Optimised CSMA/CA Protocol for Safety Messages in Vehicular Ad-Hoc Networks

Giorgia V. Rossi and Kin K. Leung
Department of Electrical and Electronic Engineering
Imperial College London, United Kingdom
Email: {giorgia.rossi12, kin.leung}@imperial.ac.uk

***Abstract*—Vehicular ad-hoc networks (VANETs) that enable communication among vehicles have recently attracted significant interest from researchers, due to the range of practical applications they can facilitate, particularly related to road safety. Despite the stringent performance requirements for such applications, the IEEE 802.11p standard still uses the carrier sensing medium access/collision avoidance (CSMA/CA) protocol. The latter when used in broadcast fashion employs a randomly selected backoff period from a fixed contention window (CW) range, which can cause performance degradation as a result of vehicular density changes. Concerns regarding the robustness and adaptiveness of protocols to support time-critical applications have been raised, which motivate this work. This paper investigates how the maximum CW size can be optimised to enhance performance based on vehicular density. A stochastic model is developed to obtain the optimal maximum CW that can be integrated in an amended CSMA/CA protocol to maximise the single-hop throughput among adjacent vehicles. Simulations confirm our optimised protocol can greatly improve the channel throughput and transmission delay performance, when compared to the standardised CSMA/CA, to support safety application in VANETs.**

***Index Terms*—Vehicular Ad-Hoc Networks, Throughput, transmission probability, MAC layer, 802.11p, CSMA/CA, Contention Window.**

I. Introduction

Vehicular ad-hoc networks (VANETs) are highly mobile wireless networks of vehicles that can communicate with each other without relying on permanent infrastructure, through a multi-hop ad-hoc connection [1], [2]. Consequently, VANETs enable a wide range of applications, even before considering the fact that they can also be integrated with cellular networks or other external infrastructure, such as unmanned aerial vehicles (UAVs) or cellular base stations as in Figure 1, to support hybrid networking [3], [4].

One of the most attractive benefits of VANETs is their capacity to drastically improve road safety, by means of exchanging safety information. In light of this, an allocated 75 MHz bandwidth at 5.9 GHz has been defined in the IEEE 802.11p (amendment of 802.11a) specifically for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. The standard defines the protocols for physical and MAC layers. In Europe, based on the IEEE 802.11p, the European Telecommunications Standards Institute (ETSI) designated a specific type of message to be broadcasted in a single hop employing the carrier sense multiple access with collision avoidance (CSMA/CA). Known as cooperative awareness messages (CAMs), they contain information relevant to safety related applications (i.e., speed and position), and are broadcasted as frequently as ten times per second to provide reliable support for safety applications that usually require low latency (as low as 100 ms) [5], [6], [7]. This is so each vehicle can constantly monitor the surrounding vehicles and infrastructure, allowing them to become aware of possible imminent threats, and to take rapid countermeasures such as sending warning messages to the drivers and neighbouring vehicles in such scenarios.

Unfortunately, the medium-access-control (MAC) protocol in the IEEE 802.11p still makes use of carrier sense mechanisms. Specifically, the standard uses the enhanced distributed channel access (EDCA) that employs the CSMA/CA protocol. The latter, in broadcast based applications, is characterised by the lack of acknowledgment (ACK) packets required to identify a transmission collision and consequently adapts the maximum contention window (CW), which is doubled following each unsuccessful transmission attempt, and has to rely on a fixed, maximum CW size instead.

Given the importance of vehicular communication applications, the performance of broadcast MAC protocols has been thoroughly investigated. It has been shown that increasing vehicular density corresponds to decreasing performance [8], [9], [10]. In particular, the broadcast CSMA/CA performance and its behaviour under different scenarios has been investigated in [11], [12], [13]. The authors in [11], [12], [13] observe, by means of extensive simulation and analysis, that the IEEE 802.11p MAC tends to behave like the Aloha protocol as the vehicular density rises, meaning that the benefits of the sensing mechanism diminishes and the transmission process merely behaves like a random transmission technique. In light of this, VANETs may be particularly vulnerable to performance degradation due to vehicular density changes. Consequently, it is questionable whether the networks are robust enough to support stringent performance requirements, particularly for safety applications.

Various solutions have been proposed to overcome the issues related to reliable broadcasting in VANETs [14], [15], [16]. For example, space division multiple access (SDMA) protocols assign different time slots relative to the vehicle location [14]. This implies that roads must be divided into segments, yet fairness can be difficult to maintain under fast changing vehicular densities that may characterise different

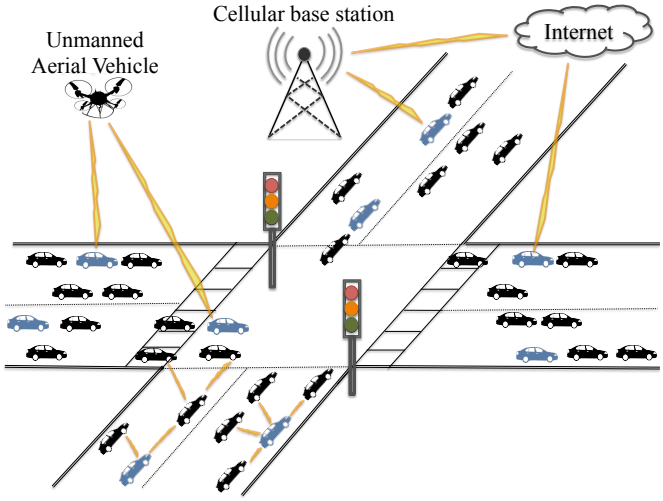

Fig. 1. Hybrid networking scenario: vehicles can communicate with other vehicles for safety or with UAVs and cellular base stations

