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VC²-MAC: A Two-Cycle Cooperative MAC Protocol in Vehicular Networks

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Abstract—With the rapid growth and evolution of the vehicular network with the highly increasing demand of vehicular traffic management, vehicular infotainment applications, and the vehicular cloud computing, massive vehicular information is required to be downloaded from roadside-deployed gateways. With the nature of high mobility and intermittent connectivity, it is challenging to provide a highly reliable media access control (MAC) protocol in vehicular networks to increase the broadcast efficiency of the information downloaded to all vehicles. This paper proposes a new MAC protocol, called the two-cycle cooperative MAC protocol (VC²-MAC), for vehicular networks. This work mainly improves an existing VC-MAC protocol with the concept of cooperative communication for vehicular networks, particularly for gateway-downloading scenarios. The VC-MAC protocol performs one cycle of relaying, which is called the one-cycle relaying MAC protocol throughout this paper. Unfortunately, many vehicles cannot successfully receive the messages from the relaying vehicles within one-cycle relaying in situations where there are intermittent link disruptions. This paper further utilizes the concept of two-cycle relaying to not only significantly improve the reachability and the downloading efficiency but also significantly reduce the packet overhead and the network access time. Finally, simulation results are examined to illustrate the performance achievements of dissemination success rate and message overhead.

Keywords—Vehicular network; cooperative communication; media access control; relay.

1 INTRODUCTION

The intelligent transportation system (ITS, [1]) is an emergent system that integrates advanced electronics, communications, information, and wireless sensor technology to provide safety and comfort for drivers on highway and urban streets. ITS is typically classified into two categories, roadside-to-vehicle communications (RVCs) and inter-vehicle communications (IVCs) [2]. With the
highly increasing demands of vehicular traffic management, vehicular infotainment applications, and the vehicular cloud computing, massive vehicular information is required to be downloaded from roadside-deployed gateways. The main purpose of intelligent transportation systems (ITSs) [1] is to provide safety-driving environment and infotainment applications to drivers. The vehicular networks are the cornerstone of the ITS. IVCs provide the data communication for each pair of vehicles. The IVC applications are the collision warning, the pre-crash sensing, and the emergency notification [3]. RVCs provide the data communication between a vehicle and roadside-deployed gateways (roadside unit) or base stations. The RVC applications are the wireless Internet access, point-of-interest notifications, tolling, and e-map downloads. The government can forward the newest traffic information to the drivers via roadside units. With the traffic information through the roadside unit, drivers may dynamically change their travel path to avoid the dangerous path. In addition, shopping malls, gas stations, and theaters can download their location-dependent information to the nearby vehicles through the roadside unit. This download traffic load is much larger than the upload traffic load [4]. The throughput of the download traffic load of the overall system performance is a very important issue to be further investigated in RVC.

With the nature of high mobility and intermittent connectivity, it is challenging to provide a highly reliable media access control (MAC) protocol in vehicular networks to increase the broadcast efficiency of the information downloaded to all vehicles with RVCs. In this paper, a new MAC protocol, called two-cycle cooperative MAC protocol (VC$_2$-MAC), is proposed for vehicular networks. This work mainly improves an existing VC-MAC protocol [4] with the concept of cooperative communication for vehicular networks, particularly for gateway-downloading scenarios. The VC-MAC protocol performs one cycle of relaying, which is called the one-cycle relaying MAC protocol throughout this paper. Unfortunately, many vehicles cannot successfully receive the messages from the relaying vehicles within one-cycle relaying in situations with intermittent link disruptions. This paper further utilizes the concept of two-cycle relaying to not only significantly improve the reachability and the downloading efficiency but also significantly reduce the packet overhead and the network access time. The proposed scheme can significantly reduce the packet overhead compared to the VC-MAC protocol [4] by performing the one-cycle MAC process twice to achieve the same purpose. This result leads to green vehicular communication by reducing the packet overhead and power consumption. To illustrate the performance achievements, simulation results are examined.

The rest of this paper is organized as follows. Section 2 discusses related works. The system model and challenges are described in section 3. Sections 4 and 5 present the details of VC$_2$-MAC protocol. Simulation results are examined in section 6. Finally, section 7 concludes this paper.

2 RELATED WORKS

Some interesting cooperative communication and cooperative downloading protocols in
vehicular network are reviewed and discussed. Some results support cooperative communication in the physical layer [5, 6, 7] to increase the system performance. CoopMAC I and CoopMAC II [5] are fully compatible with legacy systems. They can be extended to higher PHY rate systems, e.g., 802.11 a/g. Cooperation between mobile stations utilizes space diversity and makes better use of the multiple transmission rates offered by the PHY layer. Korakis et al. [6] implemented a scheme using relay stations. The scheme selects a relay station if a source station experiences a poor quality channel with a specific destination. The relay station performs the data transmission by a two-hop communication at a higher rate instead of the direct data communication at a low rate. Shankar et al. [7] enhances the existing IEEE 802.11e wireless local area network (WLAN) MAC protocol by introducing the spatial diversity provided by the user cooperation. The relaying technique is a general cooperative scheme between the source and destination to improve system performance. Some interesting results of the application layer are stated. The data infestations to vehicles on a freeway were first investigated in [8]. Yuen et al. [8] proposed that all nodes have a common interest in all files cached in the fixed infostations. When downloading files from the fixed infostations, nodes act as mobile infostations and exchange in proximity. Ahmed et al. [9] proposed a VANETCODE protocol. The VANETCODE protocol effectively enhances cooperative content sharing in VANETs with the network coding. Nandan et al. [10] proposed a SPAEN protocol, which is a cooperative strategy for content delivery and sharing in vehicular networks.

