Performance Analysis of the IEEE 802.11 MAC Protocol for DSRC Safety Applications

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***Abstract*—In this paper, we evaluate and improve the performance of the medium access control (MAC) protocol for safety applications in a dedicated short range communication (DSRC) environment. We first develop an analytical model to study the IEEE 802.11 distributed coordination function (DCF) MAC protocol that has been adopted by the IEEE 802.11p standard for DSRC. Explicit expressions are derived for the mean and standard deviation of the packet delay, as well as for the packet delivery ratio (PDR) at the MAC layer in an unsaturated network formed by moving vehicles on a highway. The proposed model is validated using extensive simulations and its superior accuracy compared to that of other existing models is demonstrated. Insights gained from our model reveal that the principal reason for the low PDR of the DCF protocol is packet collision due to transmissions from hidden terminals. We then present a novel protocol based on DCF that uses an out-of-band busy tone as a negative acknowledgment to provide an efficient solution to the aforementioned problem. We extend our analytical model to the enhanced protocol and show that it preserves predictive accuracy. Most importantly, our numerical experiments confirm that the enhanced protocol improves the PDR by up to 10%, and increases the supported vehicle density by up to two times for a range of packet arrival rates, while maintaining the delay below the required threshold level.**

***Index Terms*—DSRC, safety applications, MAC, performance analysis**

I. Introduction

DEDICATED Short Range Communication (DSRC) refers to the use of vehicle-to-vehicle and vehicle-to-infrastructure communications to improve road safety and increase transportation efficiency. While there are no commercial DSRC systems yet, recent years have seen a dramatic increase in research and development activity in the DSRC field [1]. An important DSRC application is cooperative collision avoidance (CCA), where moving cars form a network to wirelessly communicate and warn each other of changing conditions or dangers ahead on the road to avoid accidents [2]. This application requires timely communication of safety messages between vehicles with high reliability, and the medium access control (MAC) protocol has a vital role to play. In this paper, we develop an accurate performance model for the IEEE 802.11 distributed coordination function (DCF) MAC protocol that has been adopted by the IEEE 802.11p standard for DSRC applications [3]. We find that the standard broadcast protocol yields a low probability of successful message delivery for CCA, and we respond by proposing and modeling an enhanced protocol involving retransmissions to improve the reliability of message delivery.

In the survey paper [4], different MAC protocols for vehicle-to-vehicle communication networks were compared. Borgonovo et al. [5] proposed a distributed access technique called RR-ALOHA which can dynamically establish a reliable single-hop broadcast channel on a slotted/framed structure. The authors presented the mechanisms that compose the new MAC: the basic RR-ALOHA protocol, an efficient broadcast service, and the reservation of point-to-point channels that exploit parallel transmissions. A directional antenna-based MAC protocol called D-MAC is proposed in [6] which uses directional antennas to direct transmission in specific directions. In D-MAC, by using a narrow beam, interference with parallel ongoing transmissions can be reduced. Su and Zhang [7] introduced a clustering-based DSRC architecture which takes into account both reliability and delay. The authors analyzed a cluster-based multichannel communication scheme consisting of several MAC protocols to reduce data congestion and to support QoS for real-time delivery of safety messages. In particular, most intra-cluster safety messages in [7] are exchanged using TDMA broadcasts, while inter-cluster safety messages are aggregated by the cluster-head vehicles and sent using a contention-based access protocol.

The aforementioned MAC protocols use time scheduling for multiple access, which is sensitive to mobility and topology changes and requires significant reconfiguration time. Also coordination among vehicles requires knowledge of all neighboring vehicles and it takes a few time cycles to agree on a stable schedule. As a result, the access delay in such a case is relatively high. A way of possibly achieving lower delay is to use a decentralized MAC protocol, such as the IEEE 802.11 distributed coordination function (DCF) protocol [8] used in wireless LANs. DCF is based on carrier sense multiple access (CSMA) and can operate with a variety of traffic loads and does not require much reconfiguration upon a change in topology.

DCF has both unicast and broadcast operating modes. The broadcast mode is appropriate for time-critical applications like CCA because, unlike unicast, broadcast does not require the establishment of an association context between stations before data communications can commence. The broadcast could use multi-hop transmissions to enhance coverage, but recent studies suggest that a single-hop transmission is sufficient in most situations to reach all neighboring vehicles in an accident's vicinity [1]. In the rest of this paper we use the term 'broadcast' to refer to single-hop broadcast in contrast

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to multi-hop broadcast or flooding known in the literature of wireless ad-hoc networks. The problem with broadcast mode is that it is less reliable, since it cannot support any request-response handshaking procedures that improve reliability such as conventional acknowledgement or virtual carrier sensing (RTS-CTS), due to the risk of a "storm" of response packets.

To illustrate the delay performance and reliability of broadcast 802.11 DCF for CCA, we conducted ns-2 simulations [9] on a highway scenario. In this scenario, vehicles are represented as a collection of random and statistically identical stations in a one-dimensional mobile ad-hoc network and are stationary during the communication interval (further details of the simulation setup can be found in Section IV). In Fig. 1, we plot the mean of the total delay and the packet delivery ratio (PDR) (the probability of successful packet delivery) versus the vehicle density, with different curves parameterized by the triplet (data rate [Mbps], packet arrival rate [packets/sec], packet size [bytes]). We define PDR as the probability of delivering the packet to all intended receivers within the transmission range of a given transmitting node. It has been suggested in [10] that a suitable maximum delay requirement for cooperative collision warning and intersection collision warning applications is 100 ms. The same maximum allowable delay is also considered in [11], [12]. It has been specified in [13] that the PDR should be not less than 90%. With respect to these performance targets, we see from Fig. 1 that in the simulated scenarios, the delay requirement can be comfortably met, but the PDR requirement is comprehensively violated except for low packet arrival rates and very low vehicle densities. It is apparent that the conventional DCF broadcast protocol may have difficulty supporting the CCA application. To understand the underlying reasons for poor performance, we are motivated to develop an analytical model in this paper to study the behavior and to improve the performance of the protocol in unsaturated broadcast networks.

The performance of DCF has been extensively studied in the wireless LAN environment. Bianchi [14] analyzed the performance of a saturated network using a Markov chain model. In [15], Malone et al. extended the model to the unsaturated case. Tickoo and Sikdar [16] developed an alternative unsaturated model by modeling each station as a G/G/1 queue. These papers all considered unicast communications rather than broadcast communications. Rao et al. developed an analytical model to determine the probability of packet collision in the broadcast scenario [17]. However, all the above mentioned papers assume a fully connected network (i.e. there are no hidden terminals). Although there exists a wide body of literature analyzing the hidden terminal problem, several limitations of those models were highlighted in [18] for the case of unicast communication. The model in [19] attempted to capture the characteristics of the DSRC safety communications where broadcasting takes place in an unsaturated network with hidden terminals. However, the renewal theory based argument used in this model is not entirely suitable for hidden terminal analysis, as also pointed out in [18]. In particular, the model in [19] predicts a non-zero successful transmission probability with arbitrary hidden collisions. However, it can be seen that when nodes are always backlogged with packets to send (i.e. in a heavy traffic scenario), the probability of successful transmission can be zero. This is because the transmitting node as well as other hidden nodes always use the same backoff window (i.e. no retransmission is enabled) and the so-called *vulnerable period*[1] of a node could actually be larger than its backoff window, thus guaranteeing a hidden collision. Note that the model is also inaccurate when there is a very little traffic on the channel. Furthermore, the IEEE 802.11 DCF protocol was not properly modeled in [19] since the analysis assumes that a backoff is initiated for each packet at a node irrespective of whether the channel is idle or busy.

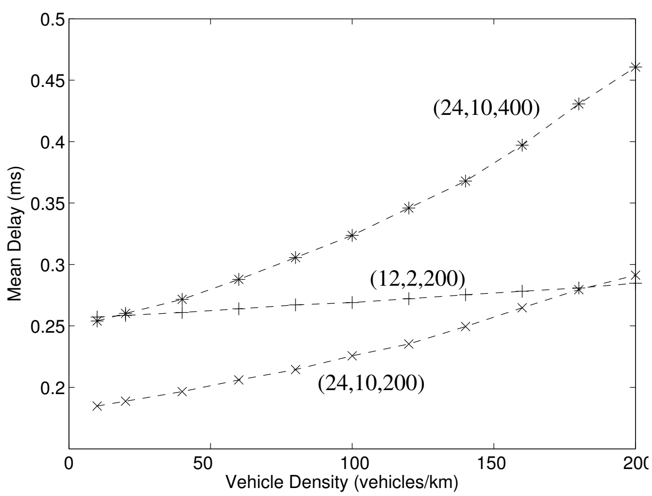
TABLE I
COMPARISON OF OUR MODEL WITH THE EXISTING MODELS IN THE LITERATURE

Model	broadcast	hidden	unsaturated
Bianchi et al. [14]	-	-	-
Malone et al. [15]	-	-	√
Tickoo et al. [16]	-	-	√
Rao et al. [17]	√	-	√
Tsertou et al. [18]	-	√	-
Chen et al. [19]	√	√‡	√
Our model	√	√	√

