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ReMAC: a novel hybrid and reservation-based MAC protocol for VANETs

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Abstract: The period in which a roadside unit (RSU) of a vehicle remains in the coverage area is too short in vehicular ad hoc networks (VANETs) in which the vehicles move at high speeds. In this short period, it is necessary for the vehicles to join the network and establish continuous communication with the RSU. To accomplish this, the RSU and vehicles need an efficient and robust media access control (MAC) protocol. In this study, a new reservation-based MAC (ReMAC) protocol in which multiple channels are used is suggested to ensure rapid connection to RSUs, smooth transition between RSUs, and efficient channel usage. The protocol uses the dedicated short-range communication (DSRC) standard's data/control channels by dividing them into multiple subchannels to support efficient channel usage, rapid service provision, and high vehicle density scenarios. The simulation of the protocol was conducted with OPNET Modeler and the performance comparisons were carried out with the metrics such as channel access delay, channel collision rate, success rate, and throughput. These are the metrics that are used in VeMAC, CFR-MAC, TMMAC, and VATMAC protocols that exist in this area. All the simulation results show in all scenarios that ReMAC significantly surpassed the current protocols.

Key words: Vehicular ad hoc networks, reservation, DSRC, multiple channel access, MAC protocol

1. Introduction

Vehicular ad hoc networks (VANETs) are a subclass of wireless sensor networks (WSNs) and consist of fast moving vehicles. Today in the intelligent transportation systems (ITS), the importance and usage of VANETs continue to increase. The vehicles forming these networks are mobile and relocate rapidly. For this reason, media access is of great importance for the network organization. The nodes establish communication with one another in the ad hoc mode and the fixed roadside units (RSUs) on the roads establish communication with one another in the infrastructure mode. Therefore, the properties of VANETs are mainly a mixture of the properties of the wireless media and the properties of different topologies (in the ad hoc mode and infrastructure mode) [1]. VANETs focus on the development of the efficient and trustable vehicle–vehicle (V2V) and vehicle–infrastructure (V2I) communication technology for the future transport systems [2]. Today, there are communication technologies allowing vehicles to establish communication with one another (V2V) or RSUs (V2I) and also providing a wireless interface implication for this. These communication technologies aim to

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ensure passenger/driver comfort by ensuring road safety, increasing traffic efficiency, and enabling a series of nonsafety applications [3,4]. In these networks, the unique properties of the vehicle network such as the difficulty of central coordination, variable nature of the wireless connections, dynamic topology, and short-term connection make multichannel coordination synchronization and media access more difficult [5]. VANETs are very dynamic and ad hoc networks that could provide very short-term connection to the infrastructure of the network and could provide more than one service within this short period [6]. These types of vehicle networks, in contrast to the other wireless communication networks, have special frequency bands assigned to them and there is no limitation of energy [7]. The increase in the comfort and safety needs of vehicle users has led to important studies in these areas by the manufacturers. The American Federal Communication Consortium (FCC) has assigned a special 75 MHz frequency band at the 5 GHz spectrum for the dedicated short-range communication (DSRC) standard. Thus the communication of the mobile vehicles with one another became more popular after this standard. The protocol batch for vehicle networks has to deal with communication between vehicles and fixed RSUs by taking the different properties of these networks into consideration. There are various difficulties in the protocol designs conducted in this area, because there is no coordination or preliminary configuration to establish VANETs [8]. The DSRC standard developed to overcome these difficulties is known as Wireless Access in Vehicular Environment (IEEE 802.11p WAVE [9]) based on the previous standards for wireless LANs [10]. The frequency band in DSRC has been divided into six service channels (SCHs) and one control channel (CCH), each one of which has a bandwidth of 10 MHz. Figure 1 shows the DSRC frequency mapping used in VANETs.

The DSRC standard provides a communication distance from 300 m to 1 km for the vehicles in the network. The standard is half duplex and could provide a data transfer speed of 6–27 Mbps [4,11].

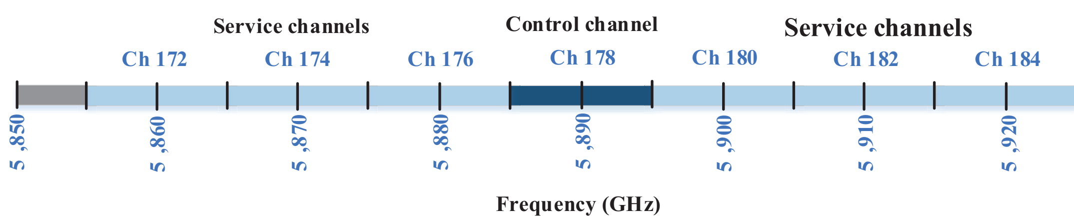


Figure 1. DSRC spectrum band and channels [12].

The media access control (MAC) layer ensures the addressing, channel access options, to establish communication of nodes with one another, and also ensures avoidance of collisions while using the media [13]. MAC protocols used in the traditional wireless networks cannot directly meet the needs of VANETs due to reasons such as frequent location changes and the rapid movement of the nodes. An efficient MAC protocol should share the communication media among the vehicles in a just and efficient way. In these types of dynamic networks, MAC protocols should be well structured to take into consideration the problems of mobile access collisions, interference, and hidden terminal/exposed node problems to increase the quality of the communication [14]. In the present article, a ReMAC protocol with the aim of easy connection of the vehicles to the network and the provision of opportunities for earlier organization of the network is suggested. The main aims of the protocol are to ensure the vehicles connect to the network with a multichannel and hybrid media access method, minimize the channel access collisions and interferences, arrange the network in a rapid way, assign the channels according to the vehicle direction, and minimize the access delays. The rest of the article is organized as follows: in Section 2, the MAC protocols proposed in this area are given. Section 3 includes the definition of the problem, the system model, and protocol details. Simulation results and performance comparisons are given in Section 4. The article finishes with the conclusion in Section 5.

2. Related work

An adaptive collision-free MAC protocol (ACFM) [15] is a MAC protocol suggested by Guo et al., using the adaptable time slot assignment mechanism in an RSU centered network and without any collision. The authors have aimed to warrant an efficient time usage for active vehicles using time-division multiple access (TDMA). Time is divided into frames and each frame is divided into 37 time slots. One of these time slots is used for sending control messages to the vehicles. The remaining 36 time slots are used to transfer data from the vehicles to their neighbors. It is specified that the same frequency should not be used in two hops to prevent interference among the neighbors. The authors have added the cycle length shortening and extension property to ensure justice in channel access. The time slot count in the CCH in ReMAC is 50 and the control packets are smaller than those in ACFM. Therefore, the ReMAC protocol affects the performance more positively when compared to ACFM.

VeMAC [16] is a multichannel, contention-free, and TDMA-based MAC protocol proposed by Omar et al. It has been designed for an RSU centered network scenario. It is aimed to prevent interference collisions by assigning discrete time slots to the RSUs and the vehicles. It is assumed that each node is equipped with two receivers. Synchronization is provided with a global positioning system (GPS). This protocol uses DSRC channels and aims to decrease the interference and access collisions in these channels. In the VeMAC protocol, the frame dimension has been adjusted to 50 ms for each direction and the dimension of the time slot is 1 ms. The next frame is awaited for the new connection request after collisions occurring while accessing the network and this is a disadvantage, because this delays the connection to the network and affects early network organization. The time slots in the suggested ReMAC protocol are much smaller than those in VeMAC and our protocol does not wait for the next frame for the new connection after the collision. For this reason, it operates much faster than VeMAC while accessing the network. Moreover, the ReMAC protocol operates more efficiently without being affected by dependence on GPS or GPS problems due to the fact that synchronization is ensured by RSU with periodical intervals with the synchronization packet delivered to all the vehicles.

