Driver-Based Adaptation of Vehicular Ad hoc Networks for Design of Active Safety Systems

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Abstract—This paper studies the need for individualizing vehicular communications in order to improve collision warning systems for an N-lane highway scenario. By relating the traffic-based and communications studies, we aim at reducing highway traffic accidents. To the best of our knowledge, this is the first paper that shows how to customize vehicular communications to driver's characteristics and traffic information. We propose to develop VANET protocols that selectively identify crash relevant information and customize the communications of that information based on each driver's assigned safety score. In this paper, first, we derive the packet success probability by accounting for multi-user interference, path loss, and fading. Then, by Monte carlo simulations, we demonstrate how appropriate channel access probabilities that satisfy the delay requirements of the safety application result in noticeable performance enhancement.

I. INTRODUCTION

Despite the increases in safety introduced into the automobile, at latest count (2010) the number of deaths is over 30,000, the number of injuries is over two million, and the number of crashes is over five million [1]. In order to reduce such causalities, the Federal communications commission has allocated 75 MHz of spectrum in the 5.9 GHz band for Dedicated Short Range Communications (DSRC). Furthermore, the IEEE 802.11p standard was presented in 2010 for Wireless Access applications in vehicular environments [2]. Rear end collisions represent some 28% of the crashes among all drivers [3]. This type of collision occurs because of the time that it takes for a driver to perceive and react to a sudden deceleration of the leader vehicle. Therefore, rear-end collision warning systems have been studied extensively. Radical improvement in the effectiveness of collision warning systems are now possible due to the progress that is being made in Vehicular Ad Hoc Networks (VANET). Vehicular ad hoc networks allow all vehicles to communicate with each other (V2V or vehicle to vehicle communications) and with technologies embedded in the infrastructure that transmit crash relevant information (V2I or vehicle to infrastructure communications). Our main contributions in this paper are as follows:

1) We find closed form expression of packet success probability for the slotted synchronous p-persistent MAC scheme in a chain of vehicles. The expression for the slotted asynchronous p-persistent is also derived.
2) We derive the average delay of reception at a vehicle in a chain.
3) We let the probability of collision dictate the transmission probabilities of the vehicles. In other words, we propose to develop VANET protocols that prioritize the communications of information based on the danger that a driver is facing. Our simulations reveal that the collision probability is drastically reduced when it is the main factor in determining the transmission probabilities of the vehicles.

II. DRIVER-BASED ADAPTATION OF WIRELESS COMMUNICATIONS

Communications between vehicles can help decrease collisions in an N-lane highway(Fig. 1). Also, it was shown in theory and simulation that assuming the equal channel access probability for all the vehicles, there is an optimal channel access probability which results in the maximum success probability and lower expected collision probability [5]. A large channel access probability leads the system to an excessive interference and consequently low success probability while a very small value reduces the success probability since the probability of the favorite transmission is low itself. In section III it is shown that there could be nonequal channel access probabilities for different vehicles leading to even lower collision probability.

A. Delay Requirements of the Safety Application

Consider a traffic stream where a chain of vehicles move with constant speed v and randomly chosen inter-vehicle spacing. When $V_0$ (the first vehicle in the chain) brakes, the driver of $V_1$ (the following vehicle), after her perception reaction time, $\tau_1$, applies the brake. Having no inter-vehicle communications employed, vehicle $V_i$ ($i > 1$) applies the brake after $\sum_{j=1}^{i-1} \tau_j$, the sum of perception reaction times up to the driver $i$. With the communications, this time will...
change to \( t_i + t_c \) in which \( t_c \) is the communications delay to inform vehicle \( V_i \). Note that \( t_c \) can be a result of direct communications from \( V_0 \) to \( V_i \) or the retransmission of \( V_0 \)'s signal by one of the vehicles in the middle. Understandably, when \( t_c < \sum_{j=1}^{i-1} t_j \), \( V_i \) has more time to react and the probability of collision is reduced (Fig. 2).

