RECV-MAC: A Novel Reliable and Efficient Cooperative MAC Protocol for VANETs

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Abstract: In vehicular ad hoc networks (VANETs), relative mobility among vehicles can result in rapid topology changes with frequent link breakage and unstable communications which cause collision and packet loss. Conversely, cooperative transmission can improve the communication reliability and can enhance communication rate with lower delay by alleviating wireless channel impairments caused by the mobility in VANETs. In this paper, a novel *r*eliable and *e*fficient *c*ooperative MAC protocol for *V*ANETs (RECV-MAC) is proposed which is designed both for safety messages and non-safety data transmission. Since a random access mechanism is the suitable and efficient because of the dynamic and open nature of VANETs, we used the random access approach i.e. carrier sense multiple access with collision avoidance (CSMA/CA) which is used by IEEE 802.11p. Therefore, the proposed RECV-MAC protocol is compatible with IEEE 802.11p. RECV-MAC ensures reliable and efficient transmission with the help of helpers which have good channel condition to both the sender and the receiver. New control messages are introduced to support cooperative communication. The mechanism is defined to choose the suitable transmission mode as well as to select the optimal helper. Vehicle mobility and overhead introduced by cooperative communication are considered. To investigate the performance of the proposed RECV-MAC protocol, Markov chain model based analytical analysis is provided. Network performance measures such as system throughput, successful transmission probability, collision probability, packet dropping rate (PDR), and delay are derived. The proposed RECV-MAC protocol is validated by numerical studies. The performance of the RECV-MAC protocol is compared with the traditional MAC model which is based on the IEEE 802.11p and a quantitative comparison with existing cooperative MAC schemes is presented. It is obvious from the comparison that the RECV-MAC performs better than IEEE 802.11p and existing cooperative MAC schemes. The numerical results demonstrate that the RECV-MAC protocol improves the performance with higher throughput, enhances reliability of communication by decreasing PDR, and decreases delay, in particular, satisfies the delay constraint of 100 ms for safety messages.

1. Introduction

Intelligent Transportation System (ITS) supports numerous applications such as congestion alleviation, safety, security, comfort and convenience, productivity and operational efficiency, environment monitoring and protection etc. Vehicular ad hoc network (VANET) is a significant element of ITS which facilitates vehicles to interconnect with each other in addition to roadside stations. VANETs provide safety related messages, such as emergency warning, road condition, accident prevention, emergency electronic brake light indication, lane-changing assistant, traffic sign or signal violation warning etc. and non-safety data, such as traffic information system, map update, weather information, web browsing, content distribution, gas station or restaurant location and price information, gaming etc.

The IEEE 802.11p standard [1] is outlined by the IEEE to support wireless access in vehicular environments (WAVE) and to provide Medium Access Control (MAC) and Physical (PHY) Layer specifications for VANETs. A 75 MHz wide spectrum in 5.850-5.925 GHz band is assigned for the Dedicated Short Range Communication (DSRC) with seven 10 MHz wide channels, one channel is control channel (CCH) and six are service channels (SCHs). The ITS G5 standard [2] has been drafted by the ETSI. In Europe, a 50 MHz wide spectrum in the frequency band of 5.875-5.925 GHz has been allocated by ETSI. The IEEE 1609.4 standard [3] controls the action of upper layer data transmissions through multiple channels, without PHY layer knowledge and defines the multi-channel operation, channel routing as well as switching for altered scenarios. According to IEEE 1609.4, the CCH is reserved for safety messages called beacons and control messages (i.e., service advertisement messages) and the SCHs are reserved for non-safety data. The period during which a vehicle stays tuned to the CCH and SCHs are referred to CCH and SCH interval, respectively. There is a guard time because of radio switching delay and time synchronization error at the beginning of all intervals. Vehicles have to tune to the identical channel at the exact time to establish correspondence with each other and for data transmission among them.

There is no guarantee of successful transmission of prime significant safety messages in the IEEE 802.11p. Non-safety data needs huge bandwidth and good channel condition for fast transmission. Moreover, communications become unstable and topology changes promptly with frequent link breakage due to high node mobility as well as relative mobility among vehicles in VANETs which cause collision and packet loss. On the other hand, cooperative communication can increase the communication link reliability by mitigating wireless channel impairments caused by mobility in VANETs. Cooperative communication [4] improves transmission performance with the assistance of neighboring nodes. A helper node is a node among the

neighboring nodes which relays packets to the receiver thanks to having a good channel condition to both the sender and receiver nodes. Due to the transmission nature of wireless communication, nearby stations can listen to the broadcast of a packet from the sender to the receiver. The overheard packet experiencing a bad channel state to the receiver can be relayed by a helper or helpers. Cooperative transmission can enhance the throughput of the whole network because of the reliability of a packet delivery with the help of helper.

The contribution of the paper is summarized as follows. In this paper, a novel reliable and efficient cooperative MAC protocol is proposed for VANETs, referred to as RECV-MAC. The main objective of the proposed RECV-MAC protocol is to enhance the reliability of communications in VANETs by mitigating impairments due to user mobility and to improve communication quality with higher throughput and lower delay, in particular, safety messages should not experience delay more than 100 ms as stated in [5]-[6]. Since a random access mechanism is the most suitable and efficient because of the dynamic and open nature of VANETs, we used the random access approach i.e. CSMA/CA which is used by the IEEE 802.11p. Therefore, the proposed RECV-MAC protocol is compatible with the IEEE 802.11p. New control messages are introduced to transmit safety messages and non-safety data such as Negative Acknowledgment (NACK), Keen To Help (KTH), Selected Helper Message (SHM), Willing To Involve in the offered service (WTI), Cooperative WAVE Service Advertisement (CWSA) etc. As cooperation initiates complexity and signaling overhead, cooperation all the time may not be beneficial or even needed. Cooperation becomes superfluous when cooperation gain is negligible compared to cost. Therefore, a scheme is required to decide whether a packet should be transmitted directly or cooperatively. An algorithm is suggested to determine an appropriate transmission mode. The cooperation gain depends on the helper and for that optimal helper selection procedure is also provided. Overhead introduced by cooperative communication and vehicle mobility are considered. Markov Chain model based analytical analysis of the RECV-MAC protocol is presented. Finally, the RECV-MAC protocol is evaluated by numerical studies. Numerical results show that the RECV-MAC protocol enhances the performance and achieves objectives.

The rest of the paper is arranged as follows. More related works are reviewed in Section 2. Section 3 illustrates the proposed RECV-MAC protocol. Section 4 presents Markov chain based performance analysis. Throughput and PDR analysis are presented in Section 5. Delay analysis is provided in Section 6. Section 7 presents the numerical results. Section 8 draws the conclusion.