With their publication called CFR-MAC [17], Zou et al. have suggested a near collision-free reservation-based MAC protocol. The mentioned protocol uses the TDMA method for media access and aims for channel access independent of the collision. The timing mechanism is like that of VeMAC and each frame is divided into two timeslot clusters to be assigned to the vehicles navigating in different directions. Because there may be interferences while moving at different speeds, the time interval set has been divided into three subclusters to use three different speed intervals for the solution of the problem. The protocol has been specified to have significantly decreased access delays and collisions. However, in the proposed ReMAC protocol, there is no speed limitation and there is no need for subclusters. The protocol succeeds in serving vehicles at different speeds thanks to its durable channel assignment algorithm.

Sidhik et al. have suggested a direction-based clustering and multichannel MAC protocol (DA-CMAC) [18] that is multichannel and could perform direction-based clustering. It is aimed to control the vehicles navigating in the same direction with a single clustering and to ensure coordination by assigning a cluster head for each cluster. The protocol aims to decrease the access and interference collisions within the channel by dividing the time slots into two groups according to their movement directions. A time interval is assigned to the nodes in the control channel and service channel to secure justice in channel access. According to the simulation results, it has been specified that the package transfer rate was increased and collisions were decreased. The suggested ReMAC protocol uses the central coordination method by RSUs and for this reason the coordination of ReMAC is easier and the network setup is faster compared with clustering-based protocols.

Babu et al. have developed a TDMA-based variable interval multichannel MAC (TM-MAC) [19] protocol. The main objective of TM-MAC is to use the TDMA and variable-interval multichannel programming for a performance increase such as high reliability and efficiency. TM-MAC has been specially designed to work on a single receiver/transmitter specified by the IEEE 802.11p/WAVE standard. It is necessary for each vehicle to attain a time slot and use this time slot to transfer the packets. The authors have suggested a MAC protocol that uses the channel access mechanism and variable-interval multichannel programming with a new way to increase the reliability and efficiency of VANETs. The ReMAC proposed in the present manuscript uses the carrier sense multiple access (CSMA), TDMA, and frequency division multiple access (FDMA) methods together for channel assignment and operates more efficiently than the TM-MAC protocol in the city scenarios. Moreover, ReMAC shows a better performance in the access collision and delay metrics.

An adaptive time division multiple access-based MAC protocol (VAT-MAC) [20] has been suggested by Cao and Lee. The dimension of each frame is recalculated for the maximum time slot usage with the adaptable time slot assignment mechanism. RSU assumes the number of vehicles that may connect to the network and calculates the optimal frame length. The authors state that the protocol increases the scalability and efficiency of the system. The hybrid media access method used in our proposed protocol, ReMAC, accelerates network access. Furthermore, because ReMAC has a more basic and efficient time slotting mechanism, it could perform faster time slotting. This is because the frame length assumption of VAT-MAC every time means additional time and processor usage, which does not exist in ReMAC.

3. Details of the ReMAC protocol

3.1. Definition of the problem and the system model

Because vehicles move so fast in VANETs, the period between the entrance to and exit from the network is very short. It is very important to be able to provide service to the vehicles within this short period. RSUs should have a robust MAC protocol that could conduct the connection setup without any problem. Within this context, the functions such as handling the intensive vehicle traffic, decreasing the channel interferences, minimizing the collisions, and decreasing the channel access delays could only be performed with a well-coordinated MAC protocol. The CSMA method causes decreases in the performance of the network due to the hidden terminal problem. The TDMA method has been developed as an alternative to CSMA to overcome this problem. However, when TDMA-based protocols are not well designed, access and interference problems occur, negatively affecting network performance [19]. Many multichannel access methods [21–24] have been suggested by researchers to minimize this decrease in performance. In the present study, a MAC protocol with multiple channels and in which different access methods are used together is suggested. The system we work on consists of RSUs that have been positioned at regular intervals on a two direction highway with rapid vehicle traffic. The vehicle movement directions have been accepted as like those of VeMAC. RSUs are the network management units that are not movable and they communicate with vehicles wirelessly. Vehicles are the mobile nodes and they have two wireless interfaces. Vehicles listen to the CCH via one of the wireless interfaces to provide the control communication and via the other one to the service channels for the information and entertainment services. The suggested protocol determines the next RSU according to the direction data of the vehicles and channel assignment is carried out for the vehicle before it enters the coverage area of the next RSU. In this way, a vehicle enters the coverage area of the next RSU by knowing which channels will be used. Therefore, except for the first one, when the coverage areas of RSUs are entered, there is no need for the channel request procedure. The vehicle does not have any contention for channel access and no contention delay is experienced in joining the network. The SCHs and CCH have been divided into subfrequency channels with equal bandwidth to provide collision-free channel access and reliable package transmission. The situation that these subchannels may be insufficient has been taken into consideration and each subchannel has been designed in such a way that they could be divided into time slots with TDMA. The number of the time slots could be dynamically adjusted according to the number of vehicles using the SCHs. The network architecture used for ReMAC is shown in Figure 2. The ReMAC protocol takes the parameter of direction into consideration and the usage of noncontiguous frequency channels is foreseen for the vehicles in different directions to prevent channel interferences.

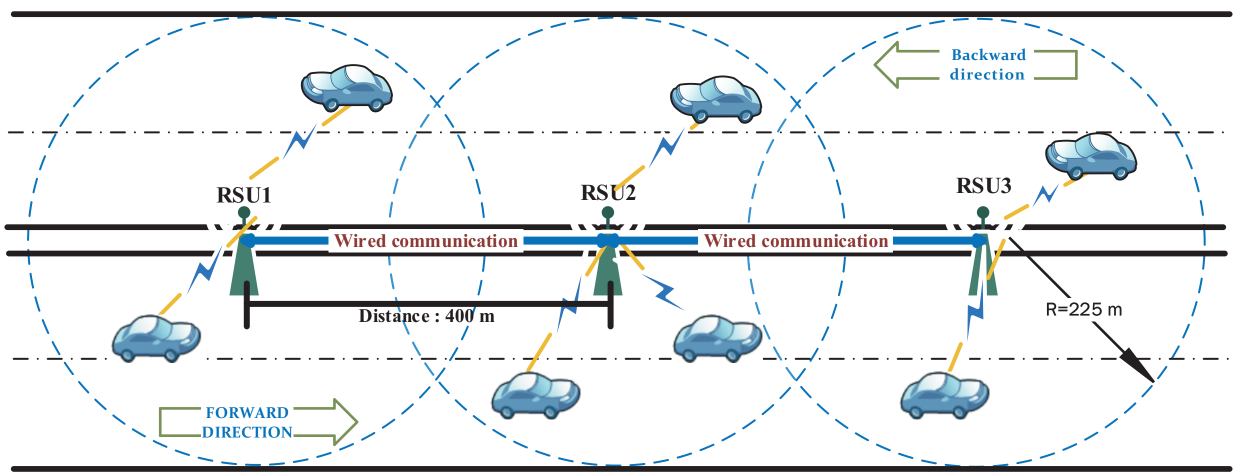


Figure 2. ReMAC network topology.

3.2. CCH and SCH organization

The CCH defined for the control communication in DSRC as default is used for the provision of control communication also in the ReMAC protocol. The vehicles moving in both directions use the CCH to send network connection requests to the RSUs, send data to the parent RSU about their status, and to state that they are still active in the network. Moreover, RSUs use the same CCH to receive the channel requests, listen to the vehicle heartbeats, and transmit the assigned channel information to the vehicles. The CCH has been divided into 8 subchannels (Figure 3) to fulfill different services and 5-kHz guard bands separate these subchannels from one another. Because there is no energy limitation in ReMAC protocol, the guard band has been selected as wide as possible to separate the subchannels from each other for the purpose of being able to decrease the interferences.

