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 a 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 index. 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[1]

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. They do reduce the behaviors that lead to crashes. However, 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). (Fig. 1). 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). In this paper, we show that tailoring the transmission probabilities of the vehicles to their drivers' safety indices results in reducing the collision probability average

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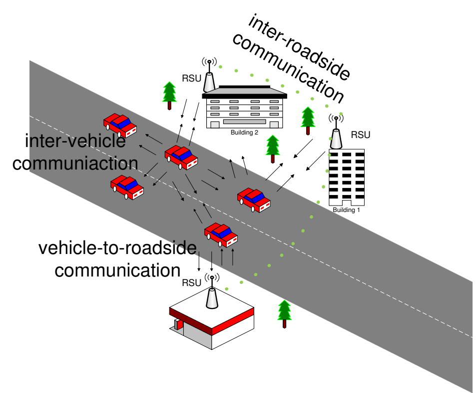

Fig. 1. VANET: Vehicular Ad-hoc NETwork

over all drivers which is equivalent to preventing deaths and injuries on highways. 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) By defining different types of collision, we let the danger that a driver is facing 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. In other words, our main goal is to show that by updating channel access probabilities with respect to expected collision probabilities, a significant reduction in highway traffic accidents will be achieved. Our simulations reveal

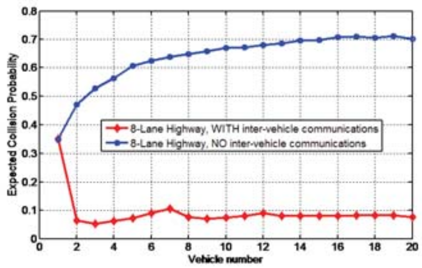

Fig. 2. Inter-vehicle communications reduces expected collision probability

that the collision probability is drastically reduced when this number is the main factor in determining the transmission probabilities of the vehicles.

We believe this is the first paper which discusses the need for individualizing VANET so as to improve safety. This approach could be the first step to show how safety applications would potentially benefit from customizing to individual drivers' characteristics using VANET and can reach to even beyond the safety applications for designing future systems.

II. DRIVER-BASED ADAPTATION OF VEHICULAR COMMUNICATIONS

Communications between vehicles can help decrease collisions in an N-lane highway(Fig. 2). It can help drivers with making proper reactions to the deceleration events especially when a driver cannot either observe or perceive the deceleration of other vehicles due to low visibility, high unexpectedness of the incident, defected brake lights, and many distractions that nowadays exist on the roads. Large channel access probabilities lead the system to excessive interferences and consequently low success probabilities while very small values reduces the success probabilities since the probability of the favorite transmission is low itself. In section III, it is shown that there could be individualized channel access probabilities for different vehicles leading to low collision probability. The distances between vehicles are randomly chosen in our simulations.

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, τ_1, applies the brake. Having no inter-vehicle communications employed, vehicle $V_i \quad (i > 1)$ applies the brake after $\sum_{j=1}^{i} \tau_j$, the sum of perception reaction times up to the driver i. With the communications, this time will change to $\tau_i + t_c$ 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 $t_c < \sum_{j=1}^{i-1} \tau_j$, which is almost always the case, V_i has more time to react and as a result the collision probability is reduced (Fig. 3).

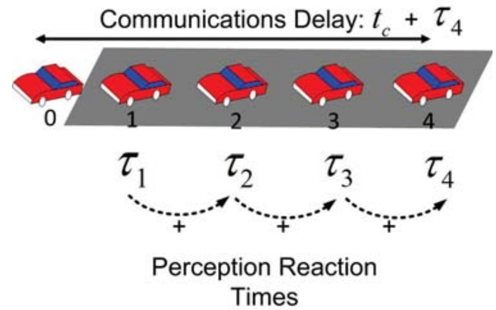

Fig. 3. Communications delay versus sum of perception reaction times. The time before a driver in a chain applies the brake.

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 $hr^{-\alpha}$, 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:

$$\begin{aligned} P_s(i) &= P\left(\frac{S}{I} > \beta\right) \\ &= P\left(\frac{hr^{-\alpha}}{\sum_{i\in\Phi} b_i h_i r_i^{-\alpha}} > \beta\right) \\ &= \prod_{i\in\Phi}\left[\frac{p_i}{1+\beta r^{\alpha} r_i^{-\alpha}} + (1-p_i)\right] \end{aligned} \tag{1}$$

where Φ 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 (Fig. 4).
Proof: see Appendix

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 Φ 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 interferers is $p_i' = p_i + p_i - p_i \cdot p_i \simeq 2p_i$. Since the probabilities are small, this approximation is tight.

