VC-MAC: A Cooperative MAC Protocol in Vehicular Networks

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***Abstract*—Vehicular networks are experiencing rapid growth and evolution under the increasing demand of vehicular traffic management and ubiquitous network connectivity. In particular, the amount of information to be downloaded from the roadside-deployed gateways is dramatically increasing. Infected by high mobility, intermittent connectivity, and unreliability of the wireless channel, it is challenging to satisfy the need for massive data transmission in vehicular networks. In this paper, we propose a novel protocol called vehicular cooperative media access control (VC-MAC), which utilizes the concept of cooperative communication tailored for vehicular networks, particularly for gateway-downloading scenarios. VC-MAC leverages the broadcast nature of the wireless medium to maximize the system throughput. Spatial diversity and user diversity are exploited by concurrent cooperative relaying to overcome the unreliability of the wireless channel in vehicular networks. We theoretically analyze the selection of an optimal relay set using a weighted independent set (WIS) model and then design a backoff mechanism to select the optimal relays in a distributed manner. We have carried out extensive simulations to demonstrate that VC-MAC effectively enhances cooperative information downloading and significantly increases the system throughput compared with existing strategies.**

***Index Terms*—Concurrent relay, cooperative communication, cooperative media access control (MAC), vehicular network.**

I. INTRODUCTION

VEHICULAR networks are experiencing rapid growth and evolution under the increasing demand of vehicular traffic management and ubiquitous network connectivity. Position and traffic information is needed by drivers to select an optimal route to a given destination, whereas television program and entertainment information is welcomed by passengers to enjoy their travel. All the aforementioned information is downloaded by vehicles from the stationary gateways (or access points; note that gateway and access point are exchangeably used in this paper), which are scattered on the roadside, connected with each other, and connected to the Internet by a predeployed wire or wireless networks. Additionally, there is a variety of position-dependent information, such as the location of restaurants, theaters, shopping malls, or gas stations in the neighborhood; and the commercial and entertainment information they provide, such as the characteristic menu of different restaurants, the performance forecast of all the theaters, the promotion activities of shopping malls, and the price of gas. All the aforementioned position-dependent information is put in the local gateway and then transmitted to the nearby vehicles. Under such an information-downloading scenario of vehicular networks, the traffic load is far from symmetric. In other words, the downlink traffic load, which is transmitted from the gateway to the vehicles, is much larger than the uplink traffic load. Hence, the throughput of the downlink channel plays a much more significant role in the overall system performance. Therefore, there is an urgent need to design a proper protocol that aims to increase the downlink transmission throughput to enhance the information-downloading efficiency from the stationary gateways to the vehicles.

However, some of the unique characteristics of vehicular networks raise significant challenges for achieving high network performance. First, the gateway is deployed in a distributed way and is not always reachable by the vehicles. The vehicles running out of the range of the gateway cannot directly communicate with the gateway. Thus, for a vehicle, the connectivity to the gateway exists or disappears during different time periods, whereas short periods of connectivity alternate with long periods of nonconnectivity. Under such a setup, during the period that the vehicle is disconnected with the gateway, the ad hoc connections among vehicles are necessary for a better data transmission quality. Second, the vehicles are running at high speed. The fast movement deteriorates the link quality even when the vehicle is connected to the gateway. Third, different vehicles can have different channel conditions. Due to multipath fading, shadow fading, and other wireless channel characteristics, while the channel from the gateway to some vehicles is good enough for a reliable transmission, the channel to the others may not be so good. All the aforementioned factors post great challenges for network performance enhancement and result in a low throughput in current vehicular networks.

To solve the aforementioned issues, some research on cooperative and collaborative downloading in vehicular networks has been done [5], [13], [14], [17]–[20]. The problem of distributing data from infostations to vehicles on a highway, to the best of our knowledge, was first investigated in [17] and followed by some further works dealing with information downloading using network coding and cooperative content sharing, such

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as the VANETCODE [5] and swarming protocol for vehicular ad hoc networks (SPAWN) [13]. However, most of these works focus on source information processing in the application layer instead of doing cooperative relay and maximizing spatial reuse in the media access control (MAC) layer. In addition to the works dealing with collaborative downloading previously described, other lines of work focus on the broadcast application in vehicular networks [15], [16]. In these protocols, all nodes broadcast their packets without any selection mechanism; thus, neither spatial reusability nor cooperative communication was exploited to enhance system performance.

On the other hand, to eliminate the damage of wireless channel fading and exploit spatial diversity, a class of new techniques, called cooperative communication, has emerged and has drawn increasing attention. The core idea of cooperative communication is that when the channel between the original source and destination is unreliable, another node that has a much better channel condition to the destination than the source is selected and forwards the packets to the destination to provide path diversity for data transmission [8]. The forwarding procedure exploits spatial diversity and user diversity, thus achieving a significant throughput gain for the whole system. However, most of the previous works concerning cooperative communication have been concentrated on developing physical-layer techniques to exploit spatial diversity and increase point-to-point throughput [9]–[12]. As for research on the cooperative MAC protocol design, the works are really limited [21]–[24]. CoopMAC I, CoopMAC II [21], and CMAC [23] are the recently proposed MAC protocols that support cooperative communication in the physical layer to increase system performance. However, all these works conduct cooperative communication using only one relay (or helper); thus, no wireless broadcast advantage is exploited, which will actually be sufficiently exploited in our protocol.

In this paper, we propose a new protocol tailored for vehicular networks mainly focusing on the MAC layer, called vehicular cooperative MAC (VC-MAC), which jointly exploits the concept of cooperative communication and takes advantage of spatial reusability under broadcast scenarios. We adopt the broadcast mechanism as our basic transmission mode at the access point, based on the observation that under the information-downloading scenario, all the vehicles are interested in the same provided information. After the broadcast of the access point, due to the unreliability of the wireless channel, several users who are in a good channel condition may correctly receive the transmission data, whereas others who are suffering from deep loss or interference cannot correctly decode the data. Under such a circumstance, we bring in the idea of cooperative communication and let the good users forward the original packets for the bad users to increase spatial diversity. If all the good users are allowed to act as relays to forward packets, there will be severe interference, and a collision will happen; therefore, we need to select only part of the good users to form an optimal relay set, which is able to avoid collision and achieve better system performance. To exploit the spatial reusability of the wireless channel, optimal relay set selection should follow the principle of maximizing the spatial reusability of the whole network. We theoretically analyze the criteria that the nodes in the optimal relay set should follow and then design a protocol to select the optimal relay set in a distributed manner. Therefore, our new MAC protocol is able to exploit the advantage of both cooperative communication and spatial reusability, eventually achieving an improved throughput by selecting an optimal relay set. The simulation conducted in ns-2 shows that our VC-MAC protocol significantly increased the total system throughput than any existing protocols.

