Optimizing the Control Channel Interval of the DSRC for Vehicular Safety Applications

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***Abstract*—Dedicated short-range communication (DSRC) technology has been adopted by the IEEE community to enable safety and nonsafety applications for vehicular ad hoc networks. To better serve these two classes of applications, the DSRC standard divides the bandwidth into seven channels. One channel, which is called the control channel (CCH), serves safety applications, and the other six channels, which are called service channels, serve nonsafety applications. The DSRC standard specifies a channel-switching scheme to allow vehicles to alternate between these two classes of applications. The standard also recommends that vehicles should visit the CCH every 100 ms, which is called the synchronization interval (SI), to send and receive their status messages. It is highly desirable that these status messages be delivered to the neighboring vehicles reliably and within an acceptable delay bound. It is obvious that increasing the time share of the CCH from the SI will increase the reliability of safety applications. In this paper, we propose two algorithms to optimize the length of the control channel interval (CCI) such that nonsafety applications have a fair share of the SI interval. One algorithm, which is called optimal channel access, is proposed to allow vehicles to access the channel with a derived optimal probability such that the successful transmission rate is maximized. The second algorithm, which is called the mobility- and topology-aware algorithm, is an adaptive scheme proposed to change the DSRC parameters based on the road and network conditions to allow the coexistence of safety and nonsafety applications on the DSRC. Vehicles will execute both algorithms in a distributed manner to achieve a high success rate within the selected CCI interval. The simulation results show that using the two new algorithms keeps the CCI below half of the SI in all scenarios while maintaining a high success rate for safety messages. This will give nonsafety applications the opportunity to work in the second half of the SI interval without jeopardizing the critical safety applications.**

***Index Terms*—Algorithm, control channel interval (CCI), dedicated short-range communication (DSRC), IEEE 802.11p, medium access control (MAC), reliability, successful transmission rate, vehicular ad hoc network (VANET).**

I. Introduction

DEDICATED short-range communication (DSRC), or IEEE 802.11p [1], has been standardized by the IEEE community to enable a new class of vehicular safety applications that will increase overall safety on roads. Vehicles have to be constantly aware of the events in their surrounding environment to prevent dangerous situations before they occur. Therefore, vehicles have to exchange their status messages (beacons) periodically every 100 ms [2]. Such a high beaconing rate may result in a large number of communication collisions particularly in high-density networks, thereby causing serious degradation in the performance of vehicular ad hoc networks' (VANETs') safety and nonsafety applications.

TABLE I
Contention Parameters for IEEE802.11p CCH [5]

AC No.	Access Class	CWmin	CWmax	AIFSN
0	Background Traffic (BK)	15	1023	9
1	Best Effort (BE)	7	15	6
2	Voice (VO)	3	7	3
3	Video (VI)	3	7	2

The IEEE 802.11p medium access control (MAC) uses carrier-sense multiple access with collision avoidance and some concepts such as priority classes from the enhanced distributed channel access IEEE 802.11e [3]. In this technology, there are four access classes (ACs) with different Arbitration Inter Frame Space Numbers (AIFSNs) to ensure less waiting time for high-priority packets, as listed in Table I, where $CW_{\min}$ and $= CW_{\max}$, respectively, represent the minimum and maximum contention windows that an AC can use in the IEEE 802.11 backoff process.

The DSRC is licensed at 5.9 GHz with a 75-MHz spectrum reserved for VANET applications. The spectrum is divided into seven 10-MHz channels and a 5-MHz guard band. One of the channels, i.e., channel 78, is called the control channel (CCH), which is dedicated for safety applications such as collision avoidance application. The other six channels, which are called service channels $(SCHs)$, will be used for nonsafety or commercial applications to make this technology more cost effective. Vehicles will synchronize the switching between the CCH and one or more of the SCHs; hence, safety-related messages will not be missed or lost. The synchronization interval (SI) contains a control channel interval (CCI) followed by a service channel interval (SCI) [4], such that the time $T_{SI} = T_{CCI} + T_{SCI}$. Increasing the CCI will enhance the reliability of safety applications and challenge the coexistence of both safety and nonsafety applications on the DSRC.

In the DSRC, vehicles should be equipped with sensors and a Global Positioning System (GPS) to collect information about their positions, speed, acceleration, and direction to be broadcasted to all vehicles within their range. These status messages should be periodically broadcast at every CCI interval.

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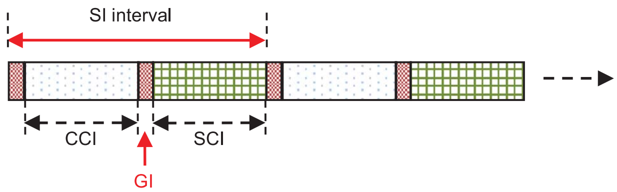

Fig. 1. SI format.

In IEEE 802.11p, vehicles will send no acknowledgement for the broadcasted packets. Therefore, the transmitter cannot detect the failure of the packet reception and, hence, will not retransmit it. This is a serious problem for safety applications.

To support both safety and nonsafety applications on the DSRC, vehicles should synchronize their switching mechanism between the CCH and SCHs. This synchronization requires that vehicles should repetitively serve safety applications on the CCH and then nonsafety applications on one or more of the SCHs, as shown in Fig. 1. It is evident that increasing the CCI will increase the reliability of the CCH and decrease the fair share of nonsafety application.

In this paper, the CCI interval will be optimized based on the successful transmission rate of status messages. The simulation results show that the current specifications of the DSRC may lead to severe performance degradation in dense and high-mobility conditions for both classes of applications. Therefore, two new algorithms are proposed and evaluated to increase the reliability of VANETs' safety applications. Vehicles will use the two proposed algorithms to achieve a high success rate for their status messages while keeping the CCI interval as minimum as possible such that nonsafety applications have a fair share of the total bandwidth.

The rest of this paper is organized as follows. In Section II, we briefly review the related work. In Section III, the system model will be introduced, and channel intervals will be derived based on the successful transmission rate. The system model is analyzed in Section IV, and a new algorithm, called optimal channel access (OCA), is introduced to increase the successful transmission rate of the CCH. In Section V, the CCI is optimized based on a certain success rate. A new algorithm called the mobility- and topology-aware (MTA) algorithm is proposed in Section VI to enhance the reliability of VANETs. The simulation setup and results are discussed in Section VII, and we conclude this paper and propose our future work in Section VIII.

II. Related Work

Most of the vehicular safety applications proposed in the literature rely on IEEE 802.11p, which uses the distributed coordination function (DCF) in its MAC protocol. Due to vehicles' high mobility and their large number within a confined area, the authors in [6]–[10] showed that VANETs suffer from low reliability due to high communication collisions particularly in high-vehicle-density networks. When the vehicles first synchronize at the CCI, most vehicles or maybe all of them have their status messages ready to be transmitted. Therefore, on the first time slot, all vehicles that are ready to transmit will sense a free channel and start transmitting their messages that will collide with each other. On the other hand, vehicles that miss the first time slot will sense a busy channel and start their backoff process. Most of these later transmissions will also end up in collisions since the minimum contention window specified in the DSRC is small.

