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# An Adaptive Multi-Channel Assignment and Coordination Scheme for IEEE 802.11P/1609.4 in Vehicular Ad-Hoc Networks

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**ABSTRACT** Vehicular ad-hoc networks (VANETs) have been developed to provide safety-related and commercial service applications on the road. The IEEE 1609.4 is a standard (legacy) designed to support multi-channels in VANETs, namely control channel (CCH) and service channels (SCHs) with fixed alternating CCH and SCH intervals. The CCH is dedicated to broadcast safety and control applications while SCHs are used to transfer service data applications. However, due to the nature of contention-based channel access scheme and the transmission of multiple applications over the CCH during a fixed interval, safety applications performance is degraded during CCH congestion in high network density scenarios. In this paper, we propose an adaptive multi-channel assignment and coordination (AMAC) scheme for the IEEE 802.11p/1609.4 in VANETs which exploits channel access scheduling and channel switching in a novel way. AMAC scheme includes an adaptive execution of the peer-to-peer negotiation phase between service providers and users for SCH resource reservations, and collision-aware packet transmission mechanisms. These two mechanisms alleviate collisions and increase packet delivery ratio (PDR) of safety applications on the CCH. Thereby, the AMAC scheme ensures an efficient and reliable quality of service (QoS) for different traffic flows and improves the time diversity among vehicles based on the traffic conditions. For performance analysis, analytical models are developed based on 1-D and 2-D Markov chain models taking into account an error-prone channels. The probabilities of successful transmission and collisions have been derived to compute PDR, and delay for safety packets in legacy standard and AMAC scheme. Analytical and simulation results indicate that the AMAC scheme reduces the collisions and increases the PDR for safety applications over the CCH compared with the legacy standard. In addition, AMAC scheme outperforms the legacy standard in terms of system throughput of service applications.

**INDEX TERMS** VANETs, channel assignment and coordination, IEEE 1609.4, multi-channel MAC.

## I. INTRODUCTION

In the last decade, Vehicular Ad-hoc Networks (VANETs) have attracted tremendous interest from both industry [1], [2], and academia [3]–[7], due to their significant applications. VANETs exploit an On-board Unit (OBU) and Roadside Unit (RSU) to achieve Vehicle-to-Vehicle (V2V), Vehicle to infrastructure (V2I), and Hybrid Vehicular (HV) communications [8]. The applications of VANETs are divided based on prioritization into two categories; safety applications with higher priority, and service applications with lower priority. The safety applications include; a) event-driven messages (emergency messages usually related to safety such as electronic brake warning, post-crash notification and oncoming traffic warning); and b) periodic messages which give information on the current status of vehicles to control the traffic (position, speed, and direction, *etc.*) [9]. On the other hand, the service applications aim to improve driving comfort and the efficiency of transportation, such as parking availability notification, parking payment, electronic toll collection, service announcements, digital maps, media downloading and internet services. Safety applications are delay-sensitive, while service applications are throughput-sensitive. Therefore, safety applications require higher priority to ensure communication reliability and timely data transmission. Generally, priories in VANETs are achieved by changing the Contention Windows (CWs) and the Arbitration Inter-Frame Spaces (AIFS) sizes, which increase the probability of successful medium access for real-time applications.

However, in order to provide different types of application in VANETs, the Federal Communications Commission (FCC) has allocated a frequency band of *5.9 GHz* in a total bandwidth of *75 MHz* to support seven channels of *10 MHz* for each channel, and *5 MHz* for guard band under the Dedicated Short-Range Communication (DSRC) protocol [10], [11]. According to the standard IEEE 1609.4 (legacy) [12], these channels are functionally divided into one control channel (CCH_178), and up to six service channels (SCHs). The CCH is used to broadcast safety-critical messages and regular traffic such as beacons and WAVE Service Announcements (WSAs), while the six other channels, SCHs, are dedicated to transmit service messages. The repeating synchronization intervals (SI) for the channels to transmit the packets are *100 ms*, and each SI is divided into CCH Interval (CCHI) of *50 ms* and SCH Interval (SCHI) of *50 ms,* thus, the time $T_{SI} = T_{CCHI} + T_{SCHI}$ [12]. According to the standard IEEE 1609.4 specifications of multi-channels, during the control channel interval, the channel activity on all service channels is suspended and vice versa. Moreover, it is mandatory for all vehicles to stay on the CCH to monitor the channel for safety and WSAs applications during the CCHI, while during SCHI the vehicles can optionally switch to SCHs to transmit service applications. Thereby, this method enables the transmission of safety and service applications to be in different channels, without missing significant applications on the CCH. In a normal case, collisions may occur if more than one vehicle starts transmitting a packet simultaneously within the same time slot. Meanwhile, transmission error may manifest due to the complex condition of a wireless channel in VANETs such as path loss, thermal noise, channel fading, or interference from other radio resources.

However, since the traffic and topology are unstable and frequently change in vehicular networks, the fixed division of SI between the CCH and SCHs does not fit well with the real vehicular network environment. The fixed division cannot provide proper bandwidth to achieve time-bounded delay and high system throughput for both safety and service applications respectively. For instance, if the remaining time for the CCHI is shorter than the transmission time of a safety application, a vehicle will be unable to disseminate a safety application which will be dropped when its lifetime has expired. On the other hand, if the traffic condition is light (sparse), the transmission of safety applications on the CCH will be occasional. Consequently, the CCH resources and interval will be wasted, while bulk service data will not have enough time to be transmitted on SCHs during the SCHI. In addition, increasing CCHI will absolutely increase the transmission of safety and control applications, and decrease the time share of SCHI. For these reasons, four channel access schemes in case of a single-radio device have lately been recommended by the IEEE 1609.4 standard; continuous CCH access, alternating CCH and SCH access, immediate SCH access, and extended SCH access schemes, as illustrated in Fig. 1.

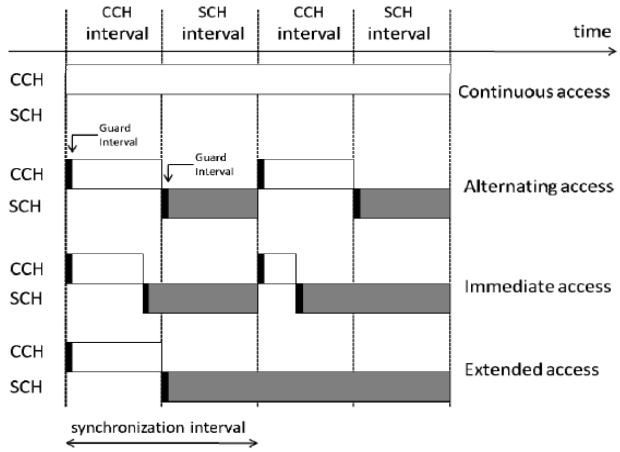


**FIGURE 1.** WAVE channel access options.

Yet, the criteria and procedures for selecting the channel access scheme type and measuring the level of congestion on the channel are not specified in the IEEE 1609.4. The policy of selecting a SCH type and setting up non-overlapping time intervals over the same SCH frequency by the providers are also not clearly defined in the IEEE 1609.4 standard draft. Moreover, according to the legacy standard and other researchers, the SCH communications resource reservation mechanism between service providers and users is implemented over the CCH during the fixed CCHI. Consequently, in heavy traffic, safety packets may suffer from severe collisions with control packets on the CCH, resulting in unreliability and low PDR of safety applications. Thus, an adaptive SCH resource reservation mechanism is needed to reduce safety packet collisions over the CCH, and ensure higher network throughput of service applications over the SCHs. Typically, the transmission of safety applications in VANETs follows broadcast mode in which the failed broadcast packet will never be detected due to the lack of acknowledgements exchange among vehicles. As a result, the CW size value for safety applications remains constant, and accordingly the collisions of safety packets are increased in heavy network conditions. For this reason, collision-aware packet transmission mechanism on the CCH is needed providing best initial CW size value according to the network conditions. This will improve time diversity among vehicles, and ensure fewer collisions and higher PDR for safety packet on the CCH.

This paper proposes an Adaptive Multi-Channel Assignment andCoordination (AMAC) scheme for IEEE 802.11p/1609.4 in VANETs to ensure efficient and reliable QoS for different traffic flows by selecting the optimal channel access scheme based on the traffic environment. The vehicles will use an AMAC scheme to achieve a high success rate of safety applications with a fair share of the bandwidth for service applications. The salient contributions of the AMAC scheme that make it different from the existing works are as follows: a) An optimal channel access scheme is announced by the RSU based on the traffic conditions to guarantee that all the safety applications can be disseminated during the CCHI and also achieve higher network throughput of service applications over the SCHs. Applications in the CCH are classified into two classes; safety applications (AC1) with higher priority, and control applications (AC2) with lower priority, such as WSAs. b) The peer-to-peer negotiation phase (PNP) between service providers and users for SCH resource reservations is adaptively executed based on the CCH conditions; (i) over the CCH if the traffic condition is light, which helps to exploit the CCH resources and interval efficiently; (ii) over the SCHs if the traffic condition is heavy in order not to adversely affect the delivery of safety applications over the CCH. Thus, transmission of safety applications can be protected from high delay and collisions. c) A collision-aware packet transmission mechanism is applied to the AMAC scheme at the beginning of each CCHI by announcing the best values of CWs sizes to be used by the vehicles according to the network conditions. These CWs sizes must be well suited to the number of vehicles on the network. Thus, the time diversity will be improved among vehicles, which will reduce collisions and increase PDR for safety packets. d) The AMAC scheme introduces a multi-channel coordination mechanism along with addressing the multi-channel hidden terminal problems to provide a contention-free SCH access by channel resource reservation on CCH. e) Analytical models based on the Markov chain for both classes of applications are presented under non-saturated conditions. The models adopt the error-prone channels to avoid overestimating saturated throughput. The back-off timer freezing with the M/M/1 queue is adopted to provide an accurate estimation of the channel access, and analyze the time performance. Moreover, back-off stages along with short retry limit for service applications are also considered in the model to accommodate the IEEE 802.11p specifications and to guarantee that no packet is served indefinitely. The main reasons for choosing unsaturated conditions in the AMAC scheme are; (i) considering the inter arrival time and burstiness in the network, (ii) real networks are often unsaturated, as well as (iii) saturated traffic sometimes makes a network unsteady [13], [14].

The rest of the paper is organized as follows: the related works are presented in section II. In section III, we describe the system model and assumptions use in this study that include multi-priority transmission strategy, measurement-based congestion detection, channel access options, collision-aware packet transmission, and distributed SCH selection and access reservation protocol. Section IV contains the theoretical analysis. Section V presents the results and performance evaluation of the proposed scheme. The paper is concluded in section VI.

## II. RELATED WORKS

In this section, we discuss the previous works which have studied multi-channel coordination schemes and variable interval access. However, authors in [15]–[17] introduced a synchronous split-phase multi-channel MAC scheme to counteract the legacy problems mentioned previously. Reference [15] proposed an adaptive multi-channel MAC protocol named dynamic interval division multi-channel MAC (DID-MMAC) protocol to fully utilize the CCH and SCH intervals adaptively based on the real-time traffic load. DID-MMAC divides the CCHI into three phases based on the type of different frames: service announcement phase (SAP), beacon phase (BP) and peer-to-peer reservation phase (PRP) with different priorities, giving PRP the lowest priority. DID-MMAC has also developed a distributed algorithm to calculate and determine the duration of PRP communication resource reservation schemes by dynamically adjusting the PRP duration according to the real-time network traffic parameters. A variable CCH interval (VCI) multi-channel MAC scheme was presented in [16], in which the length ratio between the CCH and SCHs was dynamically adjusted based on the traffic conditions. This scheme has been cited by numerous reference protocols. VCI splits the control channel into two phases, safety interval and WSA interval, with priority given to the safety interval. The roadside unit decides the interval of the CCH by broadcasting a VCI packet comprising the length of CCH interval to the vehicles in its coverage area. VCI also offers optimization of CCH intervals based on a mathematical model. However, the short retry limit in the analytical model, and the potential multi-channel hidden terminal problems were not considered in the VCI scheme.

Moreover, a variable control channel interval was proposed by [18]–[20]. Babu *et al.* [18] introduced a new multi-channel-based MAC protocol named Context Aware Variable Interval MAC (CAVI-MAC). The CAVI-MAC protocol studies the safety messages over the CCH and differentiates them into two priorities, higher and lower priority for event-driven and periodic messages respectively. The variable interval of the CCH and SCHs in the CAVI-MAC protocol depends on two factors that affect the VANETs environment: a) vehicle neighbor density, and b) context, in which context is classified into steady state (periodic messages) and non-steady state (event-driven messages). Hidden terminals are addressed mathematically in this protocol. However, the authors did not discuss the service messages in the CAVI-MAC protocol. The control channel access time in [19] can be adjusted adaptively in the range of the intra basic service set (I-BSS) based on the message traffic load. The authors considered the message load affected by several factors such as vehicle number, message size, lanes, and repeat rate, based on the equation mentioned in the paper. An adaptive multi-priority distributed multi-channel (APDM) MAC protocol for vehicular ad-hoc networks in unsaturated conditions was recommended in [20]. In the APDM MAC scheme, the packet arrival rate to the MAC layer satisfy the Poisson process. Statistics and measurement for channel coordination and channel assignment were applied to the APDM MAC scheme. After the APDM MAC scheme surveys the traffic conditions, an optimized node (ON) holding a minimal MAC address has to broadcast the optimal ratio packet (ORP) to spread out the suitable CCHI among the nodes. Nodes have to adjust the random contention interval based on the receiving ORP. A Markov model was also presented by the APDM MAC scheme to analyze and optimize the packet transmission probabilities, and dynamically adjust the ratio between the CCHI and SCHI based on the traffic conditions on the road. However, the APDM MAC scheme has implemented the PNP between service provider and users over the CCH during the CCHI in all traffic conditions. Since all the nodes keep sensing the channel for CCHI decision-making, the network overheads may occur in the APDM MAC scheme.