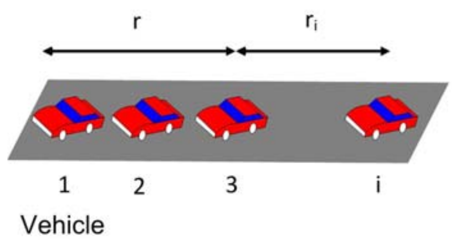

Fig. 4. A chain of vehicles. Distance between the transmitter and the desired receiver $= r$. Distance between an interferer i and the desired receiver $= r_i$.

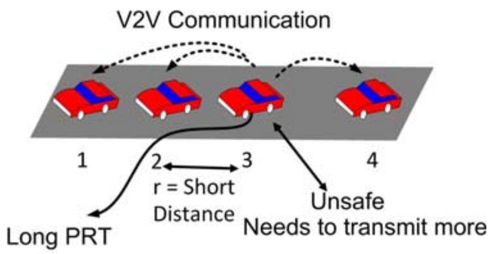

Fig. 5. Vehicle 3 needs to transmit more frequently than other vehicles because it has higher collision probability

A number of general indices of driver safety have been suggested or developed with the advent of relatively inexpensive in-vehicle sensors that can record, among other things velocity, acceleration, and lane position. We need to make it clear at the outset that we do not expect to have access to information on the age of a driver, or any other demographic information. Thus, the safety indices we develop would apply to all drivers. 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: 1. unsafe vehicles 2. safe vehicles. Unsafe vehicles are the ones which their drivers have long perception-reaction time and low distance to the vehicle in front (Fig. 5). 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

A. Estimating the Distribution of Perception Reaction Times

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 [5]. This estimation can be obtained by a regression method using just the time

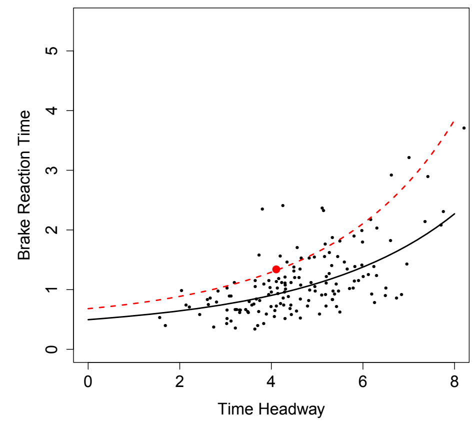

Fig. 6. An illustration of the model based on a simulated data set [5]

headway as an explanatory variable:

$$\begin{aligned} \mathbf{y}_d &\sim N(X\beta + X\gamma_d, \sigma^2 I) \\ \gamma_d &\sim N(0, \Sigma_\gamma) \end{aligned} \tag{2}$$

In this model,

- d indexes the driver
- $\mathbf{y}_d$ is a vector of the logarithms of observed reaction times for a particular driver.
- X is a matrix of covariates.
- β is a fixed vector of unknown coefficients.
- σ^2 is an unknown scalar.
- γ_d is a random vector of unknown coefficients.
- Σ_γ is an unknown matrix.

The basic idea of this model (2) is that the distribution of perception reaction times for an individual driver has a mean which is given by an overall population mean, $X\beta$, plus an offset due to the particular characteristics of that driver, $X\gamma_d$. An illustration of the model based on a simulated data set is showed in Fig. 6. It is assumed that the parameters γ_d determining the individual's offset to the overall mean follow a multivariate Normal distribution in the population. The estimated PRT distribution of an individual is illustrated in Fig. 7.

B. Communications Parameters

Communications delay is the main factor that influences the collision probability. 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 new status will be included in the new messages from this vehicle to further upstream vehicles. Therefore, We need to calculate the time it takes

TABLE I. COLLISION SCENARIOS BETWEEN V_0 AND V_1

Collision 1	Collision 2	Collision 3	Collision 4
Before V_0 stops Before V_1 Reacts	After V_0 stops Before V_1 Reacts	Before V_0 stops After V_1 Reacts	After V_0 stops After V_1 Reacts

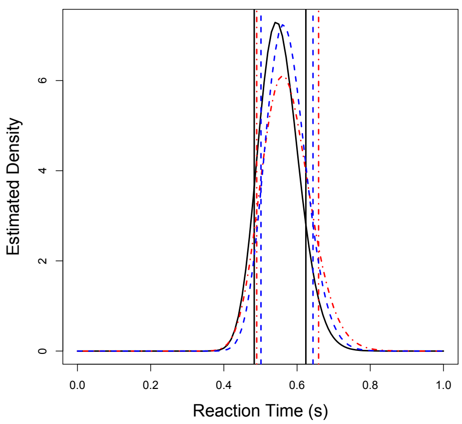

Fig. 7. Estimate of the distribution of PRTs for an individual [5]. The black curve represents the individual's "true" response time distribution. The blue and red curves are the estimated distributions for different estimates of the variance. The vertical lines are at the 10th and 90th percentiles.

