MAC Protocol Design for Vehicle Safety Communications in Dedicated Short Range Communications Spectrum

Qing Xu, Tony Mak, Jeff Ko, and Raja Sengupta

Abstract— **This paper studies the design of Medium Access Control (MAC) protocols for a vehicle or the roadside to send safety messages to other vehicles. The target is to meet vehicle safety applications' requirements of high reliability and low delay in reception. The communication is one-to-many, local, and geo-significant. The vehicular communication network is ad-hoc and highly dynamic, with potentially large number of contending nodes. We design several random access protocols residing in MAC and MAC extension layers. The protocols fit the DSRC multi-channel architecture. Analytical bounds of the protocols' performance are derived. Simulations are conducted to compare the performance of the protocols in terms of reception reliability and channel usage efficiency. The sensitivity of the protocol performance is tested under various communication conditions as well as vehicle traffic conditions. The results show that our approach is a feasible solution to the MAC design problem to support vehicle safety communications.**

I. INTRODUCTION

Efforts are being made to enhance the safety and efficiency of highway/urban traffic with the aid of wireless communication. Both vehicle-vehicle (V-V) communication and roadside-vehicle (R-V) communication are being explored. Examples of driving systems using communications include: intersection decision systems (IDS) [20], cooperative adaptive cruise control (CACC) systems [19], and automated highway systems (AHS) [8].

In support of these efforts, the Federal Communications Commission (FCC) allocated a Dedicated Short Range Communications (DSRC) spectrum at 5.9GHz. The North America DSRC standard program is established jointly under the American Society of Testing and Materials (ASTM) and the Institute of Electrical and Electronics Engineers (IEEE) to develop a set of standards for full interoperatability throughout North America.

This paper discusses the design of a Medium Access Control (MAC) protocol for V-V/R-V DSRC communications. The design is optimized for a vehicle or the roadside to send safety messages to other vehicles. The protocol is designed for use by Advanced Vehicle Safety Systems (AVSS). The following is typical of an AVSS application and its communication requirements [11].

Cooperative Collision Warning:

1) Definition
   Use vehicle-vehicle communication to collect surrounding vehicle locations and dynamics and warn the driver when a collision is likely.
2) Application needs
   a) Vehicle to vehicle communication
   b) Two-way communication
   c) Point-to-multipoint communication
   d) Allowable latency ∼ hundreds of msec
   e) Frequency (update rate) ∼ 10 Hz
   f) Data to be transmitted and/or received - position, velocity, acceleration, heading, yaw-rate
   g) Range of communication ∼ 50–300 m

Vehicle safety communications are point-to-multipoint, local, and geo-significant. The set of targeted receivers is specified as a geographic region (geo-cast [10] zone) relative to the transmitter (see Figure 1). A sender broadcasts messages to all the receivers in its communication range. The receiver determines if it is in the geo-cast zone, and thus the relevance of the message and the proper response. The geo-cast zone typically is a subset of the vehicle's close neighborhood. Hence all the targeted vehicles can be reached in one-hop. The vehicle communications network is time-varying and highly dynamic. A large number of nodes could contend for the channel (e.g. when the highway is jammed). To facilitate deployment without major modifications to the current highway system, we design *ad-hoc protocols* that work without centralized control.

The goal of vehicle safety communication MAC protocol design is to achieve *high reception reliability and low latency*. Poor performance in either is bad for AVSS.

DSRC safety messages are to be communicated in the DSRC control channel. There are non-safety messages in the control channel as well. It is important that safety communications not overly congest the control channel.

In summary, the problem we attack in this paper is *to develop an ad-hoc MAC protocol that can meet the latency and reliability requirements of safety messages in a fast changing network of vehicles, while being economical enough in the utilization of the control channel for the multi-channel operation scheme to work effectively.*

We propose several protocols in this paper. We mathematically analyze and simulate the protocols in a vehicular traffic environment. Results show that our approach meets

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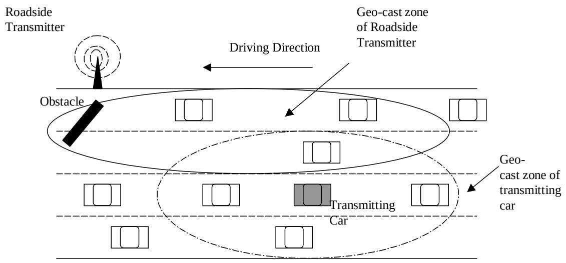

Fig. 1. The geo-cast concept

the requirements of vehicle safety communications. Our protocol significantly outperforms the IEEE 802.11 MAC protocol broadcast mode in the same environment.