Unlike the synchronous split-phase multi-channel MAC scheme, [21], [22] developed a multi-channel MAC protocol in VANETs based on WAVE alternating channel access, enabling fast dissemination of emergency packets in both intervals – the CCHI and SCHI. Dang *et al.* [21] introduced an efficient and reliable MAC protocol for VANETs (VER-MAC), exploiting the whole synchronization interval (100 ms) to broadcast emergency packets, which allows vehicles to disseminate safety packets twice during both intervals, the CCHI and SCHI, to increase the safety packet delivery ratio and support real-time transmission of safety-applications on the road. An analytical model is presented in VER-MAC for both safety and service packets based on the Markov chain. However, the VER-MAC scheme has not consider the freezing of the back-off timer in the analytical model. The fixed alternating CCH and SCH intervals were assumed in the VER-MAC scheme. The optimized length of the CCHI was proposed by [22]. Hafeez *et al.* [22] introduced two algorithms to optimize the length of the CCHI according to the network conditions, while the SCHs have a fair share of the SI. The first algorithm is named the optimal channel access (OCA) algorithm to increase the successful transmission of safety and control applications within the CCHI by deriving the optimal channel access probability. The second algorithm was proposed by [22], named the mobility and topology aware (MTA) algorithm, to set vehicle parameters adaptively based on their average speed on the road to enhance VANETs' reliability. The parameters that are dynamically adjusted in this algorithm depend on the traffic conditions, including the communication range, the minimum contention window and the length of the CCHI.

The congested channel issue in VANETs was addressed by [23] and [24], in which the authors proposed two congestion control mechanisms to provide flexible and efficient multi-channel utilization based on MAC transmission queue manipulation, where first priority is given to the safety applications. The first mechanism is called congestion measurement to detect the congestion channel either by event-driven detection or by sensing the channel usage level of both the CCH and SCHs based on the equation mentioned in the papers. The second mechanism is called multi-channel assignment to adaptively adjust the channel switching interval according to the first mechanism outcome in regard to the congestion level on the CCH and SCHs. However, the mechanisms for adjusting congestion detection threshold, decision making process, and also SCHs selection policy were not described in [24]. References [25]–[28] proposed a new protocol to greatly improve the SCH bandwidth utilization based on the original WAVE-mode channel access. The work in [25] applies immediate with extended SCHs access to the model in which the scheme allows service providers and users to stay on the chosen SCH as long as they need before returning to the CCH. A novel distributed asynchronous multi-channel MAC scheme for large-scale vehicular ad-hoc networks was offered in [27]. AMCMAC-D in [27] was developed to support multi-channel transmission over SCHs with enhancement of the QoS. The main contributions in the AMCMAC are to: a) achieve load-balancing among SCHs, b) address the missing receiver problem in a different way, c) mitigate the collision rate by employing a different post-transmission procedure, and d) utilize the SCHs efficiently by addressing the multi-channel hidden terminal problem.

Amadeo *et al.* [28] presented a WAVE-based hybrid coordination function (W-HCF) protocol to fully utilize the SCH resources efficiently relying on WAVE alternating channel access. The W-HCF protocol focuses more on the service applications, and classifies them into two classes when accessing the service channels, as QoS-sensitive and non-QoS sensitive services with higher and lower priority respectively. The SCH resources in the W-HCF protocol are first reserved for QoS-sensitive services using an accurate and efficient extra signaling and polling mechanism in order to achieve a higher throughput of infotainment applications while still keeping bandwidth available for non-QoS sensitive services. It is mandatory for the three-way handshaking scheme, TXOP Request (TXOP REQ), TXOP Response (TXOP RSP), and Acknowledgement (TXOP ACK) to occur during the SCHI in order to avoid collision with safety messages over the CCHI. However, the W-HCF scheme uses fixed alternating CCH and SCH intervals whilst implementing the TXOP negotiation over SCHs during the SCHI; as a result, in a sparse network, the system suffers from underutilization of SCHs in a sparse network, and also dissemination of safety applications on the CCH will be occasional in which the CCH resources and interval will be wasted. The dynamic contention window schemes for periodic broadcast in VANETs were proposed by [29]–[31]. However, the authors in [29]–[31] did not take into account the effects of control packets on the CCH, such as WSA packets, in their study.

**TABLE 1. Comparison of different schemes.**

| Protocol | Network condition | Channel access type | PNP execution | $W_e$ size value | Error-prone channel | Queue Length |
|---|---|---|---|---|---|---|
| Rawat et al. [29] | N/A | ACSA | N/A | Dynamic | No | N/A |
| W-HCF [28] | S | ACSA | Over SCH | N/A | No | Infinite |
| AMCMAC [27] | S | ACSA | Over CCH | Constant | No | Infinite |
| VER-MAC [21] | N-S | ACSA | Over CCH | Constant | No | Finite |
| CAVI-MAC [18] | N-S/S | VCI | N/A | Variable | No | Finite |
| Yang et al. [30] | N-S | ACSA | N/A | Dynamic | No | Finite |
| APDM- MAC [20] | N-S/S | VCI | Over CCH | Constant | No | Finite |
| Proposed AMAC | N-S | CCA/ACSA/ISA/ESA | Over CCH/SCH | Dynamic | Yes | Finite |

Note: N-S/S: Non-saturated/ Saturated, CCA: Continuous CCH Access, ACSA: Alternating CCH and SCH Access, ISA: Immediate SCH Access, ESA: and Extended SCH Access, VCI: Variable CCH Interval, N/A: Not Available.

## III. SYSTEM MODEL AND ASSUMPTIONS

An Adaptive Multi-Channel Assignment and Coordination (AMAC) Scheme for IEEE 802.11p/1609.4 in VANETs is developed to address the problems discussed in the previous sections. The AMAC scheme can ensure reliable and real-time delivery of safety applications with collision alleviation on the CCH. It also attempts to maximize the saturated throughput on the SCHs by using an optimal channel access scheme, and dynamic PNP execution between service providers and users based on the traffic conditions. In the proposed AMAC scheme, Coordinated Universal Time (UTC) scheme is inherited from IEEE 1609.4 [12] to synchronize the timeframe among all vehicles by Global Positioning System (GPS). The SI is divided between the CCH and SCHs into adjustable intervals based on the traffic conditions. During the CCHI, vehicles not only transmit safety and WSA packets, but also compile statistics and perform measurement for channel coordination and assignment. Fig. 2 shows the framework of the AMAC scheme, the safety and WSA packets are broadcasted over the CCH. Besides, the PNP for requested service between service providers and users is adaptively executed either on the CCH during CCHI if the traffic conditions are light, or on the SCHs during the SCHI if the traffic conditions are heavy. The channel access scheme type is determined by the RSU based on the CCH busy ratio (CBR) value. The WAVE nodes disseminate the safety packets, and control packets on the CCH during the CCHI with different transmission probabilities in each time slot. The WSA packets will be broadcasted by the service providers, piggybacking with service information, identities of the SCHs and Contention-Free Period to be used in the SCHs. For more clarification, Fig. 3 shows the overall diagram of the AMAC scheme.

### A. MULTI-PRIORITY TRANSMISSION STRATEGY

According to the standard specifications, safety-related packets always have the higher priority; therefore, the AMAC scheme classifies the packets during the random contention period into two priorities: higher (AC1) and lower (AC2) priorities for safety and WSA packets respectively. This kind of classification can ensure the reliable and real-time transmission of the safety packets on the CCH under dense traffic conditions. In order to support QoS for different applications

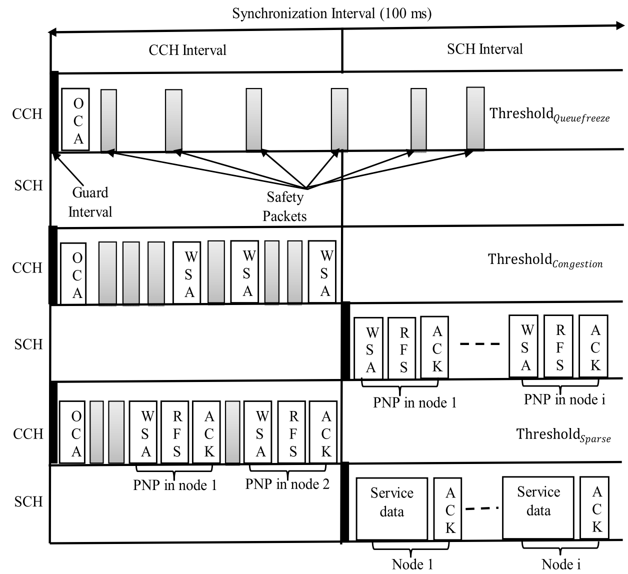


**FIGURE 2. Framework of the AMAC scheme.**

in our work, vehicles should adopt the standard rules which inherit the enhanced distributed channel access (EDCA) mechanism from the IEEE 802.11e. In the EDCA mechanism, different applications have different values of Arbitration Interframe Spacing Numbering (AIFSN) and Contention Window (CW) sizes based on the priority. The back-off counter decreases by one when the channel is idle for a period of the AIFSN time slot. In the AMAC scheme, we use a small value of AIFSN with AIFSN (AC1) = 2 and AIFSN (AC2) = 3 to improve the system throughput and timely broadcast the safety applications [20]. A packet with AC1 has a smaller AIFSN, thus, it will gain higher transmission probability and less back-off timer before transmission compared to a packet with AC2. The essential condition for the packet to be transmitted on the channel is that the channel must be idle and the back-off counter be zero. Vehicles keep sensing the channel whether it is idle or busy, and if the channel is busy, the back-off counter should be frozen. The multi priority scheme in the AMAC scheme can reduce the collisions of packet transmission among vehicles and give priority access of the safety packets to the CCH. For the analytical models, 1-D and 2-D Markov chain models in the presence of

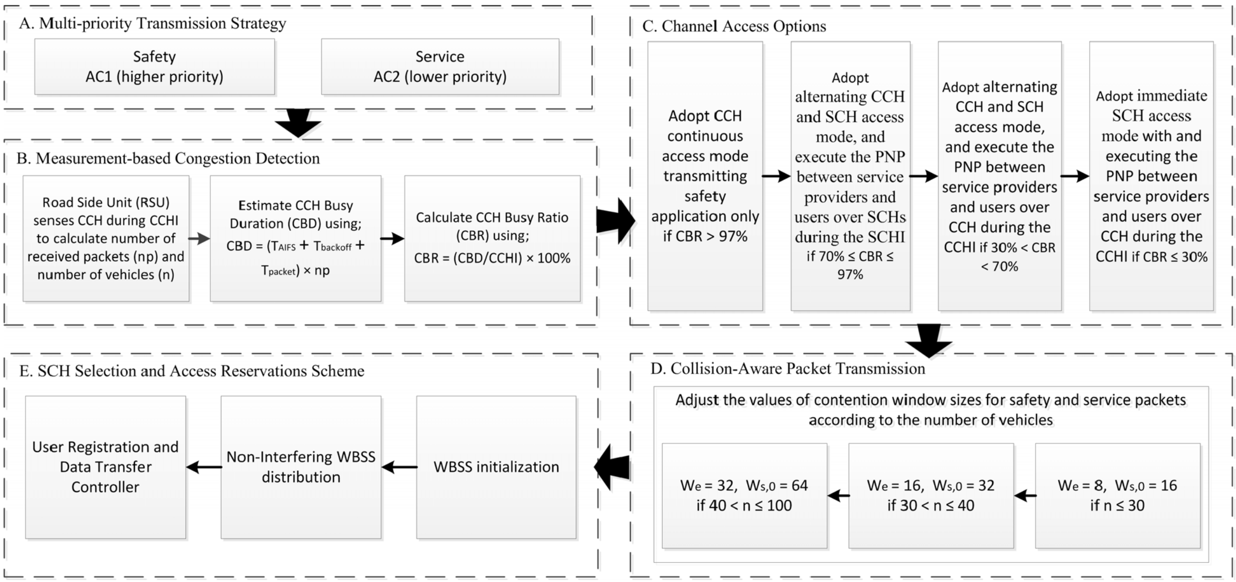


**FIGURE 3.** **Overall diagram of the AMAC scheme.**

error-prone channels under non-saturated conditions are utilized to derive the transmission probability of $\tau_e$ and $\tau_s$, in which $\tau_e$ and $\tau_s$ are the transmission probability of safety and service packets, respectively. More details about the analytical model will be discussed in Section IV.