The rest of this paper is organized as follows: Section II provides an overview of the network architecture. Section III presents the system model and provides a theoretical analysis whose result guides the protocol design. Section IV describes in detail our new MAC protocol, i.e., VC-MAC. Extensive simulations based on ns-2 [1] have been conducted to evaluate the throughput performance of the protocol, which are reported in Section V. Section VI gives a detailed description of the related works and gives an explanation of why other protocols are not practical and efficient compared with our VC-MAC under such a vehicular network scenario. Finally, Section VII concludes this paper.

II. APPLICATION SCENARIOS

Before we describe the design of MAC protocols, we first discuss the scenarios under which our protocol is applied, followed by the core problems that should be carefully considered during the design of the protocol. In vehicular networks, every vehicle is equipped with a wireless device by which the vehicle can communicate with other vehicles and stationary wireless gateways within its communication range. The stationary gateways are installed along highways at a regular interval, which can be colocated with traffic lights, gas stations, and rest areas, as discussed and evaluated in [3]–[5]. The stationary gateways provide the vehicles with traffic and other local information so that the drivers and passengers can experience much more enjoyable travel. It is assumed that the information sent from the gateway to different vehicles is identical at a specific moment. The communication between vehicles and gateways can use a variety of access technologies, such as the dedicated short-range communication [2] standard, the IEEE 802.11 standard, or the emerging IEEE 802.16 (WiMaX [6]) standard. The discussion in this paper is mainly based on the IEEE 802.11 standard.

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, as shown in Fig. 1(a). However, due to multipath fading and other unpredicted factors, not all the vehicles within the range are able to correctly decode the packets. The users who did not correctly receive the packets during the gateway's broadcasts are still in need of the packets. Therefore, they are called *potential destinations* [see D1, D2, D3, and D4 in Fig. 1(a)]. Meanwhile, the users who have already received the right copy of data have the ability to relay the packets afterward. Therefore, they are called *potential relays* [see R1, R2, and R3 in Fig. 1(a)]. As the vehicles on highways are

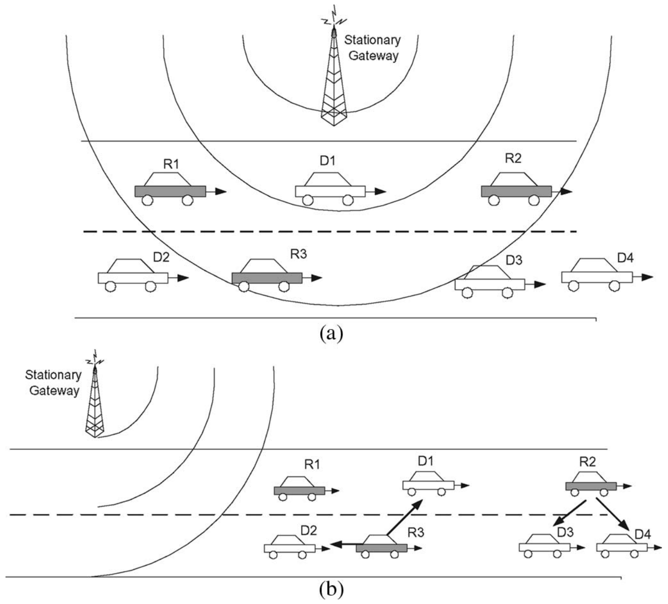


Fig. 1. Application scenarios. (a) Vehicles in the range of the gateway. (b) Vehicles running out of the range of the gateway.

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, as shown in Fig. 1(b). However, as we assumed that the vehicles are running at relatively the same speed, the potential relays are still in their neighborhood. Thus, there is a chance for potential relays to forward data to destination vehicles instead of to the gateway, which has already been disconnected with the destinations. By the principle of cooperative communication, using a suitable relay to forward the packets to the receiver brings performance enhancement. By exploiting spatial diversity, the forwarding mechanism will significantly increase system performance.

As we have described, after the gateway broadcasts data, there may exist a certain number of potential relays (i.e., three potential relays, named R1, R2, and R3 in Fig. 1) and a certain number of potential destinations (i.e., four potential relays, named D1, D2, D3, and D4 in Fig. 1) that are no longer in the range of the gateway. Our aim is to achieve maximum network throughput and to allow as many users as possible to receive the packets. As the information needed by the destinations is identical, the relays will also leverage the broadcast mechanism. Notice that there may be multiple relays simultaneously broadcasting the packets; thus, an optimal relay set, which contains multiple relay nodes, is selected to maximize the spatial reuse of the entire network. Two relays whose simultaneous transmissions cause interference in the receiver end should not simultaneously be selected in the optimal relay set. Under such a constraint, finding an optimal relay set becomes a critical problem, which significantly affects the whole network performance. As shown in Fig. 1(b), one possible relay set under the previously described constraint is the relay set containing R2 and R3 but without R1. The reason is as follows: D2 is in the transmission range of R1 and in the transmission range of R3; hence, the simultaneous transmission of R1 and R3 can cause a collision in D2. Thus, R1 and R3 cannot be selected in the relay set together. As for R2 and R3, there is no potential destination in either of their ranges. As a result, R2 and R3 can simultaneously be selected in the relay set. Is it the optimal relay set? We do not know yet. We will answer this question in the next section, where we will theoretically analyze the criteria that an optimal relay set should follow and design a MAC protocol to select the optimal relay users in a distributed manner to jointly exploit the advantage of cooperative communication and spatial reusability.

III. SYSTEM MODEL AND THEORETICAL ANALYSIS

From the previous section, we know that the entire cooperative broadcast procedure can be divided into two stages. During the first stage, which is called the *gateway's broadcast stage*, the gateway broadcasts packets to all users within its transmission range. Then, in the second stage, which is called the *random access stage*, suitable relays are selected from all potential relays and access the channel to transmit data. In our model, it is assumed that there are a total of M users in the system. After the first stage, N users, which are indexed from 0 to $N-1$, have received the packets and become potential relay users, whereas the remaining $M-N$ users become potential destination users. It is assumed that the relative position of mobile vehicles is unchanged during the whole procedure. The wireless channel is assumed to be symmetric. The key components of our model are defined here.

Channel quality: This is an $M \times M$ matrix that represents the channel condition between each pair of users. $\sigma_{i,j}$ is the signal-to-noise ratio (SNR) of the channel from user i to user j, which can be measured by each user through the last successful transmission. $\sigma_{i,j}$ is set to 0 if there is no successful transmission between user i and user j. $\sigma_{i,j} = \infty$ if $i = j$.