To overcome this serious problem, most researchers distribute the transmission process uniformly over the CCI interval. Other researchers propose a time-division multiple-access [11], [12] or cluster-based MAC protocols [13]–[15]. However, at certain stages of their protocols, they use the DCF to either select their cluster heads or assign certain time slots for vehicles to transmit in their status messages. Therefore, the question that must be answered is: How long should the CCI interval be set to avoid or minimize transmission collisions?

In [16], Wang and Hassan studied the aforementioned question using simulations. A framework that links the bandwidth share of nonsafety applications to the performance requirements of safety applications was proposed. By using only simulation experiments, the authors analyzed the existence of nonsafety applications under varied road traffic conditions and found that this type of application may have to be severely restricted during peak traffic hours to ensure that vehicular safety is not compromised.

The challenge of how to share the limited wireless channel capacity for the exchange of safety-related information in a fully-deployed VANET is addressed in [17]. In particular, this paper studied the situation that arises when the number of vehicles sending periodic safety messages is very high in a specific area. By using a strict fairness criterion among the nodes, Torrent-Moreno *et al.* proposed a power control algorithm to limit the load sent to the channel to achieve a good performance of safety-related protocols.

An architectural model to provide location-based push services through VANET and third-generation (3G)/fourth-generation (4G) systems is proposed in [18]. In this paper, Baiocchi and Cuomo tried to solve the bandwidth share issue by allowing vehicles to disseminate advertisement information about infotainment applications only through the DSRC and allow vehicles to access the real services through 3G/4G networks. This heterogeneous access may depend on coverage time, user position, and network conditions.

In contrast to previous work that drew their conclusions mainly based on simulations, we will propose an analytical model to optimize the CCI interval based on the probability of the successful transmission of status messages. Our results are found to be in agreement with the previous work that the current specifications of the DSRC may lead to severe performance degradation in dense and high-mobility conditions for both classes of applications. Therefore, two new algorithms are proposed and evaluated to increase the reliability of the CCH with the optimized CCI interval based on different network parameters. One algorithm, which is called OCA, is to increase the successful rate of status messages by deriving the OCA probability. The second algorithm, which is called the MTA algorithm, is an adaptive algorithm to allow vehicles to change their parameters based on the network conditions to enhance

TABLE II
MAIN NOTATION FOR THE ANALYTICAL MODEL

Notation	Definition
CCH	Control Channel
SCH	Service Channel
CCI	Control Channel Interval
SCI	Service Channel Interval
SI	Synchronization Interval
AC	Access Class
L	Status packet length in bits
r	Data rate
$\rho \in (0, 1]$	$T_{CCI} = \rho T_{SI}$
V_{avg}	Average vehicle speed
V_{min}	Minimum vehicle speed
V_{max}	Maximum vehicle speed
M	Number of vehicles within the communication range
L_n	Number of lanes
τ_a^*	Optimal channel access probability
W_{min}	Minimum contention window for statu message
T_s	Time slot
R	Communication range
P_s	Successful transmission rate
p	Busy channel probability
λ	vehicles arriving rate to send status messages
β_v	Vehicles density (vehicles/m)

the DSRC reliability. By minimizing the CCI interval and increasing the successful rate of status messages, nonsafety applications will have a fair share of the SI.

III. System Model

In Fig. 1, it is clear that the share of nonsafety applications on SCHs is inversely proportional to the time a vehicle stays in the CCH serving safety applications. Because safety applications have the priority on the DSRC, their performance will govern the access share of the channel. In VANETs, vehicles have to exchange their status information every SI interval to inform each other about the road conditions and their neighbors to avoid collisions. Therefore, the CCI interval has to be long enough to allow the successful transmission of all status messages. It is widely perceived that the broadcast channel will be congested when the number of vehicles is high. In [6], we showed how the increase in traffic density will increase the packet loss rate of safety applications. Table II lists all the notations for the proposed analytical model.

The model is built based on a one-way highway segment with L_n lanes in each direction. Since the communication range is much larger than the width of the road, the network in each direction of the road is simplified as a one-dimensional VANET. In this model, the distribution of vehicles on the road has a Poisson distribution, which has a memoryless property. Moreover, vehicles will determine the communication range based on their average speed from the last SI interval [19]. We consider a time-slotted vehicular network with a single wireless channel, where time is indexed by $t (t = 0, 1, 2, \dots)$. We assume that, at most, one status message, of size L bytes and data rate r b/s, can be transmitted during one time slot T_s. There are M vehicles within the communication range of R m. We further assume an ideal wireless channel and no-hidden-terminal problem, that is, the sensing range (CS) is twice the communication range (R), as shown in Fig. 2. Therefore, the only source of packet loss is the communication collisions. We define the probability of successfully transmitting a status message during the CCI interval as P_s. Therefore, the objective is to find the minimum duration of the CCI for an acceptable value of P_s.

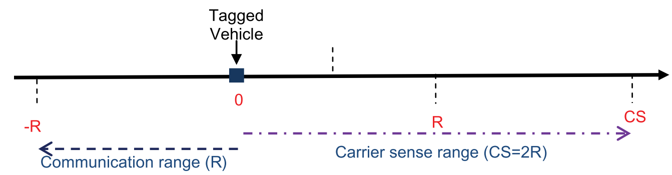

Fig. 2. VANET communication model.

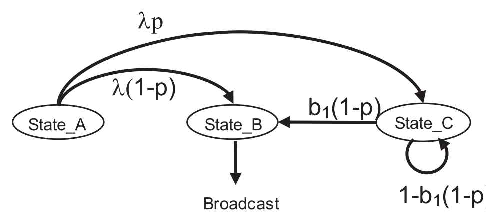

Fig. 3. System state model.

During the CCI interval and at the beginning of each time slot, a vehicle can sense the channel. If the channel is free, it will transmit its status message. Otherwise, it will go to the backoff state. We denote *State-A* as the state when a vehicle is ready to transmit, *State-B* as the transmission state, and *State-C* as the backoff state, as shown in Fig. 3.

Vehicles will pick uniformly and randomly a slot from the CCI to try to transmit their status messages. Therefore, their arrival time to the transmission state *(State-B)* is (T_{CCI}/M), and their arrival rate is

$$\lambda = \frac{M}{T_{CCI}}. \tag{1}$$

In Fig. 3, the steady-state probability of *State-C* can be found as

$$b_C = \frac{\lambda p}{1 - \lambda p \left(1 + b_1(1-p)\right)} \tag{2}$$

where b_1 and p will be defined next.