### B. MEASUREMENT-BASED CONGESTION DETECTION

In this method, we calculate the CCH busy ratio (CBR) within the CCHI to activate the congestion control mechanism based on the traffic conditions. In the AMAC scheme, the RSU monitors the CCH to detect the level of channel congestion by receiving the packets from the active vehicles within its radio coverage range in order to calculate the CBR at the end of each CCHI. Typically, every vehicle generates only one packet per synchronization interval, thereby, the RSU can easily count the number of active vehicles ($n$) within its radio coverage range based on the number of packets ($np$) successfully transmitted over the CCH. The dissemination of WSA packets uses a broadcast mode without any acknowledgement of successful reception. Hence, for reliable delivery purposes, the WSA packet should be broadcasted more than once in the same CCHI as it is recommended by the 1609.4 standard. Subsequently, a vehicle may transmit the same WSA packet more than once during the same synchronization interval. The RSU will consider all packets and calculate the CBR based on the packets received from vehicles during a CCHI in order to count the exact number of active packets within its radio coverage range. At the end of each CCHI, the RSU can estimate the CCH busy duration ($CBD$) in millisecond by using the following equation:

$$CBD = (T_{AIFS} + T_{backoff} + T_{packet}) \times np \tag{1}$$

where $T_{AIFS}$, $T_{backoff}$, $T_{packet}$, and $np$ denote the time duration of AIFS, the average back-off time, the packet transmission time, and the number of active packets within the RSU radio coverage range, respectively. According to the CBD value, the RSU can simply calculate the CCH busy ratio ($CBR$) by the following equation:

$$CBR = \frac{CBD}{CCHI} \times 100\% \tag{2}$$

Based on (2), the RSU is able to estimate the neighborhood traffic density at the end of each CCHI, and compare the $CBR$ value with a predefined threshold in order to decide which scheme type of the channel access can be used in the next synchronization interval, and also to decide where to perform the PNP between service providers and users for SCH communication resource reservations. In our work, we assume the alternating access channel for the initial synchronization interval (i.e. *50ms* for each interval, CCHI and SCHI).

### C. CHANNEL ACCESS OPTIONS

This method is based on the CCH congestion estimation mechanism outcome explained in the previous subsection. According to the 1609.4 standard recommendations, there are four schemes of channel access in multi-channel-based MAC VANETs including; continuous CCH access, alternating SCH and CCH access, immediate SCH access, and extended SCH access. However, the criteria and procedures for selecting the channel access scheme type and measuring the level of congestion on the channel are not specified in the standard. Thus, in this work, the RSU calculates the CBR at the end of each CCHI via Equation (2), then depending on the CBR value compared with predefined thresholds, the RSU decides which channel access scheme type can be used for the next SI (each SI is *100 ms* based on standard specifications). At the beginning of the next SI, the RSU broadcasts a special packet called Optimal Channel Access (OCA) packet containing the channel access scheme type to the vehicles within its radio coverage range. To guarantee reliable delivery, the RSU will broadcast the OCA packet at least twice. However, the OCA packet may not be heard by some of the neighboring vehicles because of the heavy traffic. To address this issue, a field will be added into the WSA packet to represent the channel access scheme type. Vehicles that receive the channel access scheme type for the current SI will fill this field when they disseminate the WSA packets, while other vehicles will use zero to fill this field. Nevertheless, the channel access scheme type announced by different RSUs may be various. Thus, vehicles located under multiple RSUs may hear different types of channel access scheme. In this case, the vehicles will adopt the channel access scheme type that is received from the nearest RSU based on the power strength of the OCA packet. In order to avoid heavy congestion over the CCH during traffic jams, we propose an adaptive option for the PNP between service providers and users either to be executed over the CCH if the traffic is light or over the SCHs if the traffic is heavy. In this paper, we assume that the alternating access channel scheme for the initial synchronization interval is *50 ms* for the CCH and *50 ms* for the SCHs as determined by the standard specifications. We define three thresholds for the CBR as in [23] and [32]; $Threshold_{Queufreeze}$, $Threshold_{Congestion}$, and $Threshold_{Sparse}$, with the values of 97%, 70% and 30%, respectively. The operation of the channel access options selection is performed as follows:

1) If the RSU detects that the CBR value is higher than $Threshold_{Queufreeze}$ ($CBR > 97\%$), the CCH is considered to be extremely congested. Hence, the RSU will announce to the neighboring vehicles within its radio coverage to adopt the CCH continuous access scheme. Thereby, all vehicles will remain on the CCH only in the next synchronization interval in order to provide reliable and real-time dissemination for safety applications. This scheme does not need any channel coordination.
2) If the CBR value is lower than the predefined $Threshold_{Queufreeze}$ ($70\% \leq CBR \leq 97\%$), the RSU will broadcast an OCA packet notifying the neighboring vehicles to use the alternating CCH and SCH access scheme for the next SI, with 50 ms CCH and 50 ms SCH. In this threshold, the peer-to-peer communication resource reservations between service providers and service users will be implemented over the SCHs during the SCHI to eliminate the effect of safety applications delivery over the CCH.
3) If the RSU detects that the CBR value is lower than the predefined $Threshold_{Congestion}$ ($30\% < CBR < 70\%$), the alternating CCH and SCH access scheme will be used for the next SI and the PNP between service providers and service users will be implemented during the CCHI over the CCH.
4) If the RSU detects that the CBR value is lower than the predefined $Threshold_{Sparse}$($CBR \leq 30\%$), the immediate SCH access scheme will be adopted for the next SI achieving higher throughput over the SCHs.

### D. COLLISION-AWARE PACKET TRANSMISSION

According to the legacy standard specifications, vehicles compete for a common frequency during the CCHI to exchange safety and control packets over the CCH, and optionally switch to one of the available SCHs for service data exchange during the SCHI. Therefore, under heavy network density, a huge number of vehicles contend to seize the channel at the beginning of each CCHI to broadcast safety and WSA packets by using initial CWs sizes. This may result in high collisions and low PDR for safety packets. Besides, the transmission of safety applications in VANETs follows broadcast mode in which the exponential back-off and MAC acknowledgments are disabled (the value of $W_e$ size being held constant). Thereby, if a vehicle broadcasts a safety packet, and this packet is lost during its transmission either because of collisions or channel errors, the broadcast packet will never be received by the neighboring vehicles. This is due to the lack of acknowledgements exchange among vehicles which leads to absence of retransmission for broadcasted packet in VANETs. Then, the neighboring vehicles may only obtain the updated safety information in the next SI if this vehicle successfully broadcasts its safety packet. However, in order to alleviate safety packets collisions, collision-aware packet transmission mechanism improving the time diversity among vehicles is applied at the beginning of each CCHI. The collision-aware packet transmission is based on the CCH congestion estimation mechanism outcome described in the subsection B. As explained earlier, the RSU calculates the CBR at the end of each CCHI via (2), hence, the RSU according to the number of vehicles can estimate the best CW size to be used by the vehicles in order to mitigate collisions and increase PDR for safety packets. The value of the CW size should be either doubled if the network density is high or decreased by half when the traffic condition is light, satisfied $W_e = 8 \times 2^i, (i = 0, 1, 2, \ldots)$. The RSU broadcasts the OCA packet that includes the channel access scheme type along with the best value of CW size to be adopted by the vehicles at the beginning of each CCHI. This value of the CW size should fit well with the number of vehicles and packet arrival rate on the network to ensure low collisions and delays, as well as high PDR for safety applications. More details about the best value of the CW size for our scenario will be studied in the section V.

### E. SCH SELECTION AND ACCESS RESERVATIONS SCHEME

A SCHs selection and access reservation scheme is still one of the big issues in VANETs due to the lack of guaranteed bandwidth and channel access delay. Different from the contention-based MAC mechanism in the legacy standard, the AMAC scheme proposes a new multi-channel coordination scheme in order to provide contention-free channel access over the SCHs based on Time-division multiple access (TDMA). In TDMA, a vehicle can directly transmit its data without sensing the channel state in its time slot reservation. The contention-free SCH access will definitely reduce the collisions of transmitted packets, and improve the system throughput of service applications over the SCHs.

#### 1) WAVE BASIC SERVICE SET INITIALIZATION

During the random-access interval over the CCH, a vehicle that acts as a service provider attempts to seize the channel according to the EDCA rules with transmission probability $\tau_s$ to set up and advertise its WAVE Basic Service Set (WBSS) and related service. It broadcasts a WSA packet containing all the identity fields of a SCH to be used with other additional information. The additional fields will carry the information about the reserved contention-free period called Controlled Access Period (CAP) over the SCH that has been chosen for data transfer service. The extra 4-byte field is added to the WSA packet, namely Own_SCH_Allocation which comprises two 2-byte subfields; CAP_start and CAP_end to specify the initial and end time slot duration of the reserved CAP, respectively. The CAP is required for transferring a service data over the SCHs. The time slot duration of the CAP should be tailored to accommodate service data transmission time and ACK frame that will be sent by the service provider and user over the SCHs. This CAP duration is also tailored to accommodate one or more PNP between service provider and user to transfer and receive the control frames (WSA/RFS/ACK) when the user registration occurs on the SCHs. Since WSA packets use a broadcast mode without any acknowledgement of successful reception. Therefore, for reliable delivery purposes, the WSA packet should be broadcast more than once in the same CCHI as suggested by the 1609.4 standard.

#### 2) NON-INTERFERING WBSS DISTRIBUTION

In order to set up non-interfering WBSSs on the same SCH, Other-SCH-Allocation field is added to the WSA packet. The extra Other-SCH-Allocation field in the WSA conveys the information about the CAP intervals reserved by other providers. By reading the Other-SCH-Allocation field, a provider that overhears the WSA packet can be aware of the CAP intervals reserved by the nearby providers. As a result, this mechanism helps to mitigate the multi-channel hidden terminal problems, and avoids the overlapping time intervals over the same SCH frequency.

A provider after broadcasting its own WSA packet keeps monitoring the CCH by listening to the WSA packets that are broadcasted by other providers. Accordingly, some situations may occur as follows;

- If the provider notices that its own CAP does not overlap with the received WSA packet that advertises a reserved CAP for another provider, and also its own CAP is included in the Other-SCH-Allocation field. In this case the provider knows that its CAP duration is successfully reserved. Thus, it starts PNP with the service users either on the CCH, or on the SCHs depending on the CCH conditions.
- If the provider discovers that its own CAP does not conflict with the received WSA packet that advertises a reserved CAP for another provider, but its own CAP is not in the Other-SCH-Allocation field. In this case the provider assumes that its CAP reservation has failed and will try to broadcast a new WSA.
- If the provider detects that the WSA packet advertises a reserved CAP for another provider and overlaps with its own CAP. In this case the provider has to reschedule its CAP reservation by broadcasting a new WSA packet to avoid a collision. If the provider cannot perform a new reservation during the current CCHI, it abstains from reserving a CAP in the following SCHI and waits for the next CCHI to make a new CAP reservation.

#### 3) USER REGISTRATION AND DATA TRANSFER CONTROLLER

When a service user detects a WSA packet transmitted over the CCH and is interested in the service, the user can optionally start a peer-to-peer communication resource reservation with the provider by using the RFS/ACK handshaking (PNP) mechanism. This mechanism is carried out either over the CCH or SCHs depending on the CBR value calculated via the congestion measurement mechanism. The aim of this procedure is to explicitly make an agreement between service providers and users on the data transfer service over a specific SCH and time slot duration. Assuming that a lot of service providers share the same SCH in a dense environment with different CAP intervals, each provider is able to transmit only one service application during every SI. The frames changing during the PNP mechanism are WSA, Request for Service (RFS), and Acknowledgement (ACK). Different from other works, the AMAC scheme performs the PNP mechanism between service providers and users either on the CCH or on the SCHs depending on the CCH conditions as follows:

- *User registration on the CCH*: Vehicles that act as service users can initiatively start a reservation by sending a RFS message to the provider with the ID of the service provider, SCH ID, service type, and CAP_start with CAP_end as advertised by the service provider in the WSA. Then, the service provider will decide either to accept or reject the service request based on the specific criteria for service users and channel conditions. When a user asks for a service from the service provider, the provider will know the information about the user, such as speed, position and direction. Based on these information, the provider can estimate the expected time duration that the user will remain within its coverage and in its polling list. As a result, the provider will execute a simple admission control in order to accept or reject the request. If the service provider accepts the request from the user, it will reply by the ACK message specifying the time slot duration of the reserved CAP and other information; and also, it will add the service user to its polling list waiting for the reserved CAP in the next SCHI within the same SI for data exchange; otherwise it alerts a rejection.

- *User registration on the SCH*: If the CCH is considered congested by the decision-making authority (RSU), the registrations (PNP mechanism) between service providers and users are performed on the SCHs during the SCHI. The service provider, which successfully reserves a CAP on the CCHI, has to wait and re-advertise the CAP duration on the SCH by sending a WSA packet at the beginning of its reserved CAP as in Fig. 2. Vehicles that act as service users and are interested in joining the service, which is advertised by the provider on the CCH, will record the information about the service and CAP interval waiting for the SCHI within the current SI to start a PNP mechanism with the service provider based on the EDCA rules. In this case, the data transfer service between service provider and users will be implemented on the reserved CAP during the subsequent SCHI from the next SI after the provider updates its polling list on the CCH.

If the service provider misses the connection with the service users, or it realizes after waiting for a DIFS that there are no users interested in joining the advertised service. In this case, the service provider has to send a CAP_terminate frame in order to terminate the reserved CAP and make it available for exploitation by other providers. In fact, the RFS/ACK handshaking interaction between providers and users can help to spread out the SCH ID, and the CAP duration among vehicles. Thus, this approach addresses the multi-channel hidden terminal problem, ensures different SCH selection, and also assists to reserve a non-overlapping time interval over the same SCH frequency. Whenever the vehicles receive (or overhear) the WSA packet (or PNP packets) either over the CCH or over the SCHs, they will directly update the information about SCH reservations as well as the time slot duration of each reserved CAP, which is recorded in the Network Allocation Vector (NAV). Thereby, all vehicles will know the occupancy status of each SCH. A vehicle having WSA packet will initially check the SCH usage information through its NAV in order to decide which channel to select for transferring its service data in the next SCHI, and also to guarantee time-disjoint CAP assignment over the same SCH. To provide load balancing on SCHs, a service provider has to select the SCH that accommodates the least service data packets in the next SCHI. If more than one SCH is free, the service provider will randomly select any one of the SCHs to transfer its service data. Vehicles that have failed to make a reservation or are not interested in any services can remain on the CCH.