Neighbor set: For each potential relay node, there is a set $H(n) = \{m | \sigma_{n,m} \geq \sigma_{\text{th}},\ 0 \leq m \leq M-1\}, 0 \leq n \leq N-1$, representing the neighbors of node n, which can correctly receive data when node n broadcasts packets. σ_{th} is the threshold SNR.

User capacity:

$$C(n) = \sum_{j \in H(n),\, j \neq n} \log(1 + \sigma_{n,j}), \qquad 0 \leq n \leq N-1. \tag{1}$$

This represents the capacity that user n achieves when it broadcasts packets to its neighbors.

Interference constraint: Let $B = \{b_{n,k} | b_{n,k} \in \{0,1\}\}_{N \times N}$ be an $N \times N$ matrix that represents the interference constraints among potential relay nodes. $b_{n,k} = 1$ when $\exists m$ s.t. $m \in H(n)$, $m \in H(k)$, and $0 \leq m \leq M-1$. $b_{n,k} = 1$ means that the simultaneous transmission of users n and k would lead to a collision in at least one of their common destinations. Therefore, they cannot be simultaneously selected in the relay set.

Interference-free relay node subset: $A = \{a_n | a_n \in \{0,1\}\}_{N \times 1}$ is an $N \times 1$ vector that represents a relay node selection result, which leads to no interference while they simultaneously broadcast. An interference-free selection satisfies all the interference constraints defined by B, that is, $a_i + a_j \leq 1$, if $b_{i,j} = 1, \forall 0 \leq i, j \leq N - 1$. Let $\Lambda(B, C)_{N,M}$ denote the set of interference-free relay node selections for a given set of N and M users and the constraints of B and C.

System capacity: The relay node selection maximizes the system capacity $U(A) = \sum_{0 \leq n \leq N-1} a_n C(n)$. Given this model, we can define the relay node selection problem by the following optimization function:

$$A^* = \arg \max_{A \in \Lambda(B,C)_{N,M}} U(A).$$

Our approach to solve this complex optimization problem is to reduce it to the maximum weighted independent set (WIS) problem. Given the parameter constraints of the aforementioned relay node selection problem, we manage to create an undirected graph $G = (V, E, W)$, where $V = \{0, 1, \ldots N - 1\}$. Each vertex in graph G represents a potential relay node $E = \{(i, j) | b_{i,j} = 1,\ 0 \leq i, j \leq N - 1\}$. Each edge connecting from i to j in G represents that the simultaneous transmission of node i and node j will lead to interference. $w(n) = C(n),\ 0 \leq n \leq N - 1$. The weight of each vertex $w(n)$ is defined to be the node capacity of the corresponding relay node $C(n)$. $d(n)$ denotes the degree of vertex n in graph G, which indicates the number of two-hop neighboring potential relays that cannot be selected in the same relay set with node n. Then, the problem of finding an optimal relay set in the original network can be transformed into a WIS problem, in which we are trying to find the maximum independent set I such that, for any other independent set I', $W(I) \geq W(I')$ is satisfied. Therefore, the optimization problem is converted into a WIS problem.

As is known, the maximum WIS problem is an NP-hard problem, which can be efficiently and approximately solved by a greedy algorithm. In [7], the authors showed that a greedy approach is a tight $1/\Delta(G)$ approximation of WIS, where $\Delta(G)$ is the maximum degree of the graph.

Leveraging the result in [7], we use a similar greedy algorithm, which is described as follows: First, sort the potential relay nodes by the value of $w(n)/(d(n) + 1)$ in descending order. Second, pick the first item and delete its neighbors from the node queue. Then, pick the first item in the remaining queue and delete its neighbors. Iteratively operate the preceding steps until there is no node in the remaining queue. After finishing the whole iterative operations, the nodes picked out are the relay node set, which is denoted as $\tilde{A}$. Denoting the optimal relay node set as A^*, leveraging the proof given by Sakai *et al.* [7], we know that the capacity of the network using the selected relays is a tight approximation of the optimal capacity of the network, i.e., $U(\tilde{A}) \geq (1/\Delta(G))U(A^*)$. Notice that under the scenario of vehicular networks on a highway, the average degree in the contention graph is about 4; with a maximum degree of no more than 8, the previously described greedy algorithm can achieve a reasonably good result when selecting an optimal relay set.

One important observation from the preceding analysis is that a node n with higher node capacity $w(n)$ and lower degree $d(n)$ in the contention graph has higher priority to be selected as the relay node. Here, $w(n)/(d(n) + 1)$ can be thought of as a joint measurement of relay node n's capacity (or throughput) and its influence on its two-hop neighboring potential relays. Under the guidance of the theoretical analysis of the system model, a new MAC protocol, i.e., VC-MAC, is designed to distributively select the optimal relay set. Eventually, the broadcast characteristic of the wireless channel and the spatial reusability of the whole network are exploited, and network performance is improved. We will describe this protocol in the following section.

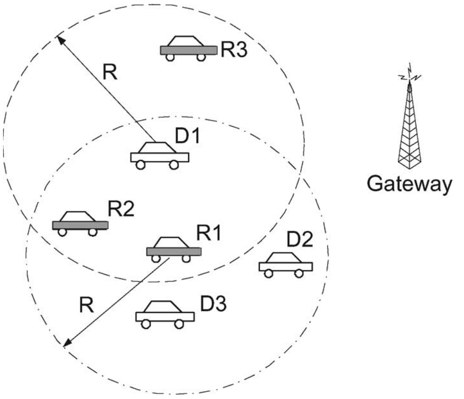


Fig. 2. Location of users in R1's two-hop range.

IV. VC-MAC PROTOCOL

The protocol is based on the IEEE 802.11 distributed coordination function, but the ready-to-send/clear-to-send (RTS/CTS) exchange is omitted because it is not necessary in broadcast mode. The whole protocol is composed of four components, namely, *gateway's broadcast period*, *information exchange period*, *relay set selection period*, and *data forwarding period*, following the time sequence. In the gateway's broadcast period, the gateway broadcasts the packets received from its own upper layer to the vehicles in its range. In the information exchange period, potential relays and potential destinations randomly back off to send out messages to inform their neighbors of their existence and use their messages to collect the channel state and topology information needed in the following part of the protocol. Then, in the relay set selection period, an approximate optimal relay set is selected from all potential relay nodes in a distributed manner by leveraging the backoff mechanism. The relay selection is under the guidance of the theoretical analysis and with the expectation of maximizing spatial reusability and user diversity. Finally, in the data-forwarding period, the selected relays forward (or broadcast more actually) the packets received from the gateway to potential destinations within its transmission range. To make it easier to understand, we give a specific network topology, as shown in Fig. 2, and show the basic packet exchange mechanism of VC-MAC in Fig. 3, where the operation in every stage of each node in Fig. 2 is depicted. In the rest of the section, most of the descriptions of the VC-MAC protocol can be referred to Fig. 3.