The joining network channel (JNCH) is a contention-based channel used by all vehicles when they enter the network for the first time. The vehicles requesting to join the network send requests to the RSU from the JNCH using the CSMA mechanism. This channel is only used to send the connection request packets during the connection process by the vehicles and they stop using this channel after the network is joined. In this way, the channel and time slots become free for new vehicles requesting to join the network. For the vehicles to be able to send their channel requests, the JNCH's time zone is separated into 8-ms frames. In addition, each one of these frames has been divided into 50 time slots 0.16 ms in size.

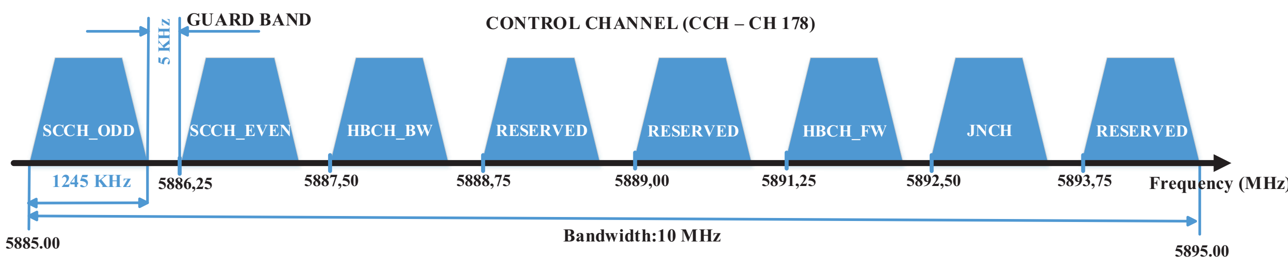


Figure 3. Control subchannels.

Each vehicle requesting to join the network could use this channel via contention with the defined CSMA algorithm independent of their directions. The scheduling channel of RSUs with odd ID (SCCH_ODD) and the scheduling channel of RSUs with even ID (SCCH EVEN) are used to send channel allocation (VCAPSingle, VCAPALL), RSU heartbeat (RSU_HB), and vehicle left the network (VLEAVE) packets. These channels have been arranged as two separate channels to provide the usage of different channels for the purpose of preventing interferences in the successive RSUs (Figure 4).

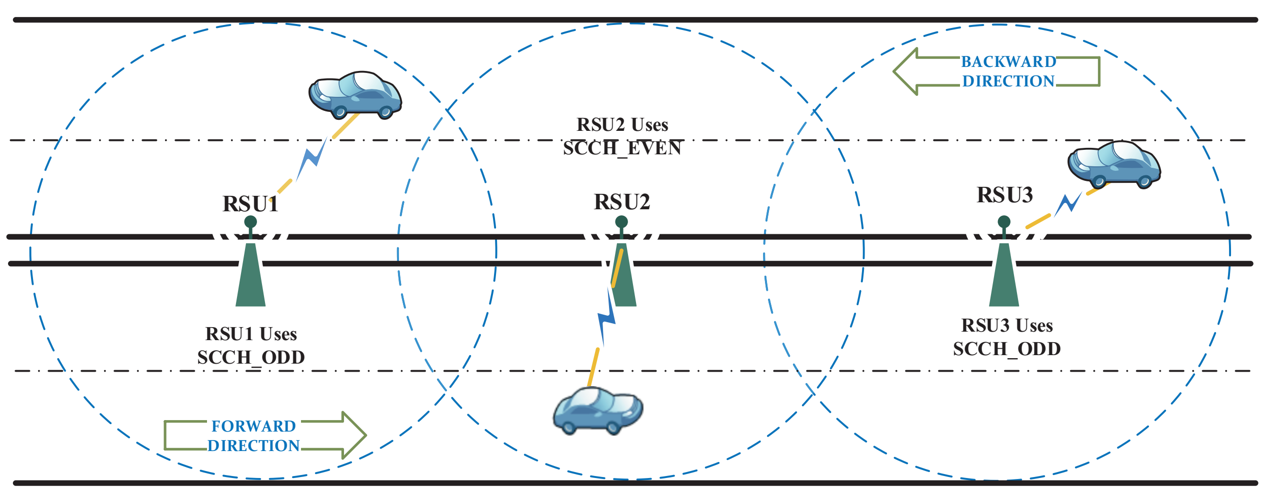


Figure 4. SCCH channel layout.

After a vehicle sends the connection request from JNCH to RSU, the RSU performs the channel assignment convenient for this vehicle and sends the scheduling packet to the vehicle upon the SCCH convenient for its ID. Therefore, all the vehicles listen to both SCCH_ODD and SCCH_EVEN channels. The vehicle receiving its scheduling package from one of these channels joins the network by adjusting the channels specified to it in the package. Vehicles send heartbeat packets (VHC_HB) to show their existence in the network after they join it. The RSU receiving these heartbeats understands that the vehicle is still within the coverage area. The RSU protects the service and control channels assigned to these vehicles. After joining the network, the vehicle sets free the contention-based JNCH channel and starts to use the heartbeat channel assigned to it. The vehicles active in the network send heartbeat packages to the RSU within their own time slots from HBCH channels. The other six channels with 10 MHz each are the service channels as explained in DSRC. In ReMAC, vehicles use these channels for multimedia and other services. For the purpose of avoiding the interferences and collisions that might occur in vehicles navigating in different directions, the Ch172, Ch174, and Ch176 channels have been assigned to the vehicles moving backwards. The Ch180, Ch182, and Ch184 channels have been assigned to the vehicles moving forwards. Moreover, each service channel has been divided into 10 subchannels with FDMA to increase the service channel count that could be assigned for the vehicles. Subchannel bandwidth is 995 kHz for each one of them and a 5-kHz guard band has been placed between two adjacent subchannels (Figure 5).

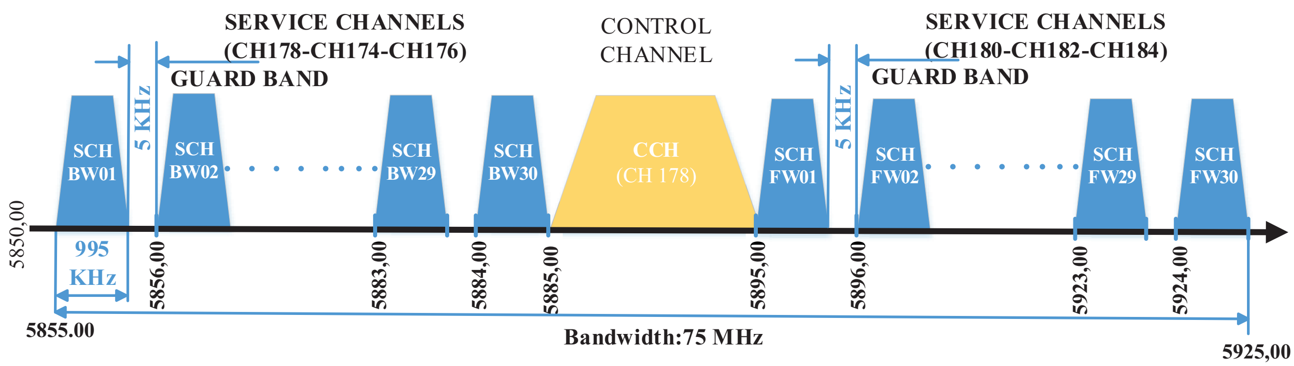


Figure 5. Channel layout for service channels.

Furthermore, when needed (when the vehicle count is above 60), an algorithm that could divide each service subchannel into time slots with TDMA has also been included in ReMAC. In this condition, the new subservice channel is formed dynamically by determining the SCH that is used least. In this way, more efficient usage of the channel is ensured by taking the just channel usage and channel occupancy rate into consideration.