road segments at the same time. Another approach exploits the time division multiple access (TDMA) mechanism that assigns a transmission slot to a vehicle [15], [16]. Originally designed to be used in a centralised fashion, vehicular networks require TDMA protocols to act in a distributed manner, which unfortunately is still not completely immune to the contention problem and can only accommodate a limited number of vehicles, given that the time slot will not be released as long as the vehicle has to transmit a packet (i.e., CAM messages have to be transmitted periodically from each vehicle). Hence, it seems reasonable to efficiently allocate transmission rights to various vehicles based on the current IEEE 802.11p MAC protocol, but by optimising the network performance according to the changing vehicle density. In [17] the authors present approaches to choose the optimal transmission probability for the slotted Aloha based on the vehicular density in networks where vehicles arrive and are distributed according to a Poisson Point Process (PPP). However, realistic constraints, such as the size of the vehicles or the estimated number of neighbouring vehicles, are not considered in the analysis.

In this paper we develop a stochastic model that accounts for realistic constraints, such as the practical vehicles size, in order to derive the optimal contention window for the CSMA/CA protocol based on the vehicular density. As a first step, to devise efficient MAC protocols for time-critical applications in VANETs, we establish the relation between the (fixed) maximum CW and the transmission probability. A model to evaluate the density-based optimal transmission probability in order to enhance the network throughput is presented and the optimal maximum CW is found. Finally, we integrate our results with the CSMA/CA protocol and present an optimised protocol that additionally accounts for the estimated number of surrounding vehicles. Extensive simulation shows the improved performance of the proposed protocol based on vehicular density when compared with the original IEEE 802.11p MAC protocol. Key contributions of this work include:

- Enhancement of the communication model with realistic constraints such as the practical vehicle size (instead of treating each vehicle as a dimensionless point) in modelling vehicular flows and estimating vehicular density.
- Derivation of the optimal maximum CW based on vehicle density, while considering the signal-to-interference ratio (SIR) and capture effect at receiving vehicles.
- Integration of the optimal maximum CW with the CSMA/CA protocol to enhance the delay and throughput performance for CAM safety messages.

The rest of the paper is organised as follows. Section II presents the network models, describing vehicle distribution, connectivity and throughput. Section III contains numerical results which illustrate the performance merits of the newly proposed CSMA/CA protocol with the maximum CW, which is optimally chosen according to the vehicle density, over the standardised protocol. Finally, conclusions are drawn in section VI.

II. System model

A. CSMA/CA broadcast model

The IEEE 802.11p MAC protocol is designed to work over a synchronisation interval (SI) of 100 ms, during which every vehicle switches between the control channel (CCH) and service channels (SCHs) for a CCH interval (CCI) and a SCH interval (SCI), respectively, such that SI = CCI + SCI. Specifically, the broadcast CSMA/CA for CAMs (i.e., safety messages) requires a 100 ms latency as well as a periodic message (packet) generation of 10 Hz for each vehicle. This means that a new packet is generated in every CCI (100 ms) for transmission. The states associated with the channel contention protocol over a single CCI are described in Figure 2. At the beginning of every CCI, all vehicles generate a new CAM (packet) for broadcast. For each packet, a backoff time is randomly selected from a fixed contention-window (CW) range of 0 to W - 1 slot times. The backoff time (counter) is then decremented every slot time when the channel is sensed idle. When the counter reaches 0, the vehicle transmits the packet. If the channel is determined to be busy, the counter is frozen. From the Markov model in Figure 2 and assuming that vehicles are able to carry out the backoff process correctly (e.g., no hidden node problem), the state transition probabilities are given by

$$\begin{cases} P\{k|0\} = \frac{1}{W}, & \text{for } k \in [0, W-1] \\ P\{k-1|k\} = 1, & \text{for } k \in [1, W-1] \end{cases} \quad (1)$$

where state k represents the current value of the backoff counter on a vehicle. Therefore, let b_k represent the probability that a vehicle is in state k. Figure 2 illustrates that every k state, or equivalently backoff value, can be directly selected with probability $\frac{1}{W}$, as shown in the first line of (1). It is additionally possible to reach a state k by sequentially decrementing the counter with probability 1, as in (1), after the

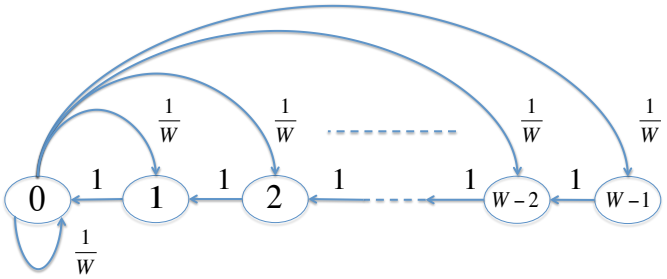

Fig. 2. Markov model of CSMA/CA Broadcast in 802.11p for every CCI interval

selection of a higher backoff value (Figure 2). In light of this, with reference to Figure 2, we can evaluate the probabilities of each state as follows

