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Modeling Channel Switching and Contention Control in Vehicular Networks

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ABSTRACT In vehicular networks, multi-channel operation standard IEEE 1609.4 is designed for vehicular communications across multiple channels. It has been revealed that such multi-channel operations may result in high contention in vehicular communications. However, existing analytical models are unable to capture the dynamic characteristic during channel switching. We develop a novel Markov model that takes into account the dynamic contention behavior during channel switching. In particular, our model reveals the high contention caused by the burst arrivals, which are the results of multi-channel operations. To combat such performance decline, we propose two solutions, a centralized equal-spaced algorithm and a distributed random-spaced algorithm. The key idea is to disperse the burst packet arrivals across the available timeframe in order to alleviate contention. Our model, validated by simulations, accurately characterizes the high contention caused by multi-channel operations. Our results demonstrate our proposed solutions can effectively mitigate packet collision, enhance reliability, and improve system throughput during the multi-channel operations.

INDEX TERMS IEEE 802.11p/WAVE, channel switching, analytical model, collision probability, delay.

I. INTRODUCTION

Vehicular networks are a novel class of wireless networks that have emerged thanks to advances in wireless communication and automotive industry. Such networks are proposed primarily for safety applications and have caused great interest and attention among researchers during recent years [1]–[3]. Vehicular wireless communications as a kind of wireless communication is different from current many wireless technologies. It depends on the recently proposed standards for vehicular networks, also called WAVE (Wireless Access in Vehicular Environments) on the DSRC (Dedicated Short Range Communications) frequency band and can meet the extremely short latency requirement for road safety messaging and control [4]–[6]. WAVE, which is based on WiFi architecture is currently considered the most promising vehicular communication technology [7]. It can be used to connect infrastructure to vehicle (I2V) and vehicle to vehicle (V2V). The WAVE is standard framework [7] and it works on 5.9GHz bandwidth of 75MHz for DSRC. Within this frequency range, the safety-related data, such as short status messages (Beacons), WBSS (WAVE-Basic Service Set) establishment and advertisement messages (WAVE Service Advertisements, WSAs), is periodically delivered by CCH (Control Channel); while the non-safety-related services, such as infotainment data based on IPv6 are submitted in SCHs (Service Channels).

In vehicular networks, there can be a large number of vehicles associated with one RSU (Road Side Unit). The traffic from these vehicles include control or safety messages in the CCH and service information in the SCH. In fact, there are potential issues of high contention when multiple WAVE devices simultaneously switch into the same channel, CCH or SCH, to transmit safety message or access services. Such burst packet arrivals may cause significant data packet collisions, and result in increased transmission delay or data loss. Our analysis and simulation results show that the network collision probability and packet delay can be as high as 30% and 5*ms* when there are 15 and 20 vehicles simultaneously switching channel from CCH to one same SCH, respectively. However, previous vehicular networks analytical model [8]–[20] underestimate such high contentions and most of them take a traditional Markov chain to analyze network performance [11]–[14], [19], [20]. References [8] and [9] discussed medium congestion access control schemes to prevent packet collision on the control channel for vehicular networks. And delay performance evaluation of safety messages are also considered in vehicular networks [10], [11]. In order to characterize the IEEE 802.11 networks, most of works use traditional methods under different conditions, including a unified analytical method [12], different priority to forward safety-related messages [13] and traditional Markov chain model [14]–[16], to improve the performance of networks. Based on the saturated throughput in [14] and [17] presented the analysis of delay at different throughput and a TDMA-based MAC protocol [18] is proposed to avoid packet collision for IEEE 802.11 network. Although channel access in vehicular networks has been analytically studied,related works neither consider the WAVE channel switching nor its effects on the VANET performance. References [19] and [20] focused on depicting the QoS performance without caring about channel switching. In this case, the vehicles involved will have multiple backoffs and transmissions, resulting in more serious collisions than a vehicle without collision. Such high contention can be an engineering issue in practice. For example, a newly vehicular network is expected to have greater performance. However, when a fraction of the vehicles last for contention, the entire vehicular networks becomes terrible and may cause network paralysis. A dynamic model was developed in [21] to characterize the burst packet arrivals in Machine-to-Machine communications. In this paper, we extend the model of [21] to characterize the dynamic behavior of vehicular networks.

