examples of ITS technologies include on-board navigation systems, crash avoidance and notification systems, electronic payment systems, and roadbed sensors.

In the United States, the Federal Communications Commission authorized the 5.9 GHz dedicated short range communications (DSRC) to be used in a wide range of advanced vehicle safety applications that require roadside-to-vehicle and vehicle-to-vehicle (V2V) communications. V2V communications network is considered a subclass of mobile ad hoc networks (MANET). Future vehicles will be equipped with DSRC devices that will communicate and collaborate to broadcast their safety-critical information to each other, such as speed, position, and heading. For DSRC, there are seven non-overlapping 10MHz channels in the 5.850-5.925 GHz band. DSRC also supports data rates of 6, 9, 12, 18, 24, 36, 48, and 54 Mbps. The advantages of DSRC are its capability of providing very low latency communications, and of transmitting broadcast messages to a maximum range of 1000 meters.

The National Highway Traffic Safety Administration (NHTSA) distributed a publication [5] that identifies intelligent vehicle safety applications enabled by DSRC. The authors compiled a list of 34 communications-based vehicle safety application scenarios. Several of these safety-applications are selected as the highest-rated mid-term applications, such as pre-crash warning, cooperative forward collision warning, lane change warning, and intersection collision avoidance. In this paper, our main contribution focuses on the intersection collision avoidance application.

According to the NCSA report [2], there are 2,481,619 crashes at intersections that caused 8,619 deaths, 848,000 injuries, and 1,625,000 in property damages. As one of the highest-rated vehicle safety applications, intersection collision avoidance system warns drivers of a possible collision with other vehicles at an intersection. The NHTSA publication [5] suggested the use of infrastructure sensors and/or DSRC communications to detect and collect information about the position, heading, velocity and turning status of all vehicles while approaching an intersection. The information obtained from the infrastructure sensors and/or DSRC communications is broadcasted to all vehicles approaching the intersection. An in-vehicle DSRC device that receives and processes such information determines whether or not a collision is imminent

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at the intersection and provides a warning to the driver.

In order to implement high-speed data transfer applications in the 5.9-GHz Intelligent Transportation Systems Radio Service (ITS-RS) Band, the physical layer (PHY) and the medium access control (MAC) layer specifications were developed as a standard for DSRC [6]. The standard specification is based on and refers to the IEEE 802.11a MAC and PHY layers.

In this paper, we developed an intersection traffic simulator using Visual C++ and OpenGL. The purpose of this simulator is to evaluate the effect of IEEE 802.11a DCF's *aCWmax* on the available bandwidth per vehicle, and on the required communication range. The scope of this analysis is only for the intersection collision avoidance system. Future research will include other safety applications to avoid collisions on highways. The rest of the paper is organized as follows. In Section II, we discuss the background in IEEE 802.11 MAC layer. In Section III, we discuss the related work. In Section IV, we describe our intersection traffic simulator. In Section V, we show our simulation results. Finally, we conclude the paper in Section VI.

II. BACKGROUND

One of the main design concerns in V2V communications is the access to the medium by several vehicles at the same time. Multiple accesses and transmissions by several vehicles at the same time can corrupt the data being transmitted. The MAC protocols provide schemes on how to access the medium and avoid data collision and corruption. The MAC protocol for the DSRC is the IEEE 802.11a. The access mechanism for the 802.11 is the distributed coordination function (DCF), which is based on carrier sense multiple access with collision avoidance (CSMA/CA). In DCF, a node that has data to transmit must wait a specific amount of channel idle time before contending for the channel. After the idle time elapses, nodes contend for the channel using a DCF random backoff timer. A random backoff algorithm chooses a *Contention Window (CW)* value between *aCWmin* and *aCWmax*. The random number, *CW*, is the number of slots the user has to sense an idle channel before the user may transmit. A slot has duration of *aSlotTime* seconds. For each slot, a node senses the channel. If the channel is idle, the node decrements its *CW* and continues to sense the channel at the next slot. If the channel is busy, the node loses the channel and stops decrementing its *CW*. On the next contention cycle, this node continues at its current value of *CW*. Once the value of *CW* reaches zero, the node can transmit. The receiver sends an acknowledgment (ACK) to the transmitter when the transmitted data is received.