## IV. ANALYTICAL MODEL

The analytical models to analyze the AMAC scheme performance comparing to the standard is presented in this section. The analytical models include; Multi-priority Transmission Model, Failure $p_f$ and Collision $p_{coll}$ Probabilities model, and Time Analysis for Safety and WSA Transmission model. The first model is used to compute the stationary probability for safety and service applications, while the second model is used to compute transmission failure probabilities of safety and service packets. On the other hand, Time Analysis for Safety and WSA Transmission model is employed to derive PDR, and delay of a safety application. In addition, it is used to derive throughput of service applications. For convenience, important notations and variables used in the analysis are summarized in Table 2.

### A. MULTI-PRIORITY TRANSMISSION MODEL

In this subsection, 1-D and 2-D Markov chains are presented to derive the stationary probability $\tau_e$ and $\tau_s$ for safety and service applications respectively, under unsaturated conditions. We add an idle state to the models to represent the empty buffer when no packet is ready for transmission. Choosing unsaturated traffic in our models is due to three reasons; (i) considering the inter arrival time and burstiness in the network, (ii) real networks are often unsaturated, as well as (iii) saturated traffic sometimes makes a network unsteady [13], [14]. The models adopt the error-prone channels to avoid overestimating the saturated throughput. Besides, the freezing of the back-off timer is adopted to provide an accurate estimation of the channel access. A Gaussian wireless error channel is adopted in our model, in which a constant channel bit error rate (BER) is supposed to be identified in advance and each bit has the same bit error probability. Moreover, back-off stages along with a short retry limit for service applications are also considered in the model to accommodate the IEEE 802.11p specifications and to guarantee that no packet is served indefinitely. The traffic arrival rate $\lambda_e$ and $\lambda_s$ for safety and service packets, respectively, follows the Poisson distribution. We assume $n$ vehicles in the network that compete to access the channel based on the EDCA scheme with no hidden terminals.

The 1-D Markov chain of safety applications ($AC_1$) is presented in Fig. 4 to analyze the probability of frame transmission $\tau_e$. Let $b_e(t)$ be the random variable representing the value of the backoff timer $(0, 1, 2, \ldots, W_e - 1)$ for a given station at time slot $t$. Since the transmission of safety applications is in broadcast mode and has the highest priority, the back-off stage is disabled. The back-off state process is denoted by $(k)$. From Fig. 4 of the state transition diagram of the 1-D Markov chain for the safety applications process, the non-null transition probabilities are written as follows:

$$\begin{cases} P(k|0) = q_e/W_e, & 0 \le k \le W_e - 1 \\ P(k|k) = p_{e,coll}, & 1 \le k \le W_e - 1 \\ P(k|k+1) = 1 - p_{e,coll}, & 0 \le k \le W_e - 2 \end{cases} \quad (3)$$

Here, the non-null transition probabilities describe the unavailability of safety packets transmission in the buffer, hence changing the station into idle $(I_e)$ state after successful transmission is as follows;

$$\begin{cases} P(I_e|0) = 1 - q_e \\ P(I_e|I_e) = 1 - q_e \\ P(k|I_e) = q_e/W_e, & 0 \le k \le W_e - 1 \end{cases} \quad (4)$$

**TABLE 2.** Notations used in the analysis.

| Notations | Description | Notations | Description |
|---|---|---|---|
| $n$ | Number of vehicles | $p_{s,c}$ | probability of transmitting a service packet with collision caused by service packets only |
| $\tau_e$ | Transmission probability of safety applications | $p_{es,c}$ | probability of transmitting a packet with collision caused by safety and service packets |
| $\tau_s$ | Transmission probability of service applications | $T_{es,i}$ | Idle slot duration for both safety and service packets |
| $p_s$ | Probability of transmitting a service application | $T_s$ | Time duration to transmit a service application |
| $p_{e,f}$ | Probability of transmitting a safety packet with failure due to collision and frame error, | $T_{e,suc}$ | Duration for transmission a safety packet successfully |
| $p_{s,f}$ | Probability of transmitting a service packet with failure due to collision and frame error | $T_{e,c}$ | Duration for transmission with collision caused by a safety packet |
| $p_{e,coll}$ | Probability of transmitting a safety packet with collision | $T_{e,SAF\_ERR}$ | Duration for transmitting a safety packet unsuccessfully due to frame error |
| $p_{s,coll}$ | Probability of transmitting a service packet with collision | $T_{s,suc}$ | Duration for transmitting a service packet successfully |
| $q_e$ | Probability of at least one packet in the buffer for safety applications | $T_{s,c}$ | Duration for a transmission with collision caused by a service packet |
| $q_s$ | Probability of at least one packet in the buffer for service applications | $T_{s,WSA\_ERR}$ | Duration for transmitting a WSA packet unsuccessfully due to frame error |
| $I_i$ | Unavailability of ith packet transmissions in the buffer | $T_{s,RFS\_ERR}$ | Duration for transmitting a RFS packet unsuccessfully due to frame error |
| $p_{e,err}$ | Probability of safety frame error | $T_{s,ACK\_ERR}$ | Duration for transmitting a ACK packet unsuccessfully due to frame error |
| $p_{s,err}$ | Probability of service frame error | $T^{s,sch}_{data\_suc}$ | Duration for transmitting a service data packet over SCH successfully |
| $p_{BER}$ | Bit error rate probability | $T^{s,cch}_{DATA\_ERR}$ | Duration for transmitting a service data packet over SCH unsuccessfully |
| $p_{e,saf\_err}$ | Probability of safety frame error rate | $T_{saf}$ | Time duration to transmit a safety packet |
| $p_{s,wsa\_err}$ | Probability of WSA frame error rate | $T_{WSA}$ | Time duration to transmit a WSA packet |
| $p_{s,rfs\_err}$ | Probability of RFS frame error rate | $T_{RFS}$ | Time duration to transmit a RFS packet |
| $p_{s,ack\_err}$ | Probability of ACK frame error rate | $T_{ACK}$ | Time duration to transmit a ACK packet |
| $p_{s,data\_err}$ | Probability of data frame error rate | $T_{SIFS}$ | Time duration of SIFS (Short Inter-Frame Space) |
| $L_{saf}$ | Safety packet size | $T_{DIFS}$ | Time duration of DIFS (DCF Inter-Frame Space) |
| $L_{wsa}$ | WSA packet size | $T_{EIFS}$ | Time duration of EIFS (Extended Inter-frame Space) |
| $L_{rfs}$ | RFS packet size | $\delta$ | Propagation delay |
| $L_{ack}$ | ACK packet size | $T_{slot}$ | The average duration of the logical time slot that might be spent per state considering state of an idle, a successful transmission, a collision or a frame error |
| $L_{data}$ | Data packet size | $T_{cchi}$ | Duration of control channel interval |
| $p_{es,i}$ | probability of idle channel, | $T_{schi}$ | Duration of service channels interval |
| $p_{e,suc}$ | probability of successful transmission for safety packet | $N_{sch}$ | Number of service channels |
| $p_{e,SAF\_ERR}$ | probability of transmitting a safety packet unsuccessfully due to the frame error, | $T_{symbol}$ | Duration of a transmission of an OFDM symbol in 802.11a |
| $p_{s,suc}$ | probability of successful transmission for service packet | $L_{ser}$ | OFDM PHY layer service field size |
| $p_{s,WSA\_ERR}$ | probability of transmitting a WSA packet unsuccessfully due to the frame error | $L_{tail}$ | OFDM PHY layer tail fields size |
| $p_{s,RFS\_ERR}$ | probability of transmitting a RFS packet unsuccessfully due to the frame error | $N_{BpS}$ | The number of encoded bites per one symbol |
| $p_{s,ACK\_ERR}$ | probability of transmitting a ACK packet unsuccessfully due to the frame error | CW | Contention window |
| $p_{es,b}$ | probability of buy channel | $w_e$ | Contention window size for safety applications |
| $p_{e,c}$ | probability of transmitting a safety packet with collision caused by safety packets only | $w_{s,i}$ | Contention window size for service applications in the ith backoff stage |

Let $b_{e,k} = lim_{t\to\infty} \mathrm{P}\{b_e(t) = k$ be the stationary distribution of the 1-D Markov chain. Given this, $k \in (0, W_e - 1)$, where $W_e$ is the contention window of safety process. From the Markov chain, the stationary distribution of idle and back-off states of safety packets are denoted by $b_{I_e}$ and $b_{e,k}$ respectively, and calculated as follows:

$$b_{I_e} = (1 - q_e)\, b_{e,0} + (1 - q_e) b_{I_e} \tag{5}$$

$$b_{I_e} = \frac{1 - q_e}{q_e} b_{e,0} \tag{6}$$

$$b_{e,k} = \frac{W_e - k}{W_e} \frac{1}{1 - p_{e,coll}} b_{e,0} \quad for\ 1 \le k \le W_e - 1 \tag{7}$$

Therefore, by using the normalization condition for stationary distribution, we obtain (8):

$$1 = b_{I_e} + \sum_{k=0}^{W_e - 1} b_{e,k} \tag{8}$$

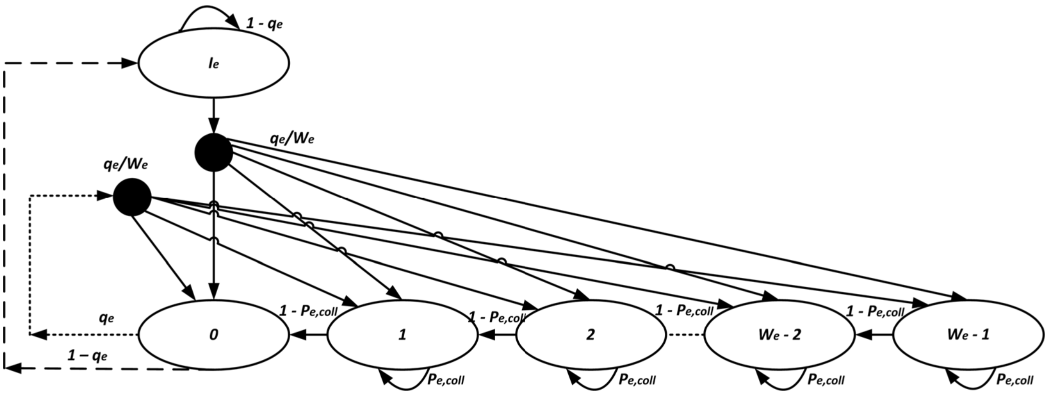


**FIGURE 4.** Markov chain model of safety applications.

Hence, from (8), we obtain (9)

$$b_{e,0} = \frac{2q_e(1 - p_{e,coll})}{2\left(1 - p_{e,coll}\right) + q_e(W_e - 1)} \tag{9}$$

Now we can express the probability of transmission frame $\tau_e$ of safety applications that a vehicle can transmit in a random chosen time slot. The vehicle can only transmit when the back-off time counter is zero ($b_{e,0}$).

$$\tau_e = b_{e,0} = \frac{2q_e(1 - p_{e,coll})}{2\left(1 - p_{e,coll}\right) + q_e(W_e - 1)} \tag{10}$$

In order to analyze the probability of frame transmission $\tau_s$, a 2-D Markov chain of service applications ($AC_2$) is developed as shown in Fig. 5. Let $s_s(t)$ and $b_s(t)$ be the random variable representing the back-off stage $(0, 1, 2, \ldots, m)$ and the value of the back-off timer $\left(0, 1, 2, \ldots, W_{s,i} - 1\right)$ for a given station at time slot $t$, respectively. Typically, the maximum value of the back-off timer relies on the back-off stage; thereby, these random variables are not independent.

$$W_{s,i} = \begin{cases} 2^{\mathrm{i}} W_{s,0}, & i \le m' \\ 2^{m'} W_{s,0}, & i > m' \end{cases} \tag{11}$$

$W_{s,0}$ is the initial size of the contention window, $W_{s,0} = (CW_{min} + 1)$, while $m'$ is the maximum number in which the contention window can be doubled, $W_{s,m'} = 2^{m'} W_{s,0} = (CW_{s,max} + 1)$. The value of $m'$ is assumed to be 5. The maximum value of back-off stages is denoted by $m$. Nevertheless, the two-dimensional $(s_s(t), b_s(t))$ processes are analyzed here with a discrete-time Markov chain at which the channel state changes. The state of this process is denoted by $(i, k)$. From Fig. 5 which displays the state transition diagram of 2-D Markov chain, the non-null transition probabilities are written as in (12). Here, the non-null transition probabilities describe the unavailability of packet transmissions in the buffer which is redirected into idle state ($I_s$) after a successful transmission.

$$\begin{cases} P(I_s|i, 0) = (1 - p_{s,f})(1 - q_s), & 0 \le i \le m - 1 \\ P(I_s|m, 0) = 1 - q_s & \\ P(I_s|I_s) = 1 - q_s & \\ P(0, k|I_s) = q_s/W_{s,0}, & 0 \le k \le W_{s,0} - 1 \end{cases} \tag{13}$$

Let $b_{s,i,k} = lim_{t\to\infty} P\{s_s(t) = i, b_s(t) = k\}$ be the stationary distribution of the Markov chain, where $i \in (0, m)$, $k \in \left(0, w_{s,i} - 1\right)$. First, note that:

$$b_{s,i-1,0} \cdot p_{s,f} = b_{s,i,0} \rightarrow b_{s,i,0} = p_{s,f}^{i} \cdot b_{s,0,0} \quad 0 < i \le \mathrm{m}$$
$$b_{s,m,0} = p_{s,f} b_{s,m-1,0} \tag{14}$$