The rest of the paper is structured as follows. Section II reviews related previous work. Section III formulates the MAC protocol design problem in the V-V/R-V communication environment under the DSRC architecture. In section IV we propose several protocols. Section V reports the numerical results based respectively on the analytical model and simulation under various vehicle traffic conditions and communication system parameters. Section VI concludes the paper and proposes future work.

II. PREVIOUS WORK

In ad hoc vehicular networks, TDMA, FDMA, or CDMA are difficult due the need to dynamically allocate slots, codes, or channels without centralized control. We find random access to be a feasible approach.

ALOHA [3] and CSMA [15] are the earliest studied random access protocols. MACA [9], MACAW [5], FAMA and its variants [7] all use the RTS/CTS scheme. Our communication is broadcast, hence RTS/CTS cannot be used.

HIPERLAN/1 [4], “Black Burst” [14], and the Enhanced Distributed Coordination Function (EDCF) of IEEE 802.11e [17] are all designed to support QoS. The HIPERLAN/1 and Black Burst approaches have no scheme to combat hidden terminals. In EDCF, when the number of contending packets of equal priority is large the probability of collision is still high. This is the case for vehicle safety communications. Reference [13] reviews the existing variants of the 802.11 DCF to support QoS. The authors conclude that the design of a mechanism to provide predictable QoS in an 802.11 network is still an open problem. Reference [21] gives overview of DSRC applications and assesses the characteristics of the IEEE 802.11 MAC and PHY layers in this context. It is anticipated that current 802.11 specifications will need to be suitably altered to meet the QoS requirements of DSRC applications.

III. THE MAC PROTOCOL DESIGN PROBLEM IN DSRC V-V/R-V COMMUNICATION

There are two performance measures, i.e., *reception probability* and *channel busy time*. The performance of a protocol is adequate if its reception probability and channel busy time are acceptable for expected safety data traffic patterns. We discuss the two measures in detail below.

Reception with a specified probability has the following meaning. Each message has an *intended communication range* and *useful lifetime* associated with it. Our performance requirement is that vehicles within the specified range receive the message within its specified lifetime with a specified probability. The motivation for such a performance definition is each safety-related message has a lifetime in which it is useful to the receiving vehicles. Typically, at the end of the lifetime next more useful message becomes available for transmission.

Channel busy time (CBT) is an important performance measure when operating in the DSRC control channel. We define CBT as the fraction of time that the channel is occupied by either a successful or collided safety packets. It represents the fraction of time when the channel cannot be used by other non-safety applications. DSRC non-safety messages are essential for use of the service channels. Thus congestion in the control channel would jeopardize the operation of all service channels and, thus, disrupt the whole multi-channel architecture. Our protocol should use the control channel economically.

IV. PROTOCOLS AND ANALYSIS

We describe our MAC protocol designs in IV-A. The performance analysis of selected protocols are reported in IV-B.

A. Description of Protocols

We make the following assumptions in the design of the protocols.

- Vehicle safety applications generate a message to be transmitted to other vehicles when an event occurs (e.g. on-board sensor measurement update, hard braking, etc.). We denote the useful lifetime as τ. The message is passed down to the MAC layer. The MAC protocol attempts to transmit the packet only within the message’s lifetime and discards the packet when the lifetime expires.
- The information in the *message* is encapsulated in a *packet* to be transmitted to other vehicles. In the homogeneous setting we study in this paper, the size of packets is time-invariant and is the same across nodes. The packet could contain the location of the sender, the targeted vehicle’s location, the nature of the event, etc. The time taken to transmit one packet is a function of the packet size and the data rate of the radio. We denote this time period as t_{trans}.
- Each moving vehicle is outfitted with a single omnidirectional antenna and a single wireless radio that can transmit and receive, but cannot do both simultaneously.