If the transmitter does not receive an ACK signal, then the transmission is unsuccessful. The value of *CW* that was selected and used in contending for the channel is doubled and another cycle of access mechanism is performed by this node. A node has *dot11ShortRetryLimit* retries to contend for the channel if transmission is unsuccessful. *CW* continues to double until it reaches *aCWmax*. It stays at *aCWmax* until a transmission is successful or the number of retries *dot11ShortRetryLimit* is reached. Then this node chooses a new *CW*. Table I shows the DSRC specifications for the parameters described in this section.

TABLE I DSRC/IEEE 802.11a Specifications

DSRC parameter	*Value*
aSlotTime	**16×10^{-6}s**
aCWmin	**15**
aCWmax	**1023**
dot11shortretrylimit	**7**

Although the DCF backoff timer and ACK mechanisms solve the contention problem, another problem in accessing the medium is the hidden node problem. Two nodes that are out of the communication range of each other may transmit at the same time to a third node that is within the communication range of the other two. IEEE 802.11 solves this problem using RTS/CTS handshake protocol. A node that sends a request-to-send (RTS) may transmit data only if a clear-to-send (CTS) is heard back from the receiver. Otherwise, the sender attempts another transmission.

III. RELATED WORK

In [7][8], the authors presented an intersection traffic simulator using IEEE 802.11 and DOLPHIN protocols. In DOLPHIN, time is divided into slots and a vehicle transmits in a time slot based on non-persistent CSMA. The authors studied the PHY layer of IEEE 802.11 against path loss and shadowing effects. They assumed that vehicles transmit their data when they are 50 *m* away from an intersection. The authors indicated that data collision and error rate are related to PHY layer errors only. The authors did not show the performance of IEEE 802.11a MAC layer on their intersection simulator. In [9], the authors developed a cooperative intersection collision warning system. The authors proposed top-level specifications for intersection collision warning system to reduce excessive and undesired warning messages. Based on their specifications, they developed a parameterized collision warning algorithm. The algorithm depends on the driver's reaction time to warning messages and on the difference in time to a collision between two vehicles. Although the authors indicated that they used a DSRC device with IEEE 802.11a/b, the authors did not show the performance of IEEE 802.11a/b on their proposed algorithm.

Researchers have also applied IEEE 802.11 MAC protocol for highway IVC networks. In [10], the authors proposed to use the IEEE 802.11 MAC protocol to disseminate crash-warning messages on a highway via IVC networks. The message disseminates through multiple vehicles by measuring the distance between the sender and the receiver of the message. The farthest receiver has shorter backoff time, and hence, the receiver wins the channel and the message disseminates faster. In a similar approach, [11] proposed to use the IEEE 802.11 MAC protocol and a reference point on the road. The message disseminates through multiple vehicles by measuring the distance between a reference point and the vehicles. In [12], the authors proposed to use dual frequency wireless communication technologies. The first is a Short

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Distance Communication (SDC) system. It is a high-speed, short-distance vehicle-to-vehicle communications system. The second is a Long Distance Communication (LDC) system. It is a low-speed, long distance communication system employing centralized networking through a base station. The idea behind using an LDC is to exchange "info-tainment" data that is a low priority than safety critical information, such as text messages and video or image data. The authors proposed to use the IEEE 802.11 MAC layer for the SDC system without showing its performance on their proposed system.

Unlike the traffic simulator in [7][8] that used DOLPHIN, in this paper, we study the MAC layer of DSRC. We evaluate the effect of IEEE 802.11a DCF's *aCWmax* on the available bandwidth per vehicle, and on the required communication range.

IV. INTERSECTION TRAFFIC SIMULATOR

In this section, we describe the structure of our intersection and the characteristics of vehicles and drivers' behavior on this intersection.

A. *Intersection Structure*

As shown in Fig. 1, there are four intersection legs. Each intersection leg has four lanes. The width of a lane is 4 *m*. There are also divisional islands between two opposite directions. The width of the island is 8 *m*. Vehicles travel on the right side of the road.