In the backoff state *(State-C)*, vehicles will choose a contention window (W_o) uniformly and randomly from $[0, \dots, W_s]$ as a backoff counter, where W_s is the minimum contention window associated with this AC (AC_0) as in Table I. At any time slot during the backoff process with probability $(1-p)$, the vehicle decrements its backoff counter if it senses an idle channel; otherwise, it freezes the counter and waits for the whole period of the ongoing transmission until the channel is idle again before decrementing its counter. Here, p is the conditional busy channel probability seen by a packet about to be transmitted and independent from any other vehicle. Once the backoff counter reaches zero inside the backoff state *(State-C)*, the vehicle broadcasts the packet. There will be no subsequent retransmissions if the packet is collided, and hence, the packet is lost. In [19], we constructed a model

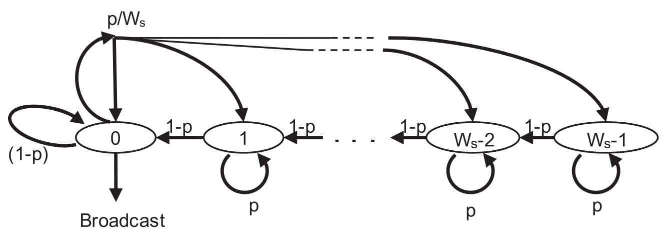

Fig. 4. Backoff Markov chain inside state *State-C*.

for this backoff counter process of IEEE 802.11p, assuming unsaturated conditions, as shown in Fig. 4, and found that the vehicle will transmit the status packet when its backoff counter reaches 1 with probability $1 - p$; otherwise, the vehicle will stay in the backoff state. From [19], we will use the steady-state probabilities b_0 and b_1 for the counter states 0 and 1, respectively. For more details of the backoff process, we refer the reader to [19]. The steady-state probabilities are

$$b_0 = \frac{2(1-p)}{2 - 3p + pW_s} \tag{3}$$

$$b_1 = \left(\frac{W_s - 1}{W_s}\right)\left(\frac{p}{1-p}\right) b_0. \tag{4}$$

In Fig. 3, it is evident that the competition for the transmission state *(State-B)* is increasing as more vehicles go to the backoff state. Therefore, the new arrival rate to the transmission state *(State-B)* is

$$\grave{\lambda} = \lambda(1-p) + \lambda p b_1 (1-p). \tag{5}$$

The busy channel probability (p) can be calculated as

$$p = \begin{cases} \grave{\lambda}, & \grave{\lambda} \leq 1 \\ 1, & \grave{\lambda} > 1. \end{cases} \tag{6}$$

By using the Newton–Raphson optimization technique, (3)–(6) can be solved to find the busy channel probability p.

To find the probability of no collision in the kth time slot, we define the following events.

Event a: when there is no new arrival in the kth time slot. The probability of event a is

$$P(a) = \left(1 - \frac{1}{T_{CCI}}\right)^M. \tag{7}$$

Event b: when there is only one vehicle in *State-A* ready to transmit in the kth time slot. The probability of event b is

$$P(b) = \frac{1}{T_{CCI}}\left(1 - \frac{1}{T_{CCI}}\right)^{M-1}. \tag{8}$$

Event c: when there is no node in the backoff state *(State-C)* that its backoff counter reaches 1, given that at least there is one node in *(State-C)*. Therefore, the probability of event c is

$$P(c) = b_C(1 - b_1)^M. \tag{9}$$

Event d: when there is only one node that its backoff counter reaches 1 in the backoff state *(State-C)*, given that there is at least one node in *(State-C)*. Therefore, the probability of event d is

$$P(d) = b_C b_1 (1 - b_1)^{M-1}. \tag{10}$$

Event e: when there is no node in the backoff state *(State-C)*. Therefore, the probability of event e is

$$P(e) = 1 - b_C. \tag{11}$$

From (7)–(11), the probability of no collision (i.e., probability of successful transmission) in the channel can be derived as

$$P_s = P(ad) + P(bc) + P(ac) + P(ae) + P(be). \tag{12}$$

Equation (12) means that the transmission in the kth time slot will be successful in the following five cases.

- Case 1: when there is no vehicle ready to transmit in *State-A* and there is only one vehicle trying to access the channel from *State-C*;
- Case 2: when there is only one vehicle ready to transmit in *State-A* and there is no other vehicle trying to access the channel from the backoff state *State-C*, given that there are vehicles in the backoff state *State-C*;
- Case 3: when there is no vehicle trying to access the channel from both states *State-A* and *State-C*, given that there are vehicles in the backoff state;
- Case 4: when there is no vehicle trying to access the channel from both states *State-A* and *State-C*, given that there are no vehicles in the backoff state;
- Case 5: when there is only one vehicle that is ready to transmit in *State-A* and there are no vehicles in the backoff state *State-C*.

IV. Analysis: Probability of Successful Transmission

Equation (12) represents the probability of successful transmission (P_s) of a node in the kth time slot. To analyze the performance of the system model, we plot P_s against the length of the CCI interval in Fig. 5. The X-axis represents the length of the CCI interval in time slots normalized by the number of vehicles M within the communication range R. It is obvious that as the CCI interval increases, the probability of successful transmission increases, but it does not reach 90%, although the CCI interval is increased to ten times the number of nodes M. Another interesting point is that, even when the minimum contention window W_s is increased from 15 to 127, the probability of successful transmission does not change much. Moreover, increasing W_s will increase the time delay for status messages to be transmitted.

To enhance the performance of the DSRC, the probability of successful transmission has to be increased while keeping the CCI interval as small as possible. To do this, we propose an OCA algorithm, which will allow vehicles to access the channel with the optimal probability that maximizes the

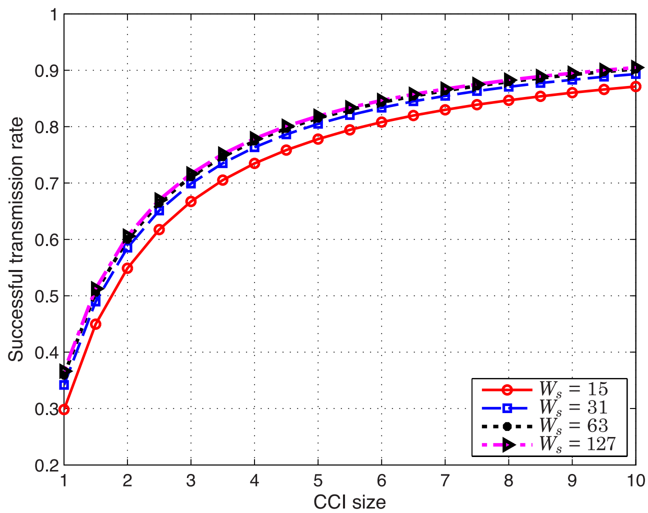

Fig. 5. Probability of successful transmission (P_s) versus the normalized length of CCI for different values of W_s, $M = 100$.

successful transmission rate. The OCA algorithm is summarized as follows.