2. Related Work

The basic access method of the IEEE 802.11 [7] and IEEE 802.11p MAC is distributed coordination function (DCF) familiar as carrier sense multiple access with collision avoidance (CSMA/CA). The performance analysis of the IEEE 802.11 DCF is provided in [8]. Most recent works are an extension of the Bianchi's analysis [8] where delay analysis is not provided. The impact of IEEE 802.11 based VANETs and throughput analysis for unicast transmission is provided in [9]. Mobility model for VANETs is presented in [10]. The impact of IEEE 802.11p in VANETs is explored in [11]-[14]. The enhanced distributed channel access (EDCA) method is used to support the quality of service (QoS). According to the IEEE 802.11p EDCA mechanism, there are four access categories (ACs) with different parameters to contend for the transmission. The impact of IEEE 802.11p EDCA method is studied in [15]-[17]. Designing MAC protocol is challenging for VANETs because of high mobility which changes topology promptly [18]. Alternatively, cooperative communication can improve the communication reliability. CCB-MAC which is a cooperative clustering based MAC protocol for VANET is suggested in [19]. CCB-MAC considered only safety messages. However, if there is no idle slot, cooperation is not possible. In [20], a cooperative MAC protocol named ADC-MAC is recommended for VANETs which is based on IEEE 802.11. ADC-MAC uses the request to send (RTS)/clear to send (CTS) access mechanism of the IEEE 802.11 which is inoperative for safety messages which are of broadcast nature. Since the RTS will be broadcast to all vehicular nodes, all vehicular nodes will send CTS which causes more collisions [5]. In [21], CAH-MAC is proposed for VANETs which is TDMA based cooperative MAC protocol. CAH-MAC supports point-to-point communication only, this protocol does not support broadcast or multicast modes of communication. In CAH-MAC, a vehicular node retains a list of its one-hop and two-hop nearby nodes for cooperation individually. Variations in traffic, channel circumstance, as well as network topology are numerous and normal in VANETs. Therefore, the information in the list may not appropriately reveal the existing channel state. In this situation, it is highly probable that the sender will not get helpers or helpers will be unsuccessful in executing cooperation which degrades throughput and causes delay in packet delivery. Moreover, in CAH-MAC, adjacent vehicular nodes cooperate by using unreserved time slots. Consequently, cooperation is not possible if there is no available time slot. In [22], an enhanced CAH-MAC is proposed to efficiently utilize a time slot by avoiding cooperation collisions. In [23], a cooperative MAC is proposed for safety messages in VANETs. A scheduling protocol based on centralized TDMA is proposed for VANETs in [24]. In [25], VeMAC is proposed for VANET which is also a TDMA based MAC protocol. The TDMA MAC protocols may result in wastage of time slots due to VANETs dynamic topology. If there are inadequate nodes in the network to utilize all the time slots of a frame, then the wastage occurs. During unreserved time slots, though the channel is idle, the sender waits for the next frame for retransmission upon a failed transmission which causes high delay and low throughput in VeMAC. Moreover, these methodologies can be ineffective in utilizing the offered radio resources. The resource sharing problem in VANETs is investigated in [26]-[27]. Message delivery technique of VeMAC for both periodic as well as event-driven safety messages is scrutinized in [28]. In [29], a novel cooperative MAC protocol is offered for safety messages in VANETs which does not satisfy the delay constraint. In [30], VC-MAC is provided for gateway downloading in VANETs. In [31], cooperative relay broadcasting (CRB) is introduced for vehicular networks where neighboring nodes rebroadcast the packet from the sender to increase the reliability of the broadcast. CRB choice is obtained proactively based on channel states. However, delay analysis is not provided in

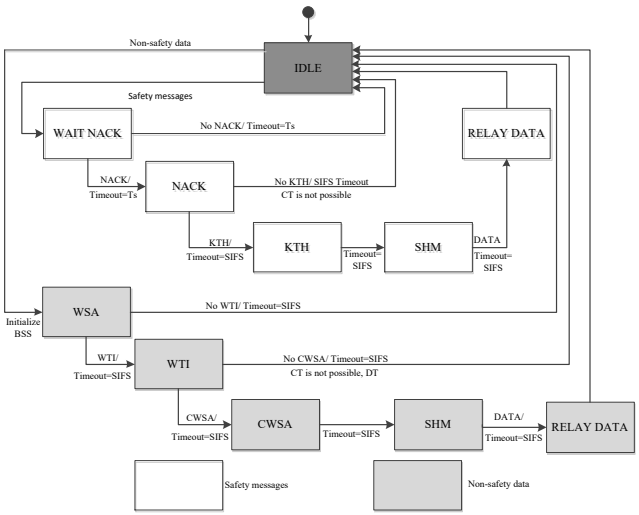


Fig. 1. *FSM of RECV-MAC protocol.*

[21], [25], and [30]-[31]. In [33], CNC-MAC is suggested for VANETs which is IEEE 802.11 based cooperative MAC protocol. The CNC-MAC protocol does not fulfil the delay requirement of safety messages. In [19], [21], [23], [25], and [29], cooperative MAC is recommended for safety messages only, and mobility is not considered. In [33]-[34], cooperative MAC protocol is suggested in VANETs for non-safety data only. A cooperative MAC is required both for safety messages and non-safety data to ensure communication quality with higher throughput, as well as reliable and efficient communication by decreasing PDR and delay. To the best of our knowledge, this proposed RECV-MAC protocol for VANETs is the first work on cooperation based transmission which is designed both for safety messages and non-safety data transmission that achieves the stated objectives.

3. Proposed Protocol

The proposed RECV-MAC protocol is discussed in this section. To support cooperative communication new control messages are introduced. NACK and KTH are introduced to exchange safety messages. To exchange non-safety data WTI and CWSA are introduced. SHM will be sent to the optimal helper after selecting the optimal helper. The internal finite state machine (FSM) of the RECV-MAC protocol is presented in Fig. 1. The FSM is outlined by Unified Modeling Language (UML). For normal packet processing, 10 internal states and 15 external events are stated in the FSM. The timer value will be fixed by following the duration of the packet header for abnormal case processing. The FSM shall be reset to the "IDLE" state when timeout occurs.

The transmission of safety messages is not acknowledged in IEEE 802.11p. Therefore, unsuccessful transmission of high priority safety messages either due to collision with other packets or channel deficiencies cannot be identified. Hence, safety messages are very important, and NACK is introduced in the RECV-MAC protocol. Packets which are negatively acknowledged will be treated as failed transmissions. These packets will be sent through cooperative communication to ensure successful transmission and improve the reliability of transmission.