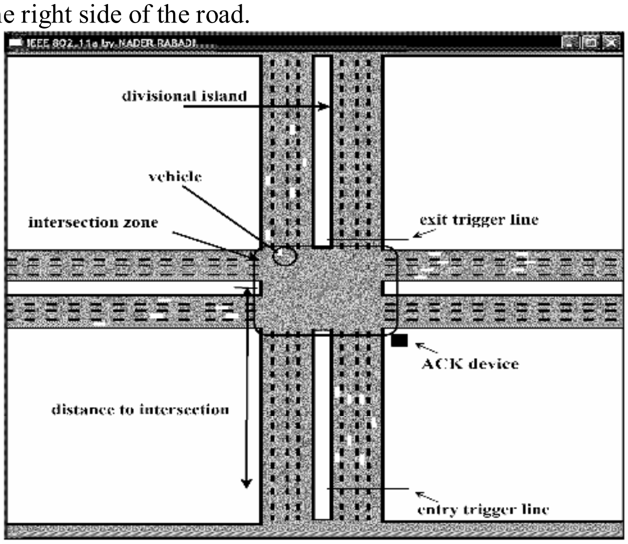

Fig. 1. The designed intersection structure. The *entry trigger line* is used to trigger vehicles approaching the intersection to start contending for the channel. The *exit trigger line* is used to trigger vehicles that are leaving the intersection to stop contending for the channel, and hence, additional bandwidth would be available for other vehicles at the intersection.

In this paper, we assume that there are sensors on the road for vehicles approaching an intersection, and for vehicles leaving the intersection. The NHTSA publication [5] suggested the use of infrastructure sensors and/or DSRC communications in vehicle safety applications. In Fig. 1, these sensors are indicated by the *entry trigger line* and *exit trigger line*. When vehicles approaching an intersection pass by the *entry trigger line*, then these vehicles start the execution of the IEEE 802.11a MAC layer. Vehicles continue the execution of the MAC layer while they are approaching the intersection zone. Vehicles stop contending for the channel and the execution of the MAC layer as soon as they pass by the *exit trigger line*.

The *entry trigger line* is installed at a pre-determined distance, d_i, from the intersection. This distance specifies the communication range of the DSRC, which is $2d_i$. If all intersection legs have an *entry trigger line*, then all vehicles that pass by these lines are within the communication range of each other. Hence, we avoided the hidden-node problem. Once a vehicle leaves the *intersection zone* and passes by the *exit trigger line*, then it is unnecessary for this vehicle to contend for the channel. This allows additional available bandwidth for use by other vehicles approaching the intersection.

B. *Vehicle and Driver Characteristics*

At the beginning of the simulation, the intersection is empty of vehicles. Vehicles are generated into the network at the *entry trigger line* for each intersection leg. Table II summarizes the characteristics of vehicles and drivers. Vehicles are generated into the network based on headway distributions among vehicles. To generate vehicles and to simulate the arrival of vehicles at the *entry trigger line*, we used the shifted negative exponential distribution with a mean headway of 3.0 *s* and a minimum headway of 1.5 *s*. The arrival time for a vehicle in a lane is the summation of headways of its leading vehicles at that same lane.

TABLE II Vehicles' and drivers' characteristics

Characteristic	*Distribution*	*Mean:* μ	*Standard deviation:* σ *Minimum: min*
vehicles' arrival time	shifted negative exponential distribution	μ = 3.0 s	*min* = 1.5 s
vehicles' maximum speed	normal distribution	μ = 65 km/h	σ = 10 km/h
vehicles' maximum deceleration	normal distribution	μ = -4 m/s^2	σ = -0.5 m/s^2
drivers' break reaction time	normal distribution	μ = 1.5 s	σ = 0.5 s

For each generated vehicle, a maximum speed and a maximum deceleration are also generated. The speed of vehicles is generated using a uniform distribution with a mean of 65 *km/h* and a standard deviation of 10 *km/h*. Similarly, the maximum decelerations of vehicles are generated using a uniform distribution with a mean of $-4\,m/s^2$ and a standard deviation of $-0.5\,m/s^2$. For all generated vehicles, we assume the length of a vehicle is 5 *m*. We also consider the drivers' reaction to warning messages. When the in-vehicle DSRC device receives broadcasted messages, it sends these messages to an in-vehicle electronic control unit (ECU). The ECU processes these messages and issues an alert to the driver if there is a possible collision with another vehicle at the intersection. The alert could be a combination of audible and indicator warnings. Humans perceive alerts and warning indicators differently from each other and with different response time. In this case, we consider the brake reaction time of drivers. The brake reaction time is the time between recognizing the alert and applying the brake. It is generated for each vehicle using a uniform distribution of a mean of 1.5 *s* and a standard deviation of 0.5 *s*.