### B. Analysis and Design

The MAC scheme that we consider is SSP (Slotted Synchronous P-persistent) where at each slot a node (vehicle) transmits with probability \( p \) and receives with probability \( 1 - p \) independent of others. The important assumption is that the slots are synchronized because of the on-board GPS devices. Moreover, since the vehicles are not faced with power constraints, the nodes can increase the transmission power to overcome the interference. In this paper, we consider path loss and Rayleigh fading for formalizing the signal propagation characteristics. If we assume that the nodes transmit with unit power, the received power at distance \( r \) is \( h r^{-\alpha} \), where \( \alpha (> 1) \) is the path loss exponent and \( h \) is the fading coefficient.

**Theorem 1.** Assuming that a node transmits a packet, the probability that a receiver at distance \( r \) receives the packet successfully is:

\[
P_s(i) = P \left( \frac{S}{I} > \beta \right)
\]

\[
= P \left( \frac{h r^{-\alpha}}{\sum_{i' \in \Phi} b_i' b_i r_i^{-\alpha}} > \beta \right)
\]

\[
= \prod_{i' \in \Phi} \left[ \frac{p_{i'}}{1 + \beta r_i^{\alpha - \alpha'}} + (1 - p_{i'}) \right]
\]

where \( \Phi \) is the set of all nodes, \( b_i \) is a Bernoulli random variable with parameter \( p_i \), \( p_i \) is the probability that node \( i \) transmits, and \( r_i \) denotes the distance from node \( i \) to the receiver.

Note that the above equation is true for an N-lane highway if we neglect the distance between the lanes. In other words, in an N-lane highway scenario, node \( i \) could be any vehicle in each of the lanes, and \( \Phi \) is the set of all vehicles moving in all lanes as every vehicle can cause interference for the desired receiver.

If the time slots in which nodes transmit are not synchronized, this scheme is named Slotted Asynchronous P-persistent. In this case, an interferer can potentially interfere with at most two time slots of another transmission. Hence, the transmission probability for the interferer is \( p_i' = p_i + p_i - p_i \cdot p_i \simeq 2p_i \). Since the probabilities are small, this approximation is tight. We assume that the less safe is a driver, the more frequently the driver needs to transmit information to the network. Moreover, the driver safety index could be changed in real time. As an example, if a driver’s brake reaction time is relatively long, then driver’s safety index will be relatively low and so more data will put on the air from the corresponding vehicle. In this paper, vehicles are simply divided into two categories:

- Unsafe vehicles
- Safe vehicles

Unsafe vehicles are the ones which their drivers have long perception-reaction time and low distance to the vehicle in front. To put it differently, unsafe vehicles have higher collision probability. Our algorithm to determine an unsafe vehicle is an iterative one. The collision probability is calculated in each iteration using only the physical parameters such as distance, velocity, .... Then, it’ll be used to see what channel access probability is suitable for a vehicle.

### III. Simulation

We proposed a method to estimate the distribution of perception reaction times for an individual driver using the data obtained from vehicular ad hoc networks [4]. Hence, the estimates of perception reaction times are available to us. Also, we know that some of the vehicles are too far from the vehicle \( V_0 \) to be able to receive the messages directly from it. Thus, when one of the vehicles in the middle gets informed and reacts to the event, the message will be forwarded to the vehicles at a greater distance from the leading vehicle. In other words, after a vehicle in the middle starts decelerating, the
If SAP scheme is employed, we need to alter the equation:

\[ \text{the tolerable delay period is: } \]

\[ V \] gives us the number of required slots on average for vehicle

\[ \text{desired receiver is obtaining the warnings, and the warning} \]

\[ \text{probability that the transmitter is sending messages, the} \]

\[ \text{access probability is assumed to be equal for all vehicles} \]

\[ R \_p \text{in which } \]

\[ \tau \] denotes the packet length.

\[ \text{represents data rate which is chosen from TABLE I while} \]

\[ R \] represents data rate which is chosen from TABLE I while \( L \) denotes the packet length. \( \tau(2) \) denotes the maximum tolerable delay to inform vehicle \( V_2 \). Let \( P^D_s \) denotes the success probability at \( V_2 \) after \( D \) transmission opportunities:

\[ P^D_s = 1 - (1 - s(i)^{-1})^D \]

\[ = 1 - \left( 1 - p_{tr} \right) \left( 1 - p_2 \right) \prod_{i \in \Phi} \left[ \frac{p_i}{1 + \beta r^{-\alpha} r_i} + (1 - p_i) \right]^D \]

This equation demonstrates the dependence of packet success probability on \( p \) and inter-vehicle distances.