Yu et al. [11] proposed a vehicular self-organizing MAC (VeSOMAC) protocol. The protocol is designed such that the time slot schedule is determined based on the relative vehicle locations to minimize the total delivery delay. The VeSOMAC protocol is suitable for emergency applications. Korkmaz et al. [12] proposed a controlled vehicular Internet access (CVIA) protocol. The CVIA protocol is to increase the end-to-end throughput while achieving fairness in the bandwidth usage between road segments.

The cooperative communication technique is useful if the unreliable channel occurs for a source node. The source node may select and forward the packets through the cooperative communication to the destination to provide a reliable data transmission [13]. Recently, Zhang et al. [4, 14] proposed a vehicular cooperative media access control (VC-MAC) protocol. This approach utilizes the concept of cooperative communication tailored for vehicular networks, especially for base station downloading scenarios, cooperatively selects multiple relay nodes to forward data simultaneously to the users in need of downloading broadcast information and maximizes the throughput of the broadcast network. The application scenarios considered in [4, 14] is as follows. The stationary gateways are scatteringly deployed along the roadside and periodically broadcast packets. When a certain gateway broadcasts the packets in the wireless channel, several vehicles that are running along the road may enter the transmission range of the gateway and get a chance to receive the packets. Any applications supporting for “geocast” communication is suitable for this work. Only a vehicle in a geocast region receives the broadcast message from the source. For
example, to broadcast emergency information within a mile radius of a fire or to broadcast a coupon for coffee within a block of a Starbuck. However, due to multipath fading and other unpredicted factors, not all the vehicles within the range are able to correctly receive the packets during the gateway’s broadcast and are still in need of the packets. Therefore, they are called potential destinations in the VC-MAC protocol. Meanwhile, the vehicles which have already received the right copy of data have the ability to relay the packets afterward. They are called potential relays. As the vehicles on highway are running at high speed, after a period of time, the potential destinations will run out of the range of the gateway and will no longer be able to communicate with the gateway. This is called as one-cycle MC protocol.

A simple and straightforward data dissemination protocol may cause the “broadcast storm” problem to have serious problems of redundant rebroadcast, contention, and collision. It has great challenges for achieving a high network performance for the VC-MAC protocol. First, the data success rate is low for a non-uniform distribution of relays. Second, the exposed terminal problem is still serious for a dense vehicular network. We observe that the data success rate is low for a non-uniform distribution of relays and the exposed terminal problem is still serious for a dense vehicular network. Under such situations, one cycle of VC-MAC protocol offers the low data successful rate and the high packet overhead. To overcome the above problems, a new two-cycle of VC²-MAC protocol is designed, which can not only improve the data successful rate but also reduce the packet overhead and network access time. The simulation results show that most of the vehicles can successfully receive the broadcast packets under the two-cycle protocol. It is not worth to develop a multi-hop MAC protocol with the high overhead. Efforts are made in this paper to develop a two-cycle protocol to improve the data success rate and reduce the packet overhead and network access time.

3 PRELIMINARY

This section describes the system model, the basic idea, and the contribution of the VC²-MAC protocol.

3.1 System Model

The system and assumption are given as follows. Basically, this work follows the same application scenarios under which the VC-MAC protocol is applied [4]. The application scenario is mainly for the freeway. The roadside-deployed gateways (roadside units) or base stations are installed along the highway at a regular interval and periodically broadcast the downloading messages. The base station can provide RVC services. The RVC can use the dedicated short-range communications (DSRC) [18, 19] standard, IEEE 802.11 standard, IEEE 802.16 (WiMAX) standard, or LTE-advanced standard.

Fig. 1 illustrates the system model of the VC²-MAC protocol. Before describing this protocol, the
potential relay set–potential destination set and second destination set are defined below. The application scenarios of this work are stated as follows. If \( t = 0 \), several vehicles enter into the transmission range of a base station and have a chance to receive the downloading messages from the base station. This work assumes that only some of the vehicles can receive the broadcast message from the base station due to some interference problem. Let potential relay set, \( PR = \{R_1, R_2, ..., R_i, R_{i+1}, ..., R_m\} \), denote a vehicle set with \( m \) vehicles in which all these \( m \) vehicles successfully received the broadcast message from the base station. A vehicle in potential relay set, \( PR \), potentially acts as a relay vehicle to forward broadcast the message to vehicles that did not receive the message in the next time cycle. Fig. 1 shows that \( PR = \{R_1, R_2\} \), where \( R_1 \) and \( R_2 \) are the potential relays. Let potential destination set \( PD = \{D_1, D_2, ..., D_i, D_{i+1}, ..., D_n\} \), denote a vehicle set with \( n \) vehicles, and all \( n \) vehicles do not successfully receive the broadcast message from base station but can correctly receive the forward message from vehicles in \( PR \). Fig. 1 shows that \( D_1 \) is a potential destination, where \( PD = \{D_1\} \). Let second destination set \( SD = \{SD_1, SD_2, ..., SD_i, SD_{i+1}, ..., SD_k\} \), denote a vehicle set with \( k \) vehicles, and all \( n \) vehicles do not successfully receive broadcast message from the base station and cannot correctly receive the forward message from the vehicles in \( PR \) due to some serious interference problem for IVC communication or because they are out of the transmission range of vehicles in \( PR \). Fig. 1 shows that \( SD = \{SD_1, SD_2\} \), such that \( SD_1 \) and \( SD_2 \) are second destinations. This work assumes that, when \( t = 1 \), all vehicles are out of transmission range of the base station. All vehicles are assumed to maintain the same velocity in this investigation.