3.3. Channel/time slot allocation process

The suggested ReMAC protocol assigns the service and control channels to vehicles in the RSU centered network by using the hybrid channel access methods and reservation according to the movement direction of the vehicle. The structures of packets used in the ReMAC protocol during all simulations are shown in Figure 6.

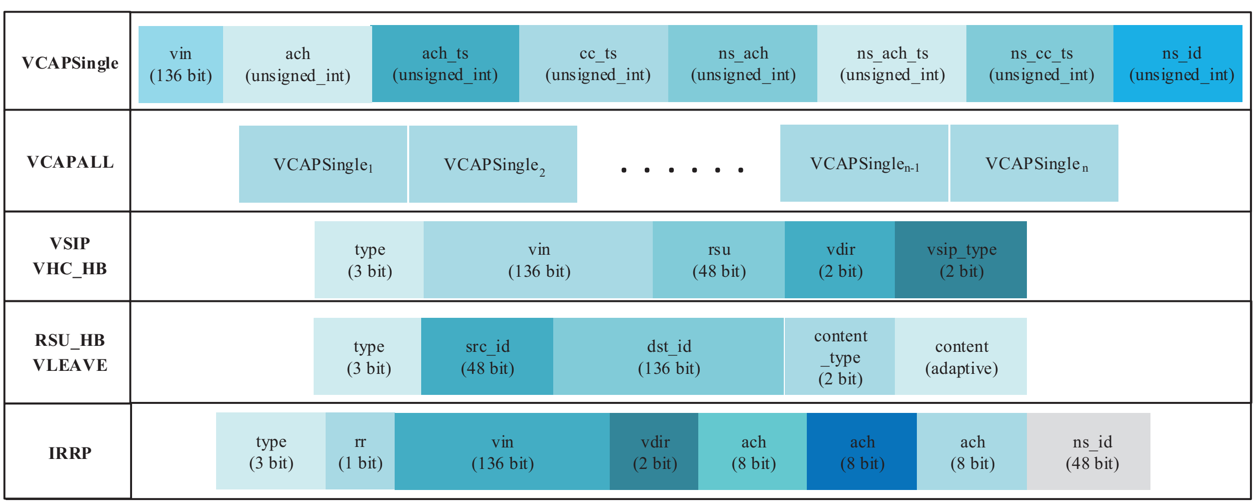


Figure 6. Packet structures.

The behaviors of the vehicles and RSUs in the network are as follows. RSUs have been adjusted as default in a way that they will listen to 8 control subchannels and 60 service channels. The RSUs also form a vehicle channel allocation table (VCAT) to store the channel assignment information of the vehicles existent in the network. In this table, CCH and SCH information assigned to the connected vehicles and those trying to connect is saved. The formats and explanations of packets used in the simulation are given in Tables 1 and 2. In addition, the RSU broadcasts the heartbeat packets (RSU_HB) that could be taken by all the vehicles at regular intervals and this event is important for the vehicles to understand which RSU coverage area they are in.

Table 1. Packet descriptions.

Packet	Packet explanation
VCAPSingle	Vehicles receiving this package understand that the RSU has accepted the request of the vehicle to join the network. Opens the package and sets the channels assigned to it. Join the network and start communicating.
VSIP VHC_HB	This packet is used to make a request to connect to the network if the vehicle is not connected. If connected to the network, it can be used to send a reservation request to the next RSU. It is also used as a heartbeat package to indicate that the vehicle is in the network. It can also be used to indicate the desire to leave the RSU network if needed.
RSU_HB VLEAVE	This packet is used to send RSU heartbeat signals that all vehicles within range can receive. The same packet is also used to drop a vehicle of the RSU from the network by editing the type field.
IRRP	This package is the packet that travels between RSUs over the wired interface during the reservation process. An RSU uses this packet when it requests a channel reservation from the next RSU for a vehicle within its coverage area, or when it responds to the neighboring RSU who made a channel request.

In addition, RSUs take the requests of the vehicles demanding to join the network by listening to the JNCH. In the initialization phase, each vehicle adjusts itself to listen to the control channel and the default data channel. After that the vehicle starts to send the channel request packets (VSIP) to the RSU from the JNCH by using the CSMA method. If an RSU receives a VSIP from the JNCH, then it assigns a data channel to the vehicle from the convenient channel group. It also assigns a time slot from the convenient heartbeat channel according to the moving direction of the vehicle making the request. It writes this assignment information to the VCAT table and prepares a configuration package (VCAPSingle) in which the target is the vehicle making the request. Afterwards, the RSU sends this package to the vehicle. If an RSU takes heartbeat packages from a vehicle, it accepts that the vehicle is in its own network. When the RSU receives a heartbeat from a vehicle, it checks the existence of this vehicle in the VCAT table; if existent, it updates its information and, when necessary, it demands a rapid channel reservation from the next RSU by using the wired connection for this vehicle. Moreover, RSUs calculate a network drop time (DT) for all the vehicles connected to them and write it in the VCAT table. It is assumed that the vehicles not sending any heartbeats until this time are disconnected from the network. In addition, the vehicles that cannot send any heartbeat due to leaving the coverage area are also deemed to have dropped out of the network after this period. In this way, the channels and time slots occupied by these vehicles are emptied and they become reusable for new vehicles that are joining the network. The protocol calculates the network DT as in Equation 1 by taking into consideration parameters such as RSU coverage area diameter, dimension, and vehicle speed. In the DT formula, t shows the simulation time at that moment, DVP shows the maximum time between two heartbeats, and RT shows the period necessary

Table 2. Packet formats.

Packet	Field	Size	Description
VCAPSingle	vin	136 bits	Vehicle's chassis number
	ach	8 bits	The number (id) of allocated SCH to the vehicle by the RSU
	ach_ts	8 bits	The time slot in the SCH assigned to the vehicle by the RSU
	cc_ts	8 bits	The time slot in the CCH assigned to the vehicle by the RSU
	ns_ach	8 bits	Service channel that the vehicle will use in the next RSU
	ns_ach_ts	8 bits	SCH time slot that the vehicle will use in the next RSU
	ns_cc_ts	8 bits	CCH time slot that the vehicle will use in the next RSU
	ns_id	48 bits	ID of the next RSU
VSIP VHC_HB	type	3 bits	Specifies the packet type. VSIP packet's type must be 001
	vin	136 bits	Vehicle's chassis number
	rsu	48 bits	The RSU ID to which the vehicle wants to connect.
	vdir	2 bits	Determines the direction of movement of the vehicle.
	vsip_type	2 bits	Type of VSIP packet. 00: RSU request, 01: Next RSU request, 10: Heartbeat, 11: Release request
RSU_HB VLEAVE	type	3 bits	Specifies the packet type. RSU_HB packet's type must be 010
	src_id	48 bits	The ID of RSU that sends the Heartbeat.
	dst_id	136 bits	The ID of vehicle which the RSU sends the heartbeat.
	content_type	2 bits	00: RSU_HB, 01: VLEAVE, 10: VCAPSingle, 11: VCAPALL
	content	adaptive	This is the field where the information of the selected packet is placed. Size varies according to the size of the information.
IRRP	type	3 bits	Specifies the packet type. IRRP packet's type must be 011
	rr	1 bit	0: Reservation request, 1: Response to the reservation request
	vin	136 bits	Vehicle's chassis number
	vdir	2 bits	Determines the direction of movement of the vehicle.
	ach	8 bits	The ID of the service channel allocated to the vehicle by the RSU
	ach_ts	8 bits	The time slot in the SCH assigned to the vehicle by the RSU
	cc_ts	8 bits	The time slot in the CCH assigned to the vehicle by the RSU
	ns_id	48 bits	The ID of the next RSU

for the vehicle to reach the coverage area of the next RSU. In the suggested protocol, the vehicles regularly send heartbeat packages once every 25 ms (T_{VHB}). If the vehicle does not send any heartbeat within 0.5 s (20 vehicle heartbeat period), it is assumed that it will be disconnected. DVP is calculated using Equation 2. The time of a vehicle to cross an RSU's coverage area is calculated as in Equation 3 depending on its speed. In Equation 3, r shows the radius of RSU coverage area and v_t shows the speed of the vehicle. In this respect, the reservation tolerance period is calculated as in Equation 4. Finally, when all the components are take into account, DT is calculated as in Equation 5. The Equations are presented in Table 3.