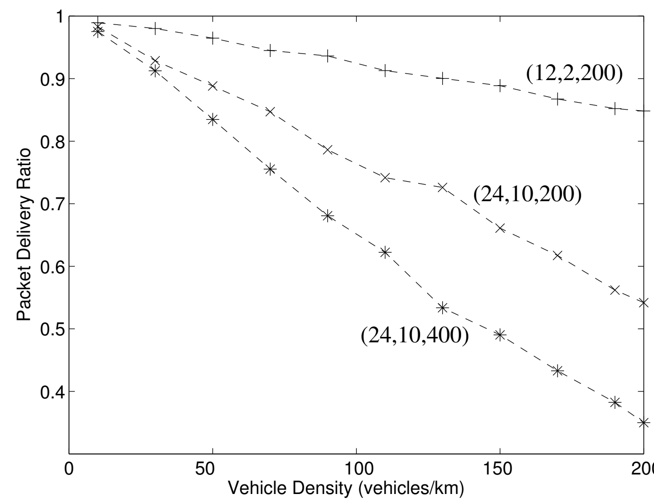
The first major contribution in this paper is an accurate analytical model for DCF in unsaturated broadcast networks both with and without hidden terminals. Table I summarizes the scope of our model relative to that of the other models described above; it shows that only [19] attempts to cover the same aspects, albeit the hidden terminal problem is not modeled accurately and is therefore marked with a "‡" in the table. We focus on the packet delay and the PDR as the two main performance metrics of interest in our study. Our model uses a mean-value decoupling approximation for the collision probability, and we apply an $M/G/1/\infty$ queueing model for each station to obtain the total packet delay. While we make necessary assumptions to keep the model simple, we show via comparison with simulation that the results are nevertheless accurate. We also provide a comparison with results from the existing model in [19] to demonstrate the superior accuracy of our model. The numerical experiments with our model reveal that the principal reason for the low PDR of DCF is packet collision due to transmissions from hidden terminals.

Our second major contribution is a set of modifications to DCF to improve the PDR when hidden terminals are present. The essential idea is to use retransmissions to trade increased delay for decreased packet loss (i.e. higher PDR). We propose that in the event of detection of an errored packet, the receiving stations transmit a negative acknowledgement (NACK) in the form of a busy tone signal in a narrow out-of-band channel. We assume that all nodes are equipped with an additional transceiver to detect such out-of-band signal. Note that a transceiver with a simple energy detector would be enough to detect the NACK signal. Senders of recent packets that hear the NACK (but that could be hidden from each other) shall then execute a backoff process and resend their last packet, and this can be repeated up to a maximum number of

[1]Vulnerable period of a tagged node is the time period during which if any hidden node commences packet transmission it will be colliding with the transmission from the tagged node.



(a)



(b)

Fig. 1. Total delay and Packet Delivery Ratio using the following parameter set: (data rate [Mbps], packet arrival rate [packets/sec], packet size [bytes])

retransmissions. To reduce the chance of successive collisions between hidden terminals, we distinguish between senders according to the delay in receiving the busy tone, and assign different backoff contention windows depending on whether the delay is short or long. We extend our DCF analytical model to the enhanced protocol, and show that our extended model preserves predictive accuracy. Most importantly, our numerical experiments confirm that compared to DCF, the enhanced protocol gives a higher PDR for a wider range of vehicle densities and packet arrival rates, while maintaining the delay below the required threshold level. The results demonstrate that our enhancement can bring the standard a step closer to the ultimate solution for safety applications, which is to meet the strict QoS requirements under arbitrary vehicle densities and network conditions.

The rest of this paper is organized as follows. In Section II, we provide an overview of DSRC challenges and standardization activities. In Section III, we describe our analytical model for DCF. We verify the accuracy of our DCF model by comparison with simulation in Section IV. Then in Section V, we describe our enhanced protocol and illustrate its performance. Finally, we conclude the paper in Section VI.

II. DSRC Challenges and Standardization Activities

The primary goals of emerging DSRC systems are to enhance road safety and to improve transportation efficiency. In this paper, we focus on the safety aspect. Road safety is supported by the transmission of routine status messages and event-driven emergency messages. Routine status messages are sent periodically to neighboring vehicles to inform them of the current status of the originating vehicle (e.g. location speed, direction), whereby the receiving vehicles/drivers can then anticipate any potential hazards (e.g. traffic jam ahead) and take necessary action. Event-driven safety messages are triggered by rapid changes in vehicle behavior such as a hard brake or an airbag explosion. To enable preventative action, it is essential that both types of safety messages are received correctly by surrounding vehicles in a timely fashion.

One of the main challenges to achieve that objective is the loss of packets due to the presence of hidden terminals. This occurs when a node is transmitting to a target node while a third node that is unaware of the transmitter also starts its transmission and causes interference at the receiver. The hidden terminal problem can afflict all decentralized wireless networks, but is particularly severe in broadcast scenarios. In the broadcast case, there are multiple receivers for each message, scattered in the transmission range of the sender. Any node that is within sensing range of any receiver but outside the transmission range of the sender is a potential hidden terminal. Therefore, the potential hidden terminal region is significantly larger than that for unicast communication.

The distinctive demands of DSRC applications, as well as the unique operating environment involving fast moving vehicles, mean that specifically tailored communication protocols are required for DSRC systems. The following subsections describe the protocols being standardized by the IEEE standards body for DSRC.

A. IEEE WAVE

In 1999, the U.S. Federal Communication Commission (FCC) allocated 75MHz of spectrum in the 5.9 GHz band for DSRC use. The DSRC spectrum is divided into seven 10 MHz wide channels, and a reserved 5 MHz channel. One of the 10 MHz channels, called the control channel, is restricted to safety communications only, while the other channels are available for both safety and non-safety usage.

The initial effort at standardizing DSRC radio technology took place in the ASTM 2313 working group [13]. Recently, the IEEE Wireless Access in Vehicular Environment (WAVE) project has published specifications for the FCC DSRC spectrum based on an OFDM air interface. IEEE WAVE encompasses the IEEE 802.11p standard [3] for the MAC and PHY, and the IEEE 1609 family of standards, which define the

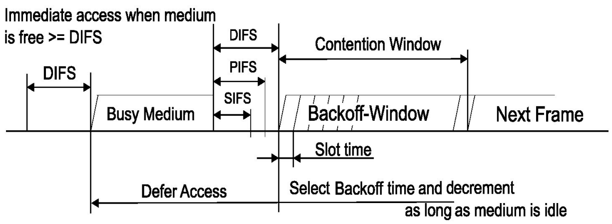


Fig. 2. IEEE 802.11 DCF basic access [8]

higher layer protocols and the protocol architecture [20]. IEEE 802.11p is based on IEEE 802.11a, but with modifications to support vehicular communications with low latency. The 802.11p MAC protocol, like other 802.11 variants, uses the distributed coordination function (DCF) for channel access.

B. IEEE 802.11 DCF protocol description

In the IEEE 802.11 DCF, nodes contend for the channel using a carrier sense multiple access mechanism with collision avoidance (CSMA/CA) as shown in Fig. 2. When a node has a packet to send, the channel must be sensed idle for a guard period known as the distributed interframe space, DIFS. If during that period of time, the channel becomes busy, then the access is deferred until the channel becomes idle again and a backoff process is initiated. Backoff intervals are slotted, and stations are only permitted to commence transmissions at the beginning of slots. The discrete backoff time is uniformly distributed in the range [0, CW - 1], where CW is called the contention window. At the first transmission attempt, CW is set equal to W, the minimum contention window. The backoff time counter is decremented by one at the end of each idle slot. It is frozen when a packet transmission is detected on the channel, and reactivated after the channel is sensed idle again for a guard period. The guard period is equal to a DIFS if the transmitted packet was error-free, and equal to the extended interframe space, EIFS, if the packet was in error. The station transmits when the backoff counter reaches zero. A collision occurs when the counters of two or more stations reach zero in the same slot. After every successful data packet transmission, a station initiates a post-transmission random backoff. If the next packet was already enqueued when the previous packet was sent, its defer time will span the entire backoff period, whereas a packet that arrives at the MAC layer after the previous packet was sent would experience only part of the backoff period, or none at all if the backoff period has already elapsed.

As already mentioned, DSRC safety messages are transmitted in broadcast mode, which is different in several ways from unicast communication for IEEE 802.11 DCF. First of all there is no ACK sent after the successful reception of a data packet, so the sender is unaware of any packet collision and there is no retransmission or augmentation of the contention window. In unicast communications, the RTS/CTS access method is provided to alleviate the hidden terminal problem. However, it is not feasible to use the RTS/CTS method for broadcast communications because it requires a handshaking exchange between sender and receiver.

III. Performance Analysis

A. System Model

Let us consider a scenario of vehicle-to-vehicle communications for CCA applications on a highway. The highway consists of several lanes with vehicles moving in both directions. In our model we make the following assumptions: A.1. vehicles on the highway can be represented as a collection of random and statistically identical stations in a one dimensional mobile ad-hoc network that are stationary during the communication interval; A.2. the transmission range and sensing range for each station are equal, deterministic and denoted by R; A.3. data packets are generated at each station according to a Poisson process with rate λ [packets/sec]; A.4. the collision probability experienced by a station is constant regardless of the state; A.5. channel conditions are ideal within the radius R, packet loss occurs solely as a result of packet collisions, and collisions lead to the loss of all collided packets.