The data collision probability increases as the number of relays increases. The relay selection method is needed to avoid data collision. The selection method is basically derived from the VC-MAC protocol [4] with a weighted independent set (WIS) model, \( c_i(d_i(x) + 1)/u_i(x) \) [20], where \( x \) denotes a relay vehicle of vehicle \( i \), \( w_i(x) \) denotes the capacity of the RSSI of vehicle \( x \) with its neighbors, \( d_i(x) \) denotes the number of relay vehicles in the transmission range of vehicle \( x \), called the degree of vehicle \( x \), and \( c_i \) is a constant. A vehicle \( x \) has a higher priority to be the relay vehicle if the vehicle \( x \) has a higher capacity \( w_i(x) \) and a lower degree \( d_i(x) \).

### 3.2 Basic Idea and Contribution

The VC-MAC protocol forwards the content downloading within one cycle through relay vehicles. It is possible that only some vehicles can successfully receive the downloading content. It is worth considering two-hop communication. Two unsuccessful scenarios are stated as follows. First, some vehicles are far away from the relay vehicles, and then the two-hop data forwarding through the vehicles of \( PR \) is necessary. This scenario is called the non-uniform relay distribution problem. For instance, in Fig. 2(a), the non-uniform relay distribution occurs. When \( t = 1 \), \( R_2 \) broadcasts the message once, and only \( D_1 \) successfully receives the message. Vehicles \( D_2 \) and \( D_3 \) are out of the transmission range of \( R_2 \), and they cannot receive the message if the VC-MAC protocol is used. Second, the exposed terminal problem occurs if the distance of some vehicles in
is too close. Fig. 2(b) indicates the exposed terminal problem if vehicle $R_1$ has a shorter backoff time than vehicle $R_2$; thus, $R_1$ can transmit the message, but $R_2$ cannot send out the message because if $R_2$ receives the message from $R_1$, then $R_2$ stops the transmission intention and remains silent. Thus, vehicle $D_3$ cannot receive the message from $R_2$.

To this end, the VC-MAC protocol may be performed twice, and the cycle time is doubled. Fig. 3 shows this example. The $R_2$ is a relay node at $t = 1$, and $R_2$ forwards the message to $D_1$. Upon $D_1$ receiving the message from $R_2$ as shown in Fig. 3(a), VC-MAC is performed again. Then $D_1$ is selected as a new relay node at $t = 2$, and $D_1$ forwards the message to $D_2$ and $D_3$, as shown in Fig. 3(b). After the two-cycle forwarding, a greater number of vehicles can successfully receive the message from the base station. However, the two-cycle forwarding requires more channel access time. There will be a trade-off problem between the throughput and the access time. Fig. 3(c) shows that two cycle times, each one including the time periods of information exchange, relay set selection, and data forwarding, are needed to perform the two-cycle forwarding operation of the VC-MAC protocol. The objective is to develop a new two-cycle MAC protocol, called the VC$^2$-MAC protocol, to significantly reduce the total time period compared to the VC-MAC protocol.

The main task of this paper is to solve the non-uniform relay distribution and mitigate the exposed terminal problems. Fig. 4 illustrates the result of the proposed VC$^2$-MAC protocol. The main difference of this approach is to add a $T_{SDA}$ in the information exchange period as illustrated in Fig. 4(c). Fig. 4(a) illustrates how the VC$^2$-MAC protocol considers the non-uniform relay distribution problem. $R_2$ and $D_1$ will be selected to be relay vehicles in the relay set selection period. Then $R_2$ forwards a message to $D_1$ in the data forwarding period, and $D_1$ immediately re-forwards the message to $D_2$ and $D_3$. Fig. 4(b) illustrates how the VC$^2$-MAC protocol mitigates the exposed terminal problem if $R_1$ and $R_2$ know the number of neighbors each has in the information exchange period. Both $R_1$ and $R_2$ are selected as relay vehicles in the relay set selection period. Finally, $R_1$ and $R_2$ can simultaneously send out the message to $D_1$, $D_2$ and $D_3$ in the data forwarding period. Fig. 4(c) shows that two cycle times of the VC$^2$-MAC protocol.

The proposed VC$^2$-MAC protocol improves the channel access time as follows. Fig. 5 shows that the VC$^2$-MAC saves $\Delta t_1 > 0$ time for the non-uniform relay distribution case because the VC$^2$-MAC protocol combines four phases, two $T_{RA}$ and two $T_{DA}$, to be three phases, $T_{RA}$, $T_{DA}$ and $T_{SDA}$. The VC$^2$-MAC protocol takes twice the $T_{SEL}$ time in the information exchange period and twice the $T_{FWD}$ time in the data forwarding period. Fig. 6 illustrates that the VC$^2$-MAC saves $\Delta t_2 > 0$ time for the exposed terminal case. The data forwarding period requires only $T_{FWD}$ time because all relays are allowed to simultaneously send out messages. Therefore, the reduced time is $\Delta t_2 = \Delta t_1 + T_{FWD}$.