Due to the chain regularities, for each $k \in (1, W_{s,i} - 1)$, the stationary distribution of idle and back-off states of service packets are denoted by $b_{I_s}$ and $b_{s,i,k}$ and calculated as follows:

$$b_{s,i,k} = \frac{W_{s,i} - k}{W_{s,i}\left(1 - p_{s,coll}\right)} \times \begin{cases} q_s\left(1 - p_{s,f}\right) \sum_{i=0}^{m-1} b_{s,i,0} + q_s b_{s,m,0} + q_s b_{I_s} & i = 0 \\ p_{s,f} \cdot b_{s,i-1,0} \quad 0 < i \le m & \end{cases} \tag{15}$$

Or

$$b_{s,i,k} = \frac{W_{s,i} - k}{W_{s,i}} \frac{1}{\left(1 - p_{s,coll}\right)} b_{s,i,0}$$

$$\begin{cases} P(i, k|i, k+1) = 1 - p_{s,coll}, & 0 \le k \le W_{s,i} - 2, \quad 0 \le i \le m \\ P(i, k|i, k) = p_{s,coll}, & 1 \le k \le W_{s,i} - 1, \quad 0 \le i \le m \\ P(i, k|i-1, 0) = p_{s,f}/W_{s,i}, & 0 \le k \le W_{s,i} - 1, \quad 1 \le i \le m \\ P(0, k|i, 0) = (1 - p_{s,f})/W_{s,0}, & 0 \le k \le W_{s,0} - 1, \quad 0 \le i \le m \\ P(0, k|m, 0) = 1/W_{s,0}, & 0 \le k \le W_{s,0} - 1, \end{cases} \tag{12}$$

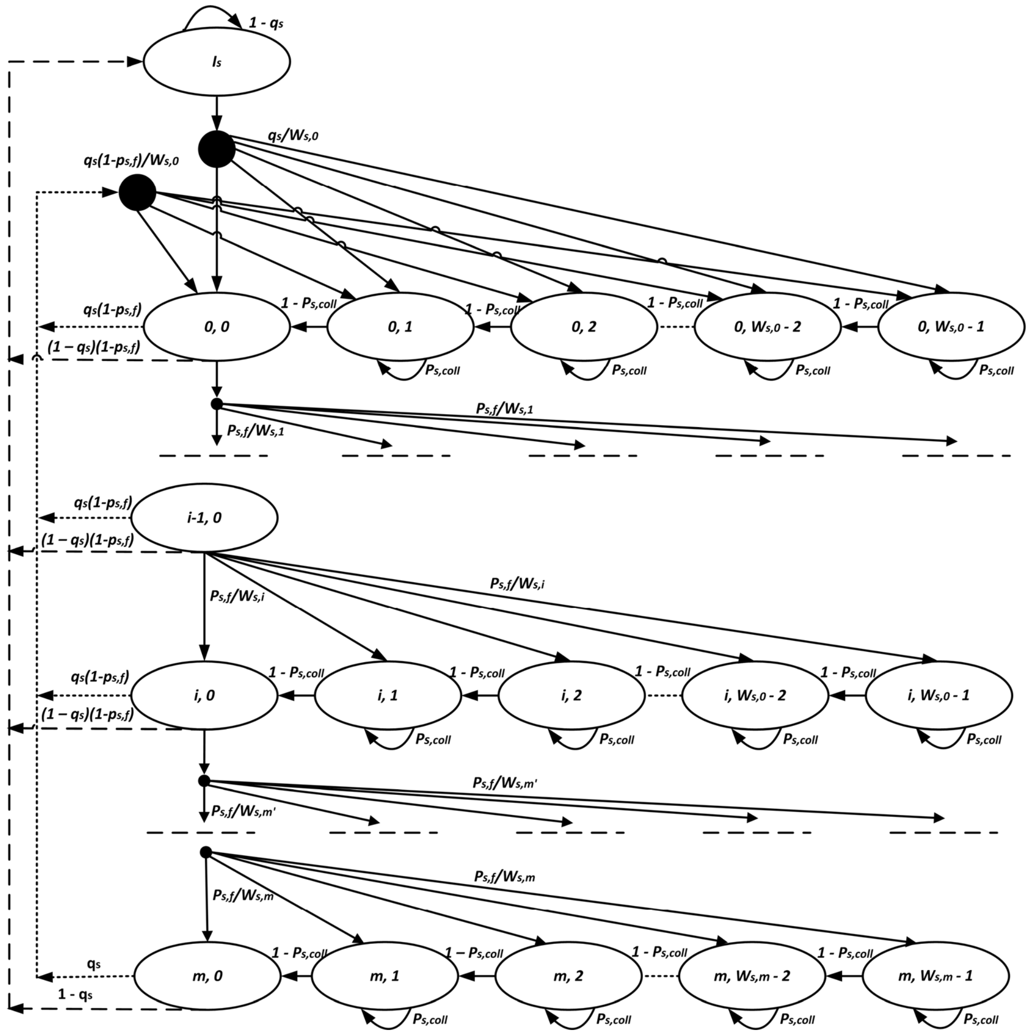


**FIGURE 5.** Markov chain model of service applications (WSAs packets).

$$for\ 0 \le i \le m, \quad 1 \le k \le W_{s,i} - 1 \tag{16}$$

$$b_{I_s} = (1-q_s)\left(1-p_{s,f}\right)\sum_{i=0}^{m-1} b_{s,i,0} + (1-q_s)\, b_{s,m,0} + (1-q_s)\, b_{I_s} \tag{17}$$

Mathematically solving (17), we obtain (18):

$$b_{I_s} = \frac{1-q_s}{q_s} b_{s,0,0} \tag{18}$$

Thereby, by using the normalization condition of stationary distribution, then

$$1 = \sum_{i=0}^{m}\sum_{k=0}^{W_{s,i}-1} b_{s,i,k} + b_{I_s} \tag{19}$$

Mathematically solving (19), we obtain (20), which depends on the values of $m$ and $m'$

$$b_{0,0} = \begin{cases} \dfrac{2(1-p_{s,f})(1-p_{s,coll})(1-2p_{s,f})q_s}{£}, & m \le m' \\ \dfrac{2(1-p_{s,f})(1-p_{s,coll})(1-2p_{s,f})q_s}{¥}, & m > m' \end{cases} \tag{20}$$

where:

$$£ = (1-2p_{s,f})(1-2p_{s,coll})\left(1-p_{s,f}^{m+1}\right)q_s + W_{s,0}\left(1-p_{s,f}\right)\left(1-\left(2p_{s,f}\right)^{m+1}\right)q_s + 2(1-p_{s,f})(1-p_{s,coll})(1-2p_{s,f})(1-q_s) \tag{21}$$

and:

$$¥ = (1-2p_{s,f})(1-2p_{s,coll})\left(1-p_{s,f}^{m+1}\right)q_s + W_0\left(1-p_f\right)\left(1-\left(2p_{s,f}\right)^{m'+1}\right)q_s + 2^{m'}W_{s,0}p_{s,f}^{m'+1}\left(1-p_{s,f}^{m-m'}\right)\left(1-2p_{s,f}\right)q_s + 2(1-p_{s,f})(1-p_{s,coll})(1-2p_{s,f})q_s \tag{22}$$

We can now express the probability of frame transmission $\tau_s$ for service applications where a vehicle can transmit a service packet in a random chosen time slot. The vehicle can only transmit when the back-off time counter is zero ($b_{s,i,0}$)

regardless of the back-off stage as in (23).

$$\tau_s = \sum_{i=0}^{m} b_{i,0} = b_{0,0} \frac{1 - p_{s,f}^{m+1}}{1 - p_{s,f}} \tag{23}$$

We notice in (10) and (23) that the values of $\tau_e$, $\tau_s$ depend on the conditional collision $p_{e,coll}$, $p_{s,coll}$, and failure $p_{s,f}$ probabilities, as well as probability of at least one packet in buffer $q_e$, $q_s$ for safety and service applications, respectively. The collision probability occurs when more than one vehicle is transmitting in the same time slot.

### B. FAILURE $p_f$ AND COLLISION $p_{coll}$ PROBABILITIES

The transmission failure probabilities $p_{e,f}$ and $p_{s,f}$ of safety and service packets are derived respectively as follows:

$$\begin{cases} p_{e,f} = 1 - (1 - p_{e,coll})(1 - p_{e,err}) \\ p_{s,f} = 1 - (1 - p_{s,coll})(1 - p_{s,err}) \end{cases} \tag{24}$$

where $p_{e,err}$ and $p_{s,err}$ denote the probability of frame error for safety and service packets respectively.

$$p_{e,err} = 1 - \left(1 - p_{e,saf\_err}\right) \tag{25}$$

$$p_{s,err} = 1 - \left(1 - p_{s,wsa\_err}\right)\left(1 - p_{s,rfs\_err}\right) \times \left(1 - p_{s,ack\_err}\right) \tag{26}$$

where $p_{e,saf\_err}$, $p_{s,wsa\_err}$, $p_{s,rfs\_err}$, and $p_{s,ack\_err}$ denote the Frame Error Rate (FERs) of safety frame error, and WSA/RFS/ACK frames error respectively. The probability of these errors can be computed from bit error probability (i.e. BER) $p_{BER}$ as follows [33]:

$$\begin{cases} p_{e,saf\_err} = 1 - (1 - p_{BER})^{L_{saf}} \\ p_{s,wsa\_err} = 1 - (1 - p_{BER})^{L_{wsa}} \\ p_{s,req\_err} = 1 - (1 - p_{BER})^{L_{rfs}} \\ p_{s,ack\_err} = 1 - (1 - p_{BER})^{L_{ack}} \end{cases} \tag{27}$$

The probability of collision transmission for safety $p_{e,coll}$ and service $p_{s,coll}$ packets are defined respectively as follows:

$$\begin{cases} p_{e,coll} = 1 - (1 - \tau_e)^{n-1} (1 - \tau_s)^n \\ p_{s,coll} = 1 - (1 - \tau_s)^{n-1} (1 - \tau_e)^n \end{cases} \tag{28}$$

Then,

$$\begin{cases} p_{e,f} = 1 - (1 - \tau_e)^{n-1} (1 - \tau_s)^n \left(1 - p_{e,err}\right) \\ p_{s,f} = 1 - (1 - \tau_s)^{n-1} (1 - \tau_e)^n \left(1 - p_{s,err}\right) \end{cases} \tag{29}$$

From (10), (23), and (29), we can solve the two unknown variables, $\tau_e$, $\tau_s$, $p_{e,f}$ and $p_{s,f}$ by using numerical techniques in order to calculate the transmission and failure probabilities for safety and service applications respectively.

### C. TIME ANALYSIS FOR SAFETY AND WSA TRANSMISSION

Our proposed scheme considers three types of thresholds in Safety and WSA Transmission probabilities, sparse, congestion, and Queuefreeze thresholds. These thresholds are determined by RSU according to the traffic conditions in the vehicular environment, as described above. However, in every time slot during the contention-based MAC scheme, the state of the channel could be idle, successful transmission, collision transmission or failure transmission due to the frame error.

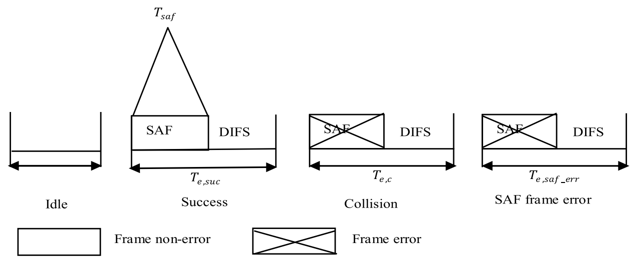


**FIGURE 6.** Time slots durations of channel states for the safety packets on CCH.

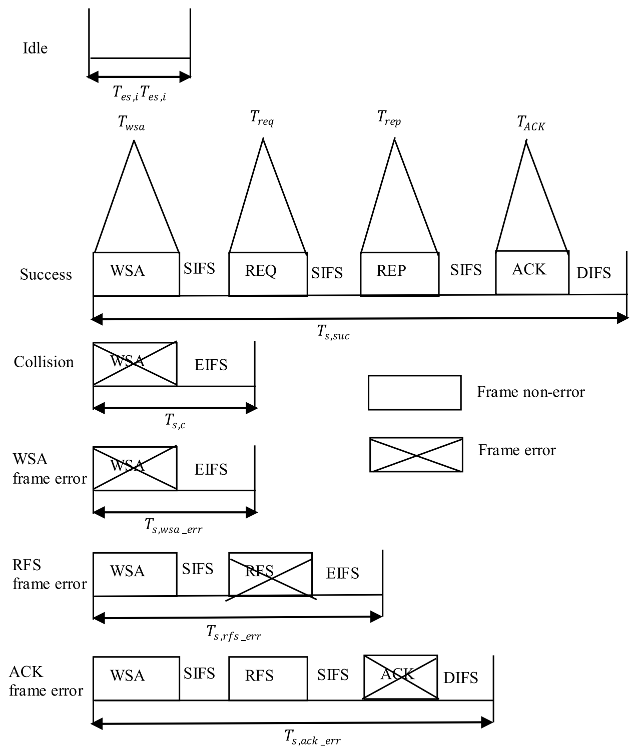


**FIGURE 7.** Time slots durations of channel states for the WSA/RFS/ACK packets on CCH.

Figs. 6 and 7 show the possibilities of time slot durations during the transmission process using the contention-based MAC scheme for a safety packet, WSA packet, and RFS/ACK packets. Moreover, Fig. 8 shows show the possibilities of time slot durations during the transmission process in SCHs during SCHI.