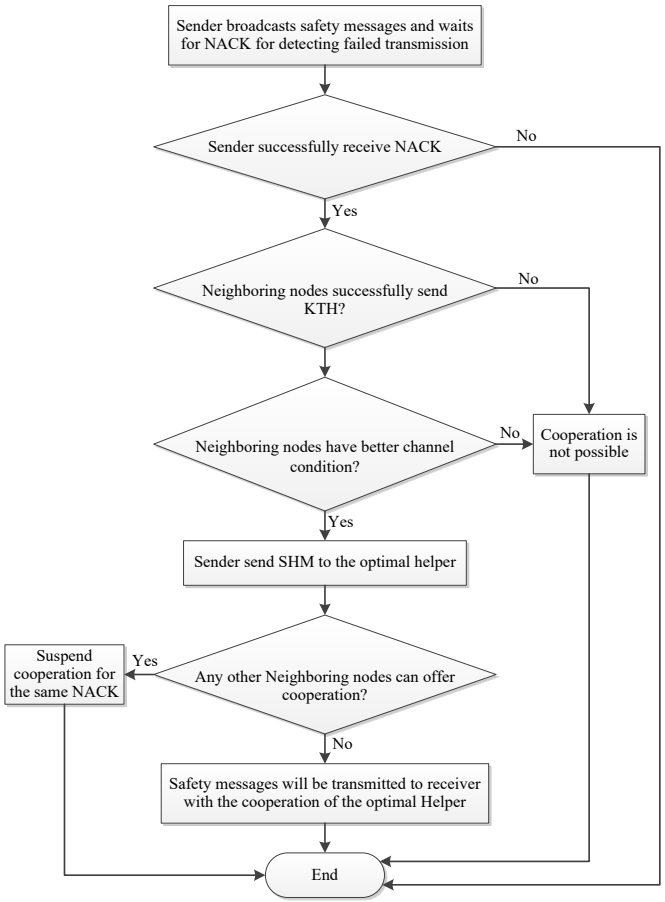


Fig. 2. *Flowchart of the RECV-MAC protocol for safety messages.*

Non-safety data transmission consumes a large amount of bandwidth. If the main channel from the sender to the receiver is unreliable, yet other neighboring nodes have a good channel state to both the sender and the receiver; then neighboring nodes can relay a packet to the receiver. Therefore, the transmission rate of non-safety data will be improved.

3.1. Delivery of Safety Messages

Safety messages will be broadcast through CCH. To ensure a reliable broadcast service, the sender should recognize the packet is successfully transmitted to the receiver or not. After safety messages are broadcast in the network, sender S will wait for NACK from any node or timeout of successful transmission time T_s. If S receives NACK, then there is a failed transmission to a node. Otherwise, if S does not receive NACK or T_s timeout occurs, then this message broadcast is successful. A node can overhear the packet transmission from sender to other nodes [21] [35]. If the node hears the message broadcast but it does not receive the message within short interframe space (SIFS) time interval, then the node will broadcast NACK for that broadcast message. The NACK includes a unique NACK ID, receiver address (RA), sender address (SA), signal-to-interference-plus-noise ratio (SINR) etc. After receiving the NACK, neighboring nodes which have better transmission rate, SINR, and good channel condition will send KTH to S. KTH includes NACK ID, packet ID, helper address (HA),

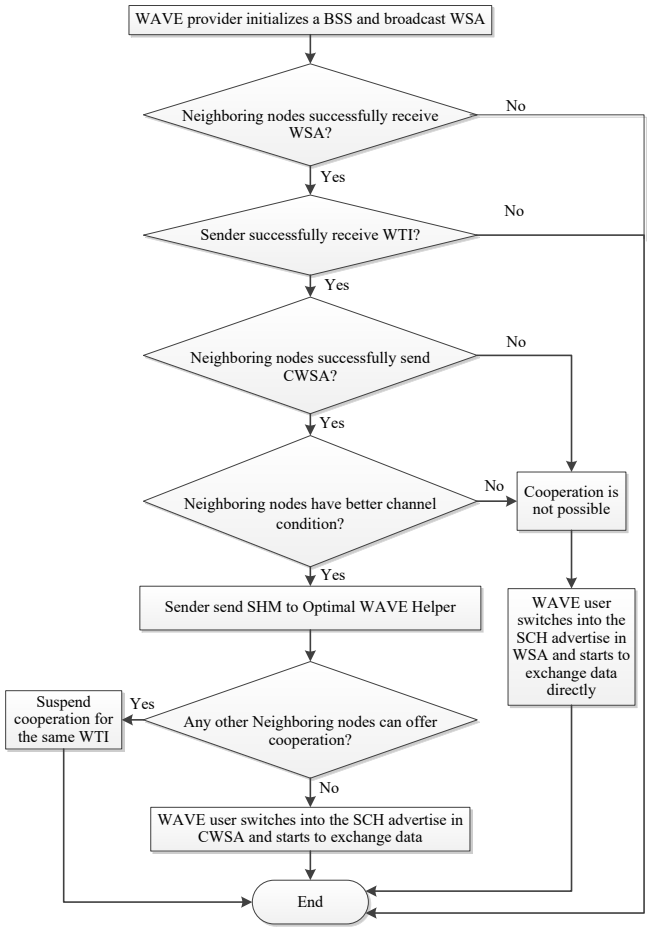


Fig. 3. *Flowchart of the RECV-MAC protocol for non-safety data.*

helper SINR (H-SINR), SA, RA etc. If S does not receive NACK from R, S can still detect failed transmission by receiving KTH. S will choose the optimal helper among neighboring nodes which have sent KTH. If there is no KTH or SIFS timeout occurs, then cooperation is not possible. After getting KTH, the node which has optimal SINR, will be chosen by S as the optimal helper. S will send SHM to the optimal helper. SHM contains NACK ID, SA, RA, optimal helper address (OHA) etc. After hearing SHM, other nodes which can offer cooperation will suspend cooperation for the same NACK. Since safety messages are broadcast, the optimal helper has the safety message which will be relayed to the receiver node. If multiple failed transmission occurred or one NACK received with some delay, the cooperation mechanism will be completed in the same way. The cooperation will be generated by sending KTH from neighboring nodes to S. Since optimal helper is chosen based on SINR, the optimal helper can be different for different NACK. Each optimal helper will send the safety message to the particular receiver. The reliability of packet delivery is increased by cooperation of helper and packet can be delivered out of network coverage of S. All the messages will be transported through CCH. Fig. 2 demonstrates the flowchart of the RECV-MAC protocol for safety messages.