$$\begin{cases} b_{W-1} = \frac{1}{W} b_0 \\ b_{W-2} = \frac{1}{W} b_0 + b_{W-1} \\ b_{W-3} = \frac{1}{W} b_0 + b_{W-2} \\ \vdots \\ b_{W-i} = \frac{1}{W} b_0 + b_{W-i+1} \end{cases} \tag{2}$$

where b_0 represent the probability that the backoff counter is zero and consequently it represents the probability that a vehicle transmits in an idle slot. By introducing the change of variable $W - i = k$ we can eventually express the probability b_k as

$$b_k = (W - k)\frac{b_0}{W} \tag{3}$$

The sum of all possible states probabilities has to be equal to 1. That is,

$$\sum_{k=0}^{W-1} b_k = 1. \tag{4}$$

By substituting (3) into (4) and rearranging we obtain

$$\sum_{k=0}^{W-1} (W - k) = \frac{W}{b_0}. \tag{5}$$

By a change of variable $n = W - k$ and using the fact that

$$\sum_{n=1}^{N} n = \frac{N(N+1)}{2}, \tag{6}$$

the relation between the CW size and the probability b_0 can be expressed as

$$W = \left\lfloor \frac{2}{b_0} - 1 \right\rfloor, \tag{7}$$

where b_0 is the probability that a vehicle starts transmitting in an arbitrary free slot time and the flooring operation is applied because the CW must be an integer value, as specified in the protocol standards.

B. Equivalence of the CSMA/CA Broadcast to Slotted Aloha

To consider the CAM safety messages exchanged based on the ETSI standardisation, we focus on the MAC protocol operation over a single CCH interval, where the messages are generated once every CCI of 100 ms for each vehicle. In fact, each vehicle generates a CAM packet synchronously at the beginning of every CCI, resulting in a saturated traffic condition (i.e., every vehicle has a packet ready for transmission). According to the CSMA/CA protocol, each vehicle selects a random backoff period from the fixed contention window (CW) range of 0 to W-1. This is because in broadcast fashion ACKs are not used to determine whether a reference packet has been successfully received or not and hence the backoff period is always chosen in the same range. When a vehicle senses the channel idle during a slot time, its backoff counter is decremented by one. On the other hand, if the channel is sensed busy, due to either successful transmission or collision, the counter remains unchanged. When the backoff counter reaches zero for a vehicle, it will start to transmit its packet at the beginning of the next slot time without additional sensing. It follows that if two or more vehicles have picked the same backoff counter at the beginning of the CCI, this will eventually commence a simultaneous transmission, causing collisions and the loss of the packets.

Due to the random selection of the backoff period and assuming perfect channel sensing by all vehicles, each vehicle that has a CAM packet to transmit, has the probability of b_0 to transmit in an arbitrary idle slot time following the beginning of the CCH interval, as illustrated in Figure 2. When the channel is occupied by any transmission, either successful or collided, the busy channel does not change any backoff counter. Consequently, by focusing only on the idle slot time, the CSMA/CA for CAMs behaves in a way identical to that of slotted Aloha protocol, where vehicles have a probability b_0 to transmit in an arbitrary time slot. Therefore the event of a vehicle transmitting is a random variable that can be described by a Bernoulli distribution expressed as

$$f(\omega, b_0) = b_0^{\omega}(1 - b_0)^{1-\omega}, \qquad \text{for } \omega \in \{0, 1\}. \tag{8}$$

In the following, we shall derive the optimal value of b_0 based on the vehicular density λ. This means that the optimal transmission probability can be expressed as a function of the density as $b_0(\lambda)$, and by substituting it in (7) we obtain the optimal maximum CW, W-1, to maximise the CSMA/CA throughput based on the vehicular density

$$W = \left\lfloor \frac{2}{b_0(\lambda)} - 1 \right\rfloor. \tag{9}$$

Before continuing, we note that the transmission time T for a CAM is assumed to be constant, regardless of whether the transmission is successful (collision-free) or not, as given by

$$T = \frac{T_H + E_P}{r_d} + AIFS + \sigma, \tag{10}$$

where T_H and E_P are the respective amount of time spent in transmitting the MAC header and the packet payload with a

data rate r_d. The signal propagation delay is denoted by σ, while the arbitration inter-frame spacing (AIFS) is the initial waiting period following every transmission.

C. Inter-Vehicles Distance Distribution Model

Let us consider the traffic source and its assumptions. A single-lane road with one traveling direction and infinite length is considered, as shown in Figure 3. This one-dimensional case can be helpful in obtaining valuable insight into increasingly complex scenarios. Vehicles are assumed to be located on the road according to a Poisson point process (PPP) with rate λ, which has been considered to be a good model to describe the physical distribution of vehicles on a road [17], [18], [19].

A limitation of a simple PPP is, however, the unrealistic assumption of vehicles as dimensionless points. In fact, the received power P_r is a function of the distance between a transmitter and a receiver and, hence, the dimension of the vehicles in the network clearly plays an important role in accounting for the signal and interference value. Therefore, in this paper we present a model that accounts for the size of the vehicles. Let us assume the vehicles have the same size z, then by the assumption of PPP, the random distance X between receivers mounted on adjacent vehicles on the single-lane roadway has a shifted exponential distribution with a probability density function (pdf)

$$f(x) = \begin{cases} \lambda e^{-\lambda(x-z)}, & x \geq z \\ \\ 0. & x < z \end{cases} \tag{11}$$

Note that the due to the PPP, distances between every two adjacent (neighbouring) vehicles are independent and identically distributed (i.i.d.) random variables.

