Design and Analysis of Highway Safety Communication Protocol in 5.9 GHz Dedicated Short Range Communication Spectrum

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Abstract— **We study the wireless communication among highway vehicles in the newly-assigned 5.9 GHz Dedicated Short Range Communication (DSRC) spectrum. A vehicle-vehicle Location-Based Broadcast (LBB) communication protocol is designed to meet highway safety applications' communication requirements. The analytical expressions of the performance of the protocol in terms of probability of transmission failure and channel occupancy are derived with commonly satisfied assumptions. The optimal relation between the performance and design parameters is obtained from the expressions. The sensitivity of the protocol performance is tested for various communication conditions as well as highway traffic conditions. Feasible combinations of the communication and highway traffic parameters are found for certain requirements on protocol performance.**

I. INTRODUCTION

DSRC (Dedicated Short Range Communications) is a short to medium range communications service that supports both public safety and private operations in roadside to vehicle and vehicle to vehicle communication environments. It is meant to be a complement to cellular communications by providing very high data transfer rates in circumstances where minimizing latency in the communication link and isolating relatively small communication zones are important.

A spectrum of 75 MHz width at 5.9 GHz was newly assigned by Federal Communication Commission (FCC) to DSRC. This new spectrum allows the US, Canadian, and Mexican Intelligent Transportation Systems (ITS) programs to evolve to a new generation of RF communications between vehicles and the roadside, and among vehicles, that enables a whole new class of communications and a new class of applications to support future transportation systems and needs. The North America DSRC standard program is formed to develop a set of DSRC standards that will support full interoperatability throughout North America while satisfying all of the application requirements [1].

The allocation of DSRC is recent and the standardization process is not finished, therefore relevant literature is rare. However the application of wireless communication and network techniques in the control of the vehicles and highway traffic has attracted much interest both in the field of communication as well as transportation study. Literature shows attempts on channel modeling [2], cooperative adaptive cruise control [3] [4], Automated Highway Systems [5], and wireless vehicle network [6]. DSRC is the first standard enabling technique to support all these work in long term.

The rest part of the paper is structured like the following. Section II introduces the concept of location based broadcast (LBB) and discusses its importance in vehicle-vehicle communication. Section III describes a LBB protocol we design and analyze in this work. Section IV summarizes the analytical results we obtained for the performance of the protocol, although we do not provide much detail of the analysis sue to space limit. Section V is the sensitivity analysis of the protocol to critical parameters in vehicle-vehicle communication system. Section VI concludes the paper.

II. LOCATION BASED BROADCAST AND UNICAST

In the most general sense, the vehicle-vehicle communication in DSRC could be classified as Location-Based Broadcast LBB and unicast. This paper is focused on the design and analysis of LBB protocols.

In Location Based Broadcast [4], sender broadcasts messages to all receivers in its communication range. It is the receiver's responsibility to determine the relevance of message and the proper response. The decision is made on basis of the relative position of the sender (e.g. in front, behind, left lane, distance, etc.), the purpose of the message(e.g. brake warning, lane change warning, accident reporting, congestion prediction, etc.), as well as the highway traffic environment. In DSRC the LBB protocol is built on top of IEEE 802.11a broadcast mode, since 802.11a has been selected by the DSRC standard committee as the MAC layer protocol. To realize LBB, wireless communication techniques must be integrated with other techniques such as Global Positioning System, Inertial Navigation System, digital map, radar, and sensor fusion. The LBB is the enabling technique for wide range of highway safety applications such as cooperative collision warning and emergency vehicle warning.

The realization of unicast vehicle-vehicle communication also requires the assistance of LBB. In order to establish initial vehicle-vehicle unicast communication, we must solve the anonymity problem in ad hoc vehicle communication networks, i.e. the communication addresses of vehicles on highway are unknown to each other at the beginning. Location Based Addressing (LBA) is needed to build (in all involved vehicles) the map between the physical location of surrounding vehicles and their communication addresses. This map basically answers the question ”What is the communication address(es) of the vehicle(s) at given position(s)? ”. LBB is essential for the realization of LBA. This is because that the LBA process depends on the vehicle-vehicle communication, while only broadcast communication is available before the addressing is accomplished. Furthermore, the address-position map must be updated at proper frequency because of the dynamic property of vehicle communication network. This update process also has to rely on LBB since when update is necessary, the configuration of unicast network may already have changed and thus unreliable. Except for the building and updating of LBA map, the unicast vehicle-vehicle communication system is not fundamentally different from standard unicast communication system, and many established techniques could be applied.