4 **The VC$^2$-MAC Protocol**
The proposed two-cycle cooperative MAC protocol (VC2-MAC) is composed of four periods: broadcast of base station, information exchange, relay set selection, and data forwarding. Initially, control packets are introduced, relay information (RI), destination information (DI), and second destination information (SDI), relay RTS (RRTS)/second RTS (SRTS) and relay CTS (RCTS)/second CTS (SCTS), where ready-to-send/clear-to-send (RTS/CTS) is used. The RI, DI, and SDI control packets are used in the information exchange period. The RRTS/SRTS and SRTS/SCTS control packets are used in the relay set selection period. The packet formats RI, DI, SDI, RRTS/SRTS, and RCTS/SCTS are shown in Fig. 7 and are to be used in the four periods. The VC2-MAC protocol is presented for non-uniform relay distribution and exposed terminal cases in section 4 and section 5, respectively. To solve the non-uniform relay distribution problem as given in Fig. 8(a), the four periods of the VC2-MAC protocol, as shown in Fig. 8(b), are developed as follows.

4.1 Broadcast of Base Station Period

In the period of broadcast of the base station, the base station broadcasts the message received from the upper layer to the vehicles in its range. The base station is deployed on the freeway and periodically broadcast the message to the vehicles. When the base station broadcasts a message, a two-cycle broadcast transmission is performed. No acknowledge message is needed for the broadcast. The formal procedure of the broadcast of base station period is given below.

Step 1: Before the base station broadcasts the message, the channel is sensed to ensure that the channel is idle. If the channel is idle, the base station broadcasts the message.

Step 2: After a base station broadcast, vehicles that receive the full message become the members of PR. This work is done with the CRC check to confirm whether there is any incorrectly received message. If PR ≠ φ, then information exchange, relay set selection, and data forwarding are performed. Otherwise, the two-cycle broadcast procedure exits.

An example is given in Fig. 8(a), where vehicles R1 and R2 successfully receive the message, PR = {R1, R2} ≠ φ.

4.2 Information Exchange Period

If PR ≠ φ, some vehicles do not receive the broadcast message from base station, and then the information exchange period is executed. For instance, Fig. 9(a) gives PR = {R1, R2}. The goal of the information exchange period is to provide the information to neighbors for vehicles in PR. The information exchange period is split into three phases, T_RA, T_DA, and T_SDA, as shown in Fig. 9(b).

For more details, the three phases start at T_i, for 1 ≤ i ≤ 3, which denote the starting times of T_RA, T_DA, and T_SDA, respectively. The packet transmission times of RI, DI, and SDI are denoted as T_RI, T_DI, T_SDI, respectively. The time length of T_RA, T_DA, and T_SDA are T_S × T_RI, T_S × T_D
$\times T_{DI}$, and $T_{SD} \times T_{SDI}$, respectively, where $TS_R$, $TS_D$, and $TS_{SD}$ are integers and are predefined in the protocol. Let $rR_i$, $rD_i$, and $rSD_i$ denote the random backoff times of $R_i$, $D_i$, and $SD_i$, respectively.

A vehicle in $PR$ sends out the RI control packet at time $T_1$ to inform other vehicles that the vehicle in $PR$ has already successfully received the broadcast message from a base station. If a neighboring vehicle only received the RI messages from vehicles in $PR$, the vehicle is added to $PD$. A vehicle in $PD$ sends out a DI packet at time $T_2$ to inform other vehicles that a vehicle in $PD$ can receive the broadcast message through vehicles in $PR$. If a vehicle in $PD$ only receives the DI packets, then the vehicle becomes a member of $SD$. The vehicle in $SD$ replies to the SDI packets at time $T_3$. The RI and DI packets include the sender ID and sending time for use in the time synchronization. The DI packet includes the neighbor list of $PR$, and the SDI packet includes the neighbor list of $PD$. After the packet exchange operation, the vehicles can collect the information of the RSSI (received signal strength indication) and the number of neighbors. The information is useful in the relay set selection period. The formal procedure of the information exchange period is given below.

**Step 1:** A vehicle in $PR$ sends out an RI packet after waiting for a random backoff time $rR_i \times T_{RI}$ from $T_1$, where $rR_i$ is an integer and $0 < rR_i < TS_R$. To achieve the time synchronization, $rR_i$ is inserted into the "time of sent" field of RI packet. After sending out the RI packet, a vehicle only receiving the RI packets become a member of $PD$.

**Step 2:** A vehicle in $PD$ receives an RI packet, and the value of $rR_i$ can be extracted from the "time of sent" field of the received RI packet. Time $T_2$ can be derived as follows.

$$T_2 = T_{RI}^{rR_i} + (TS_R - rR_i - 1) \times T_{RI},$$

where $T_{RI}^{rR_i}$ denotes the time that the vehicle in $PD$ received the RI packet. From time $T_2$, a vehicle in $PD$ also awaits a random backoff $rD_i \times T_{DI}$ to send out a DI packet, where $rD_i$ is an integer and $0 < rD_i < TS_D - 1$. The value of $rD_i$ stores the "time of sent" field of the DI packet. After sending out the DI packet, a vehicle only receiving the DI packets becomes a member of $SD$.