The vehicle listening to the SCCH channel gets the information related to the channels assigned from VCAPSingle packets and could start the communication. After this step, the vehicle chooses and sets the HBCH channel adjusted according to its direction to send the heartbeat packets to the RSU in its own time slot.

One of the innovations of the suggested protocol is the novel reservation mechanism. An RSU requests channel assignment from the next RSU for the vehicle connected to it. The RSU uses the inter-RSU reservation

Table 3. Equations for calculating drop time (DT).

Equation type	Equation
Network drop time	$DT = t + DVP + RT$ (1)
Vehicle disconnecting period	$DVP = 20 * T_{VHB} + 0.001$ (2)
RSU coverage crossing time	$t_v = \frac{2r}{v_t}$ (3)
Reservation tolerance	$RT = t_v + t_v * 0.001$ (4)
Drop time	$DT = t + DVP + RT = t + (20 * T_{VHB} + 0.001) + (t_v + t_v * 0.001)$ (5)

packet (IRRP) and wired interface to deliver this request. After the neighbor RSU answers this request and performs the channel assignment, it transmits this information to the requesting RSU as an IRRP answer. The requesting RSU updates the channel information of the vehicle in the VCAT table by adding the reservation data coming from the next RSU. In this way, the channels to be used by the vehicle in the coverage area of the next RSU are determined. Afterwards, the RSU forms a new VCAPSingle packet containing the next RSU data for this vehicle and delivers it to the related vehicle. After the vehicle receives the VCAPSingle packet from the RSU, it learns which channels will be used in the coverage area of the next RSU. Therefore, there is no need for contention to connect to the next RSU while leaving the previous coverage area and no channel access delay is experienced. When the vehicle comes to the end of the coverage area of the parent RSU, it leaves that RSU's network and connects to the network of the next RSU. When the vehicle reaches the intersection zone of two RSU coverage areas, it could take the heartbeat packets of both RSUs. In this situation, it understands that it is getting close to the end of the coverage area of the RSU to which it is connected. After that, it adjusts the channels to be used in the coverage area of the next RSU. It sends a leaving request packet (VLEAVE) to its parent RSU. In this way, its transition to the new network occurs in a rapid and unproblematic way. Then the vehicle is in the coverage area of the new RSU and it has sustained the network connection without being obliged to use the contention-based JNCH channel. This situation ensures the gaining of a long period of time in the network transitions by the protocol. In the situation when the vehicle drops out of the network, the vehicle turns the channel and time slot settings into the default settings (initialization phase). In this way, the vehicle acts like a vehicle trying to join the network for the first time, starts to listen to the media, and requests a network connection again on the JNCH when it receives an RSU heartbeat. RSUs prepare a VCAPALL package that contains the information of all member vehicles taking place in the VCAT once (at the end of a 5 heartbeat period) every 125 ms ($T_{VCAPALL} = 5 \times T_{VHB} = 5 \times 25\ ms = 125\ ms$) for synchronization. The RSU broadcasts the VCAPALL packet to all vehicles in its network. The vehicles that take this packet update their information if there is any, determine the channel and time slot modifications, and conduct network synchronization. The connection setup procedure of the suggested protocol between the vehicles and RSUs is shown in Figure 7 and the channel selection algorithm used in the assignment of the control channels and service channels is given in Algorithm 1. In the ReMAC protocol, channel assignments are conducted by taking the direction parameter into consideration. It has been aimed to decrease the interference by assigning discrete frequencies for the vehicles navigating in different directions.

If the number of vehicles in one direction is less than 30, the protocol assigns a service channel dedicated to each vehicle. As could be seen in the algorithm, a dynamic channel assignment method is used to provide maximum efficiency and fair usage in the service channels. Depending on the direction of the vehicles, channels are primarily assigned to the vehicles. If the number of vehicles in one direction is higher than the channel

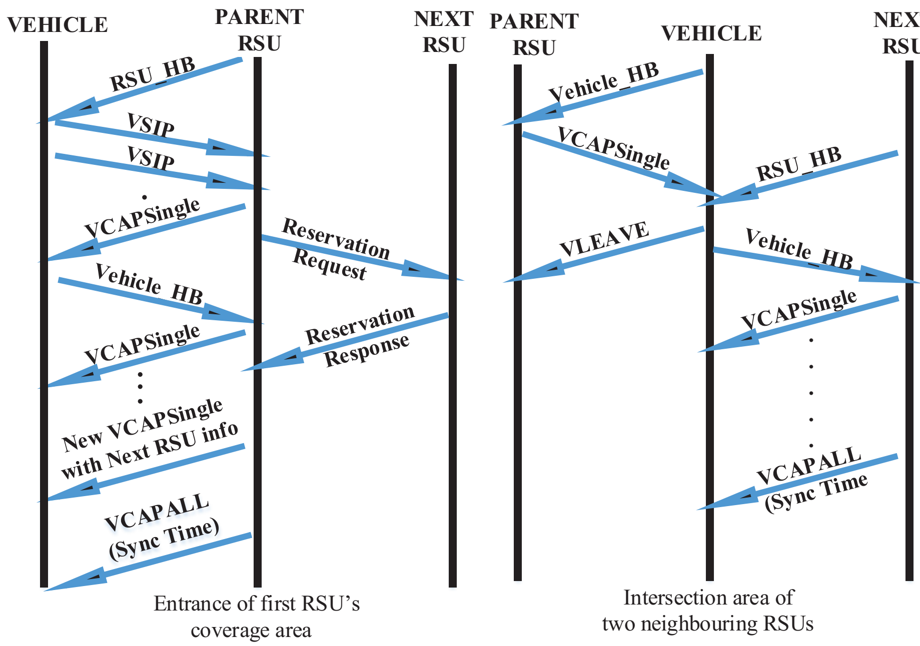


Figure 7. Connection setup procedure.

number, time division multiplexing is conducted in these channels. Before the application of TDMA, the least used channels are determined by considering the number of vehicles in the channel. Afterwards, by starting from the least used channel time slots are formed and assigned to the new coming vehicles. The lengths of these time slots are not fixed; they are calculated by dividing frame length by the total vehicle count in the channel. The ReMAC protocol contributes to fair channel usage and total communication quality with the hybrid channel allocation mechanism aiming for efficient and fair channel usage. The equations used for the channel & slot allocation mechanism algorithm are given in Table 4.

n_{ch} shows the number of the service channels (30 for each direction), ach shows the assigned service channel number, and $n_{emptych}$ shows the number of empty channels. The time slot of the service or control channel to be assigned to the vehicle is determined by calculation with the help of Equation 6. First, the number of empty channels ($n_{emptych}$) should be found to be able to determine the channel to be assigned. By considering the number of empty channels found, the channel to be assigned to the vehicle (ach) is determined with the help of the get_first_empty_ch() and get_least_used_ch() functions defined in the algorithm channel assignment mechanism (Equation 7). It can be seen from Equation 8 that if the assigned channel is empty, the total vehicle number in the channel is 1. If the channel is not empty, the total vehicle count using this channel is found with the help of the get_ch_count_in_sch() function.