Table 1 An algorithm to find the suitable data transmission mode for safety messages

1:	If (S, R) $\notin$ U
2:	then CT
3:	else if $H_i \notin U_h$
4:	then C_I
5:	end
6:	If (S, R) $\in$ U
7:	then DT
8:	else if $R_{NACK} \in U_{NACK}$
9:	then CT
10:	else if $H_i \notin U_h$
11:	then C_I
12:	end

3.2. Delivery of Non-Safety Data

A WAVE provider (S) is a road-side unit or a vehicular node transmitting non-safety data. To provide a non-safety service, S initializes a Basic Service Set (BSS). Each S announces its existence and offers services by periodically broadcasting WAVE Service Advertisement (WSA) during CCH interval. To join the advertised BSS, WSAs enclose the necessary particulars about the offered services and the network parameters, like WSA ID, BSS ID, the Provider Service Identifier (PSID), its EDCA parameter sets, its SCH, provider SINR, IP configuration parameters etc. WAVE user (R) is a node which is intended to involve in the offered services by S. R will send WTI which contains the WSA ID, WTI ID, WAVE provider address (SA), WAVE user address (RA), SINR etc. If overheard neighboring nodes (H) have better channel condition and better SINR, H will send CWSA to S during CCH interval. CWSA contains all information about WSA including WTI ID, WAVE helper address (HA), SINR and channel information. After getting CWSA, S will choose the node which has optimal SINR as an optimal WAVE helper. S will send SHM to the optimal WAVE helper (H). After hearing SHM, other nodes which can offer cooperation will suspend cooperation for the same WTI. The optimal WAVE helper will join in the BSS and S transfer the non-safety data to R through the optimal H. The optimal H switches into the SCH advertised in the WSA and R switches into the SCH advertised in the CWSA and exchange data. Otherwise, if no SHM found i.e. WAVE helper is not available, then R switches into the SCH advertised in the WSA and initiates to exchange data with the S directly. Fig. 3 presents the flowchart of the RECV-MAC protocol for non-safety data.

3.3. Transmission Mode Selection

As cooperation introduces complexity and signalling overhead, cooperation in the network may not be advantageous or even essential all the time or cases. Unnecessary cooperation should be avoided for optimal MAC protocol design. Two transmission modes are suggested in the RECV-MAC protocol for performance optimization which are direct transmission (DT) mode and cooperative transmission (CT) mode. The algorithm to achieve the appropriate data transmission mode for safety messages is provided in Table 1.

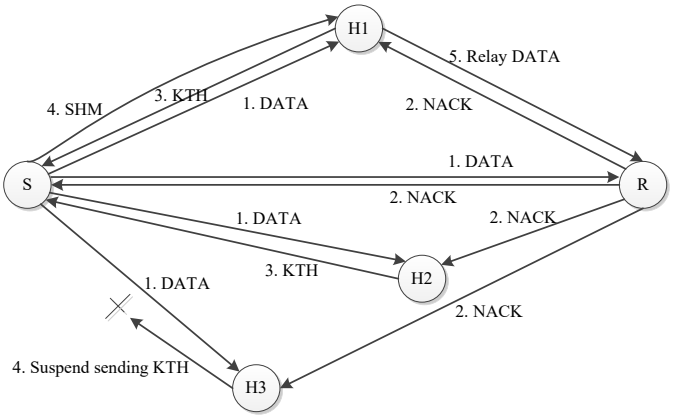


Fig. 4. *Three party handshake among the sender, the receiver and helper node or nodes for safety messages.*

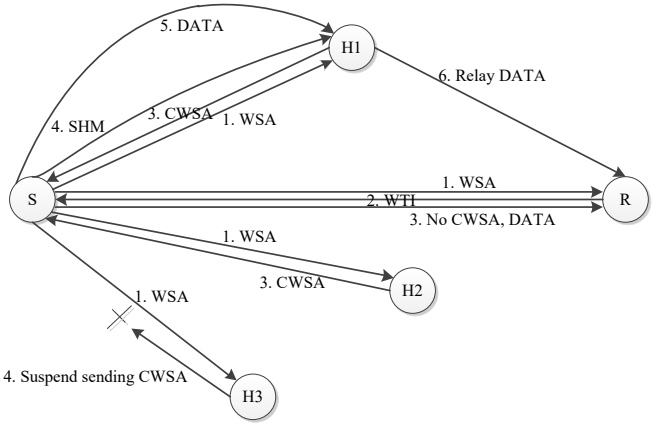


Fig. 5. *Three party handshake among the sender (WAVE provider), the receiver (WAVE user) and helper node or nodes for non-safety data.*

In this model, the VANET consists of N vehicles. Let U be the set of vehicles in the same network, S the sender, R the receiver, U_h the set of helper H_i, U_{NACK} the set of negative acknowledgment R_{NACK} where negative acknowledgment is sent by the receiver after unsuccessful transmission and C_I denotes that cooperation is not possible. For safety message, if S and R are not in the same network, then S transmits data through the CT. CT increases transmission range i.e. extends network coverage, but if there is no helper, then cooperation is not possible because the destination R is not reachable even with helper. If S and R are in the same network, then S transmits data through DT and S will avoid CT. Then S will wait for NACK. If S receives NACK, then it will be denoted as a failed transmission. If S receives NACK, then S will send safety messages through CT for the failed transmission. For non-safety data, S will transmit WSA and R will send WTI. If S gets CWSA and suitable helper, then S will transmit non-safety data through CT, otherwise DT.

3.4. Channel access

Due to the dynamic and open nature of VANETs, a random approach is the suitable and efficient [36]. The random access mechanism i.e. CSMA/CA used in IEEE 802.11p is used by the proposed RECV-MAC protocol. Therefore, the RECV-MAC protocol is compatible with IEEE 802.11p.

When a vehicle has a packet to transmit, it starts to sense the channel. If the channel is sensed idle for DCF inter frame space (DIFS) time, the vehicle transmits. Otherwise, the vehicle initiates a random backoff before transmitting to minimize the probability of collision with packets transmitted by other vehicles. The vehicular node starts a backoff process by taking backoff value arbitrarily. It is decreased by 1 when the channel is sensed idle in a slot time, and paused in the current value when the channel is sensed busy, and resumed when the channel is sensed idle again for more than DIFS. The packet will be transmitted when backoff becomes zero.

3.5. Three Party Handshake

Three party handshake among the sender (S), the receiver (R) and the helper (H) node or nodes for safety messages and non-safety data are presented in Figs. 4 and 5, respectively. For safety messages, cooperation is initiated by the R by sending NACK to S. R broadcasts NACK and initializes cooperation for failed transmission. Then all neighboring nodes which get NACK will check their channel condition for the safety message transmission. If neighboring nodes have good channel condition for the safety message transmission, then they will offer to help by sending KTH. In Fig. 4, H_1 and H_2 send KTH to S since they have good channel condition to relay the safety message. After SIFS interval, S will choose optimal helper among nodes which send KTH based on their SINR and S will send SHM to the optimal helper H_1. After hearing SHM, other nodes will suspend to send KTH for same NACK and H_3 suspends sending KTH for the same NACK. Then, the optimal helper H_1 will send the safety message to R.