We develop a novel analytical model to characterize the dynamic channel switching performance of contention-based vehicular networks. Our model, validated by simulation results, accurately predicts the collision probability and transmission delay. Our analysis results reveal high collision probability and long delay associated with channel switching in vehicular networks, while traditional analysis methods of Markov chain underestimate such measures. Based on our theoretical analysis, we propose two solutions, Equal Spaced and Random Spaced solutions. The Equal Spaced solution divides the timeframe into timeslot, and schedules the packet arrivals equally into each timeslot. This solution successfully avoids the high contention during channel switching, but requires a centrally controlled scheduler to manage the timeslot and scheduling. The Random Spaced solution distributes the packet arrivals randomly across the timeframe following a uniform distribution. This is a distributed solution that requires no prior knowledge of the users and no central control. These two solutions are designed as enhancements to the IEEE 1609.4 standard multichannel operation to alleviate contention and improve system performance during channel switching. Our analysis show that the two proposed solutions effectively mitigate packet collision, improve system throughput and reliability. In particular, the Random-spaced algorithm reduces the packet collision probability to one tenth of that of the original shared scheme of IEEE 1609.4.

The remainder of this paper is structured as follows. In Section II, The IEEE 802.11p vehicular network and IEEE 1609.4 multichannel operation standards are reviewed, and the resulted high contention scenarios are described. The new analytical model for multi-channel operation is derived in Section III. In Section IV, the proposed model is validated against simulation results and the performance of the models and proposed solutions are analyzed. Finally, conclusions and future works are provided in Section V.

II. SYSTEM MODEL AND MOTIVATION

In this section, the IEEE 1609 vehicular network standards, in particular, the 802.11p vehicular communication [22] and IEEE 1609.4 [23] multichannel operation, are reviewed. We survey their theoretical models, and identify their issues caused by applications in vehicular networks. Our novel contributions are recognized in the context of existing works.

A. IEEE1609 AND 802.11p OVERVIEW

IEEE 1609 which includes IEEE standards 1609.1 to IEEE 1609.4, and IEEE 802.11p constitutes the overall WAVE (Wireless Access in Vehicular Environments). Specifically, The IEEE 1609 framework currently consists of five parts, which are architecture (1609.0), resource manager (1609.1), security services for applications and management messages (1609.2), networking services (1609.3) and multichannel operations (1609.4).

The IEEE 802.11p standard provides wireless access in vehicular environment and its major application is to cope with safety messages present in a vehicular environment [24]. IEEE 802.11p is an approved amendment to the IEEE 802.11 standard to add wireless access in WAVE [25]. So IEEE 802.11p follows the CSMA/CA mechanism, which follows binary exponential backoff rules.

B. IEEE 1609.4 MULTICHANNEL OPERATION

The IEEE 1609.4 enables multi-channel operation on top of IEEE 802.11. The available spectrum is divided into one CCH (Control Channel) and six SCHs (Service Channels). The CCH is reserved for carrying system control beacons and high-priority safety messages, and the six SCHs are used for exchanging non-safety data packets and commercial applications. In IEEE 1609.4, the channel time is divided into synchronization intervals with a fixed length of 100 ms. The synchronization interval (SyncInterval) is divided into CCH Interval (CCHI) and SCH Interval (SCHI) [26]. They have equal-length 50 ms (including the Guard Interval (GI)), as shown in Fig. 1. During CCHI, all vehicular devices tune in the CCH to exchange control and safety information. During SCHI, vehicles optionally switch to one of the SCHs to access services.

In order to ensure two or more vehicles devices exchange their data on the same channel in the same timeframe, synchronization is needed. CCHI and SCHI are synchronized to the Coordinated Universal Time (UTC), which is provided by the Global Positioning System (GPS) [25]. GI (4∼6 ms) is

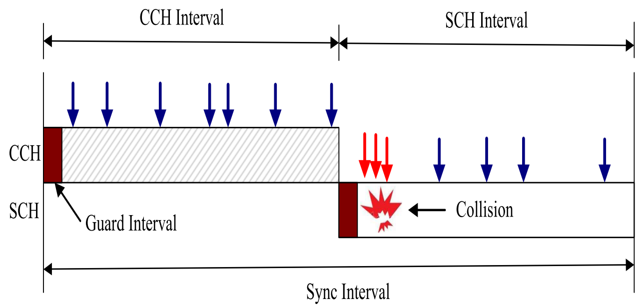

FIGURE 1. **Schematic diagram of channel switching model in vehicular networks.**

needed to make up for any time differences between devices when devices switch their single radio.

C. HIGH CONTENTION IN MULTICHANNEL OPERATION-PERFORMANCE DEGRADATION

The multi-channel operation can be challenging especially for a WAVE device with a single radio. Such a single radio device will need to monitor CCH during CCHI, and switch to one of SCHs during the SCHI for service communications. When multiple such WAVE devices switch from CCH to one of the SCHs, some of the devices may have service data packets arrived during the CCHI. At the beginning of the SCHI, these devices will start accessing the channel to transmit the service data after GI, as shown in Fig. 1. Similarly, when multiple devices switch from SCHs back to CCH, there may be safety messages that have arrived during the SCHI. At the beginning of the CCHI, these devices will start accessing the channel to transmit safety messages after GI.