**Step 3:** If a vehicle in $SD$ receives a DI packet, the value of $rD_i$ is obtained from the "time of sent" field of the received DI packet. Time $T_3$ can be derived as follows.

$$T_3 = T_{DI}^{rD_i} + (TS_D - rD_i - 1) \times T_{DI},$$

where $T_{DI}^{rD_i}$ denotes the time a vehicle in $SD$ received the DI packet. From time $T_3$, a vehicle in $SD$ await a random backoff time $rSD_i \times T_{SDI}$ to send out the SDI packet, where $rSD_i$ is an integer and $0 < rSD_i < TS_{SD} - 1$.

Fig. 9(a) provides an instance of $PR=\{R_1, R_2\}$, $PD=\{D_1\}$, and $SD=\{SD_1, SD_2\}$. Vehicle $R_1$ and $R_2$ are transmitted RI packets at $T_{RA}$. Vehicle $D_1$ transmitted DI packet at $T_{DA}$. Vehicles $SD_1$ and $SD_2$ transmitted SDI packets at $T_{SDA}$. Fig. 9(b) illustrates that vehicles in
PR, PD, and SD enter the relay set selection period at $T_1 + T_{RA} + T_{DA} + T_{SDA}$, $T_2 + T_{DA} + T_{SDA}$, and $T_3 + T_{SDA}$, respectively. A vehicle in PR acquires the number of relays, $d_i(x)$, and the capacity of PD, $w_i(x)$. Similarly, a vehicle in PD acquires the number of potential destinations, $d_i(x)$, and the capacity of SD, $w_i(x)$. These values are useful in the relay set selection period. The collision probability increases in the data forwarding period because the members of PR and PD are greater than one. Thus, vehicles in PR and PD are necessary to perform the relay set selection period.

4.3 Relay Set Selection Period

The main goal of the relay set selection period is to intelligently select the relay nodes to avoid collisions and resolve the non-uniform relay distribution problem. The relay set selection is to perform the possible relay selection twice. Let $FRG$ (first relay group) denote the first group of selected relays from PR and $SRG$ (second relay group) denote the second group of selected relays from PD or PR. The relay selection method is based on the weighted independent set model, $c_i(d_i(x) + 1)/w_i(x)$ [20], to produce the different backoff times. The values of $d_i(x)$ and $w_i(x)$ are obtained from the information exchange period to calculate the necessary backoff time. With different backoff times, some vehicles are able to transmit, and some vehicles are asked to remain silent to avoid the occurrence of collisions.

To find $FRG$ and $SRG$, four control packets are used; RRTS (relay ready to send) and RCTS (relay clear to send) are responsible for constructing the $FRG$, and SRTS (second ready to send) and SCTS (second clear to send) are responsible for finding $SRG$. The total relay set selection period is divided into $FRG$ and $SRG$ selection periods.

The RRTS starts at $T_3$, and let $T_{j}$ denote the starting time for finding $FRG$. The SRTS starts at $T_{j+1}$, where $T_{j+1}$ denotes the starting time for finding $SRG$. In the $FRG$ selection period, the vehicle in PR with the shortest backoff time sends out the RRTS packet, and the member of PD receives the RRTS packet and replies with the RCTS packet. Let $N(D_i)$ denote the set of all neighboring vehicles of $D_i$, and $N(D_i)$ does not include $D_i$. Let $PD'$ denote a vehicle set to satisfy the following condition: if $D_i$ receives RRTS and $D_i$ at least one neighbor exists such that $N(D_i) \in SD$. In the $SRG$ selection period, the vehicle in $PD'$ with the shortest random backoff time sends out an SRTS packet, and a member of SD receives the SRTS packet and replies with the SCTS packet. An example is given in Fig. 10(b). Initially, let $FRG=SRG=\phi$. The formal procedure of the information exchange period is given below.

**Step 1:** If a relay vehicle $R_i$ is in PR with the shortest backoff time, it implies that $R_i$ is the optimal relay. When the $R_i$ enters the relay set selection period at $T_{j}$, $R_i$ calculates and waits for the backoff time $c_i(d_i(x) + 1)/w_i(x)$ to broadcast the RRTS packet at $T_j + c_i(d_i(x) + 1)/w_i(x)$ to broadcast the RRTS packet at $T_j + c_i(d_i(x) + 1)/w_i(x)$. Add $R_i$ into $FRG$. In addition, if another $R_j$ receives the RRTS packet from vehicle $R_i$, $R_j$ stops the backoff time and remains silent for the data
forwarding time $T_{FW,D}$. The value of $N(R_i) \in PD$ is inserted into the “multiple destination address” field of the RRTS packet. The values of $T_K$ and $T_{FW,D}$ are inserted into the “duration” field of the RRTS packet. The information can ask other vehicles to remain silent for $T_{FW,D}$ from $T_K$, where $T_K$ is the starting time of the data forwarding period. Therefore, $FRG$ is constructed.