Assumption A.1 holds when the network topology does not change significantly during one packet transmission time, and the distance between lanes on the highway is negligible compared to the length of the network. Assumption A.2 implies that any vehicle in the range $[R, 2R]$ and $[-2R, -R]$ of a selected (tagged) vehicle is a potential hidden terminal. Let β be a vehicle density in vehicles per km on the highway. The average number of vehicles in the transmission range of the tagged vehicle (N_{tr}) including the tagged station can be computed as

$$N_{tr} = 1 + 2\beta R, \tag{1}$$

and the average number of vehicles in the potential hidden terminal area (N_{ph}) can be expressed as

$$N_{ph} = 2\beta R. \tag{2}$$

Assumptions A.3, A.4 and A.5 are common in performance studies of the MAC protocol in mobile wireless ad-hoc networks [17], [19] and help make the model analytically tractable, while still yielding meaningful indications of MAC performance. In this section, we only consider broadcasting with a single transmission attempt per packet. Thus if a packet is collided, there is no subsequent retransmission and the packet is lost. Furthermore, the effect of the post backoff period [18] on packet delay is not considered in our model.

With the above assumptions, each vehicle can be modeled as an M/G/1 queue with an infinite transmit buffer size, i.e. no packet loss due to buffer overflow. While an infinite buffer size is obviously an idealization, it may be reasonable in safety applications since there should be not many packets waiting to be broadcasted and a packet having stale content should be replaced by a new one with the most current information. Our objective is to develop a fixed point approximation to compute the collision probability and the end-to-end packet delay experienced by the tagged vehicle. To this end, the fixed point approximation is established by combining the set of equations for the collision probability expressed in terms of the delay experienced by each packet sent by the tagged station, with an opposing set of equations for the delay expressed in terms of the collision probability. We derive the former set of equations in subsection III-B and the latter in subsection III-D.

B. Collision Probability

In this subsection, we derive the collision probability without accounting for hidden terminals (i.e. "direct" collisions only), and in the next subsection, we modify the model to allow for hidden terminals. To calculate the collision probability of safety messages, first we identify three scenarios that can confront a newly-generated packet in a vehicle operating in an unsaturated network as following:

1) A packet arrives to an empty buffer and finds the channel idle for a DIFS period.
2) A packet arrives to an empty buffer and finds the channel busy.
3) A packet arrives to a non-empty buffer.

For the first case, the vehicle immediately sends the packet without performing a backoff. In this case, a collision can occur only when another packet is generated at some other vehicle within the propagation delay. As the propagation delay in the studied transmission range is negligible, we can ignore any collisions of this type. As described before, we model each station as an M/G/1/∞ queue and define ρ as the queue utilization expressed as

$$\rho = \lambda E[S], \tag{3}$$

where $E[S]$ is the average service time, to be derived in subsection III-E. From standard M/G/1/∞ queueing theory, the probability that the buffer is empty is given by $1-\rho$. We also define p_b as the probability that the channel is sensed busy when a new packet arrives. Therefore, assuming independence between an empty buffer and a busy channel, the probability of finding an empty buffer and sensing the channel idle is $(1-\rho)(1-p_b)$. The expression for p_b will be derived later in this section.

In the second case, the joint probability of a packet arrival to an empty buffer and the channel being busy due to transmission by other vehicles is $(1-\rho)p_b$.

For the last case, the probability of a packet arrival to a non-empty buffer is ρ. Note that for the last two cases, the packet must undergo the backoff process before it is transmitted. After the backoff counter reaches zero, the tagged vehicle sends the packet in the following slot, and if another vehicle sends a packet at the same slot, a collision occurs and the packets are lost.

Let τ be the probability that a vehicle attempts to transmit in an arbitrary slot given that it has a packet in the queue. We approximate τ using a mean-value approach, where we assume that τ is the same for every slot and related to the reciprocal of the mean backoff period. Specifically, letting $\bar{W}$ be the average number of backoff slots preceding a transmission, we let

$$\tau = \frac{1}{\bar{W}+1}.$$

For any vehicle other than the tagged vehicle, the probability of transmitting in any arbitrary slot is $\rho\tau$. A collision occurs when any of the $N_{tr}-1$ vehicles transmit in the same slot as the tagged vehicle given that the tagged vehicle sees either of the last two cases. So, the collision probability is given by

$$p_{dc} = (1-(1-\rho)(1-p_b))(1-(1-\rho\tau)^{N_{tr}-1}), \tag{4}$$

and the packet delivery ratio as

$$PDR = 1 - p_{dc}. \tag{5}$$

Next, we express the probability that the channel is sensed busy when a new packet arrives, p_b, as

$$p_b = (N_{tr}-1)\lambda T(1 - p_{dc}/2), \tag{6}$$

where p_{dc} is the conditional collision probability in (4) and T is the complete transmission time of a packet including the DIFS period. Equation (6) is based on quantifying the traffic load on the channel. As we have $N_{tr}-1$ vehicles other than the tagged vehicle transmitting λ [packets/sec], if there is no collision, then all the packet transmissions should take $(N_{tr}-1)\lambda T$ time each second. However, with a collision probability of p_{dc}, $(N_{tr}-1)\lambda p_{dc}$ packets will be involved in collisions. If we only consider collisions among two packets, the transmission time to send the collided packets would be $(N_{tr}-1)\lambda T p_{dc}/2$. Adjusting for this collision period we get (6).

C. Hidden Terminal Case

In the previous section, we obtained the collision probability assuming no hidden terminals. Now we present an approach to calculate the probability of collision when hidden terminals are present. We note that two necessary conditions must be satisfied to avoid collisions between packets from hidden terminals and from the tagged vehicle. Firstly, when the tagged vehicle starts its transmission, none of the hidden terminals can be in the *transmitting state*; we denote this event as H_1. We say that a hidden terminal is in the transmitting state if it is either transmitting a packet or deferring for a DIFS period associated with an immediate packet transmission. Secondly, after the tagged vehicle starts its transmission assuming H_1, none of the hidden terminals should start transmitting until after the tagged vehicle is finished; we denote this event as H_2.

For event H_1, we follow a similar argument as (6) to calculate the probability of finding all hidden terminals in the non-transmitting state. We note that the event H_1 is the complement of the event of finding at least one hidden terminal in the transmitting state; we denote this complementary event as $\overline{H}_1$. As we have N_{ph} hidden terminals transmitting λ [packets/sec], if there is no direct collision, then all the packet transmissions should take $N_{ph}\lambda T$ time each second. However, due to direct collisions among hidden terminals some packet transmissions will overlap. With the direct collision probability of p_{dc}, we have $N_{ph}\lambda p_{dc}$ such overlapping packets. If we assume no direct collision involving three or more packets, the transmission time to send the collided packets would be $N_{ph}\lambda T p_{dc}/2$. Adjusting for this collision period we can express the probability of event H_1 as

$$P(H_1) = 1 - P(\overline{H}_1) = 1 - N_{ph}\lambda T(1 - p_{dc}/2). \tag{7}$$

For event H_2, we need to calculate the probability that a packet is generated by the hidden terminal after the tagged vehicle starts its transmission and eventually collides with the transmission of the tagged vehicle. Note that packets generated at the hidden terminal in the last time portion of one DIFS period of the tagged vehicle's transmission will not collide because the hidden terminal will still be deferring for a DIFS period when the tagged vehicle finishes its transmission. Since packets arrive in each station's transmit buffer according to a Poisson process, the combined packet arrival from all the hidden terminals is also Poisson with rate λN_{ph} [packets/sec]. Therefore, the condition H_2 is met if no packet is generated at any of the hidden terminals during $t_{data} - t_{difs}$ period and the probability of such an event is expressed as

$$P(H_2) = e^{-\lambda N_{ph}(t_{data} - t_{difs})}, \tag{8}$$

where t_{data} is the transmission time of a packet and t_{difs} is the duration of DIFS period.

Considering the fact that direct collisions and collisions due to hidden terminals are independent of each other, we modify the collision probability (4) to account for the hidden collisions as follows:

$$p_c = 1 - (1 - p_{dc}) \cdot P(H_1) \cdot P(H_2). \tag{9}$$

Recall that, the PDR is defined as the probability of delivering the packet to all intended receivers within the transmission range of a given transmitting node. As such, the packet delivery ratio for hidden terminal case can be expressed as

$$PDR = 1 - p_c. \tag{10}$$

D. Expression for the Delay

In this section, we derive an expression for the packet delay using probabilistic arguments. The total delay (or sojourn time) experienced by a packet of a tagged vehicle includes the waiting time of the packet in the queue, the access delay and the complete time to transmit the packet. The access delay is defined as the time interval between the instant the packet reaches the head of the queue, to the instant when the packet transmission starts. We denote the total delay of the packet by D and write it as

$$D = Q + S = Q + A + T, \tag{11}$$

where Q and A are random variables (r.v.'s) representing the queueing delay and access delay. For each packet transmission, the channel is occupied for the duration of the actual packet transmission (t_{data}) and one DIFS; recall that we define the complete transmission time T as the sum of the actual packet transmission time and one DIFS period. We also define the service time of the queue S as the sum of the access delay A and the transmission delay T.