TABLE 1. **PHY & MAC parameters definition.**

Parameter	Value
$Data\ Rate(Mbps)$	3
$Packetsize(Bytes)$	58
$PLCP\ Header\ length(\mu s)$	8
$Preamble\ length(\mu s)$	32
$Propagation\ delay\ \delta(\mu s)$	1
$ACK(Bytes)$	38
$Slot\ time\ \sigma(\mu s)$	20
$SIFS(\mu s)$	32
$DIFS(\mu s)$	64
CW_{min}	32
CW_{max}	1024

Multi-channel devices that share the same medium perform a synchronous operation for alternating channel access. The synchronous channel switching increases collisions for the same channel in WAVE devices. To test high collision caused by channel congestion phenomenon following a channel switch using TABLE 1 system parameters in section IV, we use the MATLAB platform to simulate the channel access process at the case of 20 vehicles. Duration 50ms (4ms Guard Interval is excluded), simulation results are shown in Fig. 2. At the end of a Guard Interval, a sharp rise of the probability of collisions happens.

This is in contrast to the more commonly considered Wi-Fi scenarios in the literature [14]–[18], [27] that have a random packet arrival process, and for which the stationary collision and transmission probabilities are good approximations. We show that steady state Markov models of [11]–[15], [19], [20], and [27] are unable to characterize the high contention phenomenon shown in Fig. 2.

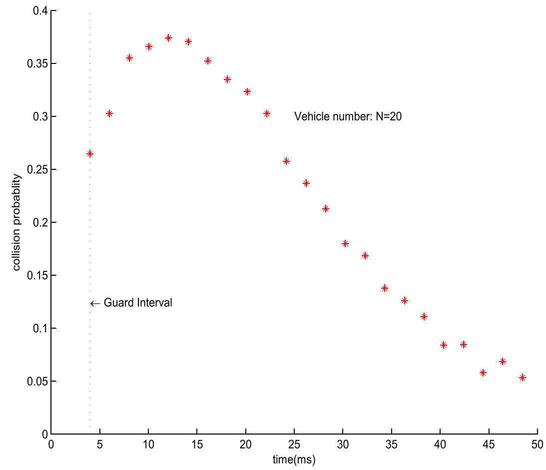

FIGURE 2. **Simulation results of high collision caused by channel congestion phenomenon following a channel switch.**

It is interesting to note that this sort of high collision problem was raised in IEEE 1609.4-2016 standard [23] in Annex B. However, no solution has been given to date. The focus of this paper is to derive a theoretical model to characterize the channel switching performance for IEEE 1609.4, and to find solutions to alleviate contention during channel switching.

III. ANALYTICAL MODEL FOR MULTI-CHANNEL OPERATION

In this section, we develop a novel analytical model to characterize the specific IEEE 1609.4 multichannel operation pattern of vehicular networks. In particular, we analyze the contention and delay behaviors of channel switching between the CCH and one of the SCHs within a Sync Interval period. We derive a model for the collision probability and delay. Two solutions are then proposed that aim to reduce the contention, collision probability and delay.

A. COLLISION PROBABILITY

The DCF mechanism utilizes a binary back-off algorithm, comprising a series of back-off stages, starting in back-off stage 0. During each back-off stage, an initial integer back-off counter is selected, the counter is counted down to zero, and then a transmission attempt is made. If the transmission attempt fails in back-off stage i, back-off stage $i+1$ commences. The initial integer back-off counter is selected uniformly from a contention window spanning 0 to $W_i - 1$ for back-off stage i. W_i doubles each back-off stage so that $W_i = 2^{\min(i,m)} W_0$, $i = 0, 1, \ldots, s$. If a back-off stage s transmission attempt fails, the packet is dropped. The values of W_0 and W_m are decided by the current version of the standard [28] in PHY-specific. The back-off counter is decremented after each *slottime* of continuous channel silence, or, when the channel is instead sensed busy sometime during the initial *slottime*, after a continuous DIFS of channel silence. For convenience, we index the network slots from the beginning of the SCHI, starting with network slot 1. The maximum number of network slots during a packet's back-off process is thus $W_R = \sum_{i=0}^{s} W_i$.