Therefore to design a communication protocol to realize LBB that satisfies the requirements of highway safety applications is one of the most important tasks in the design of DSRC system. This paper aims to provide a first attempt in solving this problem.

III. A LOCATION BASED BROADCAST PROTOCOL BASED ON REPETITION CODING

A. An Example of Highway Safety Application

The primary goal of the vehicle-vehicle communication protocol we consider is to support vehicle safety application, therefore it is necessary for us to understand the communication requirement of the safety application before designing the protocol. The following is an example application.

Cooperative Collision Warning [7]:

1) Definition
   Use vehicle-to-vehicle communication to collect surrounding vehicle locations and dynamics and warn the driver when a collision is likely.
2) Application needs
   a) Communication from vehicle to vehicle
   b) Two-way communication
   c) Point-to-multipoint communication
   d) Allowable latency $\sim$ 20–200 msec
   e) Frequency (update rate) $\sim$ 10 Hz
   f) Data to be transmitted and/or received - position, velocity, acceleration, heading, yaw-rate
   g) Range of communication $\sim$ 50–300 m

The primary task of the DSRC communication protocols we consider here is to support such safety application. It can be seen that the system has to communicate small amount of information consistently at high frequency, with low delay, and competing with many transmitters. We describe our proposed protocol to meet these challenges below.

B. The LBB Protocol

The protocol we propose works as following.

1) Vehicle safety applications generate a message to be transmitted to other vehicles when an event (e.g. braking, emergency) occurs. The safety application’s requirements provide a useful lifetime of the message. For example, after 100 msec from the braking, a brake warning message may be regarded as out of date and useless to the collision avoidance applications of other vehicles. We denote the useful lifetime as τ. The protocol attempts to transmit the packet only within the message’s lifetime and discards the packet when the message has expired.
2) The information in the *message* is encapsulated in a lower layer *packet* to be transmitted to other vehicles. The packet could contain the location of the sender, the targeted vehicle’s location (e.g. the first following vehicle, all vehicles in the adjacent lane), the nature of the event (hard braking, accident, severe road condition), etc. The time taken to transmit one packet is a function of the packet size and the channel bit rate. We denote this time period as t_{trans}.
3) The whole lifetime is evenly divided into $m = \lfloor \frac{\tau}{t_{trans}} \rfloor$ slots. The fraction of τ that is not used is quite small since in general $\tau \gg t_{trans}$ (τ is in the order of millisecond or even second while t_{trans} is in the order of microsecond. See below for detail).
4) In each of the slot, the protocol determines wether to transmit a packet in this slot by flipping an unfair coin with $P(H) = \frac{n}{m}$ and $P(T) = 1 - \frac{n}{m}$. A packet is transmitted if a head is obtained, where $n < m$ is an integer, which is the design parameter of the protocol.
5) If any one or more *packets* are transmitted without being collided, the *message* is received by all the vehicles in its communication range, and the delay is smaller than the useful lifetime of the message. On the other hand, the message transmission fails if all its transmitted packets are lost due to collisions. In this first-shot analysis we assume all transmitters have common clock therefore all the slots of various transmitters are synchronized.

Figure 1 is a illustration of the protocol. Two vehicles within interference range of each other have messages generated at same time, and the protocol makes them choose multiple slots to transmit a packet in each. Some packets collide but as long as there is at least one packet goes through the transmission is successful. Both vehicles in the figure succeed if there are no other interfering vehicles.

In the analysis below we assume that the value of n is the same for all vehicles, i.e. all vehicles have the same protocol design. From the law of large number we can see that in average each vehicle transmits the packet of one message n times, although the exact transmission number for each one particular message varies. Our protocol is therefore essentially based on repetition coding. Intuitively, repetition enhances the probability for at least one packet to get through over when transmitting only once. However excessive repetitions add burden to the channel and degrade the performance. Therefore the optimal number of transmissions n_{opt} must be found.

The protocol we proposed is relatively simple. In this first shot analysis, the LBB protocol does not "listen before transmission", and the receivers do not acknowledge the receipts. However the design and analysis of the simple protocol could provide us with insight at least in the following three aspects. Firstly, we could obtain the worst bound of the performance of smarter protocols built on basis of the study of the current one. Secondly, we could find which applications could be supported by the simple protocol and which require more complicated protocols. Lastly, we could find out which parameters have significant effects on the performance.

IV. ANALYSIS OF THE PROTOCOL

There are two communication requirements on the performance of the protocol.