To determine the access delay, we refer to the previous three cases:

1) A packet arrives to an empty buffer and finds the channel idle with probability $(1-\rho)(1-p_b)$. The access delay in this case is zero as the tagged vehicle transmits the packet without any backoff.
2) A packet arrives to an empty buffer but finds the channel busy with probability $(1-\rho)p_b$. The vehicle must wait until the ongoing transmission is finished and then perform a backoff before transmitting the packet.
3) A packet arrives to a non-empty buffer with probability ρ and when it reaches the head of the queue, a backoff is performed before transmitting the packet.

Since, the probability of a non-empty buffer is ρ, and the probability of finding the channel busy is p_b, we can express the access delay according to the above three cases as

$$A = \begin{cases} 0 & \text{w.p.} \quad (1-\rho)(1-p_b), \\ B + T_{Res} & \text{w.p.} \quad (1-\rho)p_b, \\ B & \text{w.p.} \quad \rho. \end{cases} \tag{12}$$

where T_{Res} is the residual lifetime of an ongoing packet transmission, B is the total backoff duration including periods when the backoff counter is suspended, and the notation 'w.p.' stands for 'with probability'.

During the backoff process, every slot can be interrupted by successful transmissions or collisions of packets transmitted by other vehicles. During the interruption, the backoff counter is suspended and when the backoff counter is resumed, it starts from the beginning of the interrupted slot. For simplicity, we assume every backoff slot can be interrupted at most once. This simplification should not have a significant impact on accuracy, since the probability of multiple interruptions to the same slot is small. Thus, we can express B as a random sum

$$B = \sum_{n=1}^{U} (\sigma + Y), \tag{13}$$

where σ represents the duration of a backoff slot, Y is the interruption period per slot, and U is the backoff counter value which is uniformly distributed in the range $[0, W-1]$.

If no other vehicle transmits in a given slot, an interruption does not occur and Y equals zero. If one or more vehicles transmit in that slot, then the tagged vehicle will suspend its backoff process for the duration of the complete transmission, T. Recall that the probability that a vehicle attempts to transmit in an arbitrary slot given that it has a packet in its buffer is given by τ and the probability that the buffer is non-empty is ρ. Therefore, the probability of a vehicle transmitting in an arbitrary slot is $\rho\tau$ and a backoff slot of the tagged vehicle is interrupted when any of the other $N_{tr} - 1$ vehicles transmit in that slot with probability $1 - (1-\rho\tau)^{N_{tr}-1}$. Therefore, we can write Y as

$$Y = \begin{cases} 0 & \text{w.p.} \quad (1-\rho\tau)^{N_{tr}-1}, \\ T & \text{w.p.} \quad 1-(1-\rho\tau)^{N_{tr}-1}. \end{cases} \tag{14}$$

where $1 - (1-\rho\tau)^{N_{tr}-1}$ is the probability that a slot is busy due to transmissions by other vehicles.

E. Mean and Standard Deviation

In this section, we determine the mean and standard deviation of the service time and the mean of the total delay. We express them using means and variances of the constituent random variables. From (11), since A and T are independent, we can write

$$\mathrm{E}[S] = \mathrm{E}[A] + \mathrm{E}[T], \tag{15}$$

$$\mathrm{StdDev}[S] = \sqrt{\mathrm{Var}[S]} = \sqrt{\mathrm{Var}[A] + \mathrm{Var}[T]}, \tag{16}$$

where $\mathrm{E}[X]$, $\mathrm{StdDev}[X]$ and $\mathrm{Var}[X]$ denotes the mean, standard deviation and variance of the random variable X.

Considering fixed length packets for all vehicles, we have

$$\begin{aligned} \mathrm{E}[T] &= T, \\ \mathrm{Var}[T] &= 0. \end{aligned} \tag{17}$$

From (12) the mean and variance of A can be written as

$$\mathrm{E}[A] = (1-\rho)p_b(\mathrm{E}[B] + \mathrm{E}[T_{Res}]) + \rho\,\mathrm{E}[B], \tag{18}$$

$$\begin{aligned} \mathrm{Var}[A] = {} & (1-\rho)(1-p_b)\,\mathrm{E}[A]^2 \\ & + (1-\rho)p_b(\mathrm{Var}[B] + \mathrm{Var}[T_{Res}] \\ & + (\mathrm{E}[A] - \mathrm{E}[B] - \mathrm{E}[T_{Res}])^2) \\ & + \rho(\mathrm{Var}[B] + (\mathrm{E}[A] - \mathrm{E}[B])^2). \end{aligned} \tag{19}$$

To calculate the mean and variance of the residual lifetime of an ongoing transmission, T_{Res}, we first determine the probability distribution function of T_{Res}. Note that the inter-arrival time of packets generated at each vehicle follows a memoryless exponential distribution with rate λ. So the interval between the starting time of an ongoing transmission and the arrival of a new packet at the tagged vehicle also follows an exponential distribution and we define it as $X \sim 1 - e^{-\lambda t}$. Therefore, we can represent the distribution of T_{Res} as the remaining transmission time, $Y = T - X$, conditioned on $X \leq T$.

Now, the probability distribution function of Y can be expressed as $F_Y(y) = 1 - F_X(T-y)$, where $F_Z(\cdot)$ here represents the distribution function of Z. Applying the condition $X \leq T$, we get

$$F_{Y|X\leq T}(y) = 1 - F_{X|X\leq T}(T-y) = \frac{e^{-\lambda(T-y)} - e^{-\lambda T}}{1 - e^{-\lambda T}}. \tag{20}$$

Differentiating (20), we obtain the probability density function as

$$f_{Y|X\leq T}(y) = \frac{\lambda e^{-\lambda(T-y)}}{1 - e^{-\lambda T}}. \tag{21}$$

Now, we can obtain the mean and variance of T_{Res} from (21) as follows:

$$\begin{aligned} \mathrm{E}[T_{Res}] &= \mathrm{E}[Y|X \leq T] = \int_0^T y f_{Y|X\leq T}(y)dy \\ &= \frac{T}{1 - e^{-\lambda T}} - \frac{1}{\lambda}, \end{aligned} \tag{22}$$

$$\begin{aligned} \mathrm{E}[T_{Res}^2] &= \mathrm{E}[Y^2|X \leq T] = \int_0^T y^2 f_{Y|X\leq T}(y)dy \\ &= \frac{T^2 - 2T/\lambda}{1 - e^{-\lambda T}} + \frac{2}{\lambda^2}, \end{aligned} \tag{23}$$

$$\mathrm{Var}[T_{Res}] = \mathrm{E}[T_{Res}^2] - \mathrm{E}[T_{Res}]^2 = \frac{1}{\lambda^2} - \frac{T^2 e^{-\lambda T}}{(1 - e^{-\lambda T})^2}. \tag{24}$$

TABLE II
DSRC SYSTEM PARAMETERS

Parameter	Value
W	16
Range, R	0.5 km
Slot size, σ	16 μs
SIFS	32 μs
PHY preamble	32 μs
PLCP header	8 μs
Vehicle density, β	10 – 200 vehicles/km
Data rate, R_d	12, 24 Mbps
Packet arrival rate, λ	2, 10 packets/sec
Packet length, P	200, 400 bytes

Using well-known identities for the mean and variance of a random sum [21], it follows from (13) that

$$\mathrm{E}[B] = (\sigma + E[Y])\,\mathrm{E}[U], \tag{25}$$

$$\mathrm{Var}[B] = \mathrm{Var}[Y]\,\mathrm{E}[U] + (\sigma + \mathrm{E}[Y])^2\,\mathrm{Var}[U]. \tag{26}$$

As U is a r.v. which is uniformly distributed in the range $[0, W-1]$, we have

$$\mathrm{E}[U] = \bar{W} = \frac{W-1}{2}, \tag{27}$$

$$\mathrm{Var}[U] = \frac{W^2-1}{12}. \tag{28}$$

For the interruption time Y, we can calculate the mean and variance from (14) as

$$\mathrm{E}[Y] = (1 - (1-\rho\tau)^{N_{tr}-1})T, \tag{29}$$

$$\mathrm{Var}[Y] = (1 - (1-\rho\tau)^{N_{tr}-1})((1-\rho\tau)^{N_{tr}-1})T^2. \tag{30}$$

Thus, based on (15)–(30), we can derive the mean and standard deviation of the service time in terms of p_b and ρ. Now (3), (4), (6), and (15) constitute a non-linear system of equations that can be solved iteratively to calculate ρ, p_b, p_{dc}, and $\mathrm{E}[S]$. Using those computed values we can derive the mean queueing delay, $\mathrm{E}[Q]$. Using the well-known result for the M/G/1 queue, we obtain

$$\mathrm{E}[Q] = \frac{\lambda(\mathrm{Var}[S] + \mathrm{E}[S]^2)}{2(1 - \lambda\,\mathrm{E}[s])}, \tag{31}$$

where $\mathrm{Var}[S]$ is calculated from (16). The mean total delay is then given by

$$\mathrm{E}[D] = \mathrm{E}[Q] + \mathrm{E}[S]. \tag{32}$$

IV. MODEL VALIDATION AND DISCUSSION

In this section, we present the simulation setup used to validate our analytical model and present the validation results. We used the ns simulator (version 2.28) [9] to simulate and obtain packet delay and PDR in a DSRC environment under various conditions. We adopted the patch for ns-2.28 provided in [22] where they fixed the following bug. According to the IEEE802.11 specification [8] (see Fig. 2), if the medium is sensed idle when a packet arrives at the MAC layer, the packet can be transmitted after an idle period of DIFS without any backoff. However, in the standard distribution of ns-2.28, a backoff is always started irrespective of whether the channel is idle or busy.