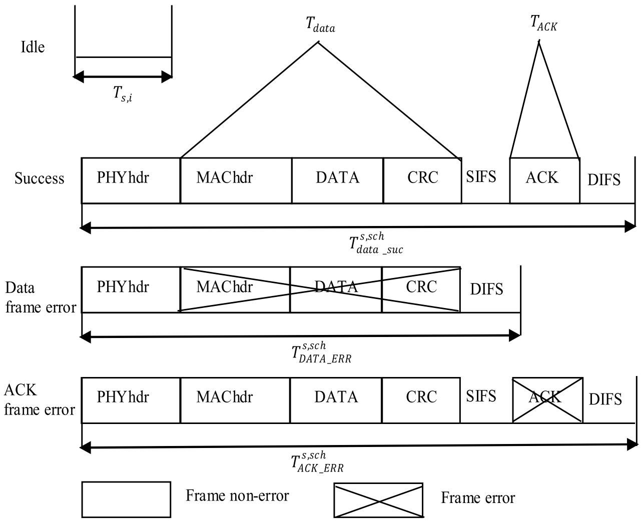


**FIGURE 8.** Time slots durations of channel states for the service data packets on SCHs.

### 1) SPARSE THRESHOLD

In this threshold, the time analysis of transmission probability of safety, WSA and RFS/ACK packets in our proposed scheme is same as in the legacy standard method. Thus, the probabilities of channel states are given by (30). Accordingly, the transmission time is calculated with adoption broadcast and unicast mechanisms as in (31).

$$\begin{cases} T_{es,i} = aSlotTime = \sigma \\ T_{e,suc} = T_{e,c} = T_{e,SAF\_ERR} = T_{saf} + \delta + T_{DIFS} \\ T_{s,suc} = T_{wsa} + T_{rfs} + T_{ack} + 3\delta + 2T_{SIFS} + T_{DIFS} \\ T_{s,c} = T_{wsa} + \delta + T_{EIFS} \\ T_{s,WSA\_ERR} = T_{wsa} + \delta + T_{EIFS} \\ T_{s,RFS\_ERR} = T_{wsa} + T_{SIFS} + T_{rfs} + 2\delta + T_{EIFS} \\ T_{s,ACK\_ERR} = T_{s,suc} \end{cases} \quad (31)$$

### 2) CONGESTION THRESHOLD

In this threshold, unlike legacy standard method, the PNP mechanism is executed in SCHs during SCHI. Thus, the control packets (RFS/ACK) will not be transmitted over CCH. Hence, the probabilities of channel states in this stage are given by (32)

$$\begin{cases} p_{es,i} = (1-\tau_e)^n(1-\tau_s)^n \\ p_{e,suc} = n\tau_e(1-\tau_e)^{n-1}(1-\tau_s)^n(1-p_{e,saf\_err}) \\ p_{e,SAF\_ERR} = n\tau_e(1-\tau_e)^{n-1}(1-\tau_s)^n p_{e,saf\_err} \\ p_{s,suc} = n\tau_s(1-\tau_s)^{n-1}(1-\tau_e)^n(1-p_{s,wsa\_err}) \\ p_{s,WSA\_ERR} = n\tau_s(1-\tau_s)^{n-1}(1-\tau_e)^n p_{s,wsa\_err} \\ p_{es,b} = 1-p_{es,i} = 1-(1-\tau_s)^n(1-\tau_e)^n \\ p_{e,c} = (1-\tau_s)^n\left(1-(1-\tau_e)^n - n\tau_e(1-\tau_e)^{n-1}\right) \\ p_{s,c} = (1-\tau_e)^n\left(1-(1-\tau_s)^n - n\tau_s(1-\tau_s)^{n-1}\right) \\ p_{s,RFS\_ERR} = p_{s,ACK\_ERR} = 0 \\ p_{es,c} = p_{es,b} - p_{e,suc} - p_{s,suc} - p_{e,c} - p_{s,c} \end{cases} \quad (32)$$

As a consequence, the transmission time of safety and WSA packets in this stage are calculated with adoption broadcast mechanisms only as in (33).

$$\begin{cases} T_{es,i} = aSlotTime = \sigma \\ T_{e,suc} = T_{e,c} = T_{e,SAF\_ERR} = T_{saf} + \delta + T_{DIFS} \\ T_{s,suc} = T_{wsa} + \delta + T_{DIFS} \\ T_{s,c} = T_{s,WSA\_ERR} = T_{wsa} + \delta + T_{EIFS} \\ T_{s,RFS\_ERR} = T_{s,ACK\_ERR} = 0 \end{cases} \quad (33)$$

### 3) QUEUEFREEZE THRESHOLD

In this threshold, the whole SI (100 ms) will be allocated to the CCH only, and thus the vehicles can provide reliable and real-time dissemination for safety applications. This stage does not need any channel coordination and hence there is no transmission opportunity for service application in SCHs. The probabilities of channel states in this stage are given by (34)

$$\begin{cases} p_{e,i} = (1-\tau_e)^n \\ p_{e,suc} = n\tau_e(1-\tau_e)^{n-1}(1-p_{e,saf\_err}) \\ p_{e,SAF_{ERR}} = n\tau_e(1-\tau_e)^{n-1}p_{e,saf_{err}} \\ p_{e,b} = 1-p_{e,i} = 1-(1-\tau_e)^n \\ p_{e,c} = 1-(1-\tau_e)^n - n\tau_e(1-\tau_e)^{n-1} \\ p_s = 0 \end{cases} \quad (34)$$

$$\begin{cases} p_{es,i} = (1-\tau_e)^n(1-\tau_s)^n \\ p_{e,suc} = n\tau_e(1-\tau_e)^{n-1}(1-\tau_s)^n(1-p_{e,saf\_err}) \\ p_{e,SAF\_ERR} = n\tau_e(1-\tau_e)^{n-1}(1-\tau_s)^n p_{e,saf\_err} \\ p_{s,suc} = n\tau_s(1-\tau_s)^{n-1}(1-\tau_e)^n(1-p_{s,wsa\_err})(1-p_{s,rfs\_err})(1-p_{s,ack\_err}) \\ p_{s,WSA\_ERR} = n\tau_s(1-\tau_s)^{n-1}(1-\tau_e)^n p_{s,wsa\_err} \\ p_{s,RFS\_ERR} = n\tau_s(1-\tau_s)^{n-1}(1-\tau_e)^n(1-p_{s,wsa\_err})p_{s,rfs\_err} \\ p_{s,ACK\_ERR} = n\tau_s(1-\tau_s)^{n-1}(1-\tau_e)^n\left(1-p_{s,wsa\_err}\right)\left(1-p_{s,rfs_{err}}\right)p_{s,ack\_err} \\ p_{es,b} = 1-p_{es,i} = 1-(1-\tau_s)^n(1-\tau_e)^n \\ p_{e,c} = (1-\tau_s)^n\left(1-(1-\tau_e)^n - n\tau_e(1-\tau_e)^{n-1}\right) \\ p_{s,c} = (1-\tau_e)^n\left(1-(1-\tau_s)^n - n\tau_s(1-\tau_s)^{n-1}\right) \\ p_{es,c} = p_{es,b} - p_{e,suc} - p_{s,suc} - p_{e,c} - p_{s,c} \end{cases} \quad (30)$$

Consequently, the transmission time of a safety packet in this stage are calculated by (35).

$$\begin{cases} T_{e,i} = aSlotTime = \sigma \\ T_{e,suc} = T_{e,c} = T_{e,SAF\_ERR} = T_{saf} + \delta + T_{DIFS} \\ T_s = 0 \end{cases} \tag{35}$$

If we assume that the service data packet size is constant, then the time slot duration to transmit a service data packet over the SCH based on the contention-free MAC scheme is expressed by:

$$\begin{cases} T^{s,sch}_{data\_suc} = T_h + T_{data} + T_{ack} + 2\delta + T_{SIFS} + T_{DIFS} \\ T^{s,sch}_{DATA\_ERR} = T_h + T_{data} + \delta + T_{EIFS} \\ T^{s,sch}_{ACK\_ERR} = T_{s,DATA\_SUC} \end{cases} \tag{36}$$

Where $T_{data} = L_{pld}/R$, $L_{pld}$ represents the payload of the service data packet, and $R$ is the transmission data rate. $T_{saf}, T_{wsa}, T_{rfs}, T_{data}$ and $T_{ack}$ are PHY-layer dependent, and frame transmissions in the unit of Orthogonal Frequency Division Multiplexing (OFDM) symbols are given by [34]:

$$\begin{cases} T_{saf} = T_{symbol}\left\lceil \frac{L_{ser}+L_{tail}+L_{saf}}{N_{BpS}} \right\rceil \\ T_{wsa} = T_{symbol}\left\lceil \frac{L_{ser}+L_{tail}+L_{wsa}}{N_{BpS}} \right\rceil \\ T_{rfs} = T_{symbol}\left\lceil \frac{L_{ser}+L_{tail}+L_{rfs}}{N_{BpS}} \right\rceil \\ T_{data} = T_{symbol}\left\lceil \frac{L_{ser}+L_{tail}+L_{data}}{N_{BpS}} \right\rceil \\ T_{ack} = T_{symbol}\left\lceil \frac{L_{ser}+L_{tail}+L_{ack}}{N_{BpS}} \right\rceil \end{cases} \tag{37}$$

Finally, the duration of the logical time slots $T_{slot}$ per state in CCH for the three stages (sparse, congestion, and queue-freeze) are given respectively by (38)-(40):

$$\begin{aligned} T^{AMAC\_sparse}_{slot} = T^{1609.4}_{slot} &= p_{es,i}T_{es,i} + p_{e,suc}T_{e,suc} \\ &+ p_{s,suc}T_{s,suc} + p_{e,c}T_{e,c} + p_{s,c}T_{s,c} \\ &+ p_{e,SAF\_ERR}T_{e,SAF\_ERR} \\ &+ p_{s,WSA\_ERR}T_{s,WSA\_ERR} \\ &+ p_{s,RFS\_ERR}T_{s,RFS\_ERR} \\ &+ p_{s,ACK\_ERR}T_{s,ACK\_ERR} \\ &+ p_{es,c}\max(T_{e,c}, T_{s,c}) \end{aligned} \tag{38}$$

$$\begin{aligned} T^{AMAC\_congestion}_{slot} &= p_{es,i}T_{es,i} + p_{e,suc}T_{e,suc} \\ &+ p_{s,suc}T_{s,suc} + p_{e,c}T_{e,c} + p_{s,c}T_{s,c} \\ &+ p_{e,SAF\_ERR}T_{e,SAF\_ERR} \\ &+ p_{s,WSA\_ERR}T_{s,WSA\_ERR} \\ &+ p_{es,c}\max(T_{e,c}T_{s,c}) \end{aligned} \tag{39}$$

$$\begin{aligned} T^{AMAC\_queuefreeze}_{slot} &= p_{e,i}T_{e,i} + p_{e,suc}T_{e,suc} + p_{e,c}T_{e,c} \\ &+ p_{e,SAF\_ERR}T_{e,SAF\_ERR} \end{aligned} \tag{40}$$

Consequently, the average duration of the overall logical time slots $T^{AMAC\_overall}_{slot}$ for our proposed scheme is defined by (41):

$$T^{AMAC\_overall}_{slot} = \frac{T^{queuefreez}_{slot} + T^{congestion}_{slot} + T^{sparse}_{slot}}{3} \tag{41}$$

However, in the next equations, $T_{slot}$ denotes the logical slot time durations for both, either for $T^{1609.4}_{slot}$ legacy scheme or for $T^{AMAC\_overall}_{slot}$ AMAC scheme.

In this model, we assume the Poisson distribution model, in which the inter arrival time is exponentially distributed. Then, from the average duration of the logical time slot $T_{slot}$, the load equation of queue probability, $q_e$ and $q_s$ for safety and service applications is given respectively by [35]:

$$\begin{cases} q_e = 1 - e^{-2\lambda_e T_{slot}} \\ q_s = 1 - e^{-2\lambda_s T_{slot}} \end{cases} \tag{42}$$

The packet delivery ratio (PDR) of the safety application is derived as the probability of having a successful transmission during a given time slot over the average number of vehicles transmitting packets in a generic time slot [21];

$$PDR = \frac{p_{e,suc}}{n_e \tau_e} = (1-\tau_e)^{n-1}(1-\tau_s)^n \tag{43}$$

The average time slot of a safety packet to execute the back-off is given by $\frac{(w_e-1)}{2}$. Thereby, the average total service time $E[X_e]$ of a safety packet which comprises the average back-off duration $\frac{(w_e-1)}{2} \times T_{slot}$ along with the transmission time is expressed by:

$$E[X_e] = \frac{(w_e-1)}{2} \times T_{slot} + T_{e,suc} \tag{44}$$

In this model, each vehicle is modeled as two independent *M/M/1* queues under an infinite buffer size along with packet arrival rate $2\lambda_e$ and the mean service rates $\mu_e = 1/E[X_e]$.