The time slot number in the service channel assigned to the vehicle may dynamically change depending on the vehicle count. If there is an empty time slot when a new vehicle comes, this time slot is assigned to the vehicle without creating a new time slot. If there are no empty time slots, a new time slot is created at the end of the frame. Empty time slot check is conducted with the is_there_empty_slot_in_sch() function defined in the channel control mechanism. If there is no empty time slot in the assigned service channel, the assigned time slot number is equal to the number of assigned channels. Otherwise, the time interval is equal to the time slot count (ts_count_in_last_frame ()) in the last frame as in Equation 9. The dimension of the time slot(l_{ts}) is

Algorithm 1: Channel & slot allocation mechanism.

```
Data: This algorithm helps the protocol for assigning available service and control channels and
      time slots to the vehicles.
Result: Assigned service&control channel and time slot numbers
if vehicle direction is BACKWARD then
  | choose backward_frequency_band(bfb) for channel allocation;
else
  | choose forward_frequency_band(ffb) for channel allocation;
end
find least used channel by find_min_vehicle_count_in_ch_list(ch_list);
while data_ch_id == 0 do
  | return first_empty_channel via check_best_ch_in_ch_table function;
  | data_ch_id = check_best_ch_in_ch_table(ch_list, vehicle_count);
  | if data_ch_id == 0 then
  |   | vehicle_count++;
  | end
end
if checked channel is not empty then
  | // for data channel
  | if vehicle direction is BACKWARD then
  |   | ch = data_ch_id-1;
  | else
  |   | ch=data_ch_id-1-BFB_ch_count-CFB_ch_count;
  |   | // Increase the number of vehicles using this channel.
  |   | ch.vehicle_count++;
  |   | allocate data_ch_id for vehicle data_channel;
  |   | // allocate data channel time slot for vehicle
  |   | ach_ts = get_first_empty_ach_ts(data_ch_id, vehicle_id);
  | end
  | // for control channel
  | ch = choose control channel;
  | // Increase the number of vehicles using this channel.
  | ch.vehicle_count++;
end
// find control_channel ID from direction
cch_id = get_cch_id_from_direction(xvdir);
// allocate first empty slot from control channel for vehicle
cc_ts = get_first_empty_cc_ts(vehicle_id, vehicle_direction);
```

calculated with the ratio of the total frame dimension(l_{fr}) to the time slot number as in Equation 10. The slot number of a vehicle (o_{ts}) in the service channel is attained with the get_first_empty_slot_in_sch(ach) function. If there is no empty time slot, n_{vach} is the time slot number of the new vehicle and it also shows the count of the vehicles in the channel (Equation 11). The assignment of the time slots in the control channel is also conducted as in the service channels.

Table 4. Equations for the channel & slot allocation mechanism.

Equation	
$n_{emptych} = \sum_{i=1}^{n_{ch}} i \times x \begin{cases} x = 1 & : \text{if channel is empty} \\ x = 0 & : \text{if channel is not empty} \end{cases}$	(6)
$ach = \begin{cases} get\_first\_empty\_ch() & : n_{emptych} = 0 \\ get\_least\_used\_ch() & : n_{emptych} > 0 \end{cases}$	(7)
$n_{vach} = \begin{cases} 1 & : n_{emptych} = 0 \\ get\_ch\_count\_in\_sch(ach) & : n_{emptych} > 0 \end{cases}$	(8)
$n_{ts} = \begin{cases} n_{vach} & : no\ empty\ slots \\ last\_frame's\_ts\_count() & : otherwise \end{cases}$	(9)
$l_{ts} = \frac{l_{fr}}{n_{ts}}$	(10)
$o_{ts} = \begin{cases} take\ first\ empty\ slot & : empty\ slots\ present \\ n_{avch} & : otherwise \end{cases}$	(11)

4. Simulation and performance evaluation

4.1. Performance metrics

The performance assessment of the ReMAC protocol has been conducted with comparison to the VeMAC, CFR-MAC, VAT-MAC, and TM-MAC protocols in the literature. In these comparisons the metrics such as two hop set occupancy (THSO), access collision rate (ACR), network joining success rate (SR), initial access collisions (IAC), joining delay (JD), average normalized throughput, and vehicle density have been used. The equations of the performance metrics are given in Table 5 (Equations 12–16).

Table 5. Performance metric equations.

Performance metric	Equation	
Two hop set occupancy (THSO)	$THSO = N_v * \frac{2R}{(L_h * S_o)}$	(12)
Access collision rate (ACR)	$ACR = \frac{\sum n_{cc}}{n_{ts}}$	(13)
Success rate (SR)	$SR = \frac{\sum n_{cv}}{\sum n_v}$	(14)
Initial access collisions (IAC)	$IAC = \sum_{i=1}^{n} cc_n$	(15)
Joining delay (JD)	$IAC = \frac{\sum_{i=1}^{n} t_c}{n}$	(16)

4.2. Performance evaluation

The simulation of the suggested protocol has been firstly carried out in a low-density scenario to show the difference of the reservation method. Figure 8 shows the network connection status of vehicles when the reservation method has been used and not used. Here 1/0 respectively shows the connected/disconnected statuses.

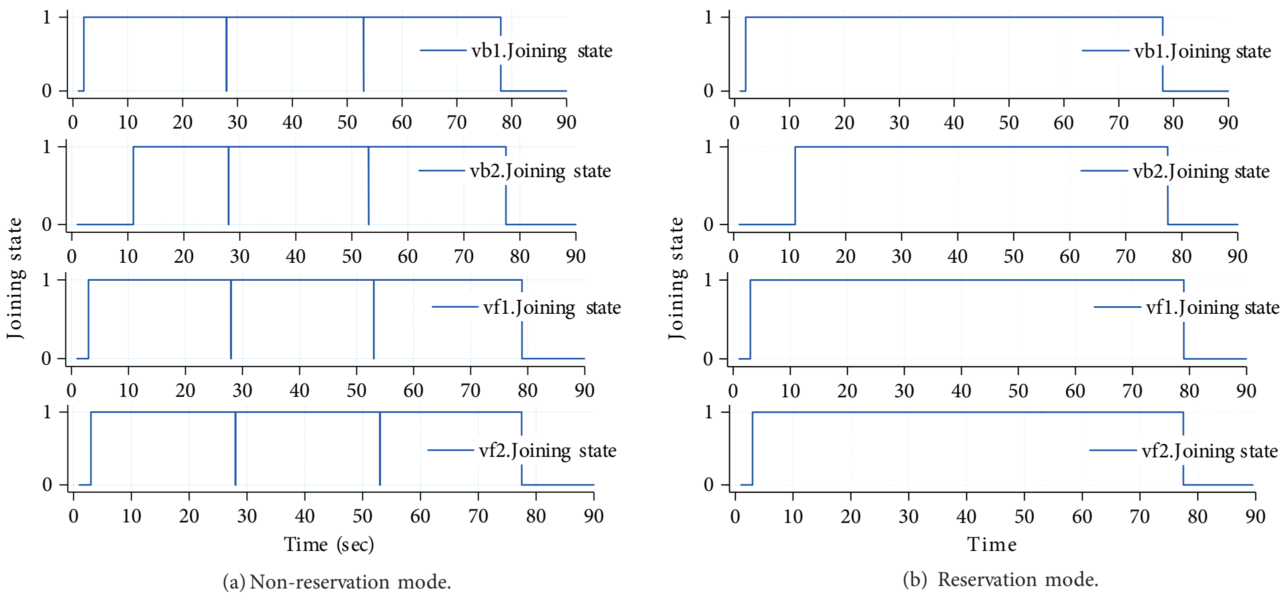


Figure 8. Joining states of vehicles to the network in nonreservation and reservation modes.