Following the method in [21], we create matrices for the transmission and collision probabilities of a representative vehicle and solve the matrices simultaneously. Let T be a $(1+s) \times W_R$ matrix of transmission probabilities, where the entry in the i^{th} row and k^{th} column, $T_{i,k}$, is the probability of a representative vehicle transmitting in back-off stage $(i-1)$ during network slot k. Similarly, let C be a $(1+s) \times W_R$ matrix of marginal collision probabilities, where $C_{i,k}$, is the probability of a representative vehicle making a failed transmission attempt in back-off stage $(i-1)$ during network slot k, due to the transmission colliding with another vehicle's transmission.

We assume each active vehicle has just one packet to transmit during the SCHI and that the packet is available when switching from the CCH to the SCH. If the packet is not successfully transmitted during the SCHI, it is assumed dropped. As such, $T_{i,k}$ is given by

$$T_{i+1,k} = \begin{cases} \frac{1}{W_0}, & i=0, k=1, \ldots, W_0, \\ \sum_{j\in\Phi(i,k)} \frac{1}{W_i} C_{i,j}, & i=1,\cdots,s,\ \Phi(i,k)\neq\phi, \\ 0, & else, \end{cases} \quad (1)$$

where, ϕ is the empty set and $\Phi(i,k)$ is the set of network slots for which a collision in back-off stage $i-1$ will possibly cause, with probability $1/W_i$, a transmission at network index k, and is given by

$$\phi(i,k) = \{j : \max(k - W_i, i) \le j \le \min(k-1, \sum_{L=0}^{i-1} W_L)\}. \quad (2)$$

We assume that the transmission process of the vehicles are independent. Hence, $C_{i,k}$ is given by

$$C_{i+1,k} = T_{i+1,k}(1 - [1 - \sum_{j=0}^{s} T_{j+1,k}]^{N-1}), \quad (3)$$

where, N is the total number of vehicles in the vehicular network.

$T_{i,k}$ and $C_{i,k}$ can be solved simultaneously by alternately evaluating (1) and (3).

The collision probability $p(N)$ experienced by N vehicles switching channels simultaneously between the CCH and one of the SCHs is given by

$$p(N) = \frac{\sum_{i=0}^{s}\sum_{k=1}^{W_R} C_{i+1,k}}{\sum_{i=0}^{s}\sum_{k=1}^{W_R} T_{i+1,k}}. \quad (4)$$

B. DELAY

The probability that a particular vehicle makes a transmission attempt from any back-off stage during network slot k is denoted $P_t(k)$ and is given by

$$P_t(k) = \sum_{i=0}^{m} T_{i+1,k}. \quad (5)$$

During each network slot, there are different possible combinations of vehicles transmitting or not. Taking a particular vehicle's perspective, we divide the combinations into five categories and define the probability for network slot k of:

- no vehicle transmitting as $P_{No}(k)$;
- the vehicle transmitting successfully as $P_{Su}(k)$;
- some other vehicles transmitting successfully as $P_{Os}(k)$;
- a collision occurring that involves the vehicle as $P_{Co}(k)$;
- a collision occurring that involves only the other vehicles as $P_{Oc}(k)$.

where,

$$P_{No}(k) = (1 - P_t(k))^N, \quad (6)$$
$$P_{Su}(k) = P_t(k)(1 - P_t(k))^{N-1}, \quad (7)$$
$$P_{Os}(k) = (N-1)P_{Su}(k), \quad (8)$$
$$P_{Co}(k) = P_t(k) - P_{Su}(k), \quad (9)$$
$$P_{Oc}(k) = 1 - (P_{No}(k) + P_t(k) + P_{Os}(k)). \quad (10)$$

The network slots can have different durations. When no vehicle transmits, the duration is a *slotTime*, denoted σ; when a collision occurs, the duration is T_{Co}; and when a successful transmission is made, the duration is T_{Su}. T_{Su} and T_{Co} are based on the IEEE 802.11p/WAVE protocol.

To calculate the delay for a packet that is successfully transmitted during network slot k, we add to the time for the successful transmission made during network slot k the average time spent in each network slot before network slot k, given that all transmission attempts made by the vehicle before network index k were unsuccessful. Denote by $Av_s(k)$ the average duration of a network slot, given a particular vehicle does not make a successful transmission during this network slot, such that

$$Av(k) = \frac{P_{No}(k)\sigma + P_{Os}(k)T_{Su} + (P_{Co}(k)+P_{Oc}(k))T_{Co}}{1-P_{Su}(k)}. \quad (11)$$

We define the average delay for a vehicle, denoted $De(N)$, as the time from the start of the vehicle's back-off process for a packet until just after the vehicle successfully transmit its packet. When N vehicles simultaneously switch their channel from CCH to one of the SCHs in one SyncInterval, $De(N)$ is

$$De(N) = P_{Su}(1)T_{Su} + \sum_{k=2}^{W_R} P_{Su}(k)(T_{Su} + \sum_{j=1}^{k-1} Av(j)). \quad (12)$$