1) A vehicle can sense the network density (how many vehicles within its communication range R) from its average speed (V_{avg}). For this, we use the same algorithm proposed in [6, eq. (23)], where Hafeez *et al.* derived the relationship between the vehicle density, their average speed on the road, and the safety distance.
2) The vehicle can adjust its communication range (i.e., its transmission power) so that it contains only M vehicles to achieve a certain successful transmission rate based on the results from the simulation and analysis sections.
3) A vehicle selects a time slot uniformly from $[0 - T_{CCI}]$, to send its status message.
4) If the vehicle is in *State-A*, it can access the channel only with probability τ_a. Otherwise, the vehicle will stay in *State-A* and go to step 3. The optimal value of τ_a^* will be derived below.
5) If a vehicle is in the backoff state, i.e., *State-C*, it will only access the channel when its backoff counter reaches zero.
6) If the CCI interval has expired and a vehicle did not send its status message, it will generate a new one for the next CCI interval.

The pseudocode of the OCA algorithm is shown in Algorithm 1.

Algorithm 1 The OCA Algorithm to Increase the Probability of Successful Transmission Within the CCI Interval.

Initial setup
A vehicle knows the number of its neighbors based on its average speed.
A vehicle selects a time slot from $[0 - T_{CCI}]$ to send its status message.
if The Vehicle is in state $state_A$ **then**
  Transmit with probability τ_a^*, if the channel is idle
else
  Go to *State-C* and transmit with probability *one* when the backoff counter is zero
end if
if The vehicle did not transmit its message and T_{CCI} is expired **then**
  Restart
else
  Exit
end if

To find the optimal value of τ_a, we define the successful access probability $P_s(\tau_a, T)$, which is the probability that a vehicle will access the channel in the kth slot within T time slots, given that $k-1$ vehicles have already accessed the channel. Therefore

$$P_s(\tau_a, T) = \sum_{k=1}^{T} \tau_a(1-\tau_a)^{k-1}(1-\tau_a)^{(M-1)-(k-1)} = \tau_a T(1-\tau_a)^{M-1}. \quad (13)$$

To find the value of τ_a that maximizes the successful access probability, we differentiate $P_s(\tau_a, T)$ with respect to τ_a as

$$\frac{d}{d\tau_a} P_s(\tau_a, T) = T(1-\tau_a)^{M-2}\left(-\tau_a(M-1)+(1-\tau_a)\right) = 0. \quad (14)$$

Therefore, the optimal value of τ_a is

$$\tau_a^* = \frac{1}{M}. \quad (15)$$

By using the optimal value τ_a^* in this algorithm, (7) and (8) become, respectively, as follows:

$$P(a)^* = \left(1 - \frac{\tau_a^*}{T_{CCI}}\right)^M \quad (16)$$

$$P(b)^* = \frac{\tau_a^*}{T_{CCI}}\left(1 - \frac{\tau_a^*}{T_{CCI}}\right)^{M-1}. \quad (17)$$

By substituting (16) and (17) in (12), we get the new probability of successful transmission P_s^*. Fig. 6 shows P_s^* versus the normalized CCI interval. It is evident that by using the proposed OCA algorithm, we can achieve a higher successful transmission rate in a shorter CCI interval. Therefore, for a given successful transmission rate, one can find the minimum CCI interval for a certain minimum contention window W_s.

V. Optimization of the Control Channel Interval

In Fig. 6, it is clear that increasing the CCI will definitely increase the probability of successful transmission. This is because vehicles will have more time slots to select from, and therefore, the probability of two or more vehicles to select the same time slot is decreasing. It is also clear that increasing the minimum contention window will increase the probability of successful transmission. This is because vehicles that are forced to go to the backoff state due to sensing a busy channel

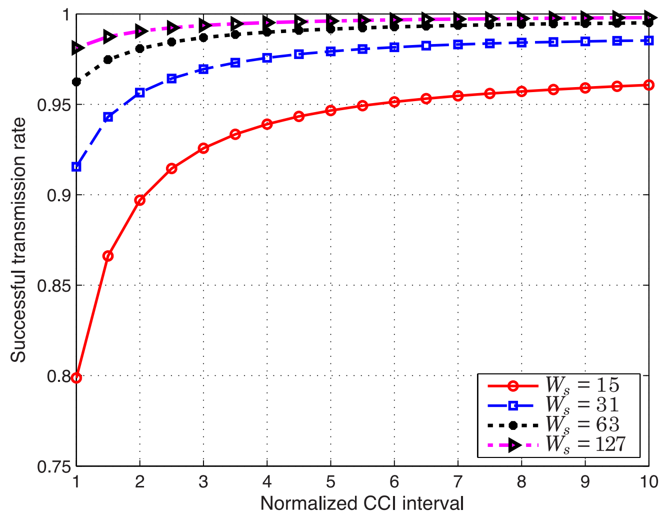

Fig. 6. Probability of successful transmission (P_s^*) versus the length of the normalized CCI for different values of W_s. $M = 100$ vehicles.

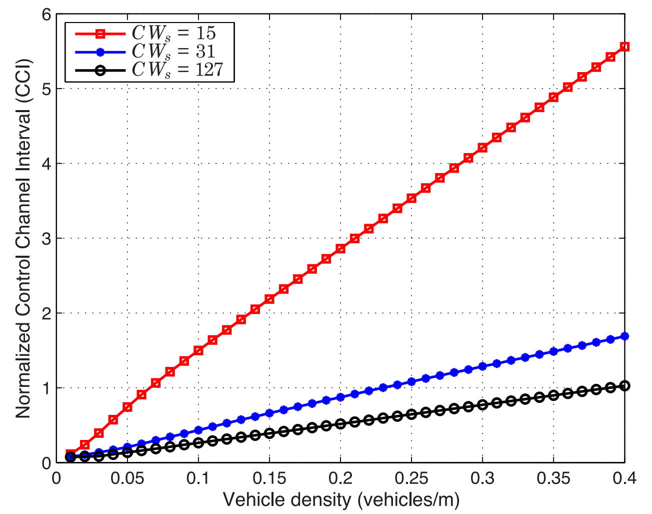

Fig. 7. Normalized CCI versus vehicle density for different values of the minimum contention window. $P_s = 95\%$.

will have a wider range of backoff counter to pick from. This will definitely decrease the probability of two or more vehicles to select the same backoff counter, and hence, their transmission ends up in a collision. Therefore, a simple solution is to increase the CCH and the minimum contention window to the maximum. Implementing this solution will lead to two serious problems. The first problem is by increasing the CCI to the maximum, the nonsafety applications will not have a share of the bandwidth and may have to be throttled particularly in a jam traffic scenario. The second problem is by increasing the minimum contention window, the safety messages may unnecessarily take a very long time to be transmitted.