A. Gateway's Broadcast Period

The gateway, which is deployed along the roadside, periodically broadcasts packets to the vehicles entering its range. In

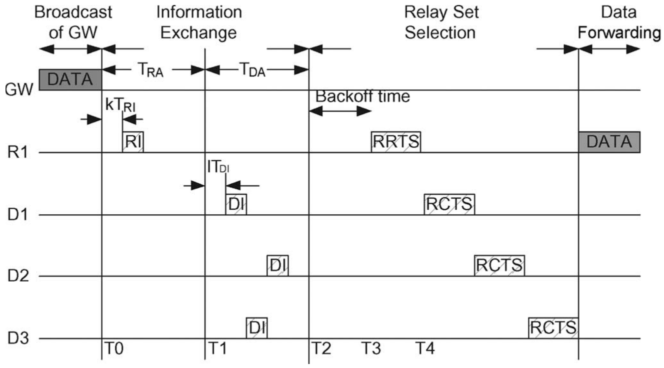


Fig. 3. Basic packet exchange mechanism of VC-MAC.

RI

Frame Control	User ID	Time of Sent	CRC

DI

Frame Control	List of Neighbors	CRC

Fig. 4. Packet format of RI and DI.

our protocol, the gateway directly transmits data packets with no handshake procedure or acknowledgement message, as it is in broadcast mode. The only thing that the gateway does before the transmission of data is sensing the channel to make sure the channel is idle. As shown in Fig. 2, after the broadcast of the gateway, R1, R2, and R3, which received the packets, become potential relays, whereas D1, D2, and D3, which did not receive the packets, become potential destinations and are ready to receive the packets forwarded by the potential relays.

B. Information-Exchange Period

In the information-exchange period, potential relays and potential destinations access the wireless channel to exchange messages, with the purpose of collecting the channel state and topology information needed for relay selection. This period is further divided into two parts, namely, relay access period and destination access period. Two novel control packets are introduced, namely, relay information (RI) and destination information (DI). While RI is sent by potential relays in the relay access period, DI is sent by potential destinations in the destination access period. The packet format of RI and DI is shown in Fig. 4, in which User ID is the ID of the sender. Time of Sent conveys the beginning sending time of the packet RI, which is used for time synchronization. List of Neighbors contains all the neighboring potential relays of the sender of the packet DI.

The operation of each node in the information exchange period is illustrated in Fig. 3 under the topology shown in Fig. 2. After the gateway has broadcast data, the user who has correctly decoded the data recognizes itself as the potential relay (e.g., R1). It then sends out an RI message after a random backoff to inform the neighbors of its potential relay identity in the relay access period. Meanwhile, the potential destinations overhearing the messages sent by potential relays construct a list of all its neighbor relays. Then, in the destination access period, each potential destination (e.g., D1, D2, and D3) also does a random backoff and then sends out a DI message containing a list of all its neighbor relays presented by user IDs. Meanwhile, each potential relay (e.g., R1) receives the message sent by potential destinations, decodes the packets that contain its own user ID, and records the received signal strength of the packets, which presents the channel condition from a certain destination to itself, i.e., $\sigma_{j,n}$, in which j is the destination node's ID, and n is the relay node's ID. Since the channel is assumed to be symmetric, the channel to the relay $\sigma_{j,n}$ is the same as that from itself, i.e., $\sigma_{n,j}$. Using $\sigma_{n,j}$, $j \in H(n)$, its capacity $C(n)$ can be calculated according to (1). The weight of the relay $w(n)$, which is equal to the capacity of the relay $C(n)$, is also achieved. Each potential relay also calculates the total number of potential relays that appear in all the neighbor lists of its neighbor destinations, which represents the degree of the relay $d(n)$. By doing the aforementioned procedure, the parameters needed for optimal relay set selection, i.e., $w(n)$ and $d(n)$, are collected and calculated. For example, R1 is aware of the three destinations (D1, D2, and D3) in its range, as well as their channel condition to itself. R1 is also aware of the two relays (R2 and R3) in its two-hop range, which may cause a collision if they simultaneously transmit packets. Assuming that the relative position of vehicles is not changed and the wireless link quality is not dramatically changed in a short time such as the information-exchange period, the accurateness of the parameters can be guaranteed.

During the protocol, the time of each node should be aligned. However, the beginning and the end of each period are calculated by each user in a distributed manner. No global synchronization is needed throughout the whole procedure. Now, we will explain this in detail. Denote the duration of the relay and destination access periods to be T_{RA} and T_{DA}, respectively. Denote the length of RI and DI packets to be T_{RI} and T_{DI}, respectively. $T_{\text{RA}} = s \cdot \text{RI}$, and $T_{\text{DA}} = t \cdot \text{DI}$, in which s and t are integers predefined in the protocol. T_{RI} and T_{DI} are also predefined and known to all nodes. In the relay-access period, each potential relay randomly chooses an integer k s.t. $0 \leq k \leq s-1$ and accesses the channel at time $T_{\text{sent}} = T_0 + k \cdot T_{\text{RI}}$ to send out the RI packet with k written in the Time of Sent area.

A node that receives an RI packet without receiving the data packets sent by the gateway recognizes itself as a potential destination. Assume that at T_{recv}, it finishes receiving RI; then, at $T_1 = T_{\text{recv}} + (s-k-1)T_{\text{RI}}$, it enters the destination access period. It then does similar random backoff as relays to randomly choose an integer l between 0 and $t-1$ and accesses the channel at $T_1 + T_{\text{DI}}$ to send out DI.

For users who did not receive either the gateway's broadcast or the potential relay's RI packet, they should always keep silent and should not implement the protocol. In fact, as they are not in any relay's range, they have no chance to receive data at all. Therefore, no protocol can help this kind of users.

For potential relays, it ends the information exchange period and enters the relay set selection period at $T_0 + T_{\text{RA}} + T_{\text{DA}}$. For potential destinations, it ends the information exchange period and enters the relay set selection period at $T_1 + T_{\text{DA}}$. In such a way, with the help of the Time of Sent area in RI messages, the network can easily be synchronized.

RRTS

Frame Control	Duration	Multiple Destination Address	CRC

RCTS

Frame Control	Duration	Destination Addresses	CRC

Fig. 5. Packet format of RRTS and RCTS.

C. Relay Set Selection Period

In this section, we first briefly introduce the core idea of selecting the approximate optimal relay set and then describe the protocol implementation in detail.