C. Vehicles Interactions:

Vehicles enter the network at the *entry trigger line* using their arrival time. Once a vehicle enters the network, it starts the IEEE 802.11a MAC protocol. If a vehicle at one of the intersection legs wins the channel, it broadcasts its velocity, heading, and position using its omni directional antenna and one of the assigned DSRC channels for the intersection collision avoidance application. We assume there is a device installed at the intersection that sends the ACK signal, as shown in Fig. 1. Vehicles from the other three intersection legs receive the broadcasted data using their in-vehicle DSRC device. Using the received data and its own speed, heading and position, the ECU in the receiving vehicle determines if its vehicle will be in the *collision zone* with the transmitting vehicle, as shown in Fig. 2. We assume the dimension of the *collision zone* is $10m \times 10m$. The ECU issues an alert to the driver, and the driver decelerates after a break reaction time. The break reaction time is applied only once when a driver receives the first alert. After the first alert, we assume the driver has been alerted, and the break reaction time will not be applied again with subsequent alerts on this intersection.

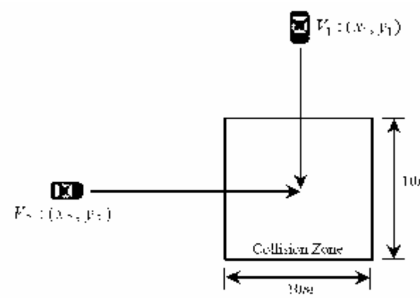

Fig. 2. The *collision zone* is used to determine if two vehicles will be in the zone to issue an alert to these two drivers.

D. Car following:

When a preceding vehicle is slower than the following vehicle, then the following vehicle decelerates to match the speed of the preceding vehicle. This is similar in operation to the adaptive cruise control (ACC) system. In the meantime, if the following vehicle receives an alert of a possible collision with another vehicle traveling from another intersection leg, then this alert may take precedence over the ACC system. The in-vehicle ECU determines if the deceleration of the driver due to ACC is enough to issue the alert. The alert will be issued if the driver needs to decelerate further in order to avoid a collision at the intersection. In our simulator, the car-following system is independent of the intersection collision avoidance system. The received broadcasted messages are used to activate the intersection collision avoidance system and not the car-following system.

V. SIMULATION RESULTS

We first set the distance to the intersection to $d_i = 100m$. Therefore, the communication range is 200*m*. Then we set *aCWmax* to 100 and we ran the simulation. We recorded the available bandwidth and speed for each vehicle entered the intersection network. We repeated this process for several values of *aCWmax*. Fig. 3 shows the average available bandwidth per vehicle for *aCWmax* of 100, 200, 400, 600, 800, and 1023. As shown in the figure, the lower the value of *aCWmax* is set, the higher the available bandwidth per vehicle is utilized. We also recorded the number of transmission failures for *aCWmax* of 100, 200, 400, 600, 800, and 1023, as shown in Fig. 4. While the transmission failures decrease with the increase of *aCWmax*, vehicle accidents occurred at *aCWmax* of 1023 and 800.

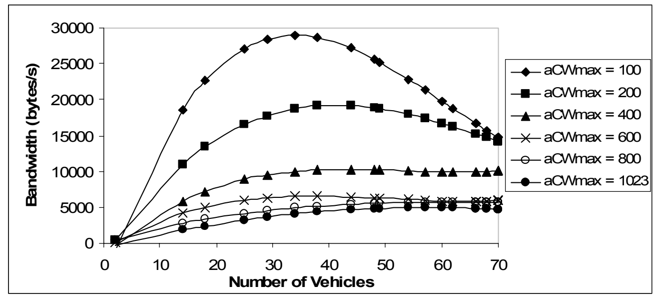

Fig. 3. The average available bandwidth per vehicle (when d_i=100*m*) for several values of aCWmax.