To solve the aforementioned problems, an optimal value of the CCI must be determined. In this sense, we define the optimal value as the minimum CCI that guarantees an acceptable predetermined successful transmission rate for a certain minimum contention window. The minimum contention window will also be determined based on the vehicle density or the number of vehicles within the communication range of the transmitter.

In Fig. 7, we used a predetermined successful transmission rate of 95% and plot the minimum (optimal) CCI normalized by the number of vehicles within the communication range versus the vehicle density for different minimum contention windows. It is clear that for a high-vehicle-density (high traffic) scenario, there is a need for a large minimum contention window. This is because using a small minimum contention window in this scenario will require very large CCI to maintain the predetermined successful transmission rate. At the same time, for a lower-vehicle-density (light traffic) scenario, it is clear that using the smaller minimum contention window will allow vehicles to send their status messages successfully within a short CCI.

It is evident that there are many conflicting parameters that affect the successful rate of status messages. Therefore, to better enhance VANET reliability, an adaptive algorithm that changes the main VANET parameters, such as the communication range (R), the minimum contention window (W_s), and the length of the CCI (T_{CCI}) based on the VANET environment, will be introduced in the following section.

VI. Mobility- and Topology-Aware Algorithm

The VANET environment is very challenging due to the speed of its nodes (vehicles) and, hence, the fast changing of their topology. That is, in a matter of seconds, the number of vehicles within the communication range R could change from very small to large number (i.e., jam scenario). Therefore, using the parameters R, W_s, and T_{CCI} with fixed values in all conditions will result in undesired performance. Therefore, a new algorithm, which is called the MTA algorithm, is introduced to allow vehicles to change their aforementioned parameters dynamically based on the situation on the road to increase the successful rate of their status messages while keeping the CCI as minimum as possible.

In MTA, we assume the following.

1) The length of the CCI is

$$T_{CCI} = \rho T_{SI} \tag{18}$$

where $0 < \rho \leq 1$, to allow for nonsafety applications to have a fair share of the bandwidth $T_{SCI} = (1 - \rho)T_{SI}$. The value of ρ depends on the size of the status packet (L), the data rate (r), minimum contention window (W_s), vehicle density (β), and the initial communication range (R) that vehicles are using as

$$\begin{aligned} \frac{\rho T_{SI}}{L/r + T_{pb}} &\geq \beta 2R \\ \rho &\geq \frac{\beta 2R}{T_{SI}}\left(\frac{L}{r} + T_{pb}\right) \end{aligned} \tag{19}$$

where T_{pb} is the processing time and the backoff delay, which depends on W_s. From (19), the value of ρ can be determined if the other parameters are used with fixed values. In our algorithm and simulation, we used a fixed value of $\rho = 0.5$ and change the other parameters based on the network density. The algorithm is also working with other values of ρ.

2) The vehicles know their current average speed (V_{avg}) and their maximum $V_{\max}$ and minimum $V_{\min}$ allowed speeds on the road.

TABLE III
RELATIONSHIP BETWEEN VEHICLE DENSITY LEVEL (β), VEHICLE SPEED LEVEL (V), AND THE AVERAGE DISTANCE BETWEEN VEHICLES IN EACH LANE (d)

Vehicle's Speed	V-level	β-level	d (meters)
$(\frac{2}{3}V_{max} < V \leq V_{max})$	V_H	β_L	50
$(\frac{1}{3}V_{max} < V \leq \frac{2}{3}V_{max})$	V_M	β_M	25
$(0 < V \leq \frac{1}{3}V_{max})$	V_L	β_H	15

3) The vehicle speed is divided into three levels: high (V_H), medium (V_M), and low (V_L) speed. Therefore, the vehicle density is also divided into three levels: low density β_L, medium density β_M, and high density β_H. The relationship between the vehicle speed levels, the vehicle density levels, and the average distance (d) between adjacent vehicles in each lane is shown in Table III.
4) Vehicles adjust their communication range (R) (or transmission power) to accommodate only the maximum number of vehicles (M) that can send their status messages within the CCI (T_{CCI}) successfully.
5) The minimum contention window size W_s can take one of three values $W_s \in [15, 31, 127]$. These three values have been selected based on the results in Fig. 6, such that the successful transmission rate is 0.94, 0.96, and 0.98, respectively. These numbers have been selected such that when $W_s = 15$, the CCI should be five times the number of vehicles within the communication range to achieve a 94% success rate. Increasing the T_{CCI} more will not result in much increase in the success rate. Similarly, when $W_s = 31$ and $W_s = 127$, the CCI should be three and two times the number of vehicles, respectively, to achieve success rates of 0.96 and 0.98, respectively.
6) Vehicles will access the channel based on the OCA algorithm, as shown in Algorithm 1 in Section IV.
7) The length of the CCI is fixed at the startup as in (18) such that the nonsafety applications have a fixed share of the bandwidth $((1-\rho)T_{SI})$.
8) The number of time slots in the CCI should be at least equal to the value that satisfies a predetermined success rate based on Fig. 6. Therefore, the following equation should be always satisfied:

$$\frac{T_{CCI}}{T_s} \geq \eta \left\lceil \frac{L_n 2R}{d} \right\rceil \tag{20}$$

where η is a design factor that can take $\eta = 5$, 3, or 2 based on the selected $W_s = 15, 31,$ or 127, respectively. This value is selected from Fig. 7 to assure that more than 94% of the vehicles manage to send their status messages successfully within the selected W_s.

Vehicles will execute the MTA algorithm after T_w s, when their average speed V_{avg} changes from a speed level to another. The pseudocode of the MTA algorithm is shown as Algorithm 2 below. Based on the current vehicle's average speed, the vehicle density will be determined, and hence, the average interdistance (d) between vehicles in each lane will be determined according to Table III. The vehicle has three choices to set the parameters η and W_s: 1) $\eta=5$, $W_s=15$; 2) $\eta=3$, $W_s=31$; and 3) $\eta=2$, $W_s = 127$. The vehicle should execute these three choices sequentially until (20) is satisfied. If the vehicle exhausted all three choices and (20) is still not satisfied, the vehicle should reduce its transmission range to $R_{\text{new}} = \gamma R_{\text{old}}$ and repeat the algorithm, where $0 < \gamma < 1$ is a design parameter. The higher the γ, the less stable the network will be, where vehicles will change their communication range very frequently. In the simulation, we set $\gamma = 2/3$.