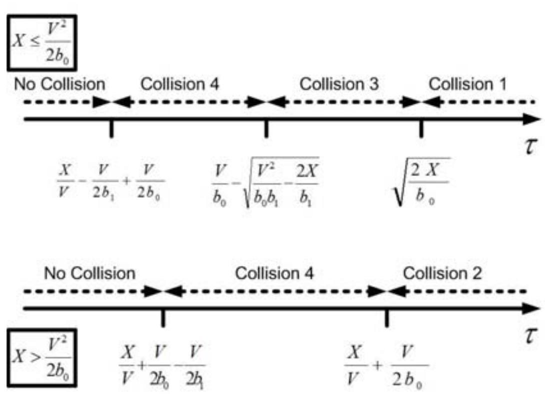

Fig. 8. Collision scenarios between vehicles V_0 and V_1 in a dense traffic.

for a message to be received by vehicle i. It is sufficient that the message be received successfully only one time, as a result the successful reception at vehicle V_i has a geometric distribution with parameter $P_s(i) * p_{tr} * (1 - p_i)$ in which $P_s(i)$ is given in equation 1. Also, p_{tr} and p_i represent the channel access probability for the transmitter and the desired receiver respectively. This parameter demonstrates the probability that the transmitter is sending messages, the desired receiver is obtaining the warnings, and the warning messages are successfully delivered, all simultaneously. This gives us the

TABLE II. IEEE 802.11P DATA RATES AND CORRESPONDING SIR DECODING THRESHOLDS

R (Mbps)	3	4.5	6	9	12	18	24
β (db)	5	6	8	11	15	20	25

number of required slots on average for vehicle V_i to receive vehicle V_0's messages:

$$s(i) = \frac{1}{P_s(i) * p_{tr} * (1 - p_i)}$$

If SAP scheme is employed, we need to alter the equation:

$$s(i) = \frac{1}{P_s'(i) * p_{tr} * (1 - p_i')}$$

in which p_i' represents the channel access probability when the time slots are not synchronized and $P_s'(i)$ denotes equation 1 using the new channel access probabilities.

The allowable number of transmission opportunities within the tolerable delay period is:

$$D = \lfloor \frac{\tau(i)R}{L} \rfloor$$

R represents data rate which is chosen from TABLE II while L denotes the packet length. $\tau(i)$ denotes the maximum tolerable delay to inform vehicle V_i which can be obtained from Fig. 8. Let P_s^D denote the success probability at V_j after D transmission opportunities:

$$P_s^D = 1 - (1 - s(j)^{-1})^D$$
$$= 1 -$$
$$\left(1 - p_{tr} * (1 - p_j) * \prod_{i \in \Phi} \left[\frac{p_i}{1 + \beta r^{\alpha} r_i^{-\alpha}} + (1 - p_i) \right] \right)^D$$

This equation demonstrates the dependence of packet success probability on p and inter-vehicle distances (Fig. 9). 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_i is:

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

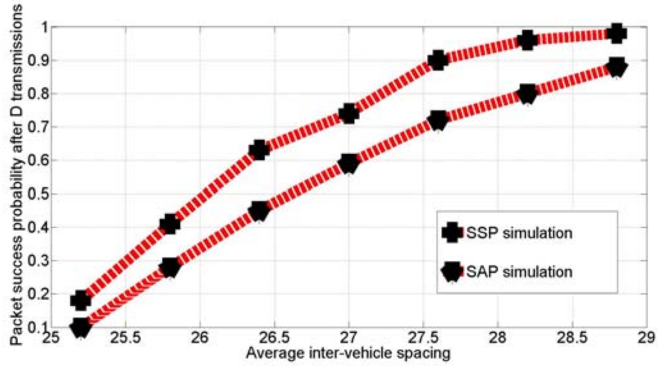

Fig. 9. Packet success probability after D transmissions using two different MAC schemes

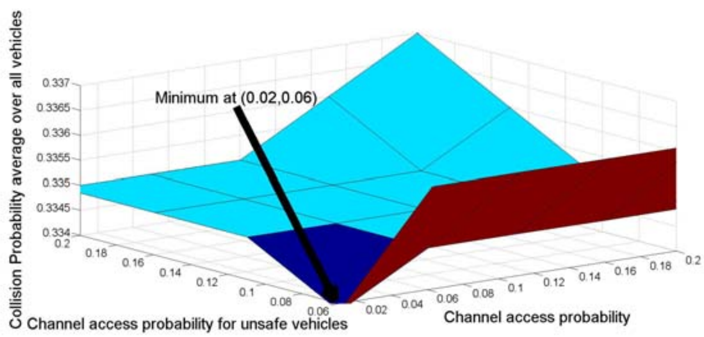

Fig. 10. X, Y, and Z axis represent channel access probability of safe vehicles, channel access probability of unsafe vehicles, and collision probability average over all vehicles respectively. Since the minimum collision probability in this case is 25% less than the scenario in which equal channel access probabilities are assigned to all vehicles, we conclude tailoring the channel access probabilities to unsafe and safe vehicles leads to reduction of collision probability