TABLE III
PACKET DELAY FOR DSRC SAFETY MESSAGES

R_d [Mbps]	λ [packets/sec]	P [bytes]	β [vehicles/km]	Mean [ms]	Mean+Std.Dev. [ms]	Mean+3Std.Dev. [ms]
12	2	200	10	0.26	0.28	0.32
12	2	200	100	0.27	0.33	0.46
12	2	200	200	0.28	0.38	0.57
24	2	200	10	0.18	0.22	0.28
24	2	200	100	0.22	0.33	0.55
24	2	200	200	0.29	0.47	0.83
24	10	400	10	0.25	0.30	0.38
24	10	400	100	0.32	0.49	0.81
24	10	400	200	0.46	0.75	1.34

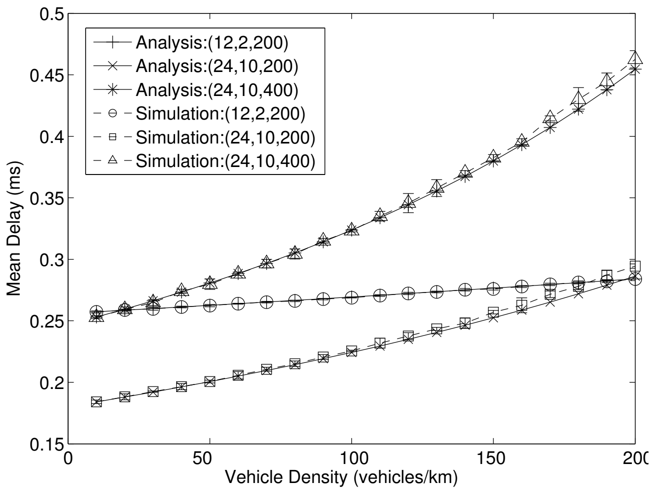


Fig. 3. Total delay for direct collision using the following parameter set: (data rate [Mbps], packet arrival rate [packets/sec], packet size [bytes])

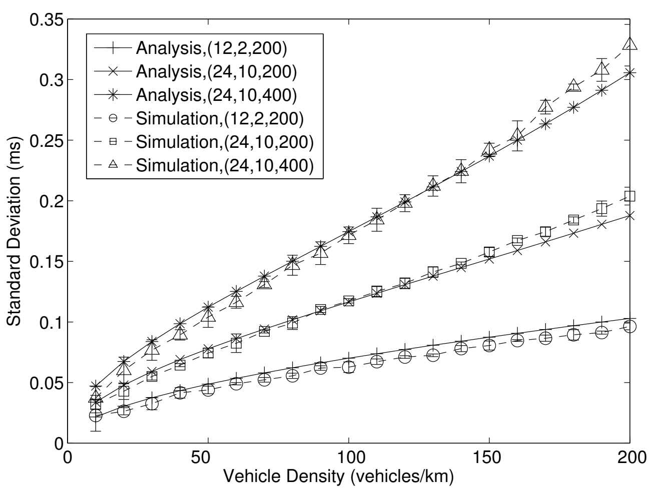


Fig. 4. Standard deviation of delay for direct collision using the following parameter set: (data rate [Mbps], packet arrival rate [packets/sec], packet size [bytes])

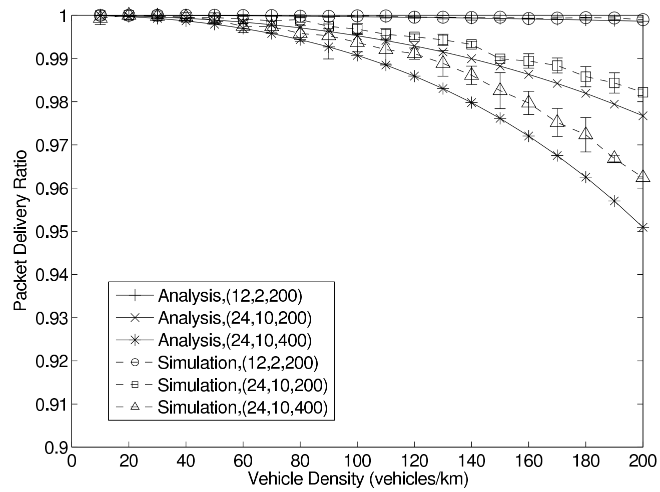


Fig. 5. Packet Delivery Ratio for direct collision using the following parameter set: (data rate [Mbps], packet arrival rate [packets/sec], packet size [bytes])

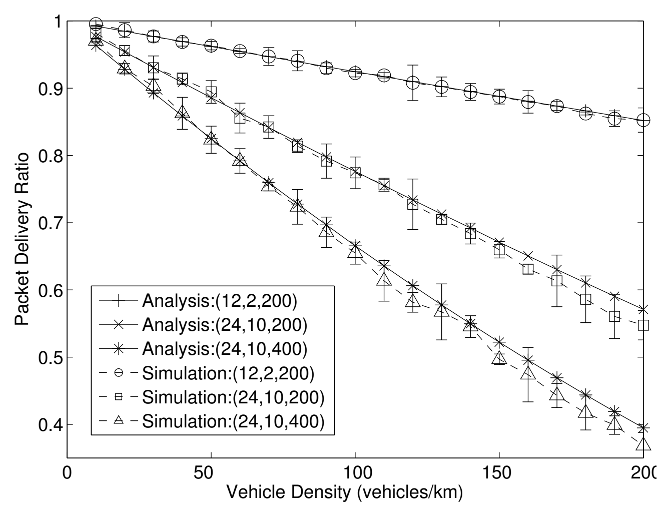


Fig. 6. Packet Delivery Ratio in network with hidden terminals using the following parameter set: (data rate [Mbps], packet arrival rate [packets/sec], packet size [bytes])

We use a ring topology in the simulation where we place vehicles on a circle to avoid any unwanted effects of stations located at the edge of the network. The radius of the circle is kept significantly larger than the transmission range of each vehicle so that the highway scenario is actually simulated. The vehicles are placed randomly on the circle where the average inter-vehicle distance is a function of vehicle density, β. Each vehicle is configured to broadcast messages with varying packet size, P and packet arrival rate, λ. All the other DSRC related parameters are listed in TABLE II.

In the following, we validate our analytical model by comparing the numerical results with the simulation results. We present results for the mean of the total delay, the standard deviation of the access delay, and the PDR. Another objective of our numerical experiments is to investigate the effect of different load conditions on the delay and PDR. All the simulation results are plotted with 95% confidence intervals.

We first present and discuss results for the direct collision case. In Fig. 3, we plot the mean of the total delay (32) as a function of vehicle density, β, with different curves parameterized by the data rate R_d [Mbps], packet size P [bytes], and packet arrival rate λ [packets/sec]. Observe that our analytical model agrees well with the simulation results. In the plotted range, the mean delay increases almost linearly with the vehicle density, with the slope for the $\lambda = 10$ case being larger compared to the $\lambda = 2$ case. The biggest delay observed is less than 0.5 ms which is well below the maximum delay constraint of 100 ms for safety applications [10].

In Fig. 4, we study the accuracy of our model in terms of the standard deviation. Note that we use the standard deviation of the service time in (16) as a proxy for the standard deviation of the total delay. We observe from the figure that the standard deviation for all cases is nearly zero for low vehicle densities. This is because the channel is mostly idle and no backoff is required by the vehicles. With increasing vehicle density, the standard deviation increases almost linearly. We note that the analysis matches well with the simulation results for all cases.

Next, we plot the packet delivery ratio for direct collisions in Fig. 5, where the analytical results are computed according to (5). The analysis provides a reasonable match with the simulation results. For the $\lambda = 2$ case, we see that the PDR is above 99% for all vehicle densities; however, for the $\lambda = 10$ case, the PDR drops with increasing vehicle density. Nevertheless, the PDR requirement of 90% stipulated by the ASTM [13] is fulfilled.

For the hidden terminal case, the distribution of the packet delay is the same as for the direct collision case. This is because there is no retransmission and the presence of hidden terminals does not affect the backoff process of the tagged vehicle. For this reason we omit the results for the mean and standard deviation of the delay when there are hidden terminals.

In Fig. 6, we plot results for the PDR according to (10) which accounts for hidden terminals and compare them with simulation. The PDR is above 90% for all cases under light load ($\beta \leq 200$) but drops linearly with increasing vehicle density. For higher vehicle densities, the PDR eventually drops below the reliability requirement of 90% for DSRC safety applications. We also observe that the PDRs for the $\lambda = 10$ cases are much worse than that of the $\lambda = 2$ case. From Figs. 5 and 6, we can compare the PDR values obtained for the hidden terminal case with that for the direct collision case. Our comparative results show that packet collision due to hidden terminals is the major source of collisions and can reduce the PDR by up to 25%.