Using (11) we can model the distance between any two non-adjacent vehicles as the sum of shifted exponentially distributed random variables. Therefore, the distance between any two non-adjacent vehicles follows a shifted Erlang distribution with pdf

$$f(x) = \frac{\lambda^k}{(k-1)!}(x-kz)^{k-1}e^{-\lambda(x-kz)} \quad x \geq z, \tag{12}$$

where $k-1$ is the number of vehicles placed between the two non-adjacent reference vehicles being considered and λ denotes the network vehicular density.

Let us define $N(r)$ as a random number of vehicles located within a given distance of $r/2$ metres in front of and behind a reference vehicle on the road. From (12), we have

$$P(N(r/2)=k) = 1 - \sum_{n=0}^{k-1} \frac{(\lambda(r/2-kz))^n e^{-\lambda(r/2-kz)}}{n!}. \tag{13}$$

From (13), the expected value of the number of vehicles $N(r)$ within distance r (i.e., at the back and front of the reference vehicle) can be obtained

$$\bar{k} = E(N(r)) = \frac{\lambda r}{1+\lambda z}, \tag{14}$$

where $\bar{k}$ represents the number of neighbouring vehicles that can be estimated by the reference vehicle through sensing. The value of λ, which will be needed in determining the optimal probability $b_0(\lambda)$ and CW parameter in the following section, can hence be evaluated using (14) based on the estimation of the average number of neighbouring vehicles.

D. Throughput Model

VANETs can enable data packet exchange from one vehicle to another in a multi-hop fashion. However, in this work we focus on communication between two adjacent (neighbouring) vehicles traveling in the same direction, as this scenario is most relevant in the context of safety applications. Hence, we focus on whether the vehicle n_j, immediately behind the transmitting vehicle n_i, can receive a packet, as shown in Figure 3. Furthermore, the system is assumed to be interference limited; that is thermal noise is not considered in our model. The analysis is performed in the case of half duplex communication. Consequently, every vehicle is restricted to either transmitting or receiving a signal at any given moment, and is not capable of doing both simultaneously.

Let us introduce the notion of communication range R_c. This is defined as the distance from a given reference vehicle within which a signal from a transmitting vehicle can be received at a power level greater than a specified threshold (commonly referred to as the receiver sensitivity) as illustrated in Figure 3. In this work, the communication range R_c is set to be identical for all vehicles within the network, as was done in [17], [19], [20], [21].

Connectivity Requirements: Two adjacent vehicles are considered to be connected if two conditions are fulfilled.

Firstly, the vehicles have to be within each other's communication range R_c, which is referred to as the event C, that is

$$d(n_i, n_j) \leq R_c. \tag{15}$$

Given that the distance between two adjacent vehicles is described by a shifted exponential distribution as seen in (11), the probability of event C, or equivalently that (15) is satisfied, becomes

$$P(C) = 1 - e^{-\lambda(R_c - z)}. \tag{16}$$

Secondly, the SIR of the signal received by vehicle n_j from the transmitting vehicle n_i has to exceed a predefined threshold γ, namely

$$SIR_{i,j} \geq \gamma. \tag{17}$$

The SIR at the receiving vehicle n_j when vehicle n_i is transmitting in the presence of M interfering vehicles, is defined as follows

$$SIR_{i,j} = \frac{P_{r(i,j)}}{\sum_{k=1}^{M} I_k P_{r(k,j)}}, \tag{18}$$

where $P_{r(i,j)}$ denotes the received power at vehicle n_j from n_i. The expression at the denominator of (18) is the total interference power at the receiving vehicle, as seen in Figure 3, and I_k indicates whether vehicle n_k is transmitting or not, taking the value of 1 with probability b_0 or 0 with probability $(1-b_0)$. As previously mentioned in Section II - *B*, I_k can be

represented as a Bernoulli variable and therefore be described by the probability mass function (pmf) in (8).

Let us assume the signal attenuation is solely a function of the distance, with a power exponent $\alpha > 2$, and every vehicle has the same transmission power P_t. In light of this, the received power $P_{r(i,j)}$ at a reference vehicle n_j is a function of the path loss α and the transmission power P_t and is formally expressed as

$$P_{r(i,j)} = P_t(d(n_i, n_j))^{-\alpha} \quad with \ \alpha > 2, \tag{19}$$

where $d(n_i, n_j)$ denotes the distance between transmitter and receiver in metres. Inserting (19) into (18), the SIR requirement expressed in (17) becomes

$$\frac{P_t}{d(n_i, n_j)^{\alpha}} \geq \gamma \sum_{k=1}^{M} \frac{I_k P_t}{d(n_k, n_j)^{\alpha}}, \tag{20}$$

The expression in (20) does not allow a closed-form expression to be obtained for the performance metrics of interest. Nevertheless, in [17] it has been shown, by means of extensive simulation, that (20) can be effectively approximated by a set of M pairwise conditions for each kth vehicle, when analysing a vehicular scenario. By applying the same approximations presented and validated in [17], (20) becomes

$$d(n_k, n_j) \geq I_k R_f \quad \forall k, \tag{21}$$

where R_f represents the interference range within which vehicles may still interfere with the communication between n_i and n_j; it is expressed as $R_f = \gamma^{1/\alpha} R_c$.

The condition expressed in (21) means that the distance $d(n_k, n_j)$ between the interfering vehicle n_k and the reference vehicle n_j exceeds the distance between vehicles n_i and n_j (that at most can be as large as the communication range R_c) by a factor of $\gamma^{1/\alpha}$. The requirement in (21) can guarantee the successful reception of a packet in terms of SIR, when it is satisfied for all possible interfering k vehicles located in the network.