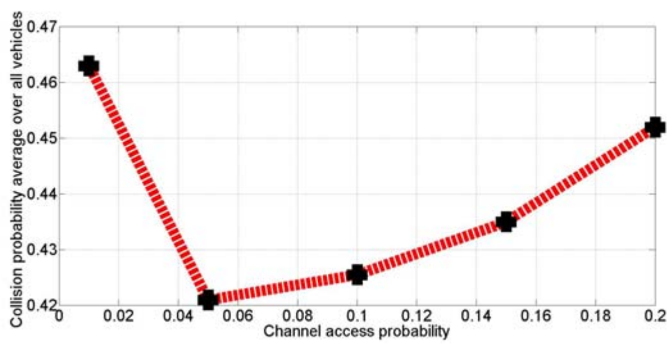

Fig. 11. Collision probability versus channel access probability. Channel access probability is assumed to be equal for all vehicles.

where $s(1) = D(1) = 0$ since there is no need for communications between two adjacent vehicles. If the distance between a vehicle and the one ahead of it is short, and also the perception-reaction time of the following vehicle is long enough, we consider the vehicle as an unsafe vehicle. Otherwise, the vehicle is a safe one. In other words, if the collision probability calculated only based on physical/traffic parameters (without considering the vehicle to vehicle communication) is higher than a threshold, the vehicle is unsafe. 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. 10 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. 11), 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 with specific probabilities more and less than p_0 respectively. In other words, the minimum collision probability in Fig. 10 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. 10) to the communications with equal channel access probabilities in its optimal range (Fig. 11). With this simulation, it becomes clear that using the driver-based adaptation of communications in warning systems has a

TABLE III. SIMULATION PARAMETERS

Velocity	$20\frac{m}{s}$
Deceleration rate	$[-4,-8]\frac{m}{s^2}$
Number of vehicles in an specific lane	10
Total number of vehicles	40
SIR decoding threshold	11 dB
Data rate	9 Mbps
Packet length	250 Bytes

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 system,if implemented, will be able to save thousands of lives in future.

IV. CONCLUSION AND FUTURE WORK

We've shown not only how we can estimate individual driver parameters from vehicular ad hoc networks [5], provide cautionary warnings which increase driver trust [4], [6], but also, in this paper, how we can then use those individual driver parameters to optimize the communications among vehicles of critical crash relevant information. Drivers characterized as safe will place less of a burden on the communications network because information from these drivers can be transmitted less often than is information from drivers who are characterized as unsafe. Thus, by taking into account the traffic and drivers' characteristics one can potentially improve the delivery of timely warning messages to drivers while substantially reducing the collision probability. Our research suggests that using this strategy the functioning of the rear-end collision warning systems can be dramatically improved as compared to similar systems which do not account for both the specifics of particular drivers and traffic. As our future work, we think that we might be able to find a safety score which can result in even higher reduction in collision probability.

V. APPENDIX

Proof of *Theorem 1*:

If there is the distance r between a transmitter and the desired receiver, the success probability is:

$$\begin{aligned}
P_s &= P(SIR > \beta) \\
&= P\left(\frac{hr^{-\alpha}}{I} > \beta\right) \\
&= \int P(h > \beta r^{\alpha} I | I = i) f_I(i) di \\
&= \int \left[1 - P(h < \beta r^{\alpha} I | I = i)\right] f_I(i) di \\
&(h \quad \text{is exponentially distributed}) \\
&= \int e^{-\beta r^{\alpha} i} f_I(i) di \quad \text{(Laplace transform)} \\
&= E\left[e^{-\beta r^{\alpha} I}\right] \\
&= E\left[e^{-\beta r^{\alpha} \sum_{i\in\Phi} b_i h_i r_i^{-\alpha}}\right] \\
&= \prod_{i\in\Phi} [E\left[e^{-\beta r^{\alpha} h_i r_i^{-\alpha}}\right] p_i + 1 - p_i] \\
&= \prod_{i\in\Phi} \left[\frac{p_i}{1+\beta r^{\alpha} r_i^{-\alpha}} + (1-p_i)\right]
\end{aligned}$$

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