1) *Channel occupancy caused by the vehicle-vehicle communication must be low*. Applications should not take too much of the channel time, such that the potentially large number of transmitters in highway environment can be accommodated (e.g. in the congested highway), and multiple safety applications could be working simultaneously.
2) *The probability of failure for message transmission must be low*. With large number of transmissions in the same channel and each transmitting frequently, just as in highway environment, packet collisions happen quite often. However low failure probability is critical for the safety application. A good protocol should perform well in this aspect.

A. Probability of Failure

We make the following two assumptions to analyze the performance of protocol in probability of failure.

1) The message generation process of each individual vehicle is a Poisson process.
2) The message generattion processes of different vehicles are identically independent.

With these two assumptions, we know immediately that the generation process of all messages is also Poisson with the rate equal to the sum of the rates of all transmitters in interference range. Assume that the rate of the Poisson process for each transmitter is λ' then the generation process of all the messages is λ = (transmitter number) * λ'.

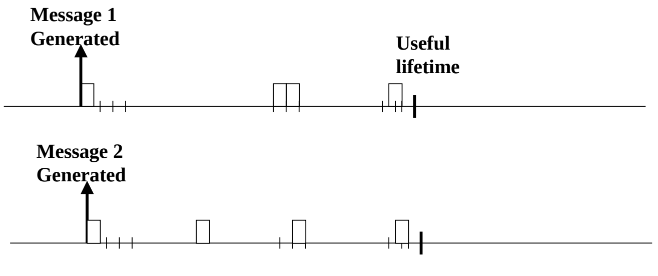

Fig. 1. The LBB Protocol

Theorem 1: The probability of failure P_f for one message satisfies the following inequality:

$$\left(1 - \frac{n}{m} + q\frac{n}{m}\right)^m < P_f < \left(1 - \frac{n}{m} + p\frac{n}{m}\right)^m$$

where,

$$p = (1 - e^{-\lambda\tau\frac{n}{m}} + e^{-\lambda\tau})$$
$$q = (1 - e^{-\lambda\tau\frac{n}{m}})$$

e is exponential base
λ is the message generation rate for all transmitters
τ is the useful lifetime
m is the total number of slots in the useful lifetime
n is the average number of transmitted *packet* for each *message*

B. Channel Occupancy

We use equation (1) as the expression of the upper-bound of the channel occupancy, i.e. the average faction of time used to transmit all the message in the channel.

$$Occupancy = \lambda * t_{trans} * n \tag{1}$$

where as stated above λ is the generation rate of all messages, t_{trans} is the time taken to transmit one packet, and n is the average number of transmitted packet for each message.

The actual channel occupancy is smaller than this value since packet collisions are not considered here. Multiple packets that collide are all counted as occupying the channel in (1), although they overlap in time therefore their effects are the same as one packet occupying the channel. If the channel occupancy calculated with (1) is satisfactory then the real channel occupancy can only be lower.

C. Performance of the Protocol: An Example

Figures 2 and 3 shows the analytical performance of the protocol with the parameters set as in Table I. This is a typical setting for the parameters for a non-congested highway environment. The description and discussion of the parameters are in subsection V-A.

In Figure 2, the horizontal axis is the value of n, and the vertical axis is the corresponding probability of failure calculated based on the upper-bound part of Theorem 1. We could observe that the probability of failure decreases with n at the beginning, and reaches a minimum value at about $n_{opt} = 23$, which is the optimal number of transmission in the sense of probability of failure. As n becomes larger after this value the probability goes up, so the performance degrades. This observation agrees with intuition. Figure 3 is the probability of failure vs. various channel occupancy, where channel occupancy is calculated with equation (1). We know that the (upper bound of) channel occupancy calculated here increases with n linearly, while the probability of failure decreases with n for $n < n_{opt}$, hence we could observe the trend

TABLE I

PARAMETERS OF THE ANALYSIS EXAMPLE

Message Generation Interval (msec)	100
Packet Size (Bytes)	200
Channel Bit Rate (Mbps)	10
Interference Range (m)	100
Average Distance Between Vehicles (m)	30
Lane Number	10