We consider now the event H_k that a single interfering vehicle n_k satisfies the condition in (21). H_k can only occur if either the vehicle n_k is not transmitting (i.e., $I_k = 0$) or if it is true that $d(n_k, n_j) \geq R_f$. Consequently, we obtain

$$P(H_k) = P\{I_k = 0 \vee (I_k = 1 \wedge d(n_k, n_j) \geq R_f)\}. \tag{22}$$

Therefore, the interference condition in (21) is fulfilled for vehicle n_k when the latter is located outside the interference range R_f from the receiving vehicle n_j. To evaluate the probability in (22), we require information regarding the vehicle density in the vicinity, which can be estimated from the average number of neighbouring vehicles from (14).

Next, let us define the event A that vehicle n_k is located outside the interfering range R_f of vehicle n_j. As given in (11), the distribution of the distances between adjacent vehicles is a shifted exponential. The distance between two non-adjacent vehicles is consequently described by a shifted Erlang distribution (12), where $k-1$ represents the number of vehicles between the non-adjacent vehicles. Combining this

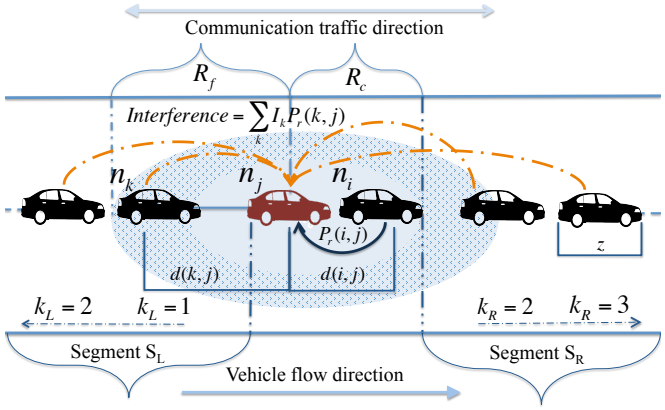

Fig. 3. Road configuration and assumptions for the analytical model

fact with the indexing scheme k for interfering vehicles as shown in Figure 3, the probability of event A occurring is

$$P(A) = \sum_{n=0}^{k-1} \frac{(\lambda(R_f - kz))^n}{n!} e^{-\lambda(R_f - kz)} \quad \forall k. \tag{23}$$

As a result of the access protocol assumption in (8), the probability that vehicle n_k does not transmit is

$$P(I_k = 0) = 1 - b_0. \tag{24}$$

Inserting (23) and (24) into (22), the probability of event H_k occurring becomes

$$P(H_k) = 1 - b_0 \left[1 - \left(\sum_{n=0}^{k-1} \frac{(\lambda(R_f - kz))^n}{n!} e^{-\lambda(R_f - kz)}\right)\right]. \tag{25}$$

The expression in (25) represent the probability of satisfying the interferer SIR condition (21) for a single vehicle n_k.

The scenario illustrated in Figure 3 shows that for every pair of adjacent vehicles n_i and n_j in the network, we can identify two separate road segments in front and behind the receiving vehicle n_j, namely S_L and S_R. They represent regions where it is possible to find other vehicles that can interfere with the transmission between n_i and n_j.

Let us define the event L that the requirement in (21) is verified for all possible interfering vehicles n_k in the road segment S_L, while R is the event that (21) is verified in region S_R. By using (25), the probability of L is expressed as follows

$$P(L) = \prod_k P(H_k). \tag{26}$$

Note that the probability of event R, for the road segment S_R, is computed in a similar manner.

Let us now define the event F in which the interference condition in (21) is satisfied for all possible interfering vehicles n_k located on both road segments S_L and S_R, for the transmission from vehicle n_i to n_j. The probability that event F occurs, by using (26), thus becomes

$$P(F) = \frac{\prod_{k=1}^{M} \left[(1-b_0) + \left(b_0 \sum_{n=0}^{k-1} \frac{(\lambda(R_f - kz))^n}{n!} e^{\lambda(R_f - kz)}\right)\right]^2}{(1-b_0) + b_0 e^{\lambda(R_f - z)}}. \tag{27}$$

Optimal Throughput: We define the data throughput T_h, from the transmitting vehicle n_i to its adjacent vehicle n_j, as successful reception subject to satisfying the conditions expressed in (15) and (21). Note that due to the half-duplex mechanism assumption, this definition additionally includes the fact that vehicle n_i is transmitting while its adjacent vehicle n_j is not (i.e. it is receiving). The combination of all these factors yields

$$T_h = P\{C \wedge F \wedge I_i = 1 \wedge I_j = 0\}. \tag{28}$$

Substituting (16), (24) and (27) into the above expression and expressing the interference range R_f in terms of communication range R_c as $R_f = \gamma^{1/\alpha} R_c$, the single-hop throughput from vehicle n_i to its neighbouring vehicle n_j becomes

$$T_h = \prod_{k=1}^{M}\left[1-b_0\left(1-\sum_{n=0}^{k-1}\frac{(\lambda(\gamma^{1/\alpha}R_c-kz))^n}{n!}e^{\lambda(\gamma^{1/\alpha}R_c-kz)}\right)\right]^2 \cdot \frac{(b_0-b_0^2)(1-e^{-\lambda(R_c-z)})}{(1-b_0)+b_0 e^{\lambda(\gamma^{1/\alpha}R_c-z)}}. \tag{29}$$

Note that in this equation the transmission probability, b_0 is the only control variable, whilst all other variables are constants for a given network. As described in Algorithm 1, it is possible to evaluate the value of λ from the estimated number of neighbouring vehicles $\bar{k}$. The optimal b_0 can then be determined from (29) as a function of λ, that is $b_0(\lambda)$, and by using (9) the optimal maximum CW size, W-1, can be evaluated based on the vehicular density.