For non-safety data, WAVE provider (S) will broadcast WSA and offer services. WAVE user (R) will send WTI to S. If neighboring nodes have better channel condition, then they will send CWSA to S. H_1 and H_2 send CWSA to offer themselves as a WAVE helper as they have better channel condition. After SIFS interval, S will choose optimal WAVE helper among H_1 and H_2 based on their SINR. S will send SHM to the optimal WAVE helper H_1 as in Fig. 5. H_3 suspends sending CWSA for the same WTI after hearing SHM. S will transmit the non-safety data to the WAVE user R through the optimal WAVE helper H_1.

3.6. Optimal Helper Selection

For both safety messages and non-safety data, optimal helper node will be chosen by the sender. Cooperation is initialized by the receiver for safety messages and by the helper for non-safety data transmission. The cooperation gain is contingent on the helper. When the number of helper is increased, the reliability of communication is also increased due to diversity gain [37].

For safety messages, the receiver (R) initiates cooperation by sending NACK. Then, neighboring nodes which have better channel condition send KTH to the sender (S). The S will choose optimal helper which has optimal SINR and S will send SHM to the optimal helper. For non-safety data, neighboring nodes which have better channel

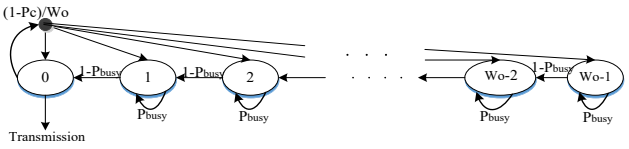


Fig. 6. *Markov chain model for the backoff process.*

condition will send CWSA to WAVE provider (S) and initiate cooperation. The nodes which send CWSA to the S are WAVE helpers. The node which has optimal SINR among WAVE helpers will be considered as optimal WAVE helper. S will send SHM to the optimal WAVE helper. The neighboring nodes which offer to help in transmitting data by sending KTH or CWSA are helper. Helpers have better channel condition. Optimal helper is the helper which has optimal SINR among helpers [38]-[40].

4. Performance Analysis

Saturated condition is considered and assumed that NACKs and KTHs are successfully received. A VANET with randomly distributed N number of vehicles running on a multi-lane road where N follows a Poisson distribution over a road segment. If L_r is the length of a road segment, then the probability mass function of N in L_r can be given as

$$P(N=n)=\frac{(D_T L_r)^n e^{-D_T L_r}}{n!}, \qquad n=0,1,2,.... \tag{1}$$

where $D_T=\sum_{l=1}^{L} D_{T_l}$, $\qquad l\in\{1,2,3,.....,L\}$.

D_T denotes the traffic density in L_r (number of vehicles/ distance/ lane) and D_{T_l} is vehicle density of lane l.

Let r be the transmission range. The average number of vehicular nodes in r can be given as

$$N_{tr}=2D_T r. \tag{2}$$

Let $\lambda_{vehicle}$ be the average arrival rate of vehicular nodes to r which can be given as [41]

$$\lambda_{vehicle}=n_L D_T v, \tag{3}$$

where n_L represents the number of lanes on the road and vehicle velocity v is uniformly distributed between v_{min} and v_{max}.

Let β be the average inter-vehicle distance which is contingent on the vehicular node length and the legal gap which should be kept between vehicular nodes that is fixed by the traffic department of the country.

$$\beta=D_{vehicle}+L_{vehicle}, \tag{4}$$

where $D_{vehicle}$ denotes the legal distance between vehicular nodes that should be kept and $L_{vehicle}$ represents the length of the vehicle.

Let $b(t)$ be the stochastic process which represents the backoff time counter for a vehicle at time t where b_c expresses the value of the backoff counter. Let W_0 denotes the contention window size, where $b_c\in(0,W_0-1)$. The Markov chain for the backoff procedure is illustrated in Fig. 6. The initial value of b_c is uniformly taken from [*0*, W_0 *-1*]. It is decreased by 1 when the channel is sensed idle in a slot time, and paused in the current value when the channel is sensed busy, and resumed when the channel is sensed idle again for more than DIFS. The packet will be transmitted when b_c is 0. Let P_c and P_{busy} be the probability of collision and channel busy, respectively.

In the Markov chain, transition probabilities are

$$P\{b_c|b_c+1\}=1-P_{busy} \qquad b_c\in(0,W_0-2) \tag{5}$$

$$P\{b_c|b_c\}=\frac{P_{busy}}{W_0} \qquad b_c\in(0,W_0-1) \tag{6}$$

$$P\{b_c|0\}=\frac{1-P_c}{W_0} \qquad b_c\in(0,W_0-1) \tag{7}$$

b_c is decreased by 1 if the channel is sensed idle in eq. (5), eq. (6) states that b_c is paused at the current value when the channel becomes busy, and eq. (7) points that the packet will be transmitted when b_c is zero.

Let $b_{b_c}=\lim_{t\to\infty}P\{b(t)=b_c\}$, be the stationary distribution of the Markov chain, then:

$$b_{b_c}=\frac{W_0-b_c}{W_0}b_0. \tag{8}$$

Since the sum of all possible states equal to one,

$$1=\sum_{b_c=0}^{W_0-1}b_{b_c}=\sum_{b_c=0}^{W_0-1}\frac{W_0-b_c}{W_0}b_0. \tag{9}$$

So,

$$b_0=\frac{2}{W_0+1}. \tag{10}$$

Let P_t be the probability of transmission that a vehicular node transmits a packet in a slot time which can be defined as

$$P_t=b_0=\frac{2}{W_0+1}. \tag{11}$$

Collision occurs if at least one of the existing N-1 vehicles is transmitting a packet in the identical slot time. Thus, P_c can be defined as

$$P_c=1-(1-P_t)^{N-1}. \tag{12}$$

The channel will be busy if minimum one vehicle is transmitting a packet within r. Since N vehicular nodes compete for the transmission, P_{busy} is

$$P_{busy}=1-(1-P_t)^N. \tag{13}$$

Let P_s be the probability of successful transmission that the current transmission is successful which can be written as

$$P_s=\frac{NP_t(1-P_t)^{N-1}}{P_{busy}}C_{ch}, \tag{14}$$

where C_{ch} denotes the channel condition. The channel can be either in good or bad state modeled by a two state Markov chain model [42].