According to the analysis of the system model, the following criteria should be satisfied by the selected relay set: 1) Relay nodes should already have the right copy of data during the first broadcast stage; 2) the selected relays should not cause a collision in the destination end when they simultaneously send packets; and 3) the system capacity of the selected relays should be maximized. Basing on the core idea of the greedy algorithm of the WIS problem, here, we use a backoff mechanism to select the relays in a distributed way. Each potential relay, once it enters the relay set selection period, immediately starts a backoff procedure. The backoff time of each node is set to be $(c(d(n)+1))/w(n)$, which is inversely proportional to $w(n)/(d(n)+1)$, where c is a constant predefined. Having $w(n)$ and $d(n)$ achieved in the previous information exchange period, $(c(d(n)+1))/w(n)$ can be calculated. The node that first finishes its backoff procedure in its local area is selected as an active relay. The other potential relay nodes, whose transmissions may cause collision with the selected node, stop their backoff procedure and are not selected as relays. By the previously described backoff procedure, a set of relays that will not collide with each other is selected, and the node with a larger $w(n)/(d(n)+1)$ has a higher selection priority.

With the purpose of notifying other users in the neighborhood of the relay selection result, two novel control packets are introduced, namely, relay RTS (RRTS) and relay CTS (RCTS). The RRTS packet is transmitted by the selected relay with the purpose of notifying the users in its one-hop range of the selection result, whereas the RCTS packet is transmitted by the potential destination of the selected relay with the purpose of notifying the relays in the two-hop range that are not to be selected in the relay set to avoid a collision.

The first user (e.g., R1 in Fig. 3) to finish the backoff time sends out an RRTS packet, which represents that it has been selected in the relay set and will broadcast data in the packet-forwarding period. The neighboring potential destinations (e.g., D1, D2, and D3 in Fig. 3) of the selected relay, after hearing the RRTS message, send out an RCTS message to inform their neighboring potential relays, except for the selected relay, to keep silent. The transmission sequence of the multiple RCTS packets is designated in the RRTS message. The packet format of RRTS and RCTS is shown in Fig. 5.

During its backoff procedure, when a potential relay overhears an RRTS or an RCTS packet, it should immediately stop its backoff and keep silent for the rest time of the protocol cycle, because the reception of an RRTS or an RCTS packet means that it is in the interference range of a better relay and, hence, should not forward data in the following stage. For example, R2 in Fig. 2 should stop its backoff at T_3 because it is in the range of R1 and will overhear the RRTS packet from R1 at T_3. Similarly, R3 in Fig. 2 should stop its backoff at T_4 because it is in the range of D1 and will overhear the RCTS packet from D1 at T_4. A potential relay beyond the two-hop range of R1 may have the chance to be selected without interfering with R1. Using the previously described relay selection algorithm, several relays will be selected to forward packets for the users who failed to receive a correct copy of data in the gateway broadcast stage. Thus, each selected relay has the largest $w(n)/(d(n)+1)$ in its local two-hop range. Meanwhile, the relay selection algorithm guarantees that simultaneous transmissions of all the selected relays will not cause a collision in any receiver node.

D. Packet-Forwarding Period

After all RCTS are received, the relays then broadcast data packets. The random access and simultaneous transmission of multiple links are realized, and spatial reusability is sufficiently exploited. Then, one cycle of the protocol is finished, and all users are silent to wait for the gateway's next broadcast.

E. Discussions

In this section, we will discuss some critical issues in the protocol design, particularly the selection of the parameters in the protocol.

1) Duration of the Relay and Destination Access Periods: The duration of the relay and destination access periods affects the protocol performance by affecting the collision probability of RI and DI messages. With a longer relay access period T_{RA} and a longer destination access period T_{DA}, the collision probability caused by the access of multiple relays and destinations is decreased, but a larger overhead is introduced. Therefore, we need to choose a suitable value for T_{RA} and T_{DA} to achieve better protocol performance. In the protocol, T_{RA} and T_{DA} are predefined system parameters and are related to the lengths of RI and DI packets, i.e., T_{RI} and T_{DI}. In the simulation, the lengths of RI and DI packets are assumed to be 10 and 20 bytes, respectively. With the basic rate equal to 2 Mb/s, taking the physical-layer preamble into consideration, T_{RI} and T_{DI} are equal to 232 and 272 μs, respectively.

It is known that $T_{\mathrm{RA}} = s \cdot T_{\mathrm{RI}}$. For two nodes, the collision probability $\Pr(\mathrm{col})$ is $1/s$. Let $s = 100$; then, $\Pr(\mathrm{col}) = 0.01$. Assume that the maximum degree of the network is 7, then the noncollision probability is $1 \times 0.99 \times \cdots \times 0.94 = 81\%$, which is acceptable. Similarly, l is also selected as 100. Then, $T_{\mathrm{RA}} = 100 \times 232\ \mu\mathrm{s} = 23.2$ ms. Similarly, $T_{\mathrm{DA}} = 100 \times 272\ \mu\mathrm{s} = 27.2$ ms.

2) Duration of the Relay-Selection Period: The duration of the relay-selection period is an important factor affecting the result of relay selection. With a short relay selection period, some potential relays that should have been selected in the relay set may not have enough time to finish their backoff procedure; thus, they cannot be selected to forward data. Without sufficiently exploiting spatial reusability, it will finally decrease the system throughput. However, with a long relay-selection period, the channel will continue to be idle for a long time after all suitable relays have been selected, which also decreases system performance. Thus, the duration of the relay-selection period should be carefully selected.

Obviously, the length of the relay-selection period corresponds to the backoff time of the potential relays, which is decided by $(c(d(n)+1))/w(n)$. With $d(n)$ and $w(n)$ relying on the particular network topology and scenario, c is the only parameter that we can decide upon, and it can be selected by analyzing the collision probability of the relay-selection backoff procedure.

Now, we analyze when the backoff relay-selection method will fail. The only case where relay selection fails is when one potential relay cannot detect that another relay is more appropriate for data forwarding. As we know, the probability of having two or more relays finish their backoff at the same time is zero. However, the probability of having them finish backoff within a time interval h is nonzero and can be evaluated. In a local area, if the time interval between the backoff finish time of the best relay and the second best relay is smaller than h, then the relay selection will fail. Here, h is equal to the sum of the duration of RRTS packets T_{RRTS}, the transition time from backoff to transmit an RRTS packet T_{trans}, and two times the maximum propagation delay T_{prop}, i.e., $h = T_{\mathrm{RRTS}} + T_{\mathrm{trans}} + 2T_{\mathrm{prop}}$. Assuming that in a local area, the backoff time of the first finished potential relay node is T_1 and that of the second is T_2, then the probability of failure selection $\Pr(\mathrm{failure}) = \Pr(T_2 < T_1 + h)$. Thus

$$\begin{aligned}\Pr(T_2 < T_1 + h) &= \Pr\left(\frac{c(d_2+1)}{w_2} < \frac{c(d_1+1)}{w_1} + h\right)\\ &= \Pr\left(\frac{d_2+1}{w_2} < \frac{d_1+1}{w_1} + \frac{h}{c}\right). \qquad (2)\end{aligned}$$

From (2), it is obvious that increasing c at each potential relay reduces the probability of a collision to zero since (2) approaches zero with increasing c. In practice, c cannot be made arbitrarily large since it also regulates the expected time needed for the network to find out the optimal relay set. After deciding c, the duration of the relay-selection period can also accordingly be decided. From the simulation, we find that 10 ms is long enough for the correct selection when the number of nodes M is equal to 50.