Algorithm 2 MTA Algorithm to Set VANET Parameters According to the Vehicles' Average Speed on the Road

```
Initial setup
R ← 300 m
L_n ← 4
d ← 50
ρ ← 0.5 {This means that the CCI is half of the SI interval.
However, the algorithm also works with any other value of ρ}
η ← 5
W_s ← 15
γ ← 2/3
for Every V_avg changed its level or T_w = 10 sec do
  if V_avg = V_H then
    d ← 50 {d is the interdistance between vehicle}
    W_s ← 15 {change the minimum contention window
     to 15}
    η ← 5 {set the length of the CCI to five times the number
of vehicles within the range R}
  else
    if V_avg = V_M then
      d ← 25
      W_s ← 31 {change the minimum contention window
     to 31}
      η ← 3 {set the length of the CCI to three times the
number of vehicles within the range R}
      end if
    else
      if V_avg = V_L then
      d ← 15
      W_s ← 127 {change the minimum contention window
     to 31}
      η ← 2 {set the length of the CCI to two times the
number of vehicles within the range R}
      end if
    end if
    if T_CCI/T_s ≥ η⌈L_n 2R/d⌉ then
execute the last three steps from Algorithm 1 and exit {appro-
priate parameters' values have been reached}
    else
R_new = γR_old {reduce the communication range}
    end if
end for
```

Vehicles execute MTA and OCA algorithms in a distributed manner such that each vehicle estimates the communication range and, hence, the number of neighboring vehicles independent from each other. In this model, the distribution of vehicles

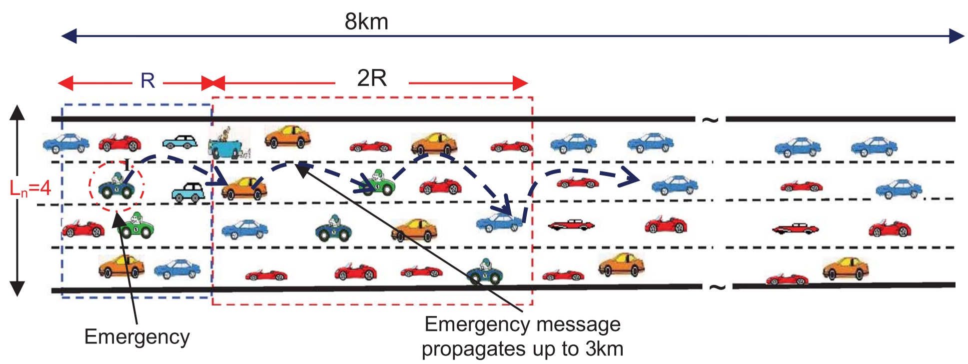

Fig. 8. Simulation network setup.

on the road has a Poisson distribution, which has a memoryless property. Moreover, vehicles will determine the communication range based on their average speed from the last SI interval. This will help in mitigating any discrepancies in estimating the communication range between vehicles.

VII. Model Validation and Simulation

Here, the performance of VANETs will be analyzed based on the probability of successful transmission derived in (12). It is assumed that all vehicles are synchronized to the CCI all the time by using the GPS. The generation time of each status packet is uniformly distributed over CCI, and all vehicles should send their status messages within that interval. Every vehicle should drop any stale status message that does not have the chance to be sent in the last SI interval and generate a new status message in every new SI interval.

The simulation is carried out based on the network simulator NS-2 [20] by using a realistic mobility model generated by MOVE [21], which is built on top of the microtraffic simulator SUMO [22]. The simulation scenario, as shown in Fig. 8, is based on a 1-D highway segment of 8000 m in length with four lanes. The vehicles' speed ranges from 80 to 120 km/h, which is typical for North American highways. The Nakagami-m propagation model is used, which has two distance-dependent parameters, i.e., the fading factor m and the average power Ω. In [23], Torrent-Moreno *et al.* performed a maximum-likelihood estimation of m and Ω for a vehicular highway scenario. They found that Ω decreases as the distance to the receiver increases, as expected from the average power in the deterministic models, that is, by d^{-2}. On the other hand, fading parameter $m = 3$ is selected for a short interdistance between the transmitter and the receiver ($d \leq 150$), since line-of-sight conditions are expected, then decrease it to $m = 1.5$ for medium distances ($150 < d \leq 300$) and make it as Rayleigh distributed, i.e., $m = 1$ for longer distances. Ω is set in each interval to be the average power calculated from a free-space propagation model; hence, receivers located within 300 m of the transmitter will receive the signal with Rician distribution, whereas others will have Rayleigh distribution. Since the receiver in NS-2 will receive the signal if its power is higher than the threshold P_{th}, the transmitting power of each vehicle is set such that the receiving power at the communication range R is the threshold (i.e., $P_t = P_{th}$), as indicated in Table IV, and the carrier-sense range is double the range R. The height of the transmitting and receiving antennas is 1.5 m, and their gain is assumed to be 1.

TABLE IV
Value of Parameters Used in Simulation

Parameter	Value
Modulation and Data rate	QPSK
Data rate r	6 Mbps
Message sizes L	256×8 Bits
Vehicle's speed	80-120km/h
Communication range R=	300m
Number of vehicles M	100
Synchronization Interval SI	100ms
Transmission power $P_t(300m)$	20 mW
Received power threshold R_{xTh}	3.162e-13
Noise-floor	1.26e-14 W
T_{tx} & T_{rx} antennas heights	1.5 m
Gain of transmitting and receiving antennas $G_t = G_r$	1
DIFS	64 μs
Minimum Contention Window W_s	15
Number of lanes (L_n)	4
γ	2/3

Each simulation typically simulates 1000 s. In the figures, the curves represent the analytical results, and the markers represent the simulation results. Table IV lists the simulation parameters used unless a change is explicitly mentioned.

Here, the performance of the proposed algorithms, i.e., OCA and MTA, will be evaluated. More specifically, we will show how the OCA algorithm will increase the probability of successful transmission of the status message and how the MTA algorithm will enhance the reliability of the DSRC while keeping the same CCI; hence, the nonsafety applications will have a fair share of the SI interval.