**Step 2:** To avoid collisions of RCTS packets, the following operations are performed. If a $D_i$ in $PD$ receives an RRTS packet, the $D_i$ waits for a backoff time $seqD_i \times T_{RCTS}$ and then replies with the RCTS packet, where $seqD_i$ denotes a sequence number based on its location, and the sequence number is small if the distance is large. The sequence number is stored in the “multiple destination address” field of the RRTS packets, and $T_{RCTS}$ is the packet length of RCTS. If a vehicle in the $PR$ receives the RCTS packets, the vehicle stops the backoff time and remains silent for the remaining time. The values of $T_K$ and $T_{FW,D}$ are stored in the “duration” field of the RCTS packet. The duration time asks the other vehicles to remain silent for $T_{FW,D}$ from $T_K$.

**Step 3:** The construction of $SRG$ is executed from $PD'$ as follows. If a vehicle in $PD'$ waits for the backoff time $T_{i}+T_{rand}/2+c_{i}(d_{i}(x) + 1)/w_{i}(x)$ and can successfully broadcast the SRTS packet, the vehicle is added into $SRG$. If another vehicle in $PD'$ receives the SRTS packet, the vehicle stops the backoff time and remains silent for the remaining time. The value of $N(PD') \in SD$ is stored in the “multiple destination address” field, and $T_{K+1}$ and $T_{FW,D}$ are stored in the “duration” field of the SRTS packet. The duration time informs other vehicles to remain silent for the $T_{FW,D}$ time starting from $T_{K+1}$.

**Step 4:** To avoid collisions of SCTS packets, the following operations are performed. If $SD_i$ receives an SRTS packet, the $SD_i$ waits for a backoff time $seqD_i \times T_{SCTS}$ and then replies with the SCTS packet, where $seqD_i$ denotes a sequence number based on its location. The sequence number is small if the distance is large. The sequence number is stored in the “multiple destination address” field of the SRTS packet. $T_{SCTS}$ is the packet length of the SCTS packet. If a vehicle in $PD'$ receives the SCTS packet, the vehicle suspends the backoff time and remains silent for the remaining time.

Fig. 10(a) illustrates an example where vehicles $R_1$ and $R_2$ broadcast RRTS packets, and $D_1$ receives the RRTS packet and replies with the RCTS packet. $D_1$ has $SD = \{SD_1, SD_2\}$, and broadcasts the SRTS message, and vehicles $SD_1$ and $SD_2$ reply with SCTS packets after receiving the SRTS message, such that $FRG = \{R_2\}$ and $SRG = \{D_1\}$, are selected for the data forwarding period, as given in Fig. 10(b).

### 4.4 Data Forwarding Period

In the data forwarding period, vehicles in $FRG$ perform the message forwarding in the first part of the data forwarding period. Vehicles in $SHG$ execute the message forwarding in the second part of the data forwarding period. The formal procedure for the data forwarding period is given below.
Step 1: All vehicles $\in FRG$ perform the message forwarding at time $T_k$.

Step 2: All vehicles $\in SRG$ execute the message forwarding at time $T_{k+1}$.

Fig. 11(a) shows an example where $R_2 \in FRG$ forwards the data to $D_1$ at time $T_k$, and $D_1 \in SRG$ forwards the data to $SD_1$ and $SD_2$ at time $T_{k+1}$, as shown in Fig. 11(b).

5 Exposed Terminal Problem

The VC$^2$-MAC protocol can reduce the exposed terminal problem, as shown in Fig. 12(a). The VC$^2$-MAC is also composed of four periods: broadcast of base station, information exchange, relay set selection, and data forwarding. However, the broadcast of base station and information exchange periods are the same as those described in section 4; thus, the details are omitted herein.

The modified relay set selection and data forwarding periods as shown in Fig. 12(b) are stated as follows.

To solve the exposed terminal problem, the relay set selection period is modified as follows. To solve the exposed terminal problem, the VC$^2$-MAC protocol performs the selection operations twice to search for the appropriate relay vehicles in the relay set selection period. Relay vehicles are selected from $PR$ and $PD$ in the non-uniform relay distribution scenario. However, relay vehicles are only selected from $PR$ in the exposed terminal scenario, as shown in Fig. 13(a). Let $PR'$ denote a vehicle set and satisfy the following condition: each $R_i \in PR'$ if the $R_i \notin FRG$, and $R_i$ cannot receive any RCTS packets from all vehicles of $PD$. The formal procedure of the modified relay set selection period is given below.

Step 1: The step is the same as step 1 of the non-uniform relay distribution scenario.

Step 2: The step is the same as step 2 of the non-uniform relay distribution scenario.

Step 3: The construction of $SRG$ is executed as follows. If a vehicle $R_i$ in $PR'$ calculates and waits for the backoff time $c_i(d_i(x) + 1)/w_i(x)$ and can successfully broadcast the SRTS packet, the vehicle $R_i$ is added to $SRG$. On the other hand, if a vehicle in $PR'$ receives the SRTS packets, the vehicle stops the backoff time and remains silent for the remaining time. The value of $N(PR') \in PD$ is stored in the “multiple destination address” field, and $T_K$ and $T_{FWD}$ are stored in the “duration” field of the SRTS packet. The duration time asks the other vehicle to remain silent for $T_{FWD}$ from $T_K$.

Step 4: The step is the same as step 4 of the non-uniform relay distribution scenario.