Given the preceding parameters, the length of a protocol cycle can be calculated. As assumed in the simulation, the packet length of the gateway is 1000 bytes, and the data rate is 2 Mb/s. Then, the length gateway's broadcast period is $1000 \times 8/(2 \times 10^6) = 4$ ms. Similarly, the length of the data forwarding period is also 4 ms. Let the length of RRTS and RCTS messages be 20 bytes; then, $T_{\mathrm{RRTS}} = T_{\mathrm{RCTS}} = 272\ \mu$s. As RCTS packets are sent according to the sequence designated in RRTS, therefore, $10 \times T_{\mathrm{RRTS}} = 2.72$ ms is enough for RRTS and RCTS packets' access when $\max(d(n)) \leq 10$. Therefore, the total cycle length is no more than $4 + 23.2 + 27.2 + 10 + 2.7 + 4 = 71.1$ ms. The interval between gateway's two broadcasting periods is 80 ms, which is longer than the protocol cycle. Therefore, the parameter we adopt is suitable.

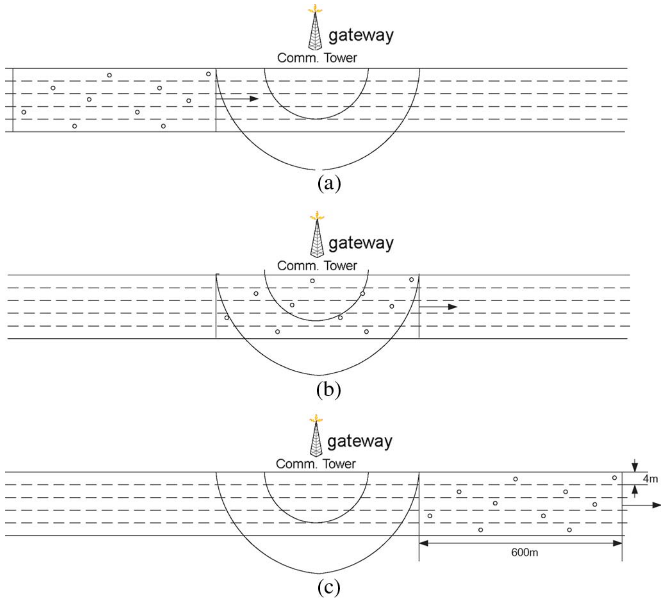


Fig. 6. Simulation scenario.

V. SIMULATION RESULTS

In this section, we show the performance evaluation of the proposed protocol VC-MAC. The simulation experiments are conducted by ns-2 [1] with version 2.29. It is assumed that there are five lanes in each direction of the highway. The lane width is assumed to be 4 m. The vehicles are randomly distributed in each lane at certain average distances. In different simulations, the average distances are changed to achieve different node densities. The gateway is deployed on the side of the highway. Consider the vehicles in a segment of the highway with a length of 600 m. The simulation is conducted from the time the vehicles enter the range of the gateway, as shown in Fig. 6(a), to the time they pass by the gateway, as shown in Fig. 6(b), until they all leave the range of the gateway, as shown in Fig. 6(c). The relevant positions of the vehicles are assumed to be unchanged. The maximum transmission range of the gateway is assumed to be 300 m, whereas the maximum transmission range of the vehicles is 100 m. The moving speed of a vehicle on a highway is supposed to be 30 m/s; thus, it costs 20 s for the vehicles to run through the range of the gateway. The physical-layer model is a two-ray ground inflection model, and the application is set to be a constant bit rate with the packet length equal to 1000 bytes and the data rate equal to 100 kb/s. The simulation parameters are listed in Table I. We compare the throughput of our protocol with three other strategies: 1) ALL-MAC; 2) SINGLE-MAC; and 3) NO-MAC. ALL-MAC represents the strategy that all the potential relays forward data after a random backoff time, whereas SINGLE-MAC means that one best relay is selected to broadcast the packets after the gateway's transmission. NO-MAC means that there are no nodes that forward packets. We will first show a toy configuration under which the relay-selection results of different protocols are presented to understand the benefit of VC-MAC. Then, the simulation results under different numbers of nodes are demonstrated to give a comparison of the performance of the three protocols and the relation between performance improvement and node density.

TABLE I
SIMULATION PARAMETERS

Number of lanes	5
Width of a lane (m)	4
Length of the simulation segment (m)	600
Trans. range of the gateway (m)	300
Trans. range of the vehicles (m)	100
Packet length of CBR $(byte)$	1000
Data rate of CBR $(kbps)$	100
T_{RA} (ms)	23.2
T_{DA} (ms)	27.2
$T_{relayselection}$ (ms)	15
$T_{forwarding}$ (ms)	5

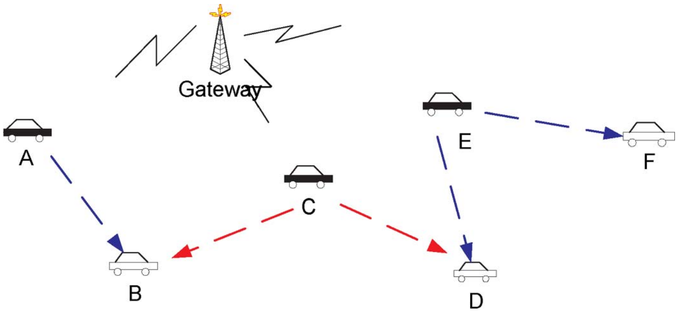


Fig. 7. Toy configuration.

