Reliable Inter-Vehicle Communications for Vehicular Ad Hoc Networks

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ABSTRACT

Safety message exchange is the most prevalent part of inter-vehicular communications which is crucial for enhancing safety and efficiency in transportation networks. Moreover, since the dissemination of safety messages directly influences our lives, their reliable delivery is of great importance. Most packet collisions in VANETs occur due to hidden nodes. In unicast communications a two-way handshaking is performed prior to the actual transmission in order to alleviate the hidden node problem. However, this procedure congests the network with a lot of overhead in case of broadcast, which is the dominant mode of communication in VANETs. Hence, in this paper we propose an alternative solution, based on retransmissions, to ensure the reliable delivery of safety messages. We argue that the specific characteristics inherent in VANETs, such as the limited density of vehicles, anticipated bandwidth and the tolerable delay, allow us to deploy a retransmission strategy. Furthermore, We prove that our proposed scheme establishes fair channel access for the consecutive retransmission opportunities of contending neighbors. Simulation results confirm that our heuristic method dramatically improves the probability of reception of safety messages regarding conventional methods.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design-Wireless Communication

General Terms

Algorithm, Performance, Theory

Keywords

Dedicated Short Range Communications (DSRC), Inter-Vehicle Communications (IVC), Vehicular Ad Hoc Networks (VANETs).

1. INTRODUCTION

Despite the undeniable beneficial impacts of transportation systems on our everyday lives, they might seem inconvenient in some circumstances. Without no doubt, many of us have experienced being trapped in heavy traffic, wasting our time and energy resources. More importantly traffic accidents are held responsible for a good portion of death causes. Annually more than 40,000 people are killed and much more injured in highway traffic accidents in the united states alone [1].

Recently, Intelligent Transportation Systems (ITS) have been proposed to improve safety and efficiency in transportation networks. The allocation of 75 MHz in the 5.9 GHz band for Direct Short Range Communications (DSRC) by FCC was a move towards this goal. The trend was further complemented by the introduction of the Vehicle Infrastructure Integration(VII) initiative by the US Department of Transportation.

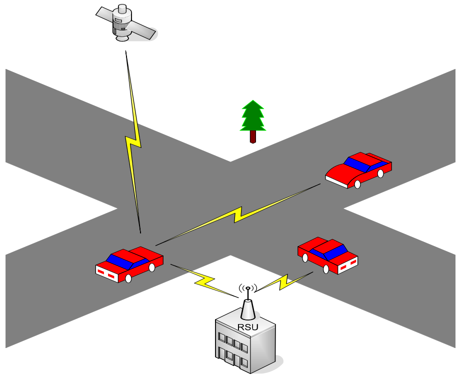

Figure 1: A generic VANET.

The 75 MHz frequency band is divided into seven 10 MHz wide channels. These channels are either utilized by the infrastructure to deliver *infotainment* to vehicles (*service channels*) or by the vehicles to exchange crucial safety related information, where the latter is mainly carried out in the *control channel.* Also a special channel is designated for the less delay-tolerant safety-of-life messages in case of the control channel being over congested.

It has previously been seen that vehicle-to-vehicle communications, through which vehicles gain information on each other's status, greatly benefits safety and efficiency in trans-

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portation networks. Safety information can be classified into *periodic* and *event-driven*. The former are periodic packets sent by each vehicle, containing information on its current status such as location, speed and acceleration; whereas the latter are messages disseminated throughout the network in case of emergency. There has been a plethora of studies considering the exchange of safety related information between vehicles in the literature [2, 3, 4]. The focus of this paper- as of most others- is on periodic safety messages. This is because event-driven messages are not generated that often and can be communicated through the safety-of-life channel anyway. Hence, they do not raise that much of capacity concern. Here, the inter-vehicular communications is *geocast* by nature, where each vehicle periodically broadcasts its status to all others in its local neighborhood.

As studied previously in the wireless area, Single-hop, long range communications decreases the throughput of wireless networks due to the increased contention for media access. Multi-hop communications is a solution for dense areas, but nevertheless it would bring about unwanted delay. Asymptotic results for VANET capacity scaling have been studied by the authors in [5, 6, 7]. In reality, DSRC radios are currently able to transmit to distances as far as 300 meters. This distance is sufficient for a high speed vehicle to come to a complete stop. Hence, considering also the strict delay requirements of DSRC communications, single-hop communications would still be the best proposed for environments such as highways [3].