Figure 2 is a illustration of the idea of repetitive transmission. Two transmitters within interference range of one receiver have messages generated at the same time. The protocol evenly divides the lifetime into $n = \lfloor \frac{\tau}{t_{trans}} \rfloor$ slots, where $\lfloor x \rfloor$ is the largest integer not greater than x. We randomly pick any k ($1 < k < n$) slots to transmit the packets. If at least one *packet* is received without collision, the *message* is received by the targeted receiver, and the delay is smaller than the useful lifetime of the message. On the other hand, the message transmission fails if all of its repeated packets are lost due to collisions. Both vehicles in Figure 2 succeed if there are no other interfering vehicles. Intuitively, repetition increases the probability at least one packet gets through. However excessive repetition burdens the channel and degrades performance, as we see later in our analytical and simulation results. Therefore the optimal number of transmissions k_{opt} must be found.

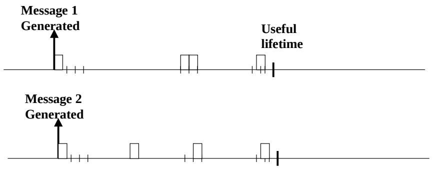

Fig. 2. The Concept of Repetitive Transmission

Our protocols are all based on the repetition ideas. The protocols are implemented in two layers, the MAC layer and MAC extension layer.

The MAC extension layer lies between the Logical Link Control layer (IEEE 802.2) and the MAC layer. Its role is to generate and remove repetitions. The state machine of the MAC extension layer is shown in Figure 3. Upon receiving a message from the LLC, the MAC Extension transits from Idle to the Repetition Generation state. In this state, the system schedules multiple repetitions of this message within its lifetime in a manner to be described below, and store them in the MAC Event Queue. The MAC Event Queue orders the packet events according to their scheduled transmission time. If the Event Queue already contains a packet for a particular time slot, the new packet replaces the old one. Once these are done, the system transits back to the Idle state, and signals the MAC for data transmission. Whenever MAC Extension receives a packet from MAC, the system transits from Idle to Repetition Removal state to eliminate any redundant packets and passes the new message up to LLC.

Below we describe each of the protocols we studied.

1) *Asynchronous Fixed Repetition (AFR)*
   In AFR, as well as all other fixed repetition protocols, the design parameter is the number of repetitions k. The protocol randomly selects k distinct slots out of the n slots constituting the lifetime. The protocol is so called since the number of repetitions is fixed. The radio does not listen to the channel before it sends a packet with AFR.
2) *Asynchronous P-persistent Repetition (APR)*

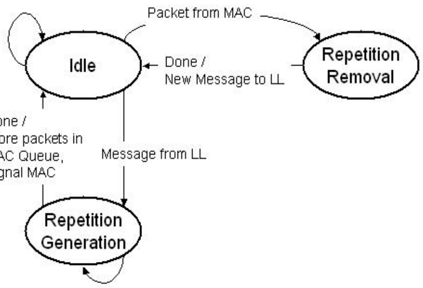

Fig. 3. MAC Extension Layer State Machine

   The p-persistent repetition protocol determines whether to transmit a packet in each of n slots in lifetime by flipping an unfair coin with $P(H) = \frac{k}{n}$ and $P(T) = 1 - \frac{k}{n}$. A packet is transmitted if the result is a head. The positive integer $k \leq n$ is a design parameter of the protocol. We can see that on average there are k transmissions in the lifetime of a message. However, for each realization the exact number of repetitions varies. Like AFR, the radio does not listen to the channel before it sends a packet.
3) *Synchronous Fixed Repetition (SFR)*
   This protocol is the same as AFR except that all the nodes are synchronized to a global clock as in slotted ALOHA[3], and all message generations as well as transmissions happen at the beginning of a slot. With this protocol, partial overlap between packets is avoided. However, synchronization would need a global clock, which is hard.
4) *Synchronous P-persistent Repetition (SPR)*
   The SPR protocol is the same as APR protocol except for the synchronization of message generation and transmission at all nodes.
5) *Asynchronous Fixed Repetition with Carrier Sensing (AFR-CS)*
   This protocol is a little more complicated. We describe it with its MAC state machine as shown in Figure 4. In the MAC idle state, the system waits for the packet event to expire. When a scheduled packet event expires, the MAC transits from the MAC Idle to the MAC Tx state. In the MAC Tx state, the system checks the channel status. If the channel is busy, the system drops the packet event. It then transits back to the MAC Idle state, and waits for the next event to expire. If the channel is idle, the system passes the packet down to the physical layer (PHY). It waits for the transmission to finish and then transits back to the MAC Idle state. In the MAC Idle, if PHY detects the preamble of a packet, the system transits to the MAC Rx state and waits for the reception to finish. Once the whole packet is received, the system checks the integrity of the packet. If the packet is corrupted, it is dropped. Otherwise, the packet is passed up to the MAC Extension layer, and the system transits back

to the MAC Idle state.