In Fig. 7, we compare our analytical model with the model of Chen et al. [19]. We plot the mean total delay versus vehicle density for the case where $R_d = 24$ [Mbps], packet arrival rate $\lambda = 10$ [packets/sec], and packet size $P = 200$ [bytes]. Observe that Chen's model significantly overestimates the delay. This discrepancy in the delay can be explained as follows. In [19], the authors assumed that for every packet, a backoff is performed before transmission, whereas according to the IEEE 802.11 DCF standard, no backoff is required if a newly generated packet arrives to an empty buffer and the channel is sensed idle for a DIFS period [8] (see Fig. 2). To clearly identify the source of improvement and accuracy in our model, we evaluate our model under the assumption that every packet undergoes backoff before transmission, and plot the resulting mean total delay as "Approximate Analysis" in Fig. 7. This result is close to that of Chen's model, confirming that the main improvement in our model compared to Chen's model in terms of delay stems from the correct handling of packets that do not undergo a backoff.

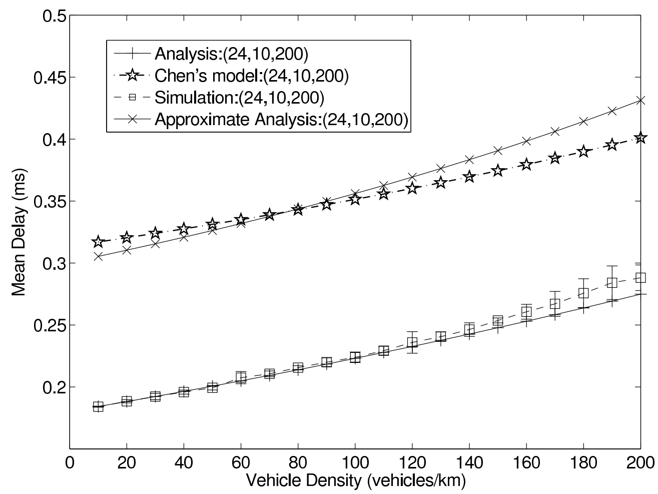


Fig. 7. Comparison of packet delay with Chen's model [19] using the following parameter set: (data rate [Mbps], packet arrival rate [packets/sec], packet size [bytes])

The PDR results from our model and Chen's model are compared in Fig. 8. Observe again that our model is a much better match with the results obtained from the ns2 simulation. Again we plot the PDR results under the assumption that every packet undergoes backoff (labelled "Approximate Analysis"), and we observe that the previous discrepancy in the delay does not account for the large inaccuracy of PDR in Chen's model. In our model, we divide the vulnerable period in to two parts — before the tagged node starts transmission and after the tagged node starts transmission, and treat them differently in contrast to a single vulnerable period in Chen's model. Also, the model in [19] assumes that the vulnerable period could be divided into a number of independent variable slots. This assumption, however, is not accurate when the average backoff duration is smaller than the vulnerable period itself [18].

For DSRC safety applications, the maximum packet delay should be constrained rather than the mean delay. To get an estimate on the maximum packet delay, we add one and three standard deviations to the mean delay and present them in TABLE III. It can be seen that the maximum value of the delay in TABLE III is 1.34 ms which is still well below the delay constraint of 100 ms reported in [10].

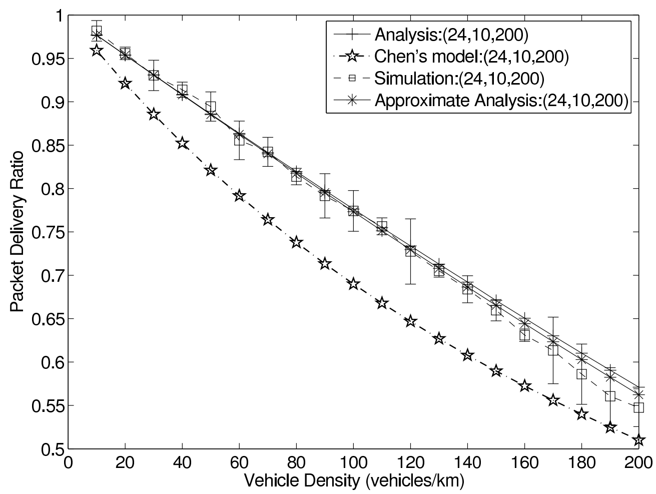


Fig. 8. Comparison of Packet Delivery Ratio with Chen's model in network with hidden terminals [19] using the following parameter set: (data rate [Mbps], packet arrival rate [packets/sec], packet size [bytes])

V. Extension of the Model

A. Existing Solutions

Our results from the previous section suggest that the DCF protocol satisfies the delay constraint but its PDR performance is susceptible to hidden terminals. In the following we review and discuss some possible enhancements from the literature that aim to improve the broadcasting performance.

In [23] and [24], retransmission of a broadcast message is proposed to improve the reliability at the MAC layer. Repeating messages either flood a network by piggybacking [23], or the repetition is carried out by an individual node randomly over the lifetime of a packet [24]. The main drawback of this approach is that it may cause too many collisions due to repetition of messages and eventually the PDR performance would degrade as shown in [25].

Significant efforts have also been made to solve the hidden terminal problem for broadcast. One approach is to extend the RTS/CTS mechanism used for unicast to broadcast. Due to multiple receivers in the broadcast environment, additional state or message type information is proposed to be included in the RTS/CTS mechanism for broadcast [26], [27]. As a result, the extended RTS/CTS mechanism becomes complex and does not guarantee absolute reliability. In [28] the authors propose a request-to-broadcast/clear-to-broadcast (RTB/CTB) scheme to alleviate the hidden terminal problem. To support reliable communication, the CTB packets are sent in the form of an energy burst (a so-called black-burst or jamming signal [29]) whose length is proportional to the distance between the receiver and the sender. The protocol with RTB/CTB, however, is sensitive to topology changes. Broadcast RTS/CTS by way of multiple unicast is also proposed in [30] with some significant overhead.

Previous ideas for mitigating the hidden terminal problem for unicast communications could also be applied for broadcast such as a busy tone in [31], [32], a contention tone in [33] or a so-called black burst in [29]. A combination of a busy tone and RTS/CTS is also proposed in [34] to be used in the data channel for broadcast communication.

On the other hand, there have been several proposals [35], [36] advocating the use of an acknowledgement (ACK) to strive for a reliable broadcast without directly addressing the hidden terminal problem. Most of these schemes, however, attempt to send multiple positive ACK messages from multiple receivers which could cause even more collisions and performance degradation. Exceptions are proposals in [27], [37] where the authors suggest the use of a negative ACK (NACK) together with RTS/CTS for reliable communication. Finally, there are also some other enhancements proposed in [38] to dynamically tune the contention window or to give safety messages priority over data packets by utilizing the enhanced DCF (or EDCA) mechanism in the IEEE 802.11e protocol.

B. Proposed Extension

In this section, we propose a simple retransmission scheme for broadcasting safety messages in the presence of hidden terminals. We do not use any extended RTS/CTS or similar mechanisms to combat hidden terminals in broadcasting, but instead rely on the retransmission of unsuccessful packets to improve reliability. To this end, we propose an out-of-band receiver-based busy tone to represent a NACK signal back to the source. The advantage is twofold. As the busy tone only represents 1 bit information about the latest unsuccessful packet, a narrow bandwidth is sufficient for this purpose. And to listen to the busy tone, a simple energy detector would suffice rather than a fully-fledged transceiver. It is because the received signal strength of a packet that is corrupted by collision is generally higher than that of a disrupted packet caused by noise. Furthermore, since packet collisions may involve transmissions from several hidden terminals, the NACK is sent by the receiver at the end of the collision period when all the involved nodes have finished their transmission.

To avoid a new packet transmission from any colliding nodes before the receiver issues the NACK, we increase the DIFS duration to span one data transmission plus a NACK transmission time. If the sender (or source) senses the busy tone (i.e. hears a NACK), it will perform a backoff and send the last packet again until the packet is received by all the nodes or the maximum transmission attempt, r, is reached. In the latter case, the packet is dropped. Because we do not use any handshake procedures (such as RTS/CTS) to avoid potential hidden collisions (i.e. collisions that are caused by hidden terminals), the same hidden nodes can collide again in the following retransmission attempts. To avoid successive collisions due to the same hidden terminals, we propose to separate the retransmission attempts using different backoff windows for different nodes involved in the collision. The backoff windows are larger compared to the transmission time of a packet. We assume that at most two nodes are involved in a hidden collision for a linear topology such as vehicles on a highway. As such, the node that hears a NACK immediately after finishing its transmission knows that it is the last node involved in the collision. This node will then use a larger contention window (four times of the normal contention window is used in our study) to select its backoff, while others keep theirs unchanged. In this way, successive collisions among the same hidden terminals will be reduced.

There are several advantages of our proposed protocol, including: (i) improved reliability of broadcast safety messages in the presence of hidden terminals; (ii) mitigation of the impact of hidden terminals in successive reattempts; and (iii) requirement of only a simple energy detector for the reception of the NACK control packet (out-of-band signalling). Note that (i) and (ii) are achieved without the need for a complex handshaking mechanism proposed for broadcasting such as the extended RTS/CTS or RTB/CTB mechanism mentioned in subsection V-A. Also the benefit of an NACK scheme is that, in a low loss environment the overhead is negligible, while we can still improve the PDR in high loss scenarios.