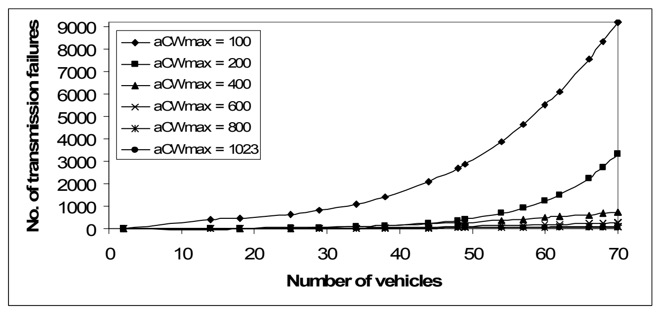

Fig. 4. Number of transmission failures per second (when d_i=100m) for several values of *aCWmax*.

As shown in Fig. 5, there are two vehicle collisions at the intersection when *aCWmax* is set to 1023. We also observed a vehicle collision when *aCWmax* is set to 800 (not shown in a figure). Although the available bandwidth per vehicle is 5kbytes/s (when *aCWmax* is 1023) seems enough to avoid a collision, there are two factors that contributed to this collision: *first*, the distance to the intersection ($d_i = 100m$) is not enough for vehicles to react and decelerate comfortably in order to avoid a collision. The aim of a warning system is to alert drivers of possible collisions and to allow them to have sufficient time to respond without panic and sudden large decelerations. *Second*, setting *aCWmax* to large values introduces additional latency in contending for the channel, and hence a lower available bandwidth per vehicle. Therefore, the broadcasted message that will alert the driver of a possible collision at the *collision zone* may be delayed and a shorter response time and a larger deceleration will be required.

Fig. 6 and Fig. 7 show the average speed of vehicles per lane for the simulation run that caused one of the vehicle collisions in Fig. 5. The shaded line in these figures indicates the lane where the accident occurred. This is to distinguish it from other vehicles at other lanes that were able to bring their speed to zero.

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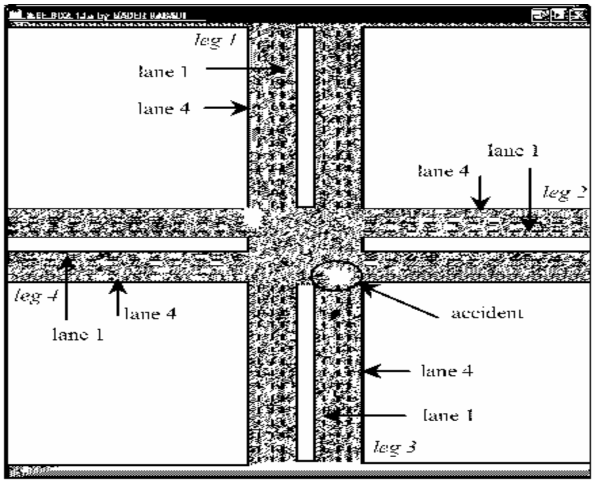

Fig. 5. An accident between two vehicles (when d_i=100*m*): the first vehicle is at lane 3, leg 3 and the second vehicle is at lane 4, leg 4.

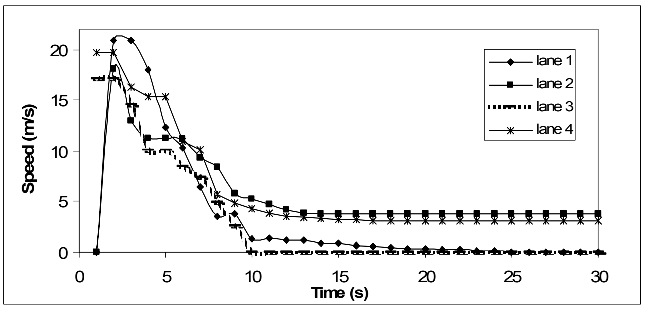

Fig. 6. The average speed per lane (when d_i=100*m*) for vehicles traveling at leg 3. Lane 3 (shaded line) shows the accident.

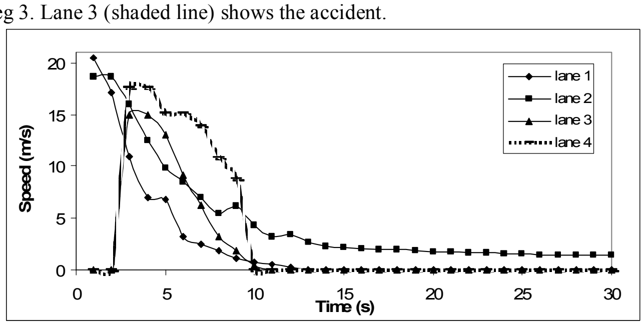

Fig. 7. The average speed per lane (when d_i=100*m*) for vehicles traveling at leg 4. Lane 4 (shaded line) shows the accident.