6) *Asynchronous P-persistent Repetition with Carrier Sensing (APR-CS)*
This protocol is similar to AFR-CS except that the repetition slots are selected in the p-persistent manner.

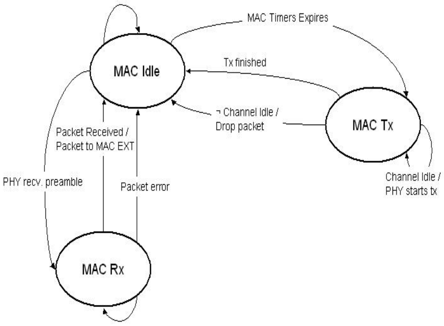

Fig. 4. MAC Layer State Machine for AFR-CS protocol

TABLE I
NOMINAL SETTING PARAMETERS

Message Generation Interval (msec)	100
Useful Life Time (msec)	100
Packet Payload Size (Bytes)	100
Desired Communication Range (m)	80
Average Distance Between Vehicles (m)	30
Lane Number	4
Worst-case Interferer Number	75

TABLE II
PARAMETERS STUDIED IN SIMULATIONS

Message Generation Interval (msec)	50, 100, 200	
Packet Payload Size (Bytes)	100, 250, 400	
Data Rate (Mbps)	6, 9, 12, 18, 24, 36, 48, 54	
Average Vehicle Distance (m)	10 (jammed)	30 (smooth)
Desired Communication Range(m)	10-100	30-300
Lane Number	4, 8	

B. *Analysis of the protocols*

In this section we present analytical results about the probability of reception failure (PRF) of two of the protocols, i.e., SPR and APR. We use these results to validate our simulation results and obtain insights into the design of all of the repetition protocols.

We make the following two assumptions in our analysis.

- The message generation process of each individual vehicle is Poisson.
- The message generation processes of different vehicles are identical and independent.

With these two assumptions, we know immediately that the generation process of all interfering messages is also Poisson with rate equal to the sum of the rates of all interferers. Assume that the rate of the Poisson process for each node is λ and the number of interfering nodes is m, then the rate of the message generation process of all these nodes is $m \cdot \lambda$ [6]. The details of the mathematical analysis are in [18]. We only summarize the results here.

With SPR, the PRF of one message at a receiver with m interferers satisfies the following inequality.

$$\left(1 - \frac{k}{n} e^{-m\lambda\tau\frac{k}{n}}\right)^n < P(\neg S) < \left(1 - \frac{k}{n} e^{-m\lambda\tau\frac{k}{n}} + \frac{k}{n} e^{-m\lambda\tau}\right)^n \tag{1}$$

With APR, the PRF of one message at a receiver with m interferers satisfies the following inequality.

$$\left(1 - \frac{k}{n} e^{-m\lambda\tau\left[2\frac{k}{n} - \frac{k^2}{n^2}\right]}\right)^n < P(\neg S) < \left(1 - \frac{k}{n} e^{-m\lambda\tau\left[2\frac{k}{n} - \frac{k^2}{n^2}\right]} + \frac{k}{n} e^{-m\lambda\tau}\right)^n \tag{2}$$

In the inequalities above, n is the total number of slots, i.e. the maximum possible number of repetitions in a message lifetime, k is the number of repetitions for the message (average value for p-persistent protocols and exact value for fixed repetition protocols), S stands for the event that at least one of the repetitions succeeds, τ is the lifetime of the message, λ is the message generation rate of each individual node, and m represents the total number of interfering nodes around a receiver.

V. NUMERICAL RESULTS AND DISCUSSIONS

We use the NS (Network Simulator) [1] to simulate the wireless communication network, and SHIFT [12] to simulate highway vehicle traffic. The detailed description of the wireless communication is in [18] and that of the vehicle traffic simulation is in [16].