$P_{d\text{-}CT}$ is the cooperation decision probability that the cooperative transmission decision is taken. The cooperative transmission decision will be taken when direct transmission fails and there is at least one suitable helper for cooperation. $P_{d\text{-}CT}$ is given as

$$P_{d\text{-}CT} = P_c(1-P_h), \tag{15}$$

where P_h is the probability of not getting helper which can be given as

$$P_h = \frac{N-h}{N}, \tag{16}$$

where h is the number of helpers. As one vehicle is the sender and another vehicle is the receiver, h ranges from 0 to $(N-2)$. Let $P_{s\text{-}CT}$ be the probability of successful transmission with cooperation that the packet transmission becomes successful with the cooperative transmission. If the transmission is successful after cooperative transmission, then the cooperation is advantageous. In cooperative communication approach, the transmission can be successful either direct transmission or cooperative transmission after failed transmission. $P_{s\text{-}CT}$ is given as

$$P_{s\text{-}CT} = P_s + P_s(1-P_s)P_{d\text{-}CT}. \tag{17}$$

Using Eq. (15) - Eq. (16) in Eq. (17) $P_{s\text{-}CT}$ can be obtained as

$$\begin{aligned} P_{s-CT} &= P_s + P_s P_c (1-P_s)\left(1-\frac{n-h}{n}\right) \\ &= P_s\left(1+\frac{P_c(1-P_s)h}{n}\right). \end{aligned} \tag{18}$$

$P_{parrival}$ is the packet arrival probability that one or more packets arrive in a time slot in each vehicular node which follows a Poisson process with a constant arrival rate λ. Since no packet arrival probability is $exp(-\lambda T_e)$, $P_{parrival}$ can be given as

$$P_{parrival} = 1-e^{-\lambda T_e}, \tag{19}$$

where T_e denotes the expected time spent by a vehicular node in each Markov state. T_e for both DT and CT can be given as

$$T_{e\text{-}DT} = (1-P_{busy})\,T_{slot} + P_{busy}P_s T_{s\text{-}DT} + P_{busy}(1-P_s)T_c, \tag{20}$$

$$T_{e\text{-}CT} = (1-P_{busy})\,T_{slot} + P_{busy}P_{s\text{-}CT}T_{s\text{-}CT} + P_{busy}(1-P_{s\text{-}CT})T_c, \tag{21}$$

where T_{slot} is the period of a slot time, $T_{s\text{-}DT}$ and $T_{s\text{-}CT}$ are the time span when a packet is successfully transmitted with direct and cooperative transmission, respectively, T_c is the duration of a collided transmission.

For the RECV-MAC protocol, $T_{s\text{-}DT}$, $T_{s\text{-}CT}$, and T_c of safety messages (sm) and non-safety data (nsd) can be written as

$$T_{s-DT(sm)} = \frac{L_h+L}{R_d} + DIFS + T_{delay}, \tag{22}$$

$$T_{s-CT(sm)} = \frac{L_h+L_{ch}+2L}{R_d} + DIFS + 3SIFS + T_{delay} + T_{NACK} + T_{KTH} + T_{SHM}, \tag{23}$$

$$T_{s-DT(nsd)} = \frac{L_h+L}{R_d} + DIFS + SIFS + T_{WSA} + T_{WTI} + T_{delay}, \tag{24}$$

$$T_{s-CT(nsd)} = \frac{L_h+L_{ch}+2L}{R_d} + DIFS + 3SIFS + T_{WSA} + T_{WTI} + T_{CWSA} + T_{SHM} + T_{delay}, \tag{25}$$

$$T_c = \frac{L_h+L}{R_d} + DIFS + T_{delay}, \tag{26}$$

where L_h and L_{ch} are the length of MAC and PHY layer header and cooperation header respectively, L denotes the transmitted packet size and R_d indicates the data transmission rate. T_{NACK}, T_{KTH}, T_{WSA}, T_{WTI}, T_{CWSA}, T_{SHM} is the time required for NACK, KTH, WSA, WTI, CWSA, and SHM, respectively. T_{delay} is the propagation delay.

Let $O_{s\text{-}CT(sm)}$ and $O_{s\text{-}CT(nsd)}$ be the overhead initialized by the RECV-MAC protocol for sm and nsd in CT mode, respectively which can be written as

$$O_{s-CT(sm)} = \frac{L_{ch}}{R_d} + 3SIFS + T_{NACK} + T_{KTH} + T_{SHM}, \tag{27}$$

$$O_{s-CT(nsd)} = \frac{L_{ch}}{R_d} + 2SIFS + T_{CWSA} + T_{SHM}. \tag{28}$$

5. Throughput and PDR Analysis

Let S be the normalized throughput. S is the data transmitted over the average duration of slot time which can be defined as

$$S = \frac{E[\text{transmitted payload length in a slot time}]}{E[\text{duration of a slot time}]} = \frac{E[p]}{T_e}. \tag{29}$$

Therefore, S for direct transmission S_{DT} and cooperative transmission S_{CT} can be given as follows

$$S_{DT} = \frac{P_s P_{busy} L}{(1-P_{busy})T_{slot} + P_{busy}P_s T_{s-DT} + P_{busy}(1-P_s)T_c}, \tag{30}$$

$$S_{CT} = \frac{P_{s-CT}P_{busy}L}{P_h[(1-P_{busy})\,T_{slot} + P_{busy}P_{s-CT}T_{s-CT} + P_{busy}(1-P_{s-CT})T_c]}. \tag{31}$$

Hence the normalized system throughput gain attained due to cooperative transmission can be computed as

$$S_{\text{gain}} = \frac{S_{CT}-S_{DT}}{S_{DT}}. \tag{32}$$

The packet dropping rate (PDR) for DT is

$$PDR_{DT} = (1-P_s). \tag{33}$$

A packet will be transmitted with CT after the failure of DT. If C_A denotes the number of cooperation attempts, the PDR for CT is

$$PDR_{CT} = (1-P_{s-CT})^{C_A}. \tag{34}$$

Therefore, the PDR gain achieved due to cooperative transmission is

$$PDR_{\text{gain}} = \frac{-(PDR_{CT}-PDR_{DT})}{PDR_{DT}}. \tag{35}$$

6. Delay Analysis

6.1. Average Access Delay

$E[D_{access}]$ is the average access delay that is the mean time duration for a packet transmission from contending for the channel to the successful transmission of the packet or drop of the packet. Two events can be happened, either the packet is successfully transmitted whether a collision happens and

no collision happens or the packet is dropped because of collision. $E[D_{access}]$ for both DT and CT can be given as

$$E[D_{access-DT}] = E[T_{waiting-DT}]P_c(1-P_c) + E[T_{waiting-DT}]P_c, \quad (36)$$

$$E[D_{access-CT}] = E[T_{waiting-CT}]P_c(1-P_c) + E[T_{waiting-CT}]P_c, \quad (37)$$

where $E[T_{waiting}]$ is the mean waiting time that is the average time interval at the backoff period. Backoff counter is chosen randomly from $[0, W_0-1]$, $E[T_{waiting}]$ for both DT and CT is