Clearly, it takes longer time for the vehicles far away from \( V_0 \) to receive the packets due to delay, however, those far vehicles (for example \( V_i \)) receive the messages notifying about the deceleration of \( V_0 \) from the vehicles \( V_1 \cdots V_{j-2} \) as well. \( V_{j-1} \) is not included since \( V_j \) can see the brake lights of \( V_{j-1} \) with no need of vehicle to vehicle communications. Taking all of the above into account, the average delay of reception at vehicle \( V_j \):

\[ D(i) = \min(\min(j \in 1, \cdots, i-2) \frac{L}{R} s(j) + \tau(j) + \frac{L}{R} s(i-j), \frac{L}{R} s(i), \frac{L}{R} s(i-1) + \tau(i-1)), \quad i > 2 \]

where \( s(1) = D(1) = 0 \) since there is no need for communications between two adjacent vehicles. We run a recursive algorithm such that the channel access probability at a specific time depends on the collision probability at the previous time.

Fig. 3 illustrates the collision probability when different channel access probabilities are assigned to unsafe and safe vehicles respectively. X axis represents the channel access probabilities for safe vehicles, Y axis shows the channel access probabilities for unsafe vehicles, and Z axis denotes the collision probabilities. Assuming equal transmission probabilities (Fig. 4), the minimum number of collisions happens at around \( p_0 \approx 0.05 \). However, 25% reduction in collision probability can be achieved when unsafe and safe vehicles transmit more and less than \( p_0 \) respectively. In other words, the minimum collision probability in Fig. 3 is located in a value greater than \( p_0 \) on Y axis and less than \( p_0 \) on X axis. Note that we are comparing this customized communications (Fig. 3) to the communications with equal channel access probability in its optimal range (Fig. 4). With this simulation, it becomes clear that the driver-based adaptation of communications used in warning systems has a noticeable advantage over these systems employing the same optimal channel access probabilities for all the vehicles and therefore has a huge advantage over the currently used warning systems. This communications

| \( R \) (Mbps) | 3  | 4.5 | 6  | 9  | 12 | 18 | 24 |
|----------------|----|-----|----|----|----|----|----|
| \( \beta \) (db) | 5  | 6   | 8  | 11 | 15 | 20 | 25 |
system, if implemented, will be able to save thousands of lives in future.

REFERENCES

[1] National Highway Traffic Safety Administration (2012a), 2010 Motor Vehicle Crashes: Overview. Traffic Safety Factors (Revised February 2012) Washington D.C.: Accessed 11/12/12.

[2] IEEE standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks-specific requirements part 11: Wireless LAN medium access control (MAC) and physical layer (PHY) specifications amendment 6: Wireless access in vehicular environments, IEEE Std 802.11p-2010, pp. 1-51, 2010.

[3] W. Najm, B. Sen, J. Smith, and B. Campbell, Analysis of light vehicle crashes and pre-crash scenarios based on the 2000 general estimates system, Tech. Rep. DOT HS 809 573, Department of Transportation, 2003.

[4] A. Rakhshan, H. Pishro-Nik, and E. Ray, Real-Time Estimation of the Distribution of Brake Response Times for an Individual Driver for Design of Active Safety Systems Using VANET, IEEE Intelligent Vehicle Symposium, 1181-1186, 2014.

[5] M. Nekoui, and H. Pishro-Nik, Analytic Design of Active Safety Systems for Vehicular Ad hoc Networks, IEEE Journal on Selected Areas in Communications/Supplement, Vol. 31, NO. 9, 2013.