A. Toy Configuration

In this simulation, there are six vehicles deployed around the gateway, as shown in Fig. 7. During the broadcast of the gateway, there are only three users (i.e., A, C, and E) that correctly received the data, which are denoted by the black cars. The network connection topology is as follows: B is in the range of A and C; D is in the range of C and E; and F is in the range of E. If we use the SINGLE-MAC strategy, only one user can be selected as the relay; suppose C is the best relay; then, only B and D can be covered, with F left out of the range of the selected relay. There are totally five users who can get the copy of data. If we use the ALL-MAC strategy, A, C, and E will simultaneously forward data; then, A and C will cause a collision in B, C and E will cause collision in D, and only F can get the data; thus, only four users can correctly receive the data. However, in our VC-MAC protocol, E has the largest $w(n)/(d(n)+1)$; thus, E is the first user who finishes the backoff procedure to send out an RRTS message. Receiving E's RRTS, D responds with RCTS. Receiving D's RCTS, C knows that there is a better relay that has been selected in its two-hop range, and its transmission will cause collision; thus, C stops its backoff procedure and keeps silent. Meanwhile, A is doing its own backoff and does not overhear any RRTS or RCTS; thus, A will forward data when its backoff time finishes. Thus, relays E and A are selected, and their forwarding enables all users to receive the data. Finally, all six users receive the right copy of data. Compared with SINGLE-MAC and ALL-MAC, VC-MAC manages to cover all the users and get a better performance.

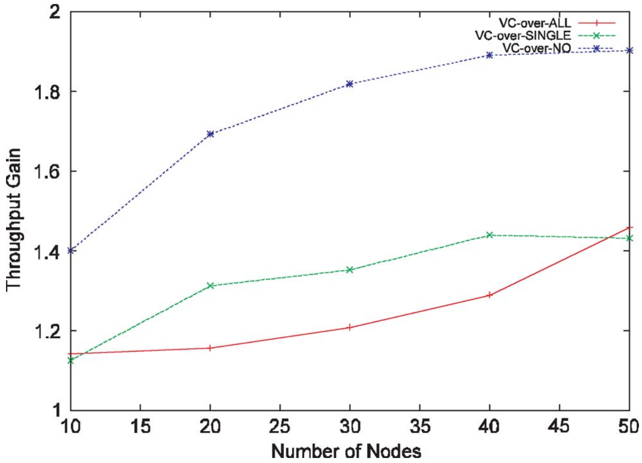


Fig. 8. Throughput gain versus number of nodes.

B. General Random Topology

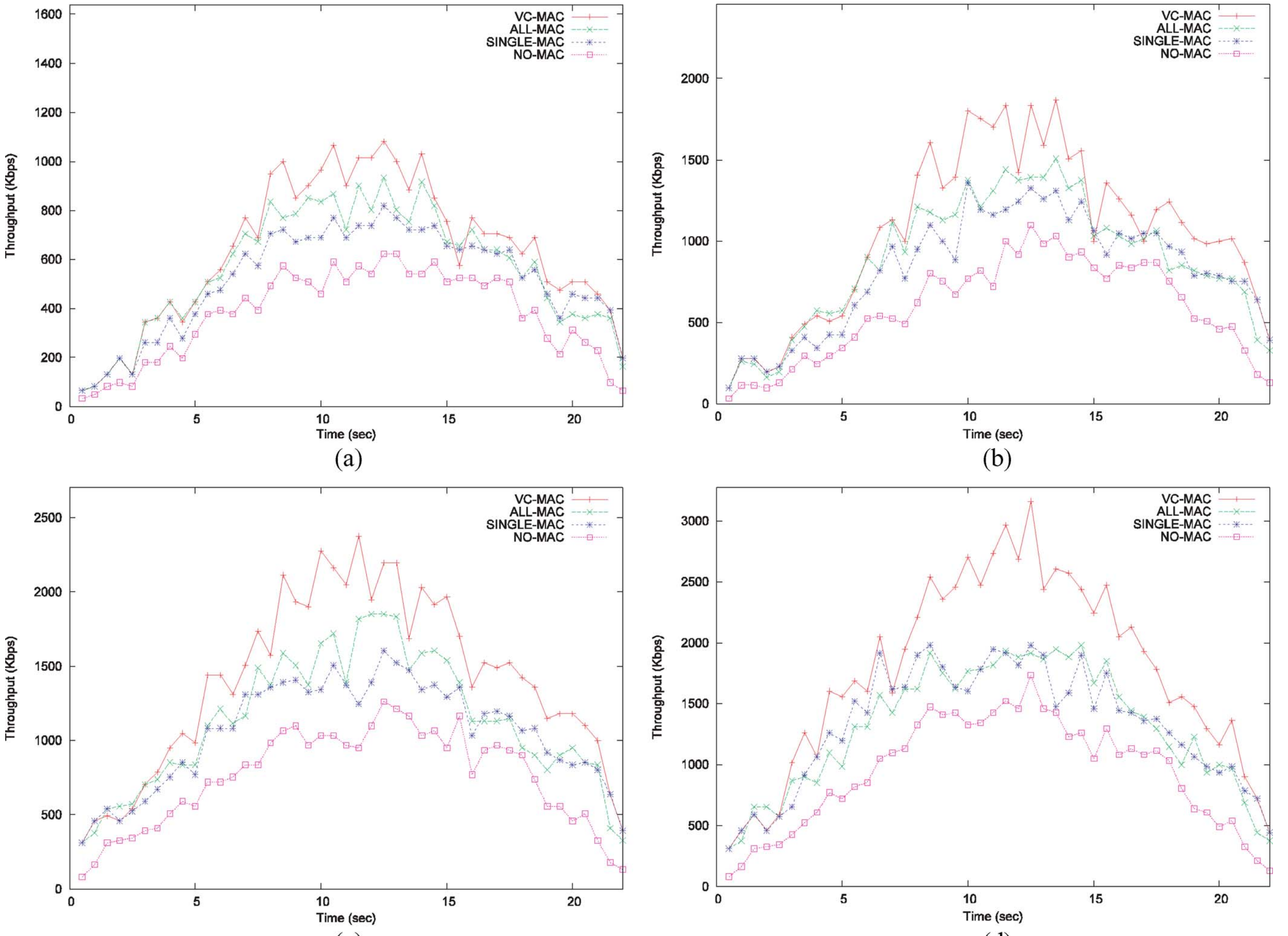
In this section, the simulation is run under random topology. The simulation scenario and the configuration have been described in Section V. Fig. 8 shows the throughput gain of VC-MAC over ALL-MAC, SINGLE-MAC, and NO-MAC versus different numbers of nodes. As shown in the figure, the gain of network throughput increases when the total user number increases. In a fixed area, a higher total number of nodes means a higher node density. With more nodes in its transmission range, the relay user can forward data packets to more potential destinations to exploit the benefit of broadcasting. In addition, when the node number increases due to the various channel conditions among the users, spatial diversity and multiuser diversity are much more easily exploited. We can also observe that when the node distribution is dense, the performance of ALL-MAC dramatically decreases. This is because the probability of collision rapidly increases when the user density is increased; thus, a lot of packets collide and are discarded during the transmission.