Furthermore, vf1 shows the first vehicle navigating in the forward direction and vb1 shows the first vehicle navigating in the backward direction. In the nonreservation mode, vehicles disconnect from the network when they are out of the coverage area of each RSU (Figure 8a). It is obvious that this situation will have a negative impact on the healthy and continuous communication of the vehicles. As seen in Figure 8b, vehicles connect to the next RSUs without spending any contention period after they are connected to the first RSU network with the help of the reservation mechanism. These vehicles do not experience any disconnection until they are out of the coverage area of the last RSU. Figure 9 shows that all vehicles have left the network of the RSU in the intersection of the RSU coverage areas in nonreservation mode. Afterwards, they are connected again to the network of the next RSU. Without doubt, due to the reconnection contention, disconnection from the network is experienced for a long time and this negatively affects the healthy transfer of data.

In the reservation-based scenario there is no contention and no disconnection is experienced. After connecting to the first RSU, a vehicle could continue to establish unproblematic communication without any disconnection from the network until the end of the parkour. The ReMAC simulation parameters used for the highway and city scenarios are shown in Table 6. Comprehensive simulations have been conducted by using the OPNET Modeler simulator to compare and analyze the performance of the ReMAC protocol with the VeMAC, CFR-MAC, VAT-MAC, and TM-MAC protocols.

The OPNET simulation environment is as follows. The simulation environment is a two way highway. The movement directions of vehicles have been expressed as forward and backward. The movement directions have been chosen like VeMAC [16]. RSUs are the fixed road side units with a unique identity number and they have a wired connection among one another for the reservation to be rapid and unproblematic. The network management units (RSUs) have been positioned at regular intervals. Each RSU has a wireless interface to establish communication with the vehicles and two wired interfaces for communication with neighboring RSUs. Vehicles have a GPS to attain and share the location data. They have two wireless interfaces for listening to control communication on the CCH and data communication on the SCH. The RSU coverage area radius has been chosen as 225 m and the distance between two neighbor RSUs is 400 m in total, because the wireless

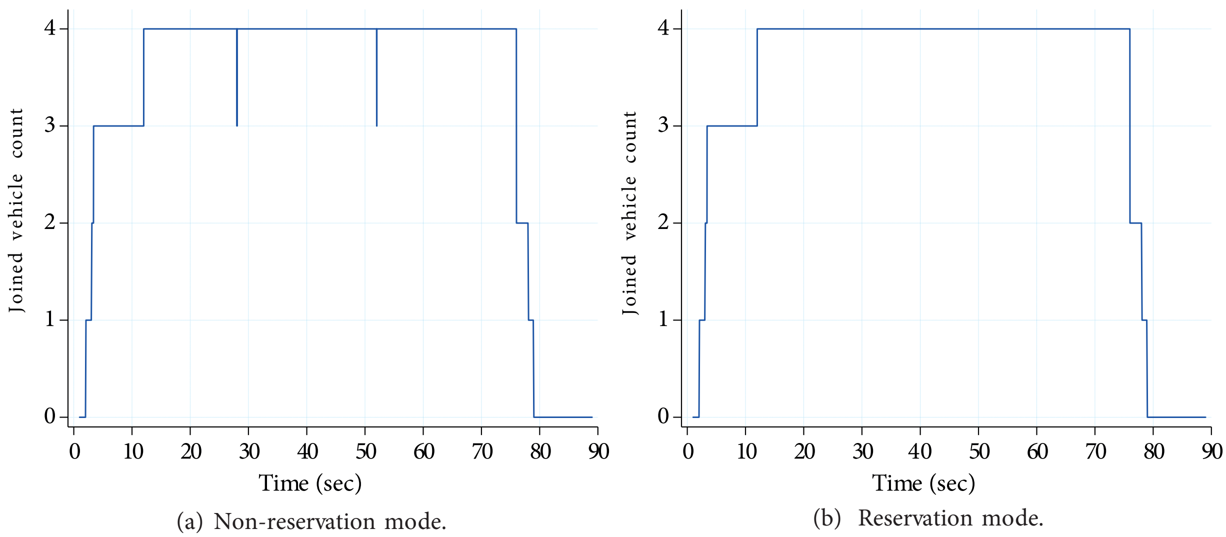


Figure 9. Total joined vehicle count in nonreservation and reservation modes.

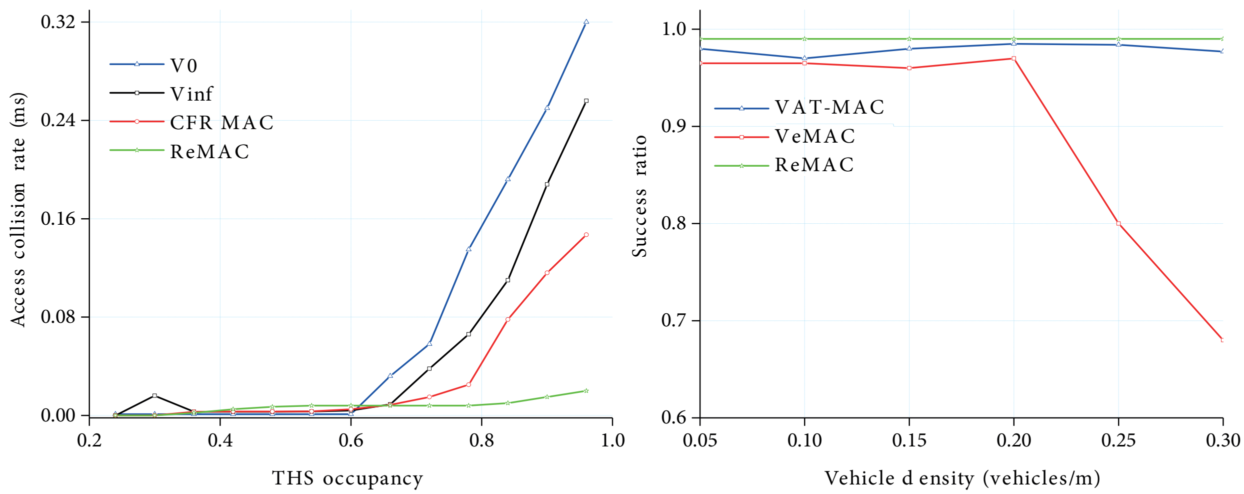
Table 6. Simulation parameters.

Parameter	Highway scenario	City scenario
Highway length (km)	1.25	1.25
Lane number/direction	4	4
Average speed (km/h)	100	50
Time slot length (ms)	0.16	0.16
Frame length (ms)	8	8
Simulation period (s)	90	120
Vehicle density (veh/km)	80 to 300 step 20	30 to 80 step 10
Two hop set occupancy	0.24 to 0.96 step 0.6	-
Control channel bandwidth (MHz)	10 (8 $\times$ 1.25)	10 (8 $\times$ 1.25)
Coverage area distance (m)	400	400

devices and antennas that provide communication at this distance have been used in the simulation. Moreover, the length of the intersecting zone between two RSUs is 50 m. In addition, the simulation has been performed in different scenarios with 30–80 vehicles/km densities for the city environment and 80–300 vehicles/km densities for the highway environment.

Figure 10 shows the access collision rate and success rate performance of ReMAC compared to its competitors. These simulations have been conducted in the highway environment. In Figure 10a, V_{inf} and V_0 are two different schemes in VeMAC [16] with the value of τ set to 0 and ∞, respectively. It shows that the access collision rate of the ReMAC protocol is less when compared to the others and it is much more successful than the others in high vehicle densities. While the best access collision rate is 0.0308, it is 0.007995 in the ReMAC protocol. This shows that the ReMAC protocol has 74.08% better performance than the best one of the compared protocols regarding the access collision rate.