Algorithm 1 Optimised CSMA

1: **for each** vehicle **do**
2: periodically monitor the radio channel in order to estimate the number of surrounding vehicles $\bar{k}$
3: calculate λ from the estimated number of neighbouring vehicles $\bar{k}$ in the interfering range R_f by using (14)
4: pick the optimal CW size (obtained from (29) and (7)) for the current value of λ
5: execute CSMA/CA procedure with optimised CW
6: **end for**

Algorithm 1 shows the steps of the proposed (optimised) CSMA/CA protocol for broadcast. In the following section, we will present the results of the protocol proposed in this paper, in comparison with the standard IEEE 802.11p MAC protocol.

III. Numerical Results

Simulation is used to validate the proposed CSMA/CA protocol which is adaptive to vehicle density, and to compare performance with the standard one. In this work, we simulate a one-lane, single-direction road that is 5 km in length. Furthermore, it is assumed that vehicles are able to estimate the number of neighbouring vehicles in the range R_f. The transmission range is assumed to be $R_t = 100$ m, $\gamma = 4$ and the path loss exponent $\alpha = 4$. The values for the broadcast CSMA/CA can be found in Table I. Using (29), Figure 4 shows how the channel throughput changes as the transmission probability b_0 varies for different vehicle densities in the network. As shown in the figure, for a given vehicle density (as reflected by the average number of vehicles located within R_f, from which we can derive the value of λ by exploiting the expression in (14)), there exists the optimal transmission probability $b_0(\lambda)$ that maximises the channel throughput.

TABLE I
Simulation Parameters

Mac Layer Parameters	Values
aSlotTime, σ	$13\mu s$
AIFS	$58\mu s$
Propagation delay, δ	$1\mu s$
MAC header, T_H	50Bytes
Packet payload, E_P	500Bytes
Data rate, r_d	6Mbit/s

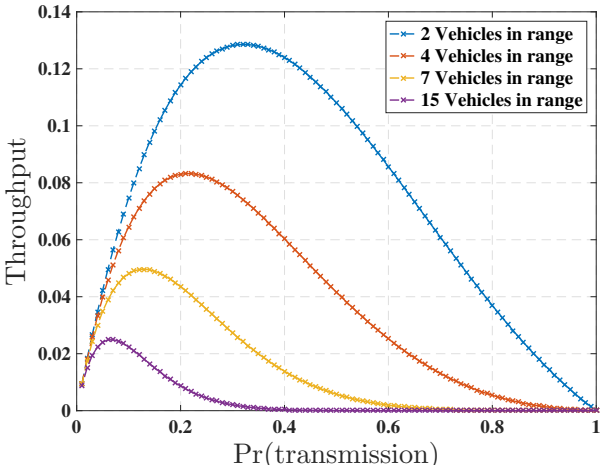

Fig. 4. Throughput as a function of the probability of transmission b_0

Substituting the optimal density-based transmission probability $b_0(\lambda)$ in (9), the optimal maximum CW to maximise the single-hop throughput, can be evaluated for different density conditions. The optimal maximum CW is displayed in Figure 5 as a function of the average number of estimated neighbouring vehicles within the interference range R_f of an arbitrary vehicle. It can be observed that the optimal contention window size increases with the vehicle density because a higher density increases the likelihood of transmission collision. Consequently, in these situations, it is advisable to choose a bigger CW to reduce collision, as suggested in Figure 5. As intuitively expected, these results also confirm that a fixed maximum CW without considering the vehicle density, as specified in the ETSI protocol standard, cannot yield the best

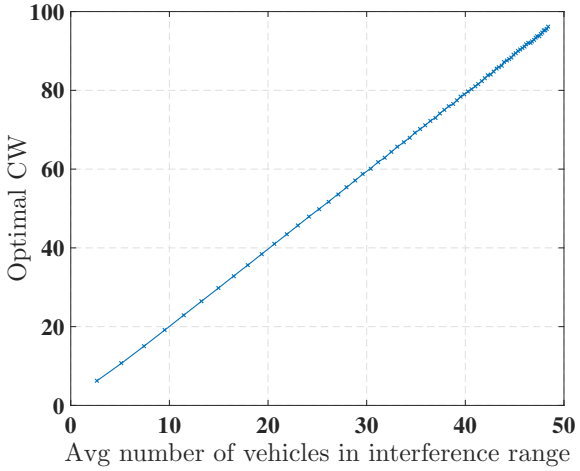

Fig. 5. Optimal maximum CW, W-1, to maximise the single-hop throughput as a function of the average number of estimated neighbouring vehicles within the interference range R_f of an arbitrary vehicle