The safety packets in one queue in the IEEE 1609.4 protocol already have the delay of $T_{schi}/2$ before being broadcasted, so the average delay of the safety packets is given by:

$$E[D_e] = \frac{T_{cchi} + T_{schi}}{4} + \frac{1}{\mu_e - 2\lambda_e} \tag{45}$$

The average number of WSA packets successfully transmitted over the CCH during the CCHI is calculated by:

$$N_{s,suc} = \frac{T_{cchi}}{T_{slot}} \times p_{s,suc} \tag{46}$$

The throughput is described as the amount of bandwidth that is allocated to the SCHs per second; thus, the saturated throughput $S$ of the service applications over the SCHs is computed as follows:

$$S_s = \frac{T_{schi} \times N_{sch} \times L_{pld} \times N_{s,suc}}{T^{s,sch}_{data\_suc} + T^{s,cch}_{DATA\_ERR} + T^{s,cch}_{ACK\_ERR}} \tag{47}$$

## V. PERFORMANCE EVALUATION

In this section, we present the numerical and simulation results of the proposed AMAC scheme to obtain a better understanding of the behavior of the safety and service packets transmission in VANET-based MAC layer. The numerical results for the AMAC scheme were conducted by using MATLAB, while the extensive simulations to validate the proposed analytical models were carried out by Simulation of Urban Mobility (SUMO) and network simulator (ns-2.34) simulators. SUMO simulates the mobility traffic in the vehicular environment, while NS-2 simulates the network. For vehicle mobility, the Shah Alam highway was taken from OpenStreetMap (OSM) to represent a highway environment. The mobility pattern was set to Random Waypoint Mobility with Obstacle Avoidance, while the driving model was set to Intelligent Driving Model (IDM) with Intersection Management and Lane Changing. As shown in Fig. 9, the selected area in Shah Alam highway is approximately 2 km with six lanes. The simulation scenario includes 100 vehicles with a GPS and a single-radio WAVE communication device. The speed of vehicles is 60 km/h.

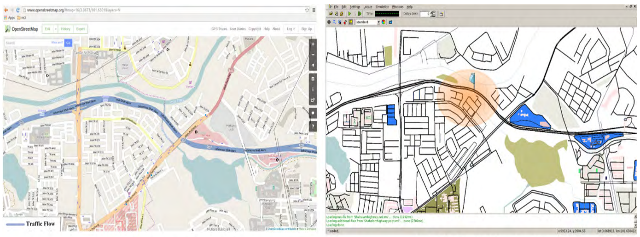
(a) Shah Alam Highway in OSM Map. (b) SUMO Graphical User Interface.

**FIGURE 9. SUMO Simulator for Vehicular Traffic Simulation (Shah Alam Highway).**

We consider one CCH and six SCHs with the same transmission data rate of 6 Mbps (QPSK modulation) based on standard specifications. Vehicles $n$ and traffic arrival rate $\lambda_e, \lambda_s$ at the MAC layer are generated according to the Poisson distribution process. Thereby, the traffic density can be increased either by increasing the number of vehicles $n$ or the traffic arrival rate $\lambda_e, \lambda_s$. Channel congestion in VANETs can be controlled by adopting a dynamic transmission range (power), CW size, and packet arrival based on the network conditions. We assume here the value of $BER = 10^{-5}$ for the channel condition, which is one of the most affected and sensitive values for the channel BER in a comparatively noisy, channel fading and unreliable wireless environment [36], [37]. All vehicles and RSU are within the transmission range of each other and can act as service providers and service users. The rest of the parameters for both analytical model and simulations are summarized in Table 3.

Fig. 10 (a-c) illustrates the collision probability, average delay, and PDR for safety packets with changing the number of vehicles in different packet arrival rate, and the CW size for safety packets is fixed $W_e = 8$ while the initial CW size

**TABLE 3. Parameters values.**

| Parameters | value |
|---|---|
| Number of SCHs | 6 |
| Number of CCH | 1 |
| Transmission data rate for each channel | 6 Mbps |
| MAC header | 272 bits |
| PHY header | 128 bits |
| Service packet size | 8000 bits |
| Safety packet size | 800 bits |
| WSA | 800 bits |
| RFS | 160 bits |
| ACK | 112 bits |
| SIFS | 16 $\mu s$ |
| Time slot $\sigma$ | 9 $\mu s$ |
| DIFS | 34 $\mu s$ |
| Propagation delay $\delta$ | 1 $\mu s$ |
| $L_{ser}$ | 16 bits |
| $L_{tail}$ | 6 bits |
| $T_{symbol}$ ($\mu s$) | 4 |
| $N_{BpS}$ | 24 |
| $W_e$ | 8 |
| $W_{s,0}$ | 16 |
| Short retry limit | 5 |
| Long retry limit | 7 |
| Frequency | 5.9 GHz |
| Number of vehicles | 10-100 |

for WSA packets $W_{s,0}$ is 16. We have chosen these three performance metrics to study the real congestion on the CCH and to obtain the best load balancing (increase reliability of safety applications). We can notice from Fig. 10 that as the number of vehicles and the packet arrival rate increase, collisions and delay increase, while the PDR decreases for safety packets. This is owing to a huge number of safety packets attempt to access the channel for transmission under fixed CW size value, resulting in high collisions and low PDR of safety packets. However, the Fig. 10 shows that the network is stable only when the packet arrival rate $\lambda_e = \lambda_s = 10pps$, although the number of vehicles increases. This is proof that $W_e = 8$, $W_{s,0} = 16$ are the best choices for the network when the $\lambda_e = \lambda_s = 10pps$. When the packet arrival rate increases ($\lambda_e = \lambda_s > 10$), the degradation of the three performance metrics is manifested as the number of vehicles increases, and thus a dynamic CWs sizes should be used based on the number of vehicles on the network.

Fig. 11 (a-c) illustrates the collision probability, average delay, and PDR for safety packets with changing the number of vehicles in different CWs sizes values and fixed packet arrival rate $\lambda_e = \lambda_s = 25pps$, respectively. Unlike [23] and [24] who chose the best values of the CW size in their study based on the delay metric, our study

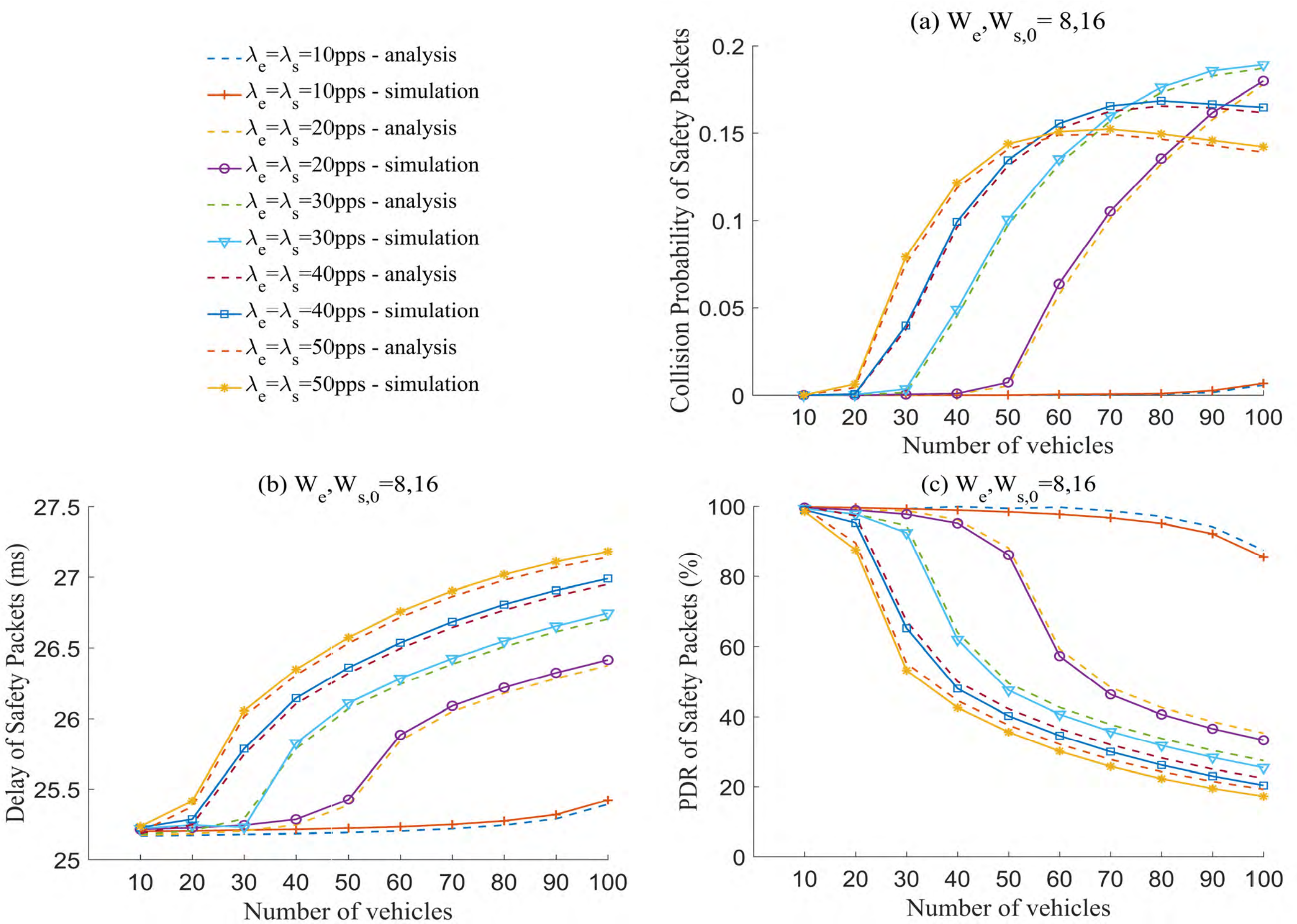


**FIGURE 10.** Performance metrics evaluation of the IEEE 1609.4 on CCH in terms of number of vehicles and packet arrival rate, with $W_e = 8$, $W_{s,0} = 16$. (a) Collision probability of safety packets. (b) Average delay of safety packets. (c) PDR of safety packets.

**TABLE 4.** Best CWs sizes for different vehicles numbers.

| Number of vehicles | 0-30 | 40 | 50-100 |
|---|---|---|---|
| Best CWs sizes, $W_e, W_{s,i}$ | 8, 16 | 16, 32 | 32, 64 |

focuses more on getting low collision and high PDR for safety packets, taking into account the delay metric as well. However, when choosing the CW size value of safety packets, the initail CW size value of service packets (WSAs) must be doubled, in order to fulfill priorities on the system according to the legacy specifications as shown in Fig. 11. It is easy to find from Fig. 11 that the collisions increase and the PDR decreases with increasing the number of vehicles on the netowk. Table 4 lists the best values of the CW size for safety packets, including the best initial values of the CW size for service packets adapting to the different number of vehicles. As seen in Fig. 11 that in light network conditions (e.g. numner of vehicles $n \leq 30$ *vehicles*), $W_e = 8$, $W_{s,0} = 16$ will be the best choice. The CWs sizes will be doubled to $W_e = 16$, $W_{s,0} = 32$, when the number of vehicles increase to 40 vehicles, ($30 < n \leq 40$). Finally, when the traffic conditions increase from muderate to heavy ($40 < n \leq 100$), the CWs sizes should be increased to $W_e = 32$, $W_{s,0} = 64$.

The optimal ratio of transmission probabilities for the packets with different priorities under various numbers of vehicles and arrival rates of $\lambda_e$ and $\lambda_s$ packets are mathematically analyzed in Fig. 12. The Fig. shows that the ratio of transmission probabilities for the packets strongly depends on the number of vehicles and traffic arrival rate. Consequently, it is notable that, when the traffic arrival rate for both safety and WSA packets is light, the network size is unsaturated, and hence the channel status is not congested and the ratio is slightly changed. However, with an increase of traffic arrival rate, the ratio of transmission probabilities significantly increases with growth in the number of vehicles. If the traffic arrival rate increases, the ratio becomes larger though the number of vehicles is fixed. For instance, when $n = 60$ *vehicles*, the ratio is 26.45 if $\lambda_e = \lambda_s = 1,000$ *pps*, while the ratio is 3.31 when $\lambda_e = \lambda_s = 50$ *pps*. This is owing to the fact that the increase of traffic arrival rate along with the number of vehicles will absolutely cause more collisions on the CCH, and decrease the transmission

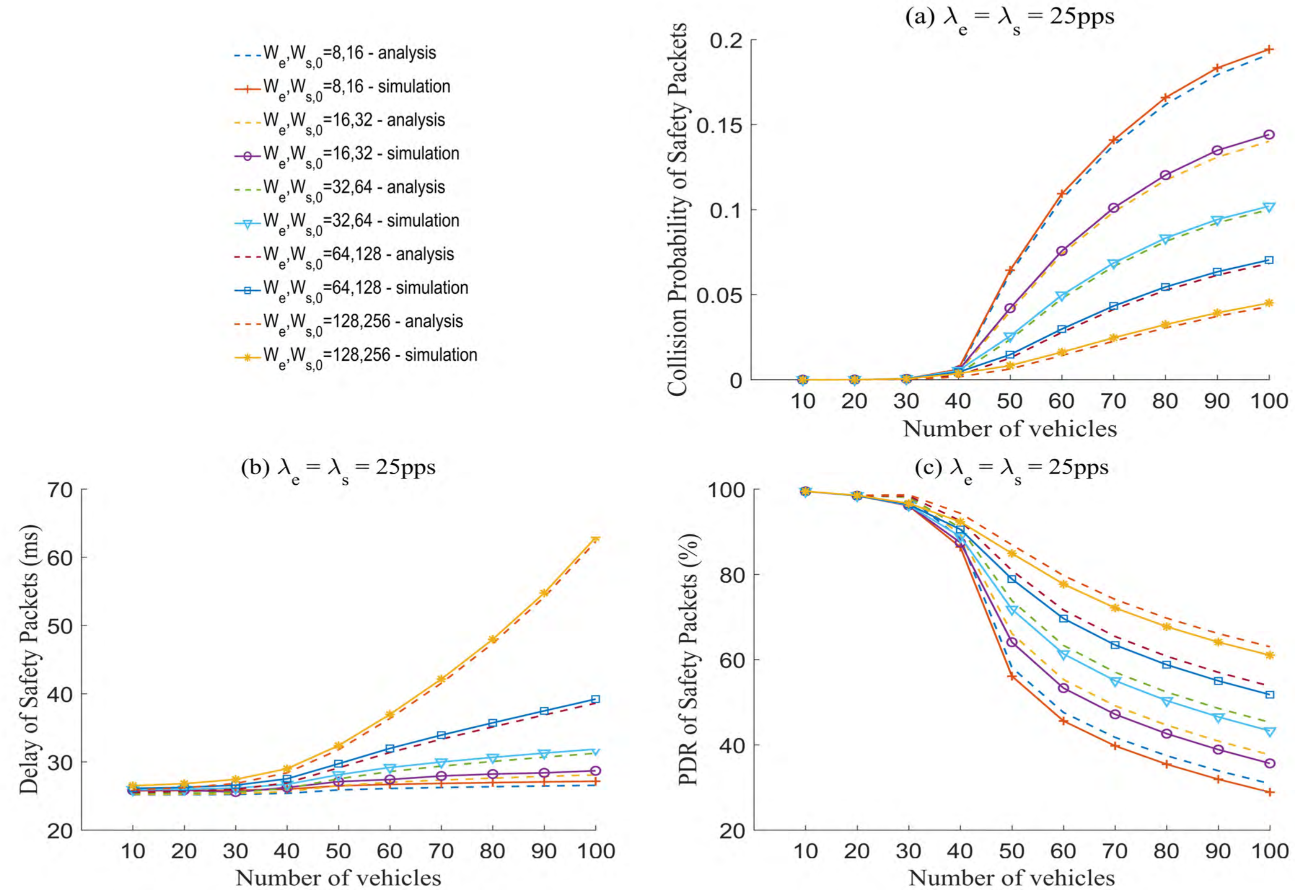


**FIGURE 11.** Performance metrics evaluation of the IEEE 1609.4 on CCH in terms of number of vehicles and contention windows sizes values, with $\lambda_e = \lambda_s = 25$ *pps*. (a) Collision probability of safety packets. (b) Average delay of safety packets. (c) PDR of safety packets.