The Media Access Control (MAC) protocol anticipated for DSRC communications is a variation of the conventional CSMA/CA scheme proposed for IEEE 802.11 communications [8]. Although here, we do not use RTS/CTS and ACK message exchange mechanisms due to the limited channel capacity. Since otherwise, these control messages would have to be exchanged with any one of a vehicle's neighbors, burdening the network with a lot of overhead. Forgoing RTS/CTS and ACK message exchanges gives rise to the *hidden node* problem, increasing the probability of packet collision. Hence, a contribution of this paper is to devise alternative solutions which would alleviate the hidden node problem without adding too much burden to the network. Moreover, we propose a fair retransmission scheme to achieve this goal. In [4], the authors propose a retransmission strategy, where the vehicles randomly choose time slots to perform retransmissions within a packet's useful lifetime. There, each vehicle performs carrier sensing prior to transmitting in a chosen time slot. This scheme not only lacks efficient use of channel capacity, but also neglects the past transmission history in assigning a time slot for the future retransmissions of a vehicle.

In brief, in our scheme, each vehicle deploys a carrier sense strategy together with random back-off to transmit a packet for several times within its useful lifetime. We will prove that our media access strategy fairly grants channel access to the subsequent retransmissions of contending neighbors.

As stated earlier, vehicles periodically exchange information on their status (obtained through their GPS) with their neighbors. Most off-the-shelf GPSs have an update rate of less than 5 Hz. That is, there is a minimum interval of 200 ms between the generation of subsequent packets. This is good enough since a high speed vehicle speeding with 80 mph in a highway would move less than 8 meters in that interval; this distance being even less for low speed vehicles in urban areas. We assume the inter arrival time of subsequent packets to be the tolerable delay for communicating it to the neighboring vehicles. We will refer to this duration as the useful lifetime of a packet, hereafter. Note that this duration should necessarily be less than the human perception time, so that a driver gets the information before observing it himself. Hence, in our algorithms we seek to deliver the packet to as many vehicles as possible (in a determined neighborhood), with as high a probability as possible, within its useful lifetime.

2. COMMUNICATION STRATEGY

As stated earlier, the MAC protocol proposed for DSRC communications is similar to CSMA/CA. In this protocol, each vehicle senses the media and waits until it is idle before sending its packet. In standard CSMA/CA protocols, to overcome the hidden node problem, a two-way RTS/CTS handshake is carried out before the actual data exchange. This is followed by an ACK by the receiver after a successful data transfer. However in inter-vehicle communications this would give rise to excessive overload due to the broadcast nature of communications. Hence it seems logical enough to deploy substitute algorithms to overcome the packet collisions caused by hidden nodes. The algorithm we propose is based on retransmitting a packet in its useful lifetime. Note that the useful lifetime (or acceptable delay to deliver a packet) is assumed to be the time interval between the generation of two subsequent data packets (which is about 200 ms for 5 GHz GPS devices). This time interval can be shared by all vehicles in a specific interference range. Note that usually the number of cars in the interference range of a specific vehicle is less than a hundred. Also the time needed to transmit a single packet is determined by the packet length and chosen data rate. If we assume a 6 Mbps data rate for vehicles operating in the 10 MHz control channel, and 250 Bytes per packet, transmission of each packet would approximately take 340 microseconds. This example is to show that even in the worst cases in terms of contention for media access (low data rate and large number of interfering cars), each vehicle can retransmit its packet several times within its useful lifetime to ensure reliable delivery and still leave free enough time slots for service data transfer. However our algorithm is designed such that in dense areas where retransmitting a packet is not always possible, the limited bandwidth is fairly divided between the vehicles.

2.1 Power Control Scheme

As discussed earlier, the prevalent kind of communications in VANET is geocast. Here, each vehicle broadcasts information on its current status to other vehicles in its geographical neighborhood. It has been previously proposed [9, 3] to choose the transmission range of vehicles according to the local density they observe. For example, in dense areas where vehicles usually move at lower speeds, transmission power can be lowered to alleviate the contention for channel access. Note that in this scenario, a smaller number of a vehicle's neighbors will receive its packets; this being fair enough due to the lower risk of accident in slow moving traffic. Hence we propose a scheme in which the transmission power is decreased in dense areas and increased in sparse areas to reach distant vehicles. Of course the maximum power is limited to the DSRC maximum transmission range which is about 300m. Furthermore, the transmission range

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is adjusted such that the number of neighbors in range of a vehicle does not exceed n_{max} in jammed areas (k_j). Also, in sparse areas, it is set to cover a minimum number of neighbors, n_{min}. Of course in regions where the inter-vehicle distancing is more than the maximum DSRC transmission range, r_{max}, connectivity is no longer preserved. We also suggest that, in mid-range vehicular densities, the transmission range is adjusted to reach between n_{min} and n_{max} neighbors. This range-density relation is depicted in Figure 2. Each vehicle chooses a transmission range r based on the density of vehicles it observes (according to Figure 2). r is known as the *geocast range* hereafter and determines the neighborhood in which all vehicles should receive the information of this specific vehicle.