Fig. 9(a)–(d) shows the network throughput under 20, 30, 40, and 50 nodes, respectively. As the distance between vehicles is not allowed to be too small in real life, the simulation with more than 50 nodes is not conducted.

The throughput is increased when vehicles are running into the range of the gateway. Then, after reaching the peak, it gradually goes down as the vehicles run out of the range of the gateway. The throughput of VC-MAC outperforms the SINGLE-MAC for 40% at most. The benefit is brought by the spatial reusability exploited in our protocol. The throughput of VC-MAC also outperforms ALL-MAC by about 30% on average, due to the collision caused by concurrent transmissions of the relays in ALL-MAC. VC-MAC has no such problems as we successfully do relay selection and collision avoidance via the exchange of the RRTS and RCTS packets. The total performance gain of VC-MAC over the nonrelay system is 70%–80% on average, which is generated by cooperative relay and broadcasting.

VI. RELATED WORK

In this section, we investigate existing works related with cooperative downloading in vehicular networks and cooperative



(a) (b) (c) (d)

Fig. 9. Network throughput. (a) Number of nodes = 20. (b) Number of nodes = 30. (c) Number of nodes = 40. (d) Number of nodes = 50.

communication. Their difference from our work is particularly emphasized.

Current protocols about the vehicular networks on cooperative downloading mainly focus on the application layer and discuss a different network scenario from our discussion. Yuen *et al.* [17] did the first work to solve the problem of distributing data from infostations to vehicles on a highway. Stimulated by the win–win principle in a social contract, two vehicles in proximity are allowed to act as mobile infostations to exchange file sections whenever both vehicles have a file that is of interest to each of them. Data diversity and multiuser diversity are exploited by information exchange, without consideration of broadcast and cooperative relay. In [13], a swarming protocol for vehicular ad hoc networks (SPAWN) is proposed as a cooperative strategy for content delivery and sharing in vehicular networks. Such a “communication-efficient” swarming protocol used a gossip mechanism that leverages the inherent broadcast nature of the wireless medium, as well as a piece-selection strategy that takes proximity into account in decisions of exchange of pieces. However, it is an application-layer protocol and mainly focuses on how to select the peer and content and how to discover neighbors. The application scenario is different from ours; in addition, media access design is not considered, and spatial reusability is not exploited.

VANETCODE [5] is a content distribution scheme tailored for the vehicular ad hoc network (VANET), which is based on the concept of network coding. In this scheme, the content is divided into smaller blocks, and the nodes linearly encode their constituent blocks. Although it has many advantages over the SPAWN protocol, it is still an application-layer mechanism, and it mainly focuses on the segmentation, coding, and recovery of the information. References [14] and [20] are two recent works on collaborative downloading in VANETs; both papers jointly considered application-layer issues such as coding with MAC-layer issues such as contention. Reference [20] investigated the performance of network coding as a solution for content distribution in VANET peer-to-peer (P2P) networks. This paper adopted an IEEE 802.11b-like MAC underlying network coding and showed through simulation that the efficiency and effectiveness of the proposed protocol result in a shorter file downloading time. Reference [14] provided a theoretical analysis of the performance limits for network coding in VANETs. Both [14] and [20] dealt with VANET P2P file networks, which differ from the downlink broadcast scenarios that are mainly discussed in our work.

There are also some adaptive broadcast protocols for inter-vehicle communication [15], [16]. An adaptive broadcast scheme for efficient Travel and Traffic Information (TTI) distribution, called provoked broadcast, is presented in [15], where the authors adaptively change the inter-transmission interval according to the significance of the event conveyed by the message in transmission. In [16], the inter-transmission interval is also adaptively changed, but it is simply set to a random number. All these protocols consider the broadcast scenario in vehicular networks, but they do not use the idea of cooperative communication to help forward the packets. In addition, every user periodically broadcasts without considering spatial reusability, which we have considered in our protocol.

Meanwhile, there are a lot of protocols exploring cooperative communication. However, most of the protocols focus on the physical layer and discuss the cooperative diversity of the system from an information theory point of view. Nosratinia *et al.* [8] gave us a complete summary of the history of cooperative communication and the various kinds of protocols proposed (such as detect and forward, amplify and forward, and coded cooperation) and investigated their system performance. Sendonaris *et al.* [11] also investigated several protocols using cooperative communication to derive a new concept cooperative diversity. Recently, Bletsas *et al.* [12] have proposed an interesting protocol that uses a backoff mechanism to select the best relay in a distributed manner. However, they only considered one relay and did not exploit spatial reusability and multiple simultaneous transmissions.

Only a few works focus on the cooperative MAC. Liu *et al.* [21] proposed a protocol that allows intermediate stations between the low-speed station and the access point to act as helpers in the transmission process. An alternative route through a high-speed station is used to send the frame in a two-hop manner. Two specific variations of the protocol, namely, CoopMAC I and CoopMAC II, are introduced. Korakis *et al.* [22] gave an implementation of the protocol proposed in [21] on the Linux testbed, where the proposed protocol is evaluated through experiments. Shankar *et al.* [23] proposed a new MAC protocol called CMAC, which enhanced the existing IEEE 802.11e WLAN MAC protocol by introducing the spatial diversity provided via user cooperation. All the aforementioned works conduct cooperative communication using one relay (or helper), which are different from our solution of selecting a relay set that contains more than one relay to transmit. As we demonstrated in this paper, spatial reuse is much more sufficiently exploited in our approach. Reference [24] was another piece of work related to cooperative MAC, but its goal is to reduce the transmit energy consumption, which is quite different from our expectation of maximizing the throughput of the network.

VII. CONCLUSION

In this paper, we have proposed a cooperative MAC protocol, namely, VC-MAC, which is designed for gateway downloading in vehicular networks. We first theoretically analyzed the selection of an optimal relay set using a WIS model. We then designed a protocol under the guidance of the analysis to cooperatively select multiple relay nodes to simultaneously forward data to the users in need of them and maximize the throughput of the broadcast network. As shown in the simulation, the proposed protocol significantly increases the system throughput. The system achieves performance enhancement using the VC-MAC protocol, because the protocol successfully exploits the broadcast characteristic of the wireless radio and increases the spatial reusability of the whole system. The benefit also comes from the sufficient utilization of the better channel condition, which is guaranteed by the delicate design of the mechanism and parameters of the protocol, such as the mechanism to select the relay nodes and the suitable backoff time set by the protocol.

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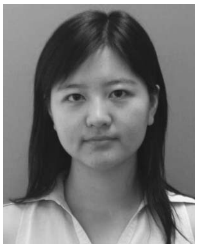

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