Fig. 13(b) gives an example where $R_1$ broadcasts the RRTS packet, and $D_1$ and $D_2$ receive the RRTS packets and reply with the RCTS packets. Only $R_2$ receives the RRTS packets and does not receive the RCTS packet, and $R_2$ broadcasts the SRTS message. Finally, $D_3$ replies with the SCTS message by receiving the SRTS message. Therefore, $FRG = \{R_1\}$ and $SRG = \{R_2\}$. The data forwarding period is modified as follows. In the data forwarding period, vehicles that are
selected in the relay set selection period forward the message, such that vehicles in \( FRG \) and \( SRG \) forward the data at time \( T_k \). Fig. 14(a) shows that \( FRG = \{R_1\} \) and \( SRG = \{R_2\} \); then \( R_1 \) and \( R_2 \) broadcast the message to \( D_1, D_2 \) and \( D_3 \) at the same time \( T_k \), as illustrated in Fig. 14(b).

6 PERFORMANCE ANALYSIS

This paper presents a combined two-cycle cooperative MAC protocol in vehicular networks. To make a fair comparison of VC\(^2\)-MAC protocol (VC\(^2\)-MAC), the VC-MAC protocol [4] is performed twice, called extended VC-MAC (called EVC-MAC in the simulation). The VC\(^2\)-MAC protocol is simulated and compared to the extended VC-MAC protocol. These two protocols are mainly implemented using the NCTUns 5.0 simulator and emulator [21]. The physical and MAC layer in this simulation adopted the 802.11b protocol. The system parameters are given in Table I.

To discuss the effect of the network density (ND) of a VANET, the simulator considers a \( 1200 \times 16m^2 \) highway scenario with various numbers of vehicles, ranging from 30 to 250. With the same road area, the ND is changed due to the different number of vehicles. The velocity of standard deviation (VSD) is a measure of the variability of each vehicle speed. A low VSD indicates that the velocities of all vehicles tend to be close to a same velocity (the mean velocity). A high VSD implies that the velocities of all vehicles are spread out over a large range of velocities. The velocity, \( \bar{v} \), of a vehicle is assumed to be from 10 to 100 km/h. In a non-uniform relay distribution, let \( RN \) denote the number of vehicles in the two-hop distance from PR divided by the total number of vehicles. In the exposed terminal scenario, let \( ET \) denote the number of vehicles in the exposed terminal situation divided by the total number of vehicles. The performance metrics to be observed are as follows.

- The dissemination success rate (DSR) is the total number of vehicles successfully receiving the broadcast message from base station or through relay vehicles in PR and PD divided by the total number of vehicles.
- The packet delivery delay (PDD) is the time cost of the data packet traveling from the base station to the last vehicle in PD or SD. The PDD is also represented as the cycle length in the VC-MAC and VC\(^2\)-MAC protocols.
- The message overhead (MO) is the total number of control messages.
- The throughput (TP) is the total number of data packets all vehicles in PR, PD, and SD received per second.

An efficient MAC protocol in vehicular networks is achieved with a high DSR, low PDD, low MO, and high TP. In the following, the simulation results are given for the dissemination success rate (DSR), packet delivery delay (PDD), message overhead (MO), and throughput (TP) from several aspects.
6.1 Dissemination Success Rate (DSR)

The simulation results of the DSR under various NDs are shown in Fig. 15. Fig. 15(a) gives the observed DSR under various NDs, with RN fixed at 0.1, 0.5, and 0.9 and \(v=100\) km/hr. The high dissemination success rate implies that the value of DSR was high. The higher the ND is, the higher the DSR. The DSR was low if the RN rate was high because more vehicles exist in the two-hop distance from vehicles in \(PR\). If a vehicle in \(PD\) cannot successfully receive the broadcast message, the vehicle in \(SD\) also cannot successfully receive the broadcast message. Fig. 15(b) shows the observed DSR under various NDs, with ET fixed at 0.1, 0.5, and 0.9, and \(v=100\) km/hr. The higher the ND is, the higher the DSR. The same DSR are obtained under various ET rates because \(FRG\) and \(SRG\) are equal to PR. Fig. 15(c) shows the observed DSR for various velocities \(v\), where RN=0.5, ET=0.5, and ND=0.5. In general, DSR decreases as \(v\) increases because the vehicle has the property of rapid location change under VSD=0 (with the constant relative location between vehicles). If a vehicle in \(PR\) successfully receives the message from a base station, the vehicle in \(PR\) can forward it to other vehicles. The DSR decreases for \(v\) greater than 40 km/hr. Fig. 15(d) shows the observed DSR under various VSDs, where RN=0.5, ET=0.5, and ND=0.5. The DSR decreases as the VSD increases because of the rapidly changeable topology. The DSR of VC\(^2\)-MAC is lower than that of EVC-MAC only if the VSD is extremely high (approximately 100 km~110 km) because the EVC-MAC executes the information exchange period twice. This high VSD condition seldom occurs on the highway.

6.2. Packet Delivery Delay (PDD)

The simulation results of the PDD under various NDs are given in Fig. 16. From the discussion in section 3, \(\Delta t1\) and \(\Delta t2\) denote the reduced time cost of the VC\(^2\)-MAC protocol compared to the VC-MAC protocol for the non-uniform relay distribution and exposed terminal cases, respectively. Fig. 16(a) shows the observed PDD under various NDs under the non-uniform relay distribution case, where RN=0.1, 0.5, 0.9, and \(v=100\) km/hr. Fig. 16(a) shows that the PDD lines of VC\(^2\)-MAC and EVC-MAC are constant. Fig. 16(a) provides the average \(\Delta t1 = 149\text{ms} = 142\text{ms} = 7\text{ms}\) for the non-uniform relay distribution case. In addition, Fig. 16(b) illustrates the observed PDD under various NDs, where ET=0.1, 0.5, 0.9, and \(v=100\) km/hr. The PDD lines of VC\(^2\)-MAC and EVC-MAC are still constant. Fig. 16(b) provides the average \(\Delta t2 = 149\text{ms} - 138\text{ms} = 11\text{ms}\) for the exposed terminal case.