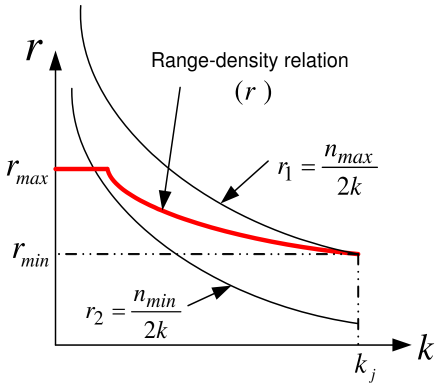

Figure 2: Range-density relation.

Each vehicle, having chosen an appropriate transmission range, will deploy the channel access algorithm described in the following section to transmit it for as many times as possible within the packet's useful lifetime (until the generation of the next packet).

2.2 Media Access Control Protocol

In this section we describe how the vehicles gain access to the channel to transmit their packets. Moreover, we introduce a scheme which fairly shares the channel between nodes and allows for the retransmission of a packet within its useful lifetime. A vehicle which has a packet to transmit listens to the channel and transmits it after finding the channel idle for DIFS amount of time. Upon transmitting its packet, other neighboring vehicles which also have a packet to send, find the channel busy and defer their transmission for a random time according to the CSMA/CA protocol. This random time is $a \times t_s$, where a is a random integer uniformly selected from $\{0, \cdots, cw-1\}$ and t_s is a unit time slot duration. A typical value for cw is 16 and t_s in the range of 20-50 microseconds depending on the physical layer modulation. Here, since a vehicle performs carrier sensing prior to transmission, the major cause of packet delivery failures are the hidden nodes. After transmitting a packet, the vehicle does not have any idea about whether it has been properly received by all intended receivers (due to the lack of ACK exchange). Hence, to overcome the probable packet collisions with that of the hidden nodes' it would retransmit the packet at a later time. To achieve this, it each time doubles its contention window size and chooses a random integer from the interval $\{0, \cdots, 2^i cw - 1\}$, where i is the retransmission trial number. Note how this scheme establishes fairness between the subsequent retransmissions of contending nodes. That is, a vehicle which has already had a chance to transmit its packet, would have to on average wait a longer time for its retransmission in comparison to a node which has not yet had a chance to transmit. To make this argument more rigorous we render the following theorem.

Theorem 1. *For a MAC protocol where nodes retransmit their packets (within the packet's useful lifetime) by doubling the initial contention window (cw) size for each retransmission trial, the probability,* p_{21}*, that a vehicle gains access to the channel twice, before a near-by vehicle has had its first chance to transmit is:*

$$p_{21} = \frac{2\sum_{i=1}^{\frac{cw}{2}-1} i(cw-1) + (\frac{cw}{2})^2}{cw^2(2cw-1)} \tag{1}$$

This probability is less than 8 percent for a typical cw size of 16.

Proof. Assume vehicle i which wants to transmit but senses the channel busy. It backs-off by choosing a random integer i_1 from $\{0, \cdots, cw-1\}$. Vehicle j, which is in vehicle i's vicinity and also seeks channel access chooses a random integer j_1 from the same interval. Note that we assume the two vehicles to be close together, i.e. share the same set of neighbors. Hence they would either both sense the channel busy (and freeze their back-off counter) or both sense it idle and decrement their counters. Now, assume that vehicle i gains access to the channel sooner (due to $i_1 < j_1$) and chooses a new integer, i_2, from $\{0, \cdots, 2cw-1\}$ in order to initiate its retransmission process. According to prior discussions, vehicle i will have a chance to retransmit prior to vehicle j's first chance only if $i_1 + i_2 < j_1$. Thus we have:

$$\begin{aligned} p_{21} &= p(i_1 + i_2 < j_1) \\ &= \sum_{x=0}^{cw-1} p(i_1 + i_2 < x | j_1 = x) p(j_1 = x) \\ &= \frac{1}{cw}[\frac{1}{cw(2cw-1)} + \frac{3}{cw(2cw-1)} + \cdots \\ &+ \frac{\sum_{m=1}^{cw-1} m}{cw(2cw-1)}] \\ &= \frac{2\sum_{i=1}^{\frac{cw}{2}-1} i(cw-1) + (\frac{cw}{2})^2}{cw^2(2cw-1)} \end{aligned}$$