C. A PROPOSED SOLUTION 1:EQUAL SPACED

In order to reduce the incidence of collisions and transmission delay, channel division is considered. Users within the same shared SCH are assigned a pre-allocated time within the shared channel. Sections III-A and III-B modeled the collision probability $p(N)$ and delay $De(N)$ for N users commencing their back-off processes together. We now consider the collision probability and transmission delay arising from being allocated a dedicated time segment within the SCH, which still might be shared with other vehicles. We assume the SCH is divided into S segments and refer to these as dedicated data channels. Users are assigned to a particular segment and will only contend for the channel during their assigned segment within the shared SCH.

The assignments to the segments need to be performed centrally to keep the assignments balanced and utilize the whole SCH. The number of users per segment is then either $\lfloor N/S \rfloor$ or $\lceil N/S \rceil$, where $\lfloor . \rfloor$ and $\lceil . \rceil$ are the floor and ceiling functions. Since more users assigned to a segment will cause more congestion and higher collision probability, the worst-case number of users per segment, denoted N', is used, giving

$$N' = \lceil N/S \rceil. \tag{13}$$

1) COLLISION PROBABILITY AND DELAY

The delay performance suffers from packet collisions, which cause more retransmissions. By dividing each SCH into equal time segments, the aim is to reduce congestion, reduce the collision probability, and hence reduce the time spent on retransmissions and the transmission delay.

Applying the method in Sections III-A and III-B to the most congested time segment, and assuming users drop their packet after their segment expires, the collision probability $p_a(N^{'})$ experienced by $N^{'}$ vehicles is given by

$$p_a(N^{'}) = p(\lceil N/S \rceil), \tag{14}$$

and the average delay $De_a(N^{'})$, within the most congested time segment, is given by

$$De_a(N^{'}) = De(\lceil N/S \rceil). \tag{15}$$

Since the number of vehicles should be known a prior for the Equal-Spaced algorithm, this is difficult for vehicular networks. We should thank the development of modern science and technology. Some short-term traffic volume forecasting methods [29]–[31], history monitoring and so on have a role to play but difficulty. Owing to spatial confined, we suppose we know the number of vehicles N a prior.

D. A PROPOSED SOLUTION 2:RANDOM SPACED

To model randomly spaced arrivals through the SCHI, the Markov Chain model of [16]and [32] is used to analyze the collision probability and transmission delay caused by channel switching between CCH and one of the SCHs. Vehicles are assumed unsaturated and packets are assumed to follow a Poisson process with an average arrival rate of one packet per SCHI, to model randomly spaced arrivals through the SCHs.

1) COLLISION PROBABILITY

The model of [16] includes post-back-off states $(0, k)_e$, $k \in [0, W_0 - 1]$, to model the network slots after a vehicle has successfully transmitted a packet and has no new packet to transmit. For more details, to consult [16] and [32].

Let b denote the stationary distribution and $b_{(0,0)_{(e)}}$ denote the stationary probability of being in state $(0, 0)_{(e)}$, then from [16] we have

$$\begin{aligned}
1/b_{(0,0)_e} &= (1-q) + \frac{q^2 W_0}{2(1-q)(1-(1-q)^{W_0})} \\
&\quad \times (W_0 + \frac{p}{1-p}((2W_0)\frac{1-p-p(2p)^{(m-1)}}{1-2p}+1)+1) \\
&\quad + \frac{q}{2(1-q)}((W_0+1)(p(1-q)-q(1-p)^2) \\
&\quad - pq(1-p)(2W_0\frac{1-p-p(2p)^{(m-1)}}{1-2p}+1)),
\end{aligned} \tag{16}$$

$$\tau = b_{(0,0)_e}(\frac{q^2 W_0}{(1-p)(1-q)(1-(1-q)^{W_0})} - \frac{q^2(1-p)}{1-q}), \tag{17}$$

$$p = 1-(1-\tau)^{N-1}, \tag{18}$$

where, q is the constant probability of at least one packet awaiting transmission per state; p is the probability of collision when a device is attempting transmission; m is the maximum back-off stage; N is the total number of vehicles; and τ is the stationary distribution transmission probability per device in a *slotTime*.

The model assumes a Poisson arrival process with an average arrival rate λ. Assuming one packet arrives per SCHI, $\lambda = 20$ *packet/s*. Let E_t be the expected duration of a state in the Markov chain in real-time. Then

$$E_t = \tau(1-p)T_{Su} + \tau p T_{Co} + (1-\tau)(1-p)\sigma, \tag{19}$$

and

$$q = 1 - exp(-\lambda E_t). \tag{20}$$

The transmission probability τ can be numerically obtained by solving (16)-(20) simultaneously.