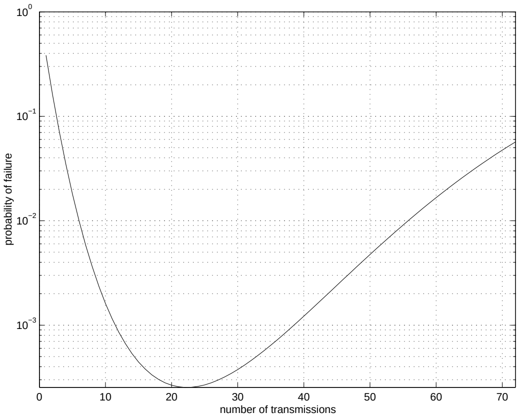

Fig. 2. Probability of failure vs. Number of Transmission

of probability of error with increasing channel occupancy. We do not plot channel occupancy for $n > n_{opt}$ since with these values of n more channel is occupied without decreasing the probability of failure. In Figure 3 the channel occupancy for 0.001 probability of failure is about 50% (number of transmissions about 10). This performance of the protocol is satisfactory since about half of the channel time is left for other applications while the probability of failure is reasonably low. Also we see that as the probability of failure decreases more and more slowly as channel occupancy gets large. Thus after some point the gain in probability of failure by occupying more channel is trivial.

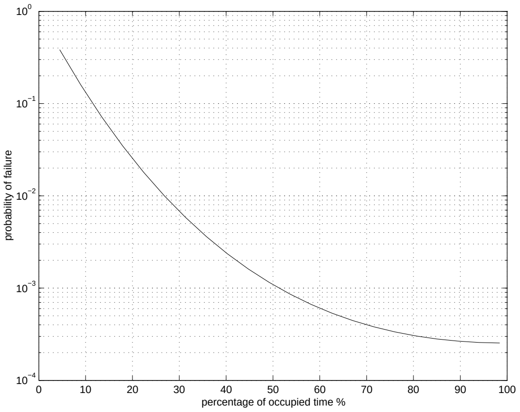

Fig. 3. Probability of Failure vs. Channel Occupancy

V. SENSITIVITY TEST OF THE PROTOCOL UNDER VARIOUS ENVIRONMENT

A. Determining Parameters of the Vehicle-vehicle Communication Performance

The parameters determining the performance of the LBB communication are the following:

1) *Message Generation Rate/Interval*
   They parameterize the frequency at which a safety application message is generated, therefore influence both probability of failure and channel occupancy. The message generation rate is the reciprocal of message generation interval. The actual message generation rate required comes from the specific safety application. We study what rate is supportable by our protocol.
2) *Packet Size*
   This parameter determines the channel occupancy. For vehicle safety application the packet size is generally not large, and is in the order of a few hundred bytes [1]. This comes from the fact that in most cases the information needs to be transmitted is the instantaneous position, velocity, acceleration, yaw rate, direction, warning, etc. All of these could be represented by a few integers. Although the packet size is small, the potentially large number of interfering vehicles and the high transmission frequency makes the performance sensitive to the packet size.
3) *Channel Bit Rate*
   The channel bit rate together with the packet size determines the time taken to transmit one packet, therefore influences the channel occupancy. The channel bit rate we use here is 10 Mbps, which is determined from the proposed DSRC standard [1].
4) *Interference Range*
   This is the range that one vehicle's transmitted signal could be interfere with other vehicles. It affects both the probability of failure and channel occupancy by determining the number of interfering vehicles. Interference range itself is determined by the transmission power and the channel model. Instead of designing the power to transmit and modeling the channel we assume directly the resulting interference range, and the actual transmit power could be calculated from the interference range once we have the channel model and the interference threshold of the specific radio. The channel modeling of DSRC band in highway environment is an on-going work of the authors [9]. In the sensitivity study we assume omni-directional antennae, therefore the interference zone of a vehicle is a circle centered at the position of its antenna with the interference range as radius.
5) *Vehicle Density/Distance*
   The vehicle density is the reciprocal of the distance between two neighboring vehicles in the same lane. Once we know this value and the interference range we could calculate the total number of interfering vehicles for an individual vehicle, which influences both the

probability of failure and the channel occupancy. Here we make an assumption that the traffic is at steady state in which all the vehicles have same constant distance from its neighboring vehicle in the same lane.

6) *Lane Number*
   When the transmission power is such that the interference zone overs all of the lanes in the direction perpendicular to the driving direction, the lane number influences the number of competing vehicles in the interference zone. The lane width we use is 3.6 meters [10]. We test our protocol in some pretty severe circumstance, including the cases where the highway has 20 lanes, e.g. when there are multiple highway bridges overhead.

We conduct sensitivity test of the protocol with the parameters listed in Table II. Wide range of parameters are tested to evaluate the performance of the protocol under various environment and the effects of different parameter to the performance are compared. Both jammed and smooth traffic cases are assessed.