$$E[T_{waiting-DT}] = \frac{(W_0-1)}{2} T_{e-DT}, \quad (38)$$

$$E[T_{waiting-CT}] = \frac{(W_0-1)}{2} T_{e-CT}. \quad (39)$$

6.2. Packet Drop Probability

The packet will be dropped because of collision. P_{drop} is the probability that a packet is dropped which can be given by

$$P_{drop} = P_c. \quad (40)$$

Let P_{fdrop} be the final packet drop probability that a packet is dropped finally. Therefore, the mean number of dropped packets in relation to a successful transmission is

$$E[X_{dpacket}] = \frac{P_{fdrop}}{1-P_{fdrop}}. \quad (41)$$

6.3. Average Time to Drop a Packet

$E[T_{drop}]$ is the average packet drop time that the average time length to drop a packet which can be written for both DT and CT as

$$E[T_{drop-DT}] = E[X_{drop}]T_{e-DT}, \quad (42)$$

$$E[T_{drop-CT}] = E[X_{drop}]T_{e-CT}, \quad (43)$$

where $E[X_{drop}]$ denotes the average number of slot times for a packet which is dropped:

$$E[X_{drop}] = \frac{W_0+1}{2}. \quad (44)$$

6.4. Average Packet Delay

The average packet delay $E[D]$ is the mean time duration from the time when the packet is prepared to be transmitted in its MAC queue up to the time of successful transmission. In computing $E[D]$, the time interval of a packet which is dropped will not be counted. Therefore, $E[D]$ can be computed for both DT and CT as

$$E[D_{DT}] = E[T_{interval-DT}] - E[X_{dpacket}]E[T_{drop-DT}], \quad (45)$$

$$E[D_{CT}] = E[T_{interval-CT}] - E[X_{dpacket}].E[T_{drop-CT}], \quad (46)$$

Table 2 Value of Parameters Used in Numerical Analysis

Parameter	Value
Slot Time, T_{slot} (μs)	20
Propagation Delay, T_{delay} (μs)	1
SIFS, DIFS (μs)	10, 50
L_h , L $(bytes)$	50, 512
NACK, KTH, SHM, WTI, WSA, CWSA $(bytes)$	20, 26, 24, 24, 25, 27
R_d, R_c, λ $(Mbps)$	11, 1, 0.5
CW size, W_0	64
Transmission range, r (m)	500
Width of a lane (m)	5
Vehicles density, D_T (veh/m)	0– 0.5
Vehicles velocity, v (km/h)	20-140
Average inter-vehicle distance, β (m)	10

where $E[T_{interval}]$ is the average packet interval that is the average time span between two successfully received packets at one receiver which can be obtained from the throughput for both DT and CT as

$$E[T_{interval-DT}] = \frac{NE[p]}{S} = NT_{e-DT}, \quad (47)$$

$$E[T_{interval-CT}] = \frac{NE[p]}{S} = NT_{e-CT}. \quad (48)$$

Using Eq. (41) - Eq. (48) the $E[D]$ for both DT and CT can be expressed as

$$E[D_{DT}] = T_{e-DT}\left(N - \frac{P_{fdrop}}{1-P_{fdrop}}\frac{W_0+1}{2}\right), \quad (49)$$

$$E[D_{CT}] = T_{e-CT}\left(N - \frac{P_{fdrop}}{1-P_{fdrop}}\frac{W_0+1}{2}\right). \quad (50)$$

7. Numerical Results

The performance of the proposed RECV-MAC protocol is assessed and the theoretical analysis is verified in this section. The numerical analysis is performed in MATLAB for a VANET of randomly distributed 100 vehicles running on a two lane road. The numerical analysis model includes main MAC behavior of the IEEE 802.11p in VANETs. Broadcast mode of safety messages (sm) and unicast mode of non-safety data (nsd) is considered. The proposed RECV-MAC protocol is compared with the traditional MAC model which is based on the IEEE 802.11p. Moreover, a quantitative comparison with existing cooperative MAC mechanisms is provided. Table 2 presents the value of parameters utilized in the numerical analysis.

Fig. 7 demonstrates throughput against number of vehicles in normal case as well as in the case of getting the helper with high probability and low probability. There is a remarkable improvement of throughput in the RECV-MAC protocol for both sm and nsd transmission in VANETs. Throughput increases until a certain point then throughput decreases which can be observed in Fig. 7. Since fewer number of vehicles may not cause collision, throughput starts

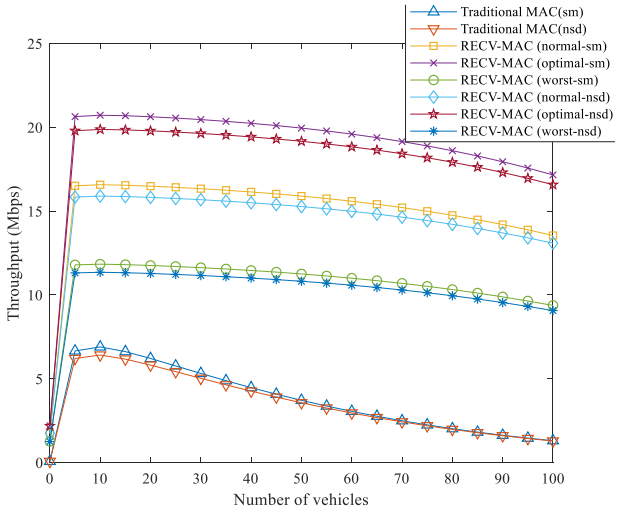


Fig. 7. *Throughput versus number of vehicles, Ph = 0.5 in normal case, Ph ≤ 0.4 in optimal case, Ph ≥ 0.7 in worst case.*