Because the frame dimension and time slot dimensions are insufficient in VeMAC, the collisions increase and the network joining rate decreases after the vehicle density increases to 200 (Figure 10b). Although the



(a) The access collision rates. (b) The success ratios.

Figure 10. The access collision rates and success rates in various vehicle density scenarios.

adjustable slot dimension mechanisms mostly work, it is seen that they have difficulty in integrating all the vehicles into the network. In ReMAC, thanks to the subchannel structure of the CCH, channels use the contended channel time slots for a very short period. In this way, free time slots are available for new vehicles and all the vehicles can join the network without any collision. Although it uses a smaller network joining channel (1245 kHz), the success rate is 99.9% in all scenarios. The ReMAC protocol is the best when compared to all other protocols.

Figure 11 shows the average normalized throughput comparisons. As seen, the throughput value is close to 1 in all protocols. This parameter is at 30% level in all scenarios for ReMAC. This situation is related to the design concept of ReMAC. As the vehicle density increases, all the vehicles could be provided with an opportunity for joining the network and ensuring unproblematic communication. Moreover, the throughput value of ReMAC lower than that of VAT-MAC is considered to be related to the control package magnitude. the control package dimension is 1000 bytes in VAT-MAC, but it is a maximum of 200 bytes in ReMAC. In addition, it is necessary to take the delivery frequency of the control packages into consideration. Furthermore, it is not clear whether this output value is for the CCH or the SCH in the reference protocols. This value has been calculated for the CCH in ReMAC. In addition, while these protocols use a combined 10 MHz control channel, ReMAC has smaller subchannels for different control processes. This helps to make the protocol more flexible and provides unproblematic network services even in heavier network traffic conditions. All protocols reach full capacity in a traffic scenario of 300 vehicles. However, it is clear that in ReMAC, in order to reach full capacity, much higher vehicle density is needed.

Figure 12 contain comparisons with VeMAC and TM-MAC protocols to show that the ReMAC protocol may be an efficient protocol in the city scenarios.

Figure 12a shows the number of collisions occurring in a contention-based channel while joining a network. When the figure is examined, it is observed that the access collision increases in the VeMAC and TM-MAC protocols when the vehicle density increases. While the average number of the collisions is 40.3 in VeMAC and 35.3 in TM-MAC, it is 0 in ReMAC and no access collision is observed in any ReMAC scenario. This means that ReMAC could realize almost collision-free network access in the city scenarios with high density. ReMAC uses the contention-based channel only at the first connection stage and after the connection installation

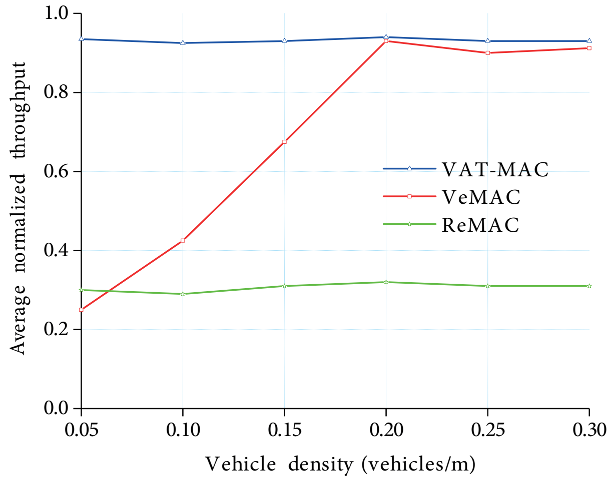


Figure 11. Average normalized throughput in various vehicle density scenarios.

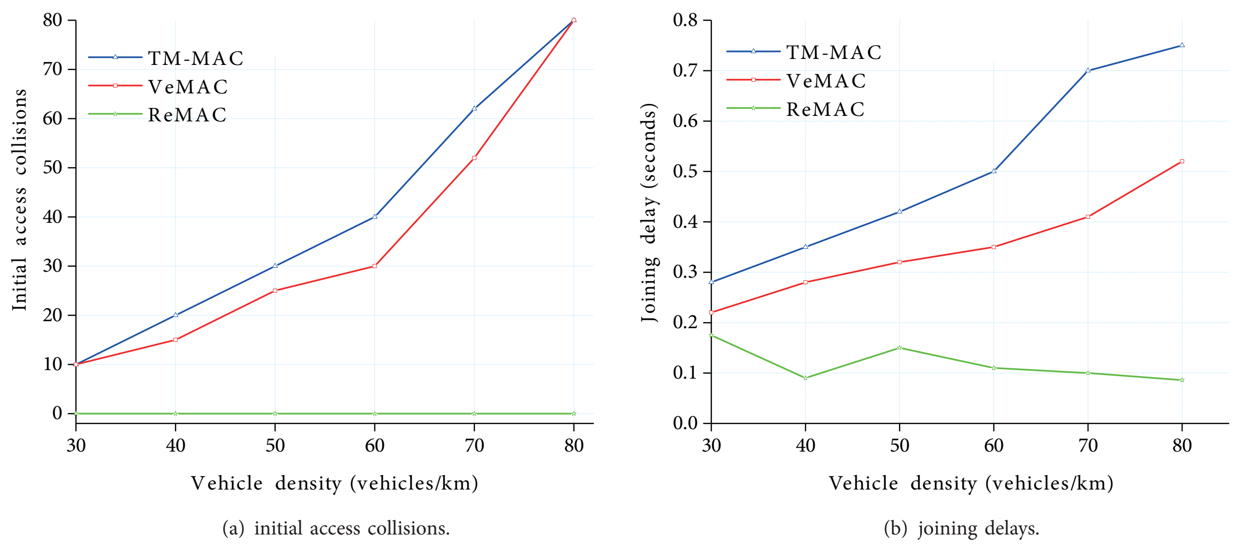


Figure 12. The initial access collisions and the joining delay comparisons in various vehicle density scenarios for the city environment.

the vehicles stop using this channel. Therefore, empty time slots that could prevent initialization contention could always exist for new vehicles in ReMAC. In addition, the efficient time slot assignment mechanism helps prevent collisions. It is clear from Figure 12b that the protocol with the best network joining delay performance is ReMAC. The delay only occurs in ReMAC in the first connection phase of the vehicles and there is no delay when there is vehicle transition among the RSUs. Therefore, joining delay occurs much lower than in the others. The access delay average is 0.5 s in VeMAC, 0.35 s in TM-MAC, and 0.122 s in ReMAC in all density scenarios. For this reason, it is observed that ReMAC shows 65.09% better performance than TM-MAC, which is the best one.

5. Conclusion

In this article, a new reservation-based multichannel and hybrid MAC protocol called ReMAC has been proposed for VANETs. The protocol provides unproblematic and almost collision-free media access together with an efficient channel assignment mechanism. Thanks to the original reservation mechanism, network access delay decreases a lot. According to the simulation results, the ReMAC protocol shows 74.08% better performance than the best protocol compared in terms of the access collision rate. While the network connection rates (success rate) decrease in high vehicle densities in the VAT-MAC and VeMAC protocols, ReMAC achieves a successful network connection rate of 99.9% in all scenarios. It is seen that the suggested protocol may have three times higher average normalized throughput when compared to the others. When the success of ReMAC in city scenarios is examined, it could be observed that the initial access could occur almost without any collision and the network connection delays are 65.09% less than in TM-MAC. As seen from the results, the ReMAC protocol ensures the joining of more vehicles to the network in a rapid and unproblematic way by decreasing the network access delays and collisions via the new hybrid channel assignment mechanism. It facilitates communication between the vehicles and RSUs by using dedicated FDMA channels.

In addition, the protocol could adapt to the rapidly changing vehicle network topologies. Consequently, the proposed protocol's throughput and performance are better than those of the reference protocols. The performance comparison shows that the ReMAC protocol is a successful protocol for both highway and city scenarios.

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