A. Performance of OCA Algorithm

To evaluate the effect of the OCA algorithm on VANET's reliability, the main simulation parameters as in Table IV are applied, and let vehicles select a time slot uniformly from the CCI interval to send their status packets. Fig. 9 shows the successful transmission rate with and without using the OCA algorithm. It is evident that the new algorithm increases the transmission successful rate dramatically. It is also clear that the time needed for most vehicles to send their status messages has decreased. For the case when the OCA algorithm is not used, vehicles need six times their number of time slots so that 80%

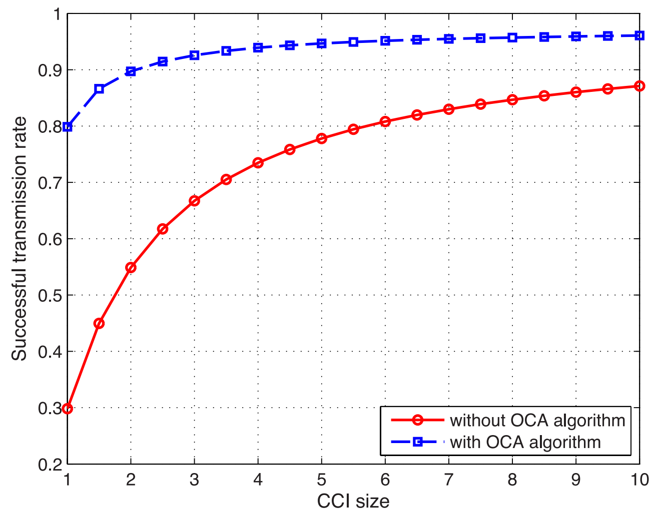

Fig. 9. Probability of successful transmission versus the CCI with and without the new algorithm. $M = 100$ vehicles, and $W_s = 15$.

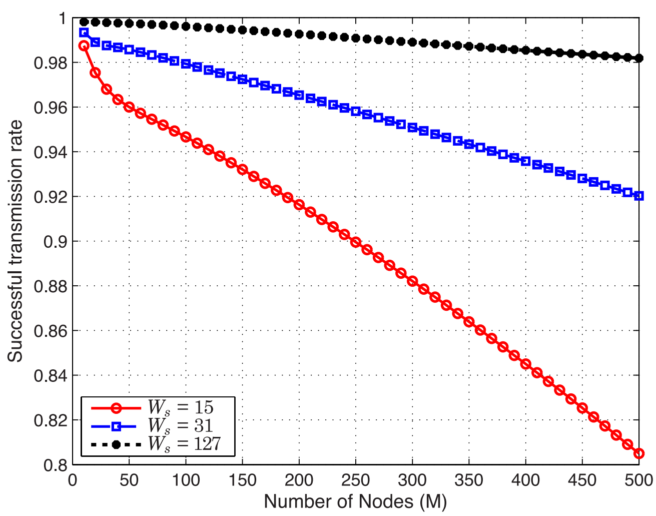

Fig. 10. Probability of successful transmission (P_s^*) versus number of nodes (M) within the range (R) for different values of W_s, and $CCI = 500$ time slots.

of them managed to send their status messages. While using the proposed algorithm, only two times their number of time slots are needed such that 91% of them can send their messages successfully. This is because in every time slot, vehicles using the OCA algorithm will access the channel with the optimal probability derived in (15) to minimize the probability of communication collisions.

B. Effect of DSRC Parameters on VANET's Reliability

To better understand the effect of different DSRC parameters on the network reliability while using the OCA algorithm, we plot the successful transmission rate versus the number of vehicles within the communication range for different values of the minimum contention window W_s in Fig. 10. We can see that as the number of vehicles (M) increases, the successful transmission rate decreases. However, as the contention window increases, the effect of increasing M decreases. This comes with a price of higher backoff time delay for status messages.

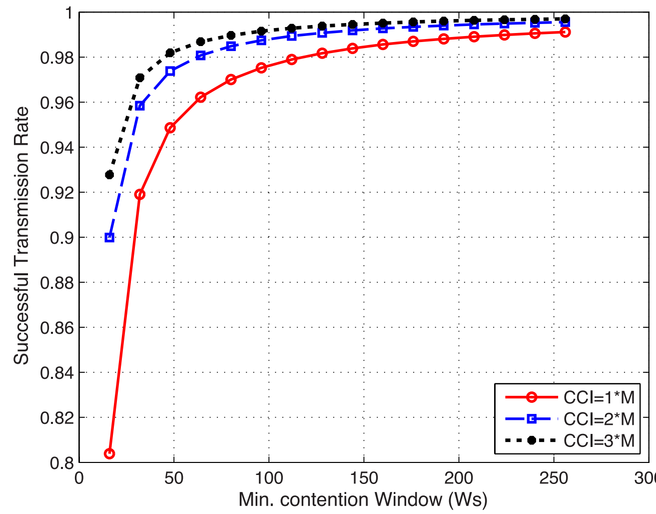

Fig. 11. Probability of successful transmission (P_s^*) versus W_s for different values of the CCI.

Fig. 11 shows the effect of the contention window on the successful transmission rate for fixed values of the CCI interval. Increasing the contention window up to a certain value will increase the successful transmission rate dramatically. After that value, increasing the minimum contention window more will not help in increasing the successful rate by much. Therefore, there will be a certain value for the minimum contention window for each used CCI and vehicle density that guarantee a successful transmission rate threshold. Therefore, for a predetermined limit of successful rate and fixed CCI interval, vehicles can select the minimum contention window that satisfies this limit. Moreover, vehicles can reduce their communication range (R) and, thus, the number of neighbouring vehicles M, to further achieve the desired successful rate with smaller W_s, as shown in Fig. 10.

C. Performance of MTA Algorithm

In Fig. 11, it is obvious that using fixed values of the communication range and minimum contention window will lead to a lower success rate, particularly in high-vehicle-density scenarios. This means that not all vehicles will have the opportunity to send their status messages. The solution to allocate more time for the CCH will help in increasing the successful rate, but, at the same time, it will decrease the share of the nonsafety applications. Therefore, these parameters should be dynamically adjusted and based on the traffic conditions. Fig. 12 shows the successful rate versus the vehicle density when applying the proposed MTA algorithm with fixed CCI $(T_{CCI} = 50$ ms) for different values of the initial communication range R. The vehicles in this algorithm sense the network density from their average speed and then adjust their minimum contention window (W_s) and communication range (R) accordingly to allow all nodes to send their status messages successfully. The CCI has been kept constant to half of the SI $(T_{SI} = 100$ ms). Therefore, the nonsafety applications will have a fair share (50%) of the bandwidth. It is also obvious that, no matter what the initial value of R, the algorithm manages to maintain the successful rate above 95%.

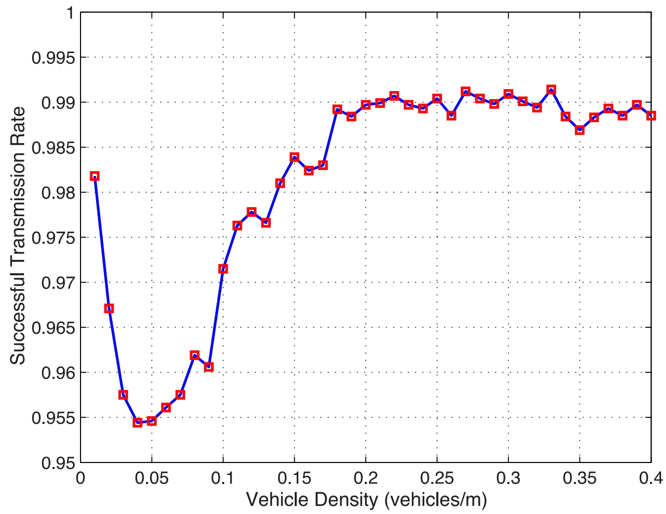

Fig. 12. Probability of successful transmission (P_s^*) versus vehicle density. $T_{CCI} = 50$ ms.