6.3 Message Overhead (MO)

The simulation results of the MO under various NDs are shown in Fig. 17. The higher the value of MO is, the larger the number of packets will be. Fig. 17(a) shows the observed MO under various NDs, where RN = 0.1, 0.5, 0.9 and \(v=100\) km/hr. In general, the MO was high if the ND was high. If the ND is close to 1.0, VC\(^2\)-MAC can save more MO than EVC-MAC because VC\(^2\)-MAC uses a lower number of control messages than VC-MAC. Fig. 17(b) shows the observed MO under
various NDs, where ET = 0.1, 0.5, and 0.9, and v=100 km/hr. The MO was high if the ND was high because that the number of vehicles in PD increased if ND was high. Fig. 17(c) shows the observed MO for various v, where RN=0.5 and ET=0.5. The MO was low if v was high.

6.4 Throughput (TP)

Fig. 18 shows the simulation results of throughput (TP) for run time and various velocities. The higher the value of TP is, the higher network utilization will be. Fig. 18(a) shows the performance of the throughput vs. run time, where RN=0.1, 0.5, 0.9 and v=100 km/hr. When run time=0 s, all vehicles are within the transmission range of a base station. The TP is increased quickly. The TP is decreased at run time =10 s because some vehicles are out of the transmission range of the base station. When run time =21.6 s, all vehicles are out of the transmission range of the base station. It still has throughput because some possible relay vehicles exist for the data forwarding. Fig. 18(b) shows the performance of the throughput vs. run time, where ET= 0.1, 0.5, and 0.9, and v=100 km/hr. In general, the TP of VC²-MAC is higher than that of EVC-MAC. Fig. 18(c) shows the performance of the throughput vs. velocity v, where RN=ET=0.5. In general, the TP decreases as the velocity v increases due to the rapidly changeable topology.

7  CONCLUSION

In this paper, a new MAC protocol, called the two-cycle cooperative MAC protocol (VC²-MAC), was developed for vehicular networks. This new protocol actually improves the VC-MAC protocol for vehicular networks, which is a one-cycle relaying MAC protocol. The VC²-MAC protocol utilizes the concept of two-cycle relaying not only to improve the reachability and the downloading efficiency but also to reduce the packet overhead and the network access time. Finally, simulation results were provided to illustrate the performance achievements of the proposed protocol. This VC²-MAC protocol is designed for the highway scenario. The future work may further investigate the VC²-MAC protocol in an urban scenario.

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REFERENCES


Table I: Simulation parameters.

<table>
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<tr>
<th>Variable</th>
<th>Description</th>
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<tr>
<td>Number of lanes</td>
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<tr>
<td>Width of a lane</td>
<td>4m</td>
</tr>
<tr>
<td>Transmission range of base station</td>
<td>300m</td>
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<tr>
<td>Transmission range of vehicles</td>
<td>100m</td>
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<tr>
<td>Vehicles velocity</td>
<td>20m/s – 30m/s</td>
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<tr>
<td>Length of simulation segment</td>
<td>600m</td>
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<tr>
<td>Road of simulation segment number</td>
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</tr>
<tr>
<td>Packet length of CBR</td>
<td>100 bytes</td>
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<tr>
<td>Data rate of CBR</td>
<td>2Mbps</td>
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<tr>
<td>Number of vehicles in one segment</td>
<td>30 – 250</td>
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<tr>
<td>The cycle of base station broadcast</td>
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</tbody>
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Figure 1: System model.
Figure 2: (a) the non-uniform relay distribution problem, and (b) the exposed terminal problem.

Figure 3: Example of VC-MAC protocol.
**Figure 4:** Example of VC$^2$-MAC protocol.

**Figure 5:** The comparison of time costs of VC$^2$-MAC and VC-MAC protocols for the non-uniform relay distribution case.
Figure 6: The comparison of time costs of VC²-MAC and VC-MAC protocols for the exposed terminal case.

Figure 7: Packet formats of VC²-MAC protocol.
Figure 8: Example of VC²-MAC protocol: (a) the non-uniform relay distribution scenario and (b) the detailed cycle.

Figure 9: Information exchange period of non-uniform relay distribution case.
Figure 10: Relay set selection period of non-uniform relay distribution case.

Figure 11: Data forwarding period of non-uniform relay distribution case.
Figure 12: Example of The Vc²-MAC protocol: (a) the exposed terminal scenario and (b) the detailed cycle.

Figure 13: Relay set selection period of exposed terminal case.
Figure 14: Data forwarding period of exposed terminal case.
Figure 15: Performance of dissemination success rate vs. (a)(b) network density, (c) velocity, and (d) velocity of standard deviation.

Figure 16: Performance of packet delivery delay vs. network density.
Figure 17: Performance of message overhead vs. (a) (b) network density and (c) velocity.
Figure 18: Performance of throughput vs. (a) run time and (c) velocity.