2) DELAY

When vehicle l completes a transmission, the vehicle begins post back-off. The vehicle chooses an initial post-back-off counter of k, and a packet arrives after j states. Then the average time until the packet is transmitted successfully by a particular vehicle source will be

$$\Delta = \sum_{k=0}^{W_0} \frac{1}{W_0} \sum_{j=0}^{\infty} q(1-q)^j \Delta_{jk}, \tag{21}$$

where

$$\Delta_{jk} = \begin{cases} (k-j)L_s + (1-p)T_s + p(T_c+K_1), \\ k \geq j, \\ (1-p)((1-p)T_s + p(T_c+K_1)) + pK_0, \\ k < j, \end{cases} \tag{22}$$

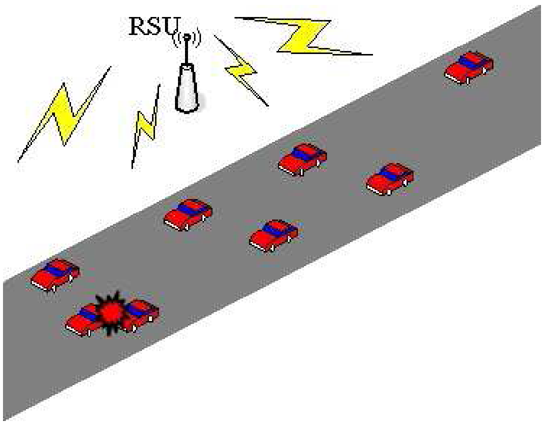

FIGURE 3. Network scenario.

$$K_0 = \sum_{j=0}^{\infty} \frac{2^{min(j,m)}W_0 - 1}{2} p^j L_s + \sum_{j=1}^{\infty} jp^j(1-p)T_c + T_s; \quad (23)$$

$$K_1 = \sum_{j=1}^{\infty} \frac{2^{min(j,m)}W_1 - 1}{2} p^j L_s + \sum_{j=2}^{\infty} jp^j(1-p)T_c + T_s. \quad (24)$$

and L_s is the mean state duration if a particular vehicle is silent. K_0 is the mean time for vehicle l to transmit a frame beginning with a $stage - 0$ back-off and K_1 is the mean time for vehicle l to transmit beginning with a $stage - 1$ back-off. T_s and T_c are the expected time taken for a successful transmission and collision transmission from a particular vehicle, respectively.

IV. PERFORMANCE ANALYSIS FOR THE PROPOSED MODEL

In this section, our proposed model is validated, and the model is then used to analyze our two proposed solutions about the performance improvements on collision and delay. The throughput and packets loss rate results are also presented in this part.

A. SCENARIO SETUP

Our model and solutions applications are validated against simulation tool MATLAB. We setup the simulated vehicular networks which closely follow the IEEE 802.11p basic specifications and contain one RSU and N vehicles. Fig. 3 gives a case of network scenario, in which various types of messages are transferred among vehicles. Each vehicle has a single radio, which is aligned to the SyncInterval, and operates according to IEEE 1609.4 multi-channel operation standard. We assume that each active vehicle transmits one packet per SyncInterval. The basic vehicular networks system parameters are listed in Table 1.

B. COLLISION PROBABILITY MODEL VALIDATION

Fig. 4 plots the collision probability when N vehicles switch from CCH to one of the SCHs at a SCH interval. Our model results calculated from our theoretical analysis (4) are plotted in a line. Simulation results are also shown in circles.

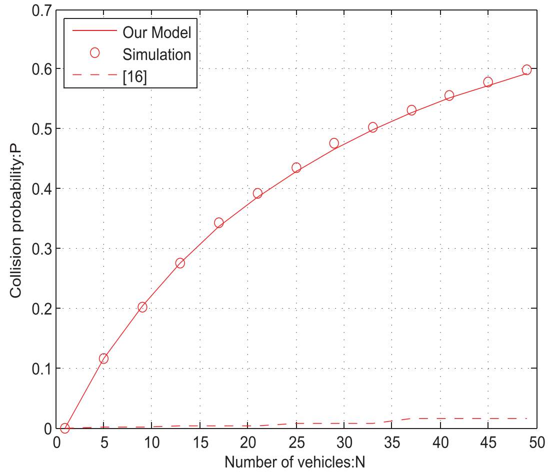

FIGURE 4. Collision probability when N vehicles switch channel from CCH to one of the SCHs.