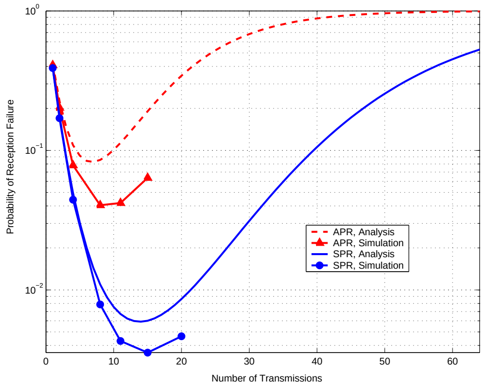

Fig. 5. Validation of Simulation Results with Analytical Model

A. *Validation of Simulation*

Figure 5 shows the analytical and simulated PRF of the APR and SPR protocols in the nominal setting summarized in Table I. The analytical plots are from inequalities (1) and (2). For both APR and SPR, the upper and lower bounds are too close to be distinguished, thus we only plot one of them. The analytical and simulation results match well. In both analysis and simulation, we see there is an optimal probability of persistence in each slot for both protocols. Repetitively transmitting packets beyond this number congests the channel and degrades the performance of the protocol. The optimal probability of persistence k_{opt}, is $15 \cdot \lfloor \frac{t_{trans}}{\tau} \rfloor$ for the SPR protocol, and $7 \cdot \lfloor \frac{t_{trans}}{\tau} \rfloor$ for the APR protocol.

The reason that the simulation results are consistently better than the analytical ones is the following. Since the message generation process is Poisson rather than periodic, the lifetime of two or more consecutive messages from the same node can overlap. The repeated packets of a prior message can thus select the same time slot to transmit as the packets of a later message. In the mathematical analysis we treat previous messages the same as messages from the other nodes, i.e. the node's packets from a prior message can collide with its packets from a later message. In simulation we let the packets from the latest message overwrite any colliding packets from earlier messages. This is more realistic. Therefore we see an enhanced performance in simulation.

B. Comparison of Protocols in the Nominal Setting

Figure 6 shows the PRF of all our protocols in the nominal setting. The solid black horizontal line in the middle is the simulated performance of 802.11 broadcast. Clearly, the synchronous protocol outperforms the asynchronous protocols. This is like the Aloha results [3]. Also for the same repetition method, a CSMA protocol is better than a non-CSMA protocol. This result is expected since in CSMA each node listens before transmission, therefore avoid many potential collisions. The reception failures for CSMA protocols are mostly due to hidden terminals. Fixed repetition protocols outperform p-persistent protocols. The reason is that the fixed repetition protocols are better at maintaining the number of repetitions for each message, i.e. there is less fluctuation between the actual number of repetition of each message and the expected number of repetitions.

Among the six candidate protocols, four yield lower PRF than 802.11. The best two are AFR-CS and SFR. They both achieve a minimum probability of failure of 0.0008, which is more than one order of magnitude lower than that of 802.11. This shows that repetition helps combat interference by giving a transmitter more chances to transmit. Synchronizing the transmissions among nodes and adding CSMA to the protocol bring about the same level of benefit. However, it is easier for the radios to listen to the channel before transmitting than to synchronize the transmissions of all nodes to a global clock. Therefore we prefer AFR-CS to SFR for deployment.

Figure 7 shows the CBT of the three fixed repetition protocols and 802.11 under the nominal setting. With the same number of repetitions, APR and AFR yield about equal CBT. The same relation holds between SPR and SFR, and between APR-CS and AFR-CS. For clarity we do not show the CBT of the p-persistent protocols in Figure 7. As is expected, the CBT increases with the number of repetitions. Among the simulated protocols, AFR-CS has the lowest CBT at the same number of repetitions. With this protocol, less than half the channel time is occupied by vehicle safety applications, leaving time for non-safety communications. Since there is no repetition in the 802.11 MAC protocol, its CBT is much lower than repetition protocols. Combining the observations from Figures 6 and 7, we conclude that in the nominal setting AFR-CS is the best protocol amongst those described in IV-A.