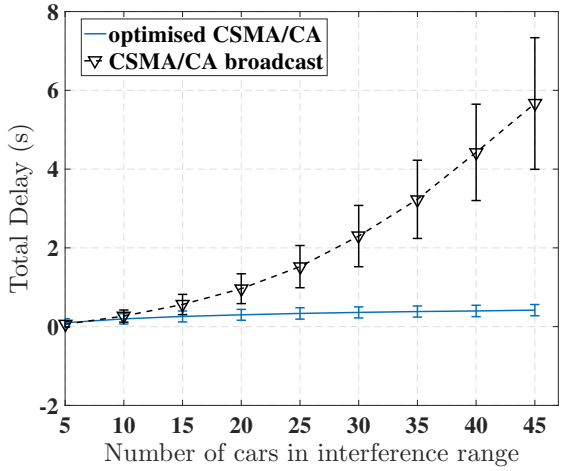

Fig. 7. Average total delay for a vehicle to collect all CAM messages from its neighbours as a function of the average number of neighbouring vehicles within the interference range R_f

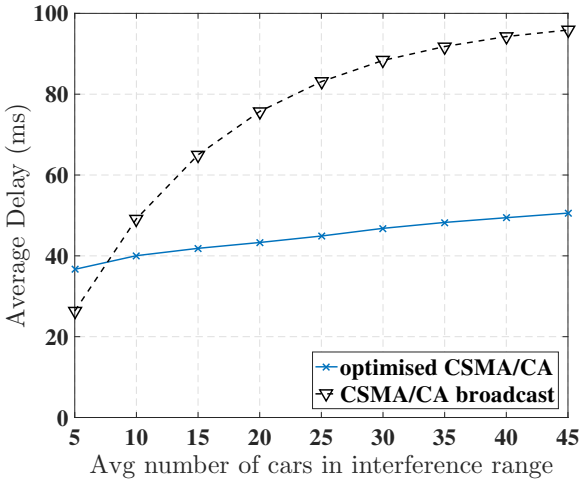

Fig. 6. Average transmission delay in a CCI for the standardised and proposed protocol as a function of the average number of neighbouring vehicles within the interference range R_f

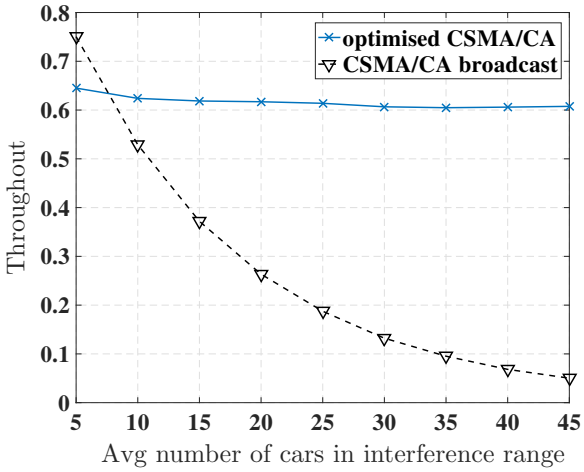

Fig. 8. Throughput for the standardised and proposed protocol as a function of the average number of neighbouring vehicles within the interference range R_f.

achievable throughput.

The average transmission delay in a CCI as a function of the average number of neighbouring vehicles within the interference range R_f is depicted in Figure 6. The delay is defined from the time a vehicle generates a CAM packet at the beginning of the CCI of 100 ms until the packet is transmitted. Each vehicle is assumed to have a buffer of one packet. Due to the safety application under consideration, each CAM packet is expected to be transmitted with a delay of less than 100 ms; that is, before the end of the corresponding CCI. So, if a second packet has been generated at the beginning of the next CCI before the first packet is transmitted, the second packet is assumed to overwrite the first one still in the buffer (e.g., to replace the obsolete information). In this case, the delay for the first packet that has missed the latency requirement is assumed to be 100 ms in the simulation. Figure 6 depicts the average packet delay for the standardised CSMA/CA broadcast protocol and our proposed protocol with the optimised CW as a function of vehicle density. As shown in the figure, the new protocol offers much lower delay than the standardised protocol because the CW is optimally selected according to vehicle density by the new protocol to avoid transmission collision.

Figure 7 depicts the average total delay for the proposed (optimised) and standard protocol as a function of the average average number of neighbouring vehicles within the interference range R_f. The vertical bars in the figure represent one standard deviation around the average delay. The total delay metric is defined as the average amount of time that a vehicle waits before CAMs from all its neighbours are received. As shown in the figure, the proposed protocol offers much lower delay than the standard protocol because the

CW is optimally selected according to vehicle density by the new protocol to avoid transmission collision. In fact, each time a collision occurs, the packets involved are not received and new transmissions can be possible in the next CCI. This increases the total delay in receiving all CAM packets from the neighbours. Vehicle clustering mechanisms for internetworking and road-safety applications strongly rely on the timely reception of accurate status information from neighbouring vehicles. Hence, by offering low latency, the optimised protocol can support such real-time applications.

Finally, the throughput for the standardised and the new protocol is compared in Figure 8. By adapting the CW as a function of vehicle density, the proposed protocol is clearly able to maintain throughput performance despite increasing density. By contrast, since the standardised CSMA/CA protocol has a fixed maximum CW, a greater number of collisions occur as the number of vehicles on the road increases.