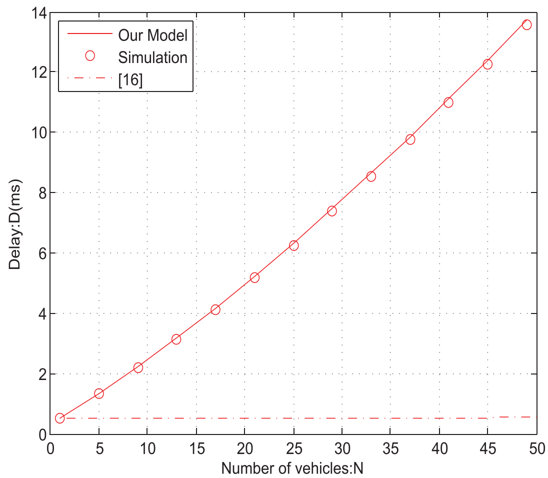

FIGURE 5. Packet delay when N vehicles switch channel from CCH to one of the SCHs.

It can be seen that analytical model results (solid line) closely match simulation results (circles) for the collision probability. In process of channel switching from CCH to one of the SCHs, it can be noted that the collision probability rapidly increases with the rise in the number of vehicles. In this case, when 15 vehicles simultaneously switch channel from CCH to one same SCH, the collision probability reaches 30%. In this case, the network traffic load is light. Using traditional steady-state Markov model, e.g. [16], the results (in dashed line) are far from the simulation results. These results show that traditional Markov chain is unable to model the contention caused by channel switching between CCH and one of the SCHs.

C. DELAY MODEL VALIDATION

Fig. 5 shows the result of the packet delay calculated from our analytical model (12) with simulation result for different number of vehicles N in vehicular networks. Similarly, it can be seen that analytical model result (solid line) closely match the delay obtained from the simulation result (circles). When 20 vehicles switch channel simultaneously to one of the SCHs to transmit their packets, each vehicle device experiences an average delay of 5 ms, which is much larger than the delay experienced by a vehicle device transmitting in an uncontested CCH and SCH period.

Fig. 5 also shows the result from the traditional Markov chain model of [16]. It can be seen that the delay predicted by [16] is corresponding towards the minimal contention predicted by the model in Fig. 4 and again indicates that traditional Markov chain analysis inadequately models the contention congestion phenomenon following channel switching between CCH and one of the SCHs.

D. COLLISION PROBABILITY WITH TWO PROPOSED SOLUTIONS

This model can also be used to guide designs to improve vehicular network performance. Two solutions are proposed in sections III-C and III-D: Equal Spaced and Random Spaced, respectively.

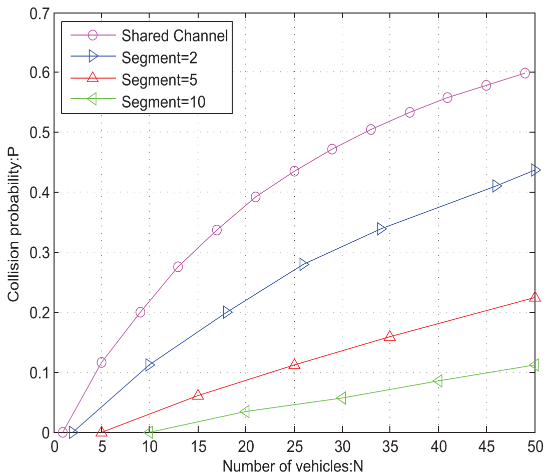

FIGURE 6. Collision probability when the shared channel is divided into multiple uniform segments and ***N*** vehicles are allocated evenly amongst them.

The collision probabilities of Equal-spaced solution was calculated from our analytical model (14) which is shown in Fig. 6, where the shared channel is divided into two, five and ten segments/timeslots. Roughly equal number of vehicles is scheduled in each timeslot to transmit their data. It can be seen that the collision probability decreases with the number of timeslots. When the number of timeslots is large enough (larger than the number of vehicles) the collision probability is close to zero. However, in practice, the number of vehicles is not known a prior. As a result, it is difficult to decide and allocate vehicles to their dedicated timeslots.

The results from the proposed solution 2, Random spaced algorithm, with simulation results are shown in Fig. 7. Compared with the original scheme, the proposed random spaced algorithm reduces the collision probability to around one tenth of that of the original scheme.