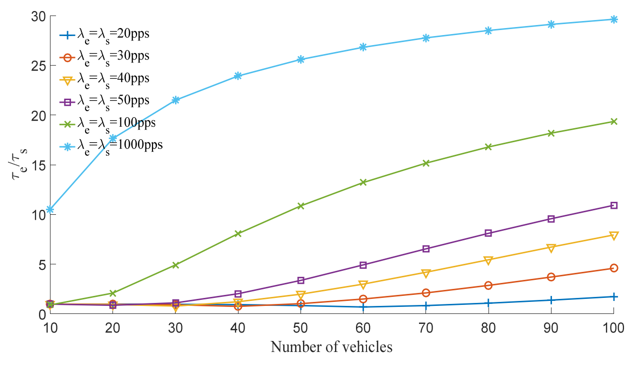


**FIGURE 12.** Optimal ratio of transmission probabilities.

probability of WSA packets due to more back-off vehicles and the prioritized transmission of the safety packets. In addition, the short retry limit is applied to the analytical model for WSA packets in order to accommodate the 802.11p specifications, which means that the vehicles keep contending for the channel. Whenever the packets face a collision, the new back-off algorithm will be generated with doubling the CW size value to minimize the collision probability with other transmitting vehicles till doubling the CW size reaches the maximum value of $2^{m'}W_s$. In $m'$ stage, if the packet still fails in transmission, it keeps contending for the channel with the same CW size of $2^{m'}W_s$ till the short retry limit is exhausted. Thus, this approach also leads to more collisions of the WSA packets since the back-off value remains the same from stage $m'$ to stage $m$.

In our work, we assume a constant packet arrival rate $\lambda_e = \lambda_s = 25$ *pps* as in [21], while the number of vehicles $n$ is varied, and the CWs sizes are dynamic based on the vehicle density estimation to control the CCH congestion. In this part we also investigate the collisions, delay and PDR of safety packets on the CCH, as well as the system throughput of service packets on the SCHs for the proposed AMAC scheme and legacy. Fig. 13 shows the collision probability of safety packets on the CCH versus the number of vehicles when $\lambda_e = \lambda_s = 25$ *pps*. It is notable from Fig. 13 that when the network traffic is relatively sparse ($n \leq 30$ *vehicles*), the value of collision probability is low and the network is stable for both schemes. In contrast, when the network traffic becomes dense ($n > 30$ *vehicles*), the value of collision probability is high. This is due to the fact that the increment of vehicles number leads to higher competition among the vehicles to access the channel in the network, which definitely prompts a higher

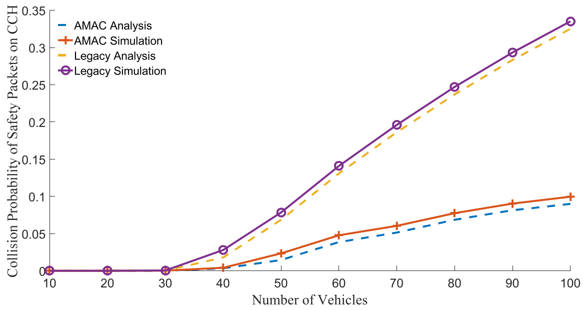


**FIGURE 13.** Collision probability of safety packets on CCH versus number of vehcles, ($\lambda_e = \lambda_s = 25$ *pps*).

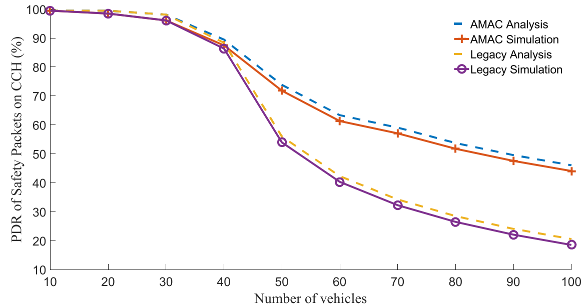


**FIGURE 15.** Packet delivery ratio of safety applications on CCH under different number of vehcles, ($\lambda_e = \lambda_s = 25$ *pps*).

collision rate. Howevere, Fig. 13 shows that when the network size becomes larger and the CCH is congested, the collision value in the proposed AMAC scheme is lower compared with the legacy standard. This is because, unlike the legacy standard, the AMAC scheme offers two approches, collision-aware transmission packet mechanism, and an adaptive PNP mechanism between service providers and users. Explicitly, when the traffic condition is heavy and the CCH utilization is congested, the AMAC scheme increases the initial CWs among vehicles and also performs the PNP between service providers and users on the SCHs during the SCHI. These two approaches can improve the time diversity among vehicles and also reduce the types of competing packets for transmission over the CCH during the CCHI. As a result, the safety packets collisions will be alleviated on the CCH. From Fig. 13 we can observe that the AMAC scheme reduces the safety packet collisions on the CCH by 67.70 %.

Fig. 14 describes the effect of the various numbers of vehicles on the average delay of safety packets over the CCH. It can be seen from the Fig. 14 that the significant effect on the delay on the CCH starts when the number of vehicles increases from moderate to heavy ($n > 30$ *vehicles*). It is clear that the number of vehicles is directly proportional to the average service times $E[X_e] = 1/\mu_e$. Explicitly, as the number of vehicles increases, the queue and service time increase as well and this certainly leads to longer delay for safety packets to access the channel.

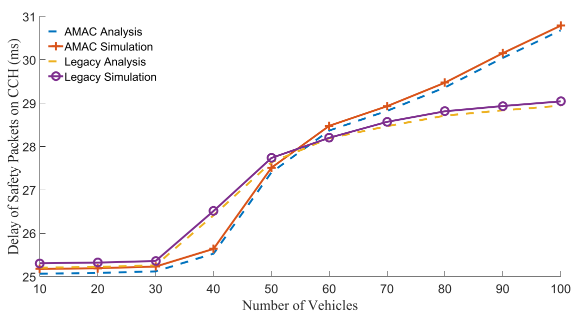


**FIGURE 14.** Average delay of safety packets on CCH versus number of vehicles, ($\lambda_e = \lambda_s = 25$ *pps*).

However, we can observe from Fig. 14 that, in the normal wireless vehicular environments ($n \leq 30$ *vehicles*), the performance for both the legacy standard and AMAC scheme is quite similar, while the legacy standard outperforms the proposed AMAC scheme when the network size becomes larger. This is because under heavy conditions, the AMAC scheme adopts the collision-aware transmission packet mechanism increasing the initial CWs for both safety and service packets. As a result, this will cause a slight increase in delay and reduce the collisions of safety packets. As shown in Fig. 14 that, the AMAC scheme increases the delay on the CCH by 1.353%, which is still very insignificant value compared to collision reduction for safety packets.

Fig. 15 represents the performance of the AMAC scheme and the legacy standard in terms of PDR with respect to the different numbers of vehicles when $\lambda_e = \lambda_s = 25\,pps$. Fig. 15 shows that along with the increase of vehicles number, the PDR decreases rapidly. The reason for this observation is that as the number of vehicles increases, a lot of packets will be lost due to serious collisions that may occur on the CCH, which will adversely affect the PDR of safety packets.

However, Fig 15 displays that under light traffic condition when $n \leq 40$ *vehicles*, the PDR for both schemes are high, while when traffic condition is high ($n > 40$ *vehicles*), the significant deterioration in the PDR is manifested. However, the proposed AMAC scheme improves the PDR on the CCH by 24.582 % compared with the legacy standard. This is because a collision-aware packet transmission and an adaptive PNP mechanisms are proposed by the AMAC scheme.

The throughput is described as the amount of bandwidth that is allocated to the SCHs per second. Fig. 16 illustrates the system throughput on the SCHs with respect to the different numbers of vehicles when the service data packet is 1,000 bytes and $\lambda_e = \lambda_s = 25$ *pps*. It is clear from Fig. 16 that when the network traffic is relatively sparse, the system throughput on the SCHs is significantly high, and the AMAC scheme greatly outperforms the legacy standard. When the $n = 20$ *vehicles*, the AMAC scheme has a roughly 105.72% improvement on the throughput of service data on the SCHs with respect to the legacy scheme. This is because under dense network traffic environments, the AMAC scheme adopts immediate and extended SCH access. Hence, AMAC scheme enables the vehicles to have more time to transmit service packets on the SCHs unlike the fixed

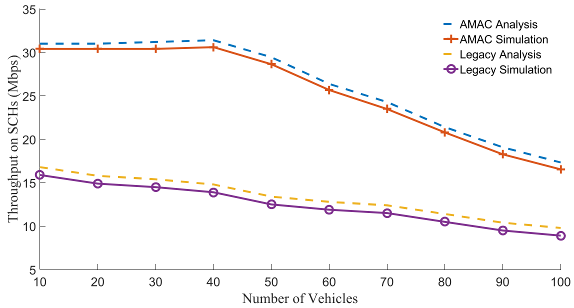


**FIGURE 16.** System throughput of service data on SCHs versus number of vehicles ($\lambda_e = \lambda_s = 25$ *pps*).

interval (*50 ms*) as in the legacy standard. The contention-free SCH access also assists the AMAC scheme in improving the system throughput. Moreover, the system throughput rapidly decreases as the number of vehicles increases. This is because of the high collision probability and the high priority of safety packets in accessing the channel, which reduce the transmission opportunity for service packets.

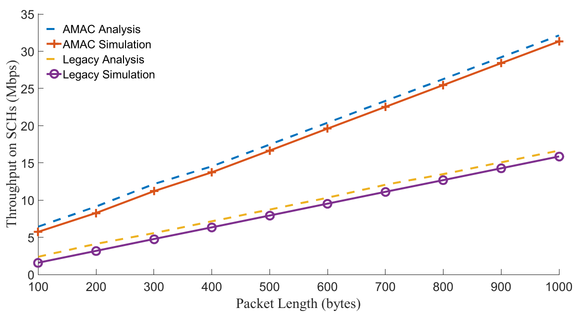


**FIGURE 17.** System throughput of service data on SCHs under different packet length ($n = 50$ *vehicles*, $\lambda_e = \lambda_s = 25$ *pps*).

Fig. 17 represents the system throughput on the SCHs in terms of different service data packet length when $n = 50$ *vehicles* and $\lambda_e = \lambda_s = 25$ *pps*. It is notable from Fig. 17 that the performance gain in both schemes increases linearly as the packet length growths.

The results clearly show that the AMAC scheme improves the system throughput on the SCHs compared to the legacy standard. This is due to the contention-free SCH access as well as the immediate and extended SCH access in the AMAC scheme. This enables the vehicles on the network to transmit the service packets without contention and obtain more transmission time on the SCHs.

## VI. CONCLUSION

In this paper, we propose an Adaptive Multi-channel Assignment and Coordination (AMAC) scheme under non-saturated conditions to enhance the performance of IEEE 802.11p/1609.4 in VANETs. By using the measurement-based congestion detection mechanism in the AMAC scheme, the system is always aware of the real-time traffic situation in order to adopt suitable multi-channel switching type and adaptively execute the PNP between service providers and users. Collision-aware packet transmission is also provided by the AMAC scheme to mitigate collisions and increase PDR of safety packets over CCH. Moreover, 1-D and 2-D Markov chain models were employed in the presence of error-prone channels under non-saturated conditions to analyze the packet transmission probabilities for safety and service applications with higher and lower priorities respectively. The probability of successful transmission, transmission error and collisions were derived and used to compute the delay and PDR of safety applications and also the system throughput of service applications. Both analytical and simulation results indicate that the AMAC scheme reduces the collisions and increases the PDR of safety applications over the CCH, and also improves system throughput of service applications over the SCHs. Thus, transmission of delay-sensitive and throughput-sensitive applications are enhanced by the AMAC scheme.

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