Figure 4 shows the result of the sensitivity test for jammed traffic cases. Plotted here are the bounds of feasible parameter combinations that achieve the following two communication requirements:

1) Probability of Failure smaller than 0.01
2) Channel Occupancy lower than 50%

For example, the dashed-cube curve is for the case when there are 20 lanes and the packet size is 200 bytes. The data indicates that if the interference range is 20 meters, i.e. 2 vehicles in front and two in back in the same lane are covered, then the minimum message generate interval is 200 msec, i.e. 5 messages per second. It is impossible to transmit at higher rate with such interference range, without violating the communication requirements. On this same curve we observe that when the interference range is larger than 40 meters, no message generate interval we tested (50 $\sim$ 500 msec) could achieve the two communication requirements. The area under the curve is infeasible while the area above it is feasible for the communication requirement. That means, given the interference range, the message generation interval values could not be smaller than corresponding values on the curve, and given message generation interval, the interference range cannot be larger than the corresponding value on the curve. Otherwise the communication requirements cannot both be met. We see that when the environment is less severe the feasible area is larger. For example, the feasible area for "100 bytes, 10 lanes" case is larger than "200 bytes, 20 lanes" case.

VI. CONCLUSION

The concept of location based broadcast is introduced for vehicle-vehicle communication in 5.9 GHz DSRC spectrum. The communication requirements of highway safety applications are discussed. A LBB protocol is designed and mathematically analyzed. The performance of the protocol is evaluated under wide range of communication parameters and highway traffic conditions.

TABLE II
PARAMETERS OF SENSITIVITY ANALYSIS

Message Generation Interval (msec)	50, 100, 200, 300, 400, 500	
Packet Size (Bytes)	100, 200	
Channel Bit Rate (Mbps)	10	
Average Distance Between Vehicles (m)	7 (jammed)	30 (smooth)
Interference Range (m)	7-70	30-300
Lane Number	10, 20	

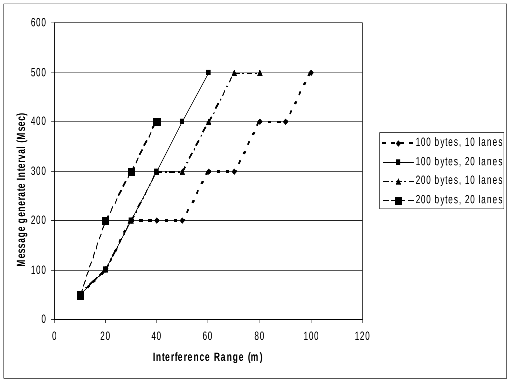

Fig. 4. Sensitivity Test Results: Jammed Highway, Probability of Failure $\leq$ 0.01, Channel Occupancy $\leq$ 50%

The future improvements of the LBB protocol include addition of selective acknowledgments, carrier sensing, situation-based adaptive transmission power control, and exploration on other coding schemes than repetition code.

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REFERENCES

[1] http://www.leearmstrong.com/dsrc/dsrchomeset.htm

[2] A. Kato,K. Sato, and M. Fujise, "Wave propagation characteristics of inter-vehicle communication on an expressway", *Eighth World Congress on Intelligent Transportation Systems*, Sydney, Australia, 2001.

[3] J. VanderWerf, N. Kourjanskaia, S. Shladover, H. Krishnan, and M. Miller, "Modeling the effects of driver control assistance systems on traffic", *U.S. National Research Council Transportation Research Board 80th Annual Meeting*, Washington, D.C., January, 2001.

[4] Q. Xu, K. Hedrick, R. Sengupta, and J. VanderWerf, "Effects of Vehicle-vehicle/roadside-vehicle communication on Adaptive Cruise Controlled Highway Systems", *IEEE Vehicular Technology Conference Fall 2002*, Vancouver, Canada, September, 2002.

[5] K. Hedrick, Q. Xu, M. Uchanski, "Enhanced AHS Safety Through the Integration of Vehicle Control and Communication", *California PATH Research Report*, UCB-ITS-PRR-2001-28, 2001

[6] L. Briesemeister and G. Hommel, "Disseminating Messages among Highly Mobile Hosts Based on Inter-vehicle Communication", *IEEE Intelligent Vehicle Symposium*, Piscataway NJ, 2000.

[7] H. Krishnan, personal communication

[8] J. Carbaugh; D.N. Godbole; R. Sengupta, "Safety and capacity analysis of automated and manual highway systems". *Transportation Research Part C (Emerging Technologies)*, Vol.6C, No.1-2, Elsevier, Feb-April 1998. pp.69-99.

[9] http://path.berkeley.edu/DSRC

[10] *California Highway Design Manual*, Department of Transportation of California, 1995