IV. Conclusion

As a step toward the design of efficient MAC protocol tailored for VANETs, we have established the relation between the maximum CW size and the transmission probability b_0. By exploiting the equivalence between the slotted Aloha and the broadcast CSMA/CA protocols, we have developed a stochastic model, including realistic constraints such as the practical vehicle size, to derive the optimal transmission probability and in turn the optimal maximum contention-window size based on the vehicle density. This can drastically help reduce the contention amongst vehicles operating under stringent time constraints, such as in road safety applications, and maximise the single-hop throughput among adjacent vehicles. Furthermore, we have proposed an amended protocol that integrates the optimal maximum contention-window size and accounts for the more realistic estimated number of surrounding vehicles $\bar{k}$ rather than rely merely on the theoretical value λ. Results from extensive experimental simulation have revealed significant performance improvement in terms of channel delay and throughput when compared with the standardised protocol over a wide range of vehicle densities.

A possible extension to this work can focus on the derivation of an accurate estimation mechanism of the vehicle density by sensing the number of neighbouring vehicles. Since the performance of the proposed CSMA/CA protocol depends on the density estimate, its accuracy is important. The performance study in this work essentially assumes a buffer of one single packet for each vehicle, which is reasonable for the CAM or certain safety applications with periodic packet generation. Another area of extension is to consider multiple buffers for other time-critical applications where packet generation can be bursty.

Acknowledgment

The authors would like to thank the U.K. Defence Science and Technology Laboratory (DSTL) for funding of this research through the National U.K. PhD programme.

References

[1] S. Yousefi, M. Mousavi, and M. Fathy, "Vehicular ad hoc networks (vanets): Challenges and perspectives," in *ITS Telecommunications Proceedings, 2006 6th International Conference on*, June 2006, pp. 761–766.

[2] H. Hartenstein and K. Laberteaux, "A tutorial survey on vehicular ad hoc networks," *Communications Magazine, IEEE*, vol. 46, no. 6, pp. 164–171, June 2008.

[3] G. V. Rossi, Z. Fan, W. Chin, and K. K. Leung, "Stable clustering for ad-hoc vehicle networking," in *IEEE WCNC*, March 2017.

[4] G. V. Rossi and K. K. Leung, "Optimised csma protocol to support efficient clustering for vehicular internetworking," in *IEEE WCNC*, March 2017.

[5] "Ieee guide for wireless access in vehicular environments (wave) - architecture," *IEEE Std 1609.0-2013*, pp. 1–78, March 2014.

[6] ETSI, "Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service," Tech. Rep., 2013.

[7] European Telecommunications Standards Institute, "Intelligent Transport Systems (ITS); Access layer specification for Intelligent Transport Systems operating in the 5 GHz frequency band," ETSI, EN 302 663 V1.2.1, July 2013.

[8] S. Eichler, "Performance evaluation of the ieee 802.11 p wave communication standard," in *IEEE VTC*, 2007, pp. 2199–2203.

[9] K. Bilstrup, E. Uhlemann, E. G. Strom, and U. Bilstrup, "Evaluation of the ieee 802.11 p mac method for vehicle-to-vehicle communication," in *IEEE VTC*, 2008, pp. 1–5.

[10] G. V. Rossi and K. K. Leung, "Performance tradeoffs by power control in wireless ad-hoc networks," in *IWCMC*, July 2013, pp. 1343–1347.

[11] S. Subramanian, M. Werner, S. Liu, J. Jose, R. Lupoaie, and X. Wu, "Congestion control for vehicular safety: synchronous and asynchronous mac algorithms," in *Proceedings of the ninth ACM international workshop on Vehicular inter-networking, systems, and applications*. ACM, 2012, pp. 63–72.

[12] Z. Tong, H. Lu, M. Haenggi, and C. Poellabauer, "A stochastic geometry approach to the modeling of dsrc for vehicular safety communication," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 5, pp. 1448–1458, May 2016.

[13] T. Nguyen, F. Baccelli, K. Zhu, S. Subramanian, and X. Wu, "A performance analysis of csma based broadcast protocol in vanets," in *IEEE INFOCOM, 2013*.

[14] R. S. Tomar and S. Verma, "Enhanced sdma for vanet communication," in *WAINA*, March 2012, pp. 688–693.

[15] X. Jiang and D. Du, "Ptmac: A prediction-based tdma mac protocol for reducing packet collisions in vanet," *IEEE Transactions on Vehicular Technology*, vol. PP, no. 99, pp. 1–1, 2016.

[16] H. A. Omar, W. Zhuang, and L. Li, "Vemac: A tdma-based mac protocol for reliable broadcast in vanets," *IEEE Transactions on Mobile Computing*, vol. 12, no. 9, pp. 1724–1736, 2013.

[17] G. V. Rossi, K. K. Leung, and A. Gkelias, "Density-based optimal transmission for throughput enhancement in vehicular ad-hoc networks," in *IEEE ICC*, 2015.

[18] J. Wu, "Connectivity analysis of a mobile vehicular ad hoc network with dynamic node population," in *GLOBECOM Workshops, 2008 IEEE*, Nov 2008, pp. 1–8.

[19] H. Takagi and L. Kleinrock, "Optimal transmission ranges for randomly distributed packet radio terminals," *Communications, IEEE Transactions on*, vol. 32, no. 3, pp. 246–257, Mar 1984.

[20] P. Gupta and P. R. Kumar, "The capacity of wireless networks," *IEEE Transactions on Information Theory,*, vol. 46, no. 2, pp. 388–404, 2000.

[21] J. Deng, Y. S. Han, P.-N. Chen, and P. Varshney, "Optimal transmission range for wireless ad hoc networks based on energy efficiency," *Communications, IEEE Transactions on*, vol. 55, no. 9, pp. 1772–1782, Sept 2007.