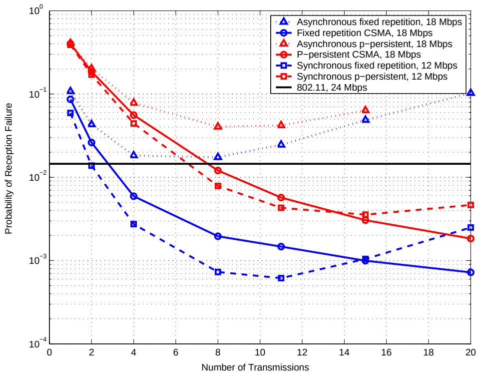

Fig. 6. Probability of Reception Failure for Proposed Protocols in the Nominal Setting

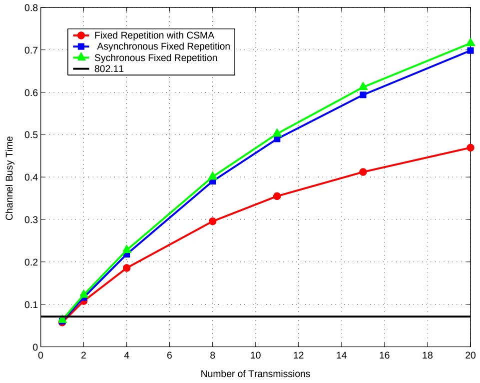

Fig. 7. Channel Busy Time for Fixed Repetition Protocols in the Nominal Setting

C. Sensitivity of the AFR-CS Protocol on Design Parameters

We have done a sensitivity analysis for all the parameters in Table II. From this analysis one can find the feasible subregion of the parameters that achieves given communication requirements. We set the communication requirements to be:

- Probability of reception failure < 0.01
- Channel busy time $< 50\%$

Figure 8 shows the feasible region in parameter space. The three curves represent three cases with different packet sizes. The region below each curve is infeasible, while the region above is feasible. The figure shows that as interference increases, each node has to generate messages less frequently in order to meet the communication requirements. At the same time, larger packet size has a negative impact on the performance by decreasing the feasible region. The feasibility results provide us with constraints in design. The larger the feasible region, the easier it is to design the safety application. For example, when the packet payload is 100 bytes, if the worst-case interferer number is 150, the nodes cannot transmit messages more than 10 times per second; while if the worst-case interferer number is smaller than 40, the nodes can transmit as many as 20 messages per second without violating the communication requirements. If the interferer number is larger than 110 for the 400-Byte case, or if the interferer number is larger than 160 for the 250-Bytes case, no message interval can satisfy the communication requirements. For reasonable packet sizes, we observe a large feasible region around the nominal setting. The worst-case interferer number is 75. This indicates that our protocol is a feasible approach for the common settings in vehicle safety communication.

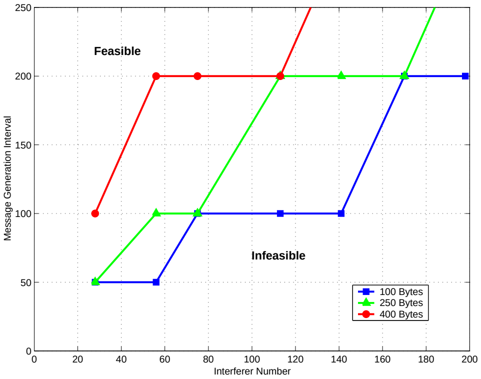

Fig. 8. Feasibility Regions for Probability of Reception Failure < 0.01 and Channel Busy Time $< 50\%$

VI. CONCLUSION

The design of MAC protocol for vehicle safety communications in 5.9 GHz DSRC spectrum is studied. Several protocols based on repetition coding are proposed. We analytically study two of the protocols. We simulate all of the proposed protocols in the vehicle communication environment. The analytical results match well with the simulation results. From among the proposed protocols, we find that AFR-CS meets the requirement of vehicle safety communication. We study the sensitivity of AFR-CS to a wide range of design parameters and find the feasible regions of the protocol for requirements on PRF and CBT. The results show our approach is a feasible solution to the MAC protocol design problem for vehicle safety communications.

Possible future work includes the adaptation of transmission power in the heterogenous environment, design of a more efficient coding scheme than repetition, and simulation with a stochastic V-V communication channel model.

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