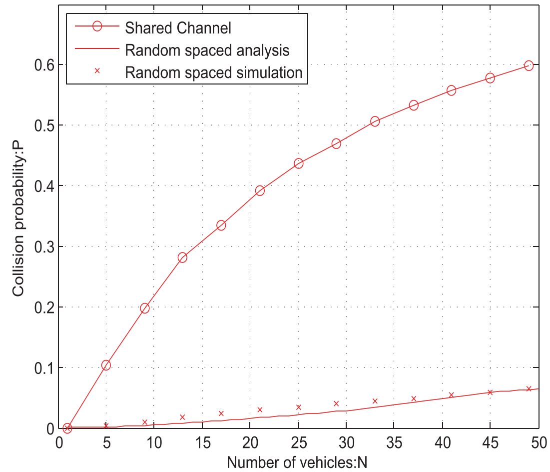

FIGURE 7. Collision probability versus number of vehicles for original scheme and random spaced algorithm.

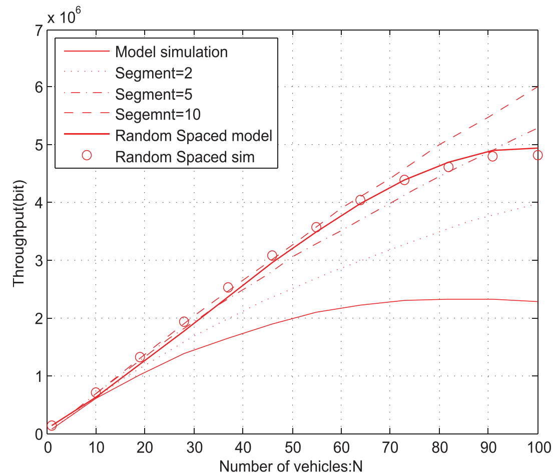

FIGURE 8. Throughput versus number of vehicles for original scheme, equal-spaced segments, and random spaced algorithm.

E. THROUGHPUT AND PACKET LOSS RATE

For the three cases: original shared channel, equal-spaced channel, and random spaced channel, Fig. 8 reports the different throughput values obtained in these cases. It shows how the normalized throughput of the network system depends on the total normalized offered vehicles number.

It can be seen that there is a linear relationship between the number of vehicles and the system throughput when the system is well below saturation. However, then as the number of vehicles increase, the system throughput reaches saturation, and the saturation throughput reaches higher for the proposed algorithms than the original shared scheme. For Equal-Spaced algorithm, the throughput is higher with the increase of segments. For Random-Spaced algorithm, the throughput is close to the throughput at case of segment 10, but level off as the number of vehicles is larger than 65.

Fig. 9 shows packet loss rate obtained for the three cases. It shows that packet loss is reduced with the proposed two

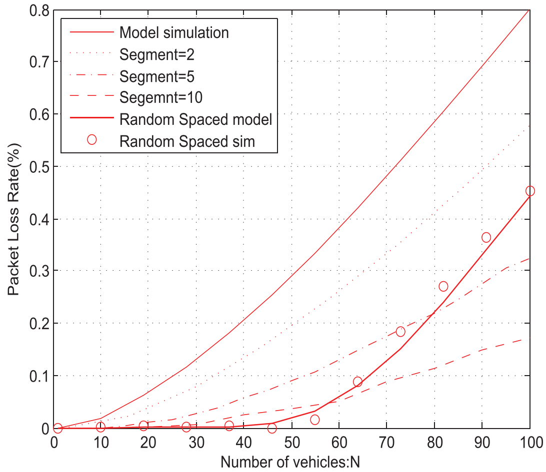

FIGURE 9. **Packet loss rate versus number of vehicles for original scheme, equal-spaced segments, and random spaced algorithm.**

solutions compare with the original shared channel scheme. For the Equal-Spaced algorithm, the packet loss is reduced as the number of segments increases. The Random-Spaced algorithm achieves the lowest packet loss for small networks, i.e. less than 50 vehicles, but starting to drop more packets as the number of vehicles increases to beyond 65.

V. CONCLUSIONS

The high contention issue of IEEE1609.4 multi-channel operation is investigated. An analytical model was developed to characterize the dynamics of burst packet arrivals caused by channel switching. Our model revealed detailed contention behavior, including collision probability, delay, and throughput, of the multi-channel operations.

Based on the analytical model, we proposed two solutions to improve the multi-channel operation performance. The Equal-Spaced algorithm used a centralized scheduler to schedule vehicles into equally divided timeslots within a timeframe. The Random-Spaced algorithm dictated that each vehicle randomly choose a start time within the timeframe to start its transmission. Our analytical results, validated by simulations, demonstrated that the proposed two solutions effectively alleviate data collision, reduce packet loss, and improve system throughput.

This paper mainly takes into account switching from control channel to service channel. The case of switching from service channel to control channel will be considered in future work.

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