Fig. 12 shows that the successful transmission rate stays above 95% in all scenarios from light traffic to heavy (jam) traffic. This is because vehicles first start with a large communication range, and as the vehicle density increases, the successful rate decreases. Vehicles will keep using the same communication range until the number of neighboring vehicles reaches a certain threshold based on Table III. This explains why there is a dip in the success rate as vehicle density increases while keeping the same range. When the vehicle density threshold is reached, vehicles reduce the used communication range to a smaller value such that all the neighboring vehicles will have a chance to send their messages successfully. In the MTA algorithm, the range of vehicle density is divided into three levels, i.e., light, medium, and heavy density, and vehicles change their DSRC parameters when they move from one level to another or when the CCI is not enough to accommodate all neighboring vehicles to send their messages with the predetermined successful transmission rate.

D. Bandwidth Share Between Safety and Nonsafety Applications

Fig. 5 showed earlier that no matter how much the CCI been increased, the successful transmission rate stays below an acceptable threshold when VANETs use the same values of the DSRC parameters in all scenarios. Therefore, the nonsafety applications have to be throttled or canceled, and allocate all the SI to safety applications particularly in high-vehicle-density networks. To overcome this problem, we apply both OCA and MTA algorithms in all vehicle traffic scenarios from light to heavy (jam) conditions and measure how much time is needed for all vehicles to send their status messages with a high successful rate (95%). The results are shown in Fig. 13 for different values of the initial communication range R. It is interesting to see that under all network conditions, no matter what the initial value of the communication range R is, the safety applications did not take more than 40 ms. This means that the SI can be equally divided between safety and nonsafety applications.

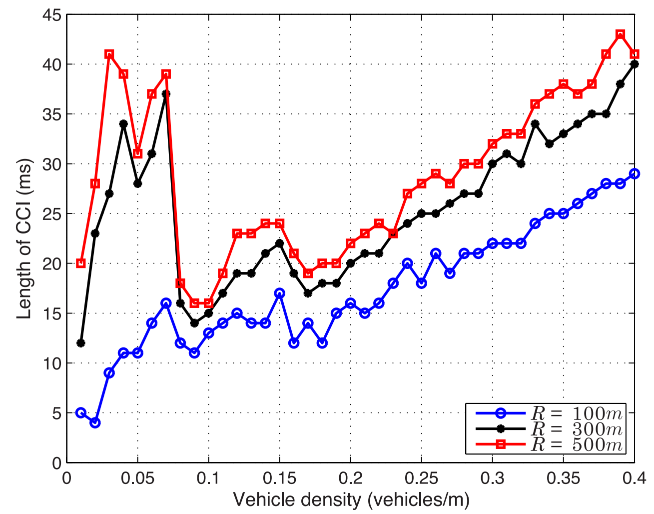

Fig. 13. Length of the CCI in milliseconds versus vehicle density. $P_s = 95\%$.

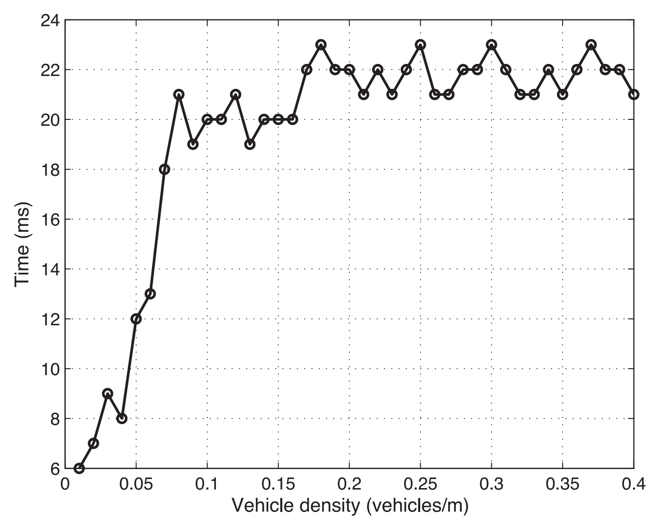

Fig. 14. Time for emergency message to reach a distance of 3000 m versus vehicle density. $P_s = 95\%$.

The fairness between safety and nonsafety applications that the MTA algorithm will give comes with a price of increasing the time propagation for emergency messages. Since the MTA algorithm reduces the communication range as the network density increases to maintain fairness, the emergency message, such as accident warning, that should be propagated longer following the accident will make many more hops to reach its intended distance.

To evaluate the effect of the MTA algorithm in an accident scenario, the main simulation parameters as in Table IV are applied, and let one vehicle send an emergency message that should propagate for a distance of 3000 m after the accident scene. The emergency message will have higher priority than regular safety messages since it will apply the parameters of AC 3 as in Table I. This emergency message will be rebroadcasted in every hop based on the $NTTP$ algorithm described in [24]. Fig. 14 shows the time delay until the emergency message reaches the intended distance while using the MTA algorithm with an initial value of $R = 300$ m. It is clear that as the network density increases, the emergency message will take longer to cover the intended destination. However, that time is still within the CCI limit. Therefore, even in jam conditions, limiting the CCI to 50% of the SI will allow emergency messages to propagate to their maximum distance.

VIII. Conclusion and Future Work

In this paper, the CCI of the DSRC has been studied. It has been shown that the current specification of the DSRC parameters will lead to a low successful transmission rate. Therefore, two new algorithms have been proposed. One algorithm, which is called OCA, has been proposed to increase the successful transmission rate of status safety messages. The second algorithm, which is called the MTA algorithm, has been proposed to increase the reliability of the CCH in the DSRC while keeping the CCI as minimum as possible to give a fair share of the bandwidth to nonsafety applications. The two algorithms are working together such that vehicles access the channel with the optimal probability governed by OCA while executing the MTA algorithm in a distributed manner. A vehicle, which is based on the sensed network density, can adjust its minimum contention window and its transmission power (i.e., communication range) and, thus, the number of neighboring vehicles to achieve a certain successful rate. We conducted many simulations to validate the proposed work and found that the proposed algorithms have increased the reliability of VANET's safety application dramatically compared with the default setup of the DSRC parameters. This increase in reliability and fairness comes with a price of increasing the time delay for emergency messages to propagate to cover the accident area. However, that delay is still within the CCI time. The analytical results (curves) match those obtained via simulation (markers).

For future work, the new algorithms will be studied in heterogenous-network scenarios with a hidden-terminal problem.

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