In the next subsection we will investigate the effectiveness of this retransmission mechanism. To this end, the analytical model developed in Section III is extended to cover the NACK based retransmission protocol.

C. Enhanced Protocol Performance Analysis

In the case of retransmissions, the direct collision probability calculated in (4) will be different for the first attempt and successive attempts. So, we distinguish between them by denoting $p'_{dc,i}$ as the direct collision probability in the i_{th} attempt. For the first attempt, the probability $p'_{dc,0}$ is similar to (4), but for the successive attempts, the probability $p'_{dc,i}$ would be different as there is always a backoff between successive attempts. So, we can express the direct collision probability as

$$p'_{dc,0} = (1-(1-\rho)(1-p'_b))(1-(1-\rho\tau)^{N_{tr}-1}), \quad (33)$$

$$p'_{dc,i} = p'_{dc,1} = (1-(1-\rho\tau)^{N_{tr}-1}), \quad (34)$$

where p'_b represents the busy probability modified from (6) to incorporate retransmissions and it is expressed as

$$p'_b = m(N_{tr}-1)\lambda T(1-p'_{dc}/2), \quad (35)$$

where, m is the expected number of attempts per packet (to be derived later) and p'_{dc} is the average direct collision probability calculated from

$$p'_{dc} = \frac{p'_{dc,0} + (m-1)p'_{dc,1}}{m}. \quad (36)$$

Furthermore, recall that two necessary conditions H_1 and H_2 must be met to avoid hidden terminal collision. As our DIFS period is now longer than the actual packet transmission time, those conditions are slightly changed.

The first condition, H_1, assumes that when the tagged node starts its transmission no other hidden node can be in the transmitting state. But due to the longer DIFS, it is now possible that when the tagged node starts its transmission, a hidden node is in the transmitting state waiting for the end of its DIFS and by the time it starts actual transmission the tagged node already finishes its transmission. For the second condition, H_2, we note that if H_1 condition is met, H_2 cannot occur as by the time a hidden terminal is allowed to transmit (after a DIFS period), the tagged vehicle would have finished its transmission. So, we only have H_1 in this case which we differentiate for the first attempt, $H'_{1,0}$, and any successive attempts, $H'_{1,i}$. We define the probability of no hidden collision for the first attempt as

$$P(H'_{1,0}) = 1 - mN_{ph}\lambda 2t_{data}(1-p'_{dc}/2). \quad (37)$$

If there is a collision in the first attempt between two nodes, one of the nodes will increase its contention window which will reduce the chance of successive collisions. Still we need to calculate the probability of successive collision, p_{scv}. We note that a successive collision happens when the node with the larger contention window starts transmitting before the other node finishes its transmission. The mean time taken by the first node to finish its second transmission after the second node finishes its first transmission is $t_{data}/2 + (W-1)/2$. Now, denoting the larger contention window used by the second node as W', we can calculate the probability of successive collision as

$$p_{scv} = \frac{t_{data}/2 + (W-1)\sigma/2}{W'\sigma}. \quad (38)$$

Now, we can assume that collision due to all other hidden nodes in the potential hidden range behave the same as previously. As such, the probability of no hidden collision for the successive attempts would be

$$P(H'_{1,i}) = P(H'_{1,1}) = 1 - m(N_{ph}-1)\lambda 2t_{data}(1-p'_{dc}/2)p_{scv}. \quad (39)$$

Because direct collisions and collisions due to hidden terminals are independent, we get the expressions for the collision probabilities as

$$p'_{c,0} = 1-(1-p'_{dc,0})P(H'_{1,0}), \quad (40)$$

$$p'_{c,i} = 1-(1-p'_{dc,1})P(H'_{1,1}). \quad (41)$$

The expected number of transmission attempts is given as

$$\begin{aligned} m &= 1 + p'_{c,0} + p'_{c,0}p'_{c,1} + p'_{c,0}p'^{2}_{c,1} + \cdots + p'_{c,0}p'^{r-2}_{c,1} \\ &= 1 + p'_{c,0}\frac{1-p'^{r-1}_{c,1}}{1-p'_{c,1}}. \end{aligned} \quad (42)$$

To calculate the packet delivery ratio, we note that a packet is dropped when all the transmission attempts fail. So, the PDR can be expressed as

$$PDR = 1 - p'_{c,0}p'^{r-1}_{c,i}. \quad (43)$$

Now, we define the access delay conditioned on the number retransmission as A_i, where the packet transmission is completed either successfully or unsuccessfully after i retransmission. With the collision probability $p'_{c,i}$ on each attempt, we can calculate the probability of i retransmission and express the access delay A as

$$A = \begin{cases} A_0 & \text{w.p.} \quad (1-p'_{c,0}), \\ A_i & \text{w.p.} \quad p'_{c,0}p'^{i-1}_{c,1}(1-p'_{c,1}), \\ A_{r-1} & \text{w.p.} \quad p'_{c,0}p'^{r-2}_{c,1}. \end{cases} \quad (44)$$

where the access delay for first transmission attempt, A_0 is similar to our previous model without retransmission

$$A_0 = \begin{cases} 0 & \text{w.p.} \quad (1-\rho)(1-p'_b), \\ B + T_{Res} & \text{w.p.} \quad (1-\rho)p'_b, \\ B & \text{w.p.} \quad \rho. \end{cases} \tag{45}$$

and access delay for successive transmission attempt, $A_i (i \geq 1)$ is defined as

$$\begin{aligned} A_i &= A_{i-1} + B_i + T \\ &= A_0 + \sum_{j=1}^{i} (B_j + T), \end{aligned} \tag{46}$$

where B_i is the backoff duration for i_{th} retransmission attempt.

To calculate B_i we note that for each successive transmission attempt, the tagged node chooses its backoff counter with equal probability either in the range $[0, W-1]$ or in the range $[0, W'-1]$, where W' is the increased contention window. The backoff duration for the first case is the same as B defined in (13). For the second case, we define the backoff duration as

$$B' = \sum_{n=1}^{U'} (\sigma + Y), \tag{47}$$

where U' is the backoff counter value which is uniformly distributed in the range $[0, W'-1]$. Now we can define the backoff duration for the i_{th} retransmission attempt as B_i.

$$B_i = B_1 = \begin{cases} B & \text{w.p.} \quad 0.5, \\ B' & \text{w.p.} \quad 0.5. \end{cases} \tag{48}$$

From the above equation, the expected value and variance of B_1 can be calculated as

$$\mathrm{E}[B_1] = (\mathrm{E}[B] + \mathrm{E}[B'])/2, \tag{49}$$

$$\begin{aligned} \mathrm{Var}[B_1] &= (\mathrm{Var}[B] + (\mathrm{E}[B] - \mathrm{E}[B_1])^2)/2 \\ &+ (\mathrm{Var}[B'] + (\mathrm{E}[B'] - \mathrm{E}[B_1])^2)/2. \end{aligned} \tag{50}$$

To get the expected value and variance of the access delay, we first calculate the expected value and variance of the access delay for each transmission attempt. For the first transmission attempt, the distribution of A_0 in (45) is a conditional distribution, thus the we have

$$\mathrm{E}[A_0] = (1-\rho)p'_b(\mathrm{E}[B] + \mathrm{E}[T_{Res}]) + \rho\,\mathrm{E}[B], \tag{51}$$

$$\begin{aligned} \mathrm{Var}[A_0] &= (1-\rho)(1-p'_b)\,\mathrm{E}[A_0]^2 \\ &+ (1-\rho)p'_b(\mathrm{Var}[B] + \mathrm{Var}[T_{Res}] \\ &+ (\mathrm{E}[A_0] - \mathrm{E}[B] - \mathrm{E}[T_{Res}])^2) \\ &+ \rho(\mathrm{Var}[B] + (\mathrm{E}[A_0] - \mathrm{E}[B])^2). \end{aligned} \tag{52}$$

From (46), noting that A_0, B_j, T are all independent of each other, we can calculate the expected value and variance of the access delay for any retransmission attempt, A_i as

$$\mathrm{E}[A_i] = \mathrm{E}[A_0] + i(\mathrm{E}[B_1] + T), \tag{53}$$

$$\mathrm{Var}[A_i] = \mathrm{Var}[A_0] + i\,\mathrm{Var}[B_1]. \tag{54}$$

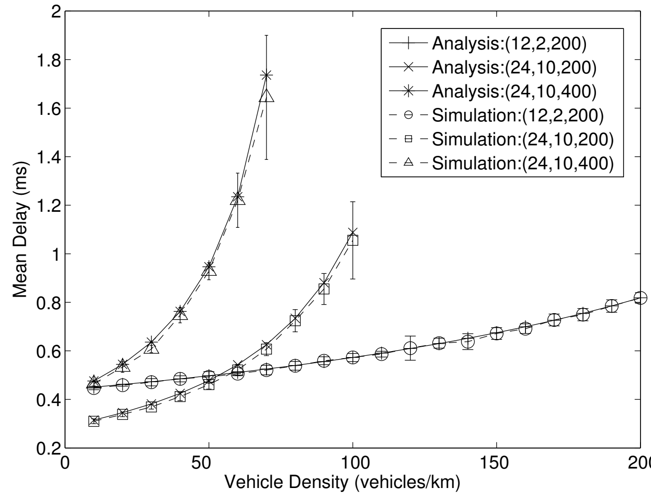


Fig. 9. Total delay for proposed protocol with three transmission attempts using the following parameter set: (data rate [Mbps], packet arrival rate [packets/sec], packet size [bytes])