As mentioned earlier, $p_{21} \simeq 0.08$ for $cw = 16$. This value would be much less for p_{31} which is the probability that vehicle i would get a third chance for transmitting the same packet prior to vehicle j's first turn. Thus, one can see how this algorithm fairly divides channel resources among competing vehicles for their retransmission turns.

Moving a step further, we enhance our algorithm by accounting for the vehicular density in determining the contention window size for the subsequent retransmissions of a vehicle. As intuitive as it may seem, we propose a larger increase for the contention window size of vehicles in dense areas, as opposed to sparse areas. That is, a vehicle, after transmitting a copy of its packet, backs off and waits for its

	$k = 50$	$k = 100$	$k = 150$	$k = 200$
strategy 1	5.96	5.39	4.83	4.7
strategy 2	5.54	4.95	4.18	3.77

Table 1: Average number of retransmissions for strategy 1 (normal) and strategy 2 (density dependent CW size)

next turn by choosing a random integer from the interval

$$\{0, \cdots, \lfloor 2^{(i+\frac{k}{k_j})} cw \rfloor - 1\}$$

where i is the retransmission trial number, k is the vehicular density as observed by the vehicle and k_j is the jam density which is about 250 vehicles/mile/lane. This method will be referred to as the retransmission strategy with density-dependent CW size adjustment.

As mentioned earlier, in [4], the authors propose a number of retransmission strategies to overcome the hidden node problem. One of the best performing strategies in terms of reception probability turns out to be the Synchronous Fixed Repetition (SFR) which we have used to evaluate the performance of our proposed method against. In this scheme, the synchronized vehicles randomly choose time slots to perform retransmissions within a packet's useful lifetime. The number of retransmission opportunities is fixed for all nodes and is optimally determined off-line. Figure 3 shows the performance of the proposed schemes in terms of the probability of reception by neighbors in the geocast region. It is clear from the figure that both of the proposed retransmission strategies, outperform the SFR method by efficiently utilizing the available resources. Also one should notice the enhancement we gain through density dependent CW size adjustment especially for higher vehicular densities.

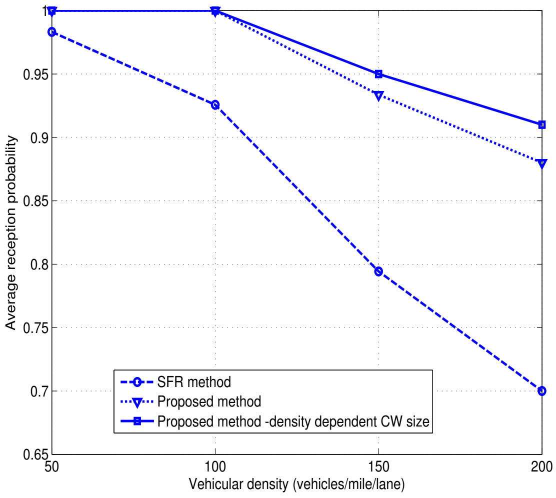

Figure 3: Average reception probabilities for neighbors in the geocast range.

Table 1 shows the number of retransmissions for different vehicular densities and for each of the two proposed strategies. As it can be seen from the table, the retransmission strategy with density dependent CW size adjustment, on average uses lower number of retransmissions and yet performs better according to Figure 3. The lower number of retransmissions leaves more free time for vehicles to switch into the service channels and benefit from other services such as infotainment, if available.

3. CONCLUSION

In this study, we proposed some methods to ensure reliable delivery of safety messages in vehicular ad hoc networks. To alleviate the hidden node problem which arises in VANETs due to the lack of RTS/CTS exchange, we proposed to retransmit each packet for several times within its useful lifetime. This is possible due to the sufficient channel capacity dedicated for inter-vehicle communications which proves adequate even in jammed scenarios. The retransmissions are carried out through a random back-off procedure which fairly grants channel access to contending neighbors for their consecutive retransmissions. Simulation results confirm the effectiveness of our scheme in increasing the reception probability for safety message exchange in vehicular ad hoc networks.

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