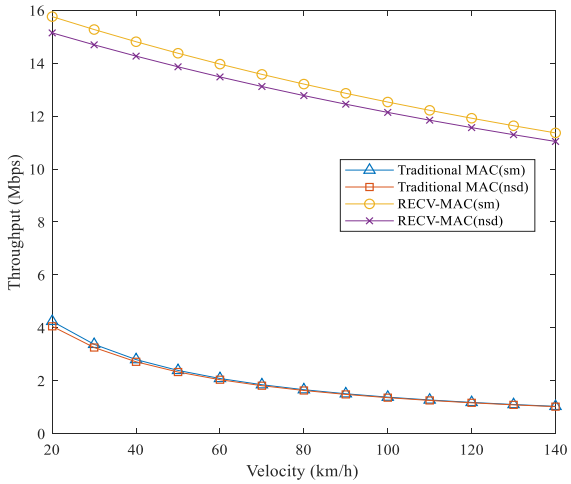


Fig. 8. *Throughput against velocity.*

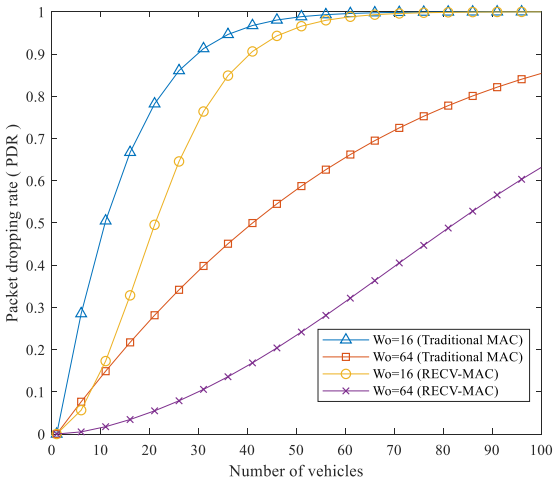


Fig. 9. *Packet dropping rate (PDR) versus number of vehicles.*

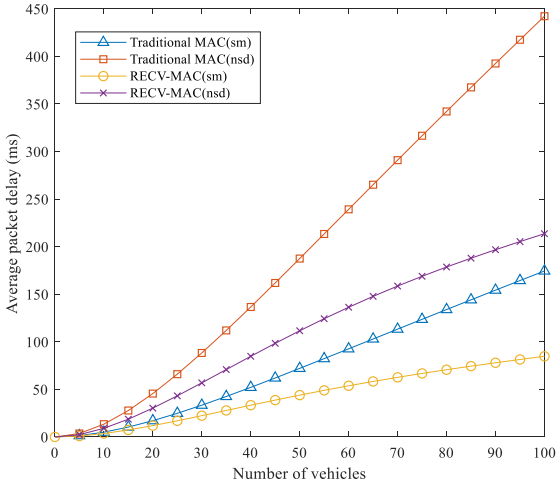


Fig. 10. *Average packet delay against number of vehicles.*

to increase with increasing vehicles, but after the number of vehicles further increases, then more vehicles would cause more collisions and throughput falls. It is also noticeable that higher probability of getting helper will increase throughput, since S-R link will be more reliable to transmit the packet and the transmission will be faster with good channel condition through cooperation. The throughput for the RECV-MAC protocol in optimal case is higher than normal due to the availability of helper. Nevertheless, the opposite scenario is perceived in worst case due to the unavailability of helper. More cooperation gain can be achieved with the more helpers. Fig. 8 depicts the throughput versus vehicle velocity. The throughput decreases with increasing velocity because high relative mobility among vehicles can result in rapid topology changes which causes unstable communications. Nevertheless, RECV-MAC protocol improves throughput for both sm and nsd transmission in VANETs under different vehicle velocity.

Fig. 9 shows the packet dropping rate (PDR) versus number of vehicles. PDR is rising with increasing number of vehicles as the probability of collision increases. When there are more vehicular nodes, the possibility of packet arrival increases which will result in more collisions. However, the PDR gain of the RECV-MAC protocol is significant. The RECV-MAC protocol ensures reliable transmission by decreasing PDR. Moreover, the comparison between different contention window sizes (W_0) is provided. When W_0 is larger, extended back-off time lessens collision as well as reduce packet loss, thus the PDR is decreased.

Fig. 10 shows the average packet delay against number of vehicles. The average packet delay increases with the number of vehicles because there would be more packets to transmit. For transmission, these additional packets would contend for the channel in the identical time slot which results in enlarged channel busy probability as well as collision probability. Therefore, the average packet delay is increased. Since RECV-MAC decreases the final packet drop probability and increases the probability of successful transmission, the average packet delay is reduced. Fig. 11 depicts average packet delay versus velocity. Average packet delay is increasing radically while the velocity is increasing because topology changes promptly with mobility which causes collision as well as packet loss due to frequent link breakage and unstable communications. However, RECV-MAC protocol decreases delay both for sm and nsd transmission in VANETs and fulfills the requirement of latency 100 ms for sm.

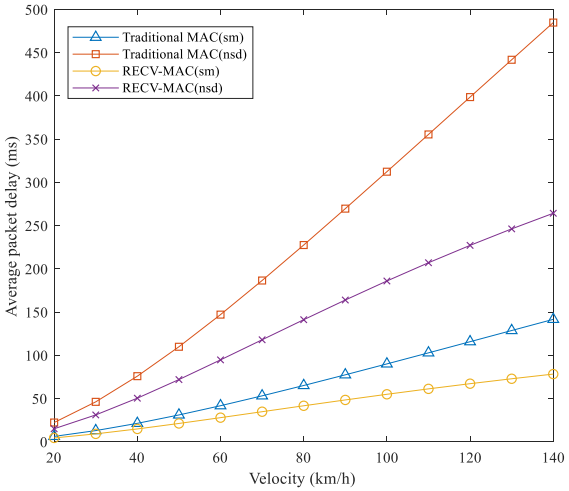


Fig. 11. *Average packet delay versus velocity.*

Under the same network scenario in existing cooperative MAC mechanisms, maximum throughput achieved is about 3.5 Mbps, 3.5 Mbps, 6 Mbps, 7 Mbps, and 8 Mbps in [20], [30], [34], [33], and [32], respectively. On the other side, in RECV-MAC protocol achieves maximum throughput about 20 Mbps. Delay analysis is not provided in [21], [25], and [30]-[31]. Delay constraint of safety messages is not satisfied in [28]-[29], and [33]. Alternatively, the RECV-MAC protocol fulfills the 100 ms delay constraint of safety messages in VANETs.

8. Conclusion

In this paper, we have proposed a novel reliable and efficient cooperative MAC protocol for VANETs referred to as RECV-MAC. The RECV-MAC protocol was designed to support both safety messages and non-safety data transmission. Since a random access mechanism is the most suitable and efficient because of the dynamic and open nature of VANETs, we used the random access approach i.e. CSMA/CA which is used by the IEEE 802.11p. Therefore, the proposed RECV-MAC protocol is compatible with the IEEE 802.11p. New control messages were introduced to ensure effective cooperative communication. An algorithm was proposed for selecting suitable data transmission mode. Optimal helper selection mechanism was also described. We presented an analytical analysis of the RECV-MAC protocol which is based on Markov chain model. The parameters that could impact performance were taken into consideration. Mobility and overhead introduced by cooperative communication were considered. The relationship among parameters and performance metrics were derived. Network performance measures such as system throughput, collision probability, successful transmission probability, PDR, and delay were derived. We assessed the performance of the RECV-MAC protocol through numerical analysis. Numerical results reveal that the RECV-MAC protocol provides noteworthy enhancement in system throughput and also satisfies 100 ms strict delay requirement of safety messages in VANETs. Furthermore, the reliability of the communication is increased by decreasing PDR. RECV-MAC protocol achieved the stated objectives. Extensive performance analysis of RECV-MAC protocol includes future research works. We shall consider non-saturated condition, different vehicle density or traffic scenarios etc.

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