Finally, putting the expected value and variance of the access delay for each transmission attempt, A_i in (44) we have

$$\begin{aligned} \mathrm{E}[A] &= (1-p'_{c,0})\,\mathrm{E}[A_0] + \sum_{i=1}^{r-1} p'_{c,0}p'^{i-1}_{c,1}(1-p'_{c,1})\,\mathrm{E}[A_i] \\ &+ p'_{c,0}p'^{r-1}_{c,1}\,\mathrm{E}[A_{r-1}], \end{aligned} \tag{55}$$

$$\begin{aligned} \mathrm{Var}[A] &= (1-p'_{c,0})\{\mathrm{Var}[A_0] + (\mathrm{E}[A_0]) - \mathrm{E}[A])^2\} \\ &+ \sum_{i=1}^{r-1} p'_{c,0}p'^{i-1}_{c,1}(1-p'_{c,1})\{\mathrm{Var}[A_i] + (\mathrm{E}[A_i]) - \mathrm{E}[A])^2\} \\ &+ p'_{c,0}p'^{r-1}_{c,1}\{\mathrm{Var}[A_{r-1}] + (\mathrm{E}[A_{r-1}]) - \mathrm{E}[A])^2\}. \end{aligned} \tag{56}$$

Next, we present analytical and simulation results for the mean of the total delay and the PDR for our proposed retransmission protocol. For the following set of results, the maximum number of transmission attempts, r is set to 3. We restrict our observations up to PDR=85% which covers the required PDR threshold of 90% stipulated by the ASTM [13].

In Fig. 9, we plot the mean of the total delay using (32) as a function of vehicle density, β, with different curves parameterized by the data rate R_d [Mbps], packet size P [bytes], and packet arrival rate λ [packets/sec]. Observe that our analytical model falls within the 95% confidence interval of the simulation results. We note that for the $\lambda = 2$ case the mean delay compared to Fig. 3 is proportionately larger due to longer DIFS used for our proposed protocol. For the $\lambda = 10$ cases, the mean delay increases sharply because of more collision and subsequent retransmissions . However, the largest delay observed is still less than 2 ms which is well below the maximum delay constraint of 100 ms for safety applications [10].

In Fig. 10, we plot results for the PDR according to (43) and compare them with simulation. As mentioned earlier, we plot the PDR results in the range above PDR=85%. For the

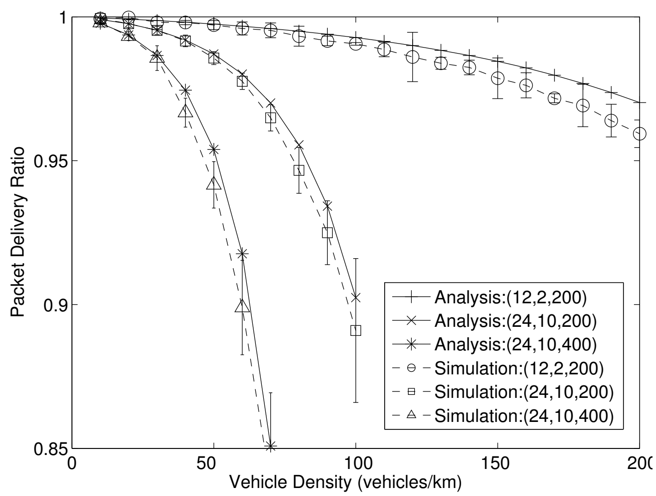


Fig. 10. Packet Delivery Ratio for proposed protocol with three transmission attempts using the following parameter set: (data rate [Mbps], packet arrival rate [packets/sec], packet size [bytes])

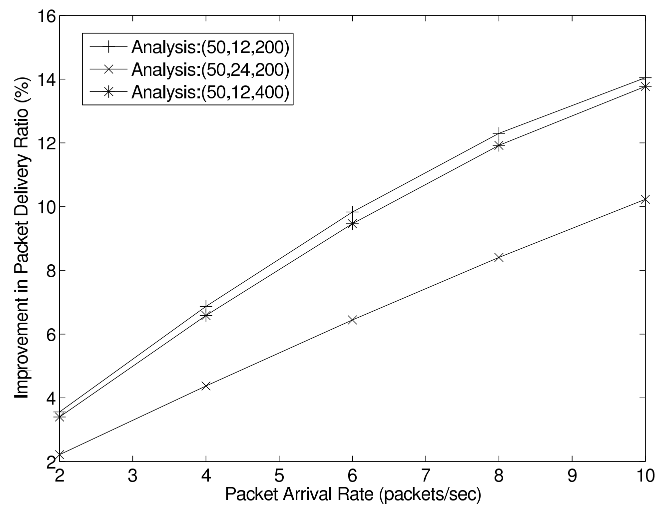


Fig. 11. Improvement in Packet Delivery Ratio for proposed protocol with three transmission attempts using the following parameter set: (vehicle density [vehicles/km], data rate [Mbps], packet size [bytes])

TABLE IV
PDR WITH REDUCED TRANSMISSION RANGE USING 24 [MBPS] DATA RATE AND 10 [PACKETS/SEC] ARRIVAL RATE

P [bytes]	β [vehicles/km]	Single Tx 500 m	NACK based ReTx protocol 500 m	250 m
200	60	0.856	0.973	0.994
	100	0.774	0.898	0.984
	150	0.660	0.549	0.955
400	60	0.792	0.903	0.977
	90	0.686	0.700	0.947
	120	0.582	0.207	0.900

$\lambda = 2$ case, we observe that the PDR is always better than 95% which is a significant improvement over Fig. 6. In particular, at $\beta = 200$ we observe a 10% increase in PDR value with the enhanced protocol. For the (24,10,200) and (24,10,400) cases in Fig. 10, the PDR eventually falls below 90% at $\beta = 60$ and $\beta = 100$, respectively. However, similar performance can *only* be observed in Fig. 6 using the original protocol at a much lower density, at $\beta = 30$ for (24,10,200) case, and at $\beta = 50$ for (24,10,400) case. Thus the enhanced protocol can support up to two times the vehicle density for the required PDR threshold. Overall, Fig. 10 shows a significant improvement in terms of PDR using our proposed protocol.

Using the analytical model, the improvement in PDR of the proposed protocol compared to that of single transmission is shown in Fig. 11 for various arrival rates. The vehicle density is fixed at 50 vehicles/km. The improvement is increasing with increased arrival rate up to 14% at $\lambda = 10$ for both (50,12,200) and (50,24,400) cases. In general, we see that increasing packet arrival rate has similar effect on PDR as increasing vehicle density as in both cases the network load is increased.

It can be observed from our results that for light and medium traffic loads, the proposed extension is an effective one as it improves PDR and extends the range of vehicle densities where the strict QoS requirement of safety applications is met. At very high vehicle density (and traffic load), there are scenarios where the PDR falls short of the required value. To address these situations, the proposed protocol could be combined with some other approach that reduces the effective channel load; examples of ways to reduce the channel load are to adaptively reduce the transmission range or message rate when the observed traffic load is high [39]. To demonstrate the PDR performance of our NACK-based protocol if used in conjunction with a reduced transmission range, we provide some simulation results in Table IV for a 250 m transmission range for various packet sizes and vehicle densities. For comparison purposes, we include simulation results for a 500 m transmission range for both the NACK-based scheme and conventional DCF. It can be seen from the table that the NACK-based scheme satisfies the 90 % PDR requirement for a 250 m range. While the detailed algorithms to adaptively adjust the transmission range are out of the scope of this paper, examples in Table IV suggest that the required QoS can be met at high densities of vehicles by combining our out-of-band NACK scheme with an adaptive transmission range approach.

VI. CONCLUSION

We develop in this paper an analytical model to evaluate the performance of the IEEE 802.11 MAC protocol for safety applications in the DSRC environment. Using the model, we obtain expressions for the mean and standard deviation of the packet delay, as well as an expression for the packet delivery ratio at the MAC layer. Comparison with the simulation results confirms the accuracy of our analytical model over a range of vehicle densities and packet arrival rates. Based on the results obtained we find that hidden terminals have a detrimental impact on the PDR which may compromise the reliability required for safety applications. On the other hand, the packet delay of safety messages is found to be well below the required threshold level. These findings enable us to develop a novel MAC protocol based on the IEEE 802.11 DCF where we use retransmissions to trade increased packet delay for decreased packet loss. We extend the analytical model to evaluate the performance of the enhanced protocol, and show that it maintains the predictive accuracy. From our numerical results we find that the enhanced protocol can improve the PDR by up to 10%, and increase the supported vehicle density by up to two times for a range of packet arrival rates, while maintaining the delay below the required threshold level.

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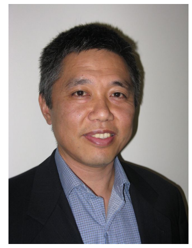

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