We can avoid a vehicle collision by either using a lower value of *aCWmax* or by increasing the distance to the intersection, d_i. From our simulation results shown in Fig. 3, values of *aCWmax* that are less than 800 provides a higher available bandwidth per vehicle and a collision-free intersection. Therefore, it is unreasonable to increase the distance to the intersection, hence the communication range, and use large values of *aCWmax*. To evaluate the effect of increasing the distance, we set the distance to the intersection to $d_i = 150m$ and repeated the same simulation runs for *aCWmax* of 100, 200, 400, 600, 800, and 1023. We noticed one instance of the simulation runs when *aCWmax* is set to 1023 that caused a vehicle collision. Although the increase in the distance to the intersection had prevented accidents for large values of *aCWmax*, the average available bandwidth per vehicle is higher at low values of *aCWmax*.

VI. CONCLUSION

In this paper, we developed an intersection traffic simulator to study the settings of the IEEE 802.11 DCF's *aCWmax* on the available bandwidth per vehicle and on the required communication range to avoid a collision at an intersection. From our simulation results, we can conclude that a communication range of 200*m* is sufficient for the intersection collision avoidance system. Furthermore, setting the value of *aCWmax* to 200 will provide drivers with sufficient time to respond to alerts and warning indicators without panic and sudden large decelerations.

REFERENCES

[1] National Center for Statistics and Analysis (NCSA), http://www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/RNotes/2006/810568.pdf.

[2] National Center for Statistics and Analysis (NCSA), http://www-nrd.nhtsa.dot.gov/pdf/nrd-30/NCSA/TSFAnn/TSF2004.pdf

[3] http://www.itsa.org

[4] http://www.its.dot.gov

[5] U.S Department of Transportation, National Highway Traffic Safety Administration, Vehicle Safety Communications Project; Task 3 Final Report; Identify Intelligent Vehicle Safety Applications Enabled by DSRC, March 2005.

[6] Standard Specification for Telecommunications and Information Exchange Between Roadside and Vehicle Systems — 5 GHz Band Dedicated Short Range Communications (DSRC) Medium Access Control (MAC) and Physical Layer (PHY) Specifications, ASTM E2213–03, September 2003.

[7] A. Dogan, G. Korkmaz, Y. Liu, F. Ozguner, U. Ozguner, K. Redmill, O. Takeshita, and K. Tokuda, "Evaluation of intersection collision warning system using an inter-vehicle communication simulator," in *Proc. of the 7th International IEEE Conference on Intelligent Transportation Systems*, Oct. 2004, pp. 1103 – 1108.

[8] A. Avila, G. Korkmaz, Y. Liu, H. Teh, E. Ekici, F. Ozguner, U. Ozguner, K. Redmill, O. Takeshita, K. Tokuda, M. Hamaguchi, S. Nakabayashi, and H. Tsutsui, "A complete simulator architecture for inter-vehicle communication intersection warning systems," in *Proc. of IEEE Intelligent Transportation Systems*, Sept. 2005, pp. 461 – 466.

[9] R. Miller, Q. Huang, "An adaptive peer-to-peer collision warning system," in *Proc. of 55th IEEE Conference on Vehicular Technology*, May 2002, pp. 317 - 321 vol.1.

[10] L. Briesemeister, L. Schafers, and G. Hommel, "Disseminating messages among highly mobile hosts based on inter-vehicle communication", in *Proc. of the IEEE Intelligent Vehicles Symposium*, October 2000.

[11] T. Nagaosa, Y. Kobayashi, K. Mori, and H. Kobayashi, "An advanced CSMA inter-vehicle communication system using packet transmission timing decided by the vehicle position", in *Proc. of the IEEE Intelligent Vehicles Symposium*, June 2004.

[12] K. A. Redmill, M. P. Fitz, S. Nakabayashi, T. Ohyama, F. Ozguner, U. Ozguner, O. Takeshita, K. Tokuda, and W. Zhu, "An incident warning system with dual frequency communication capability," *IEEE Intelligent Vehicles Symposium*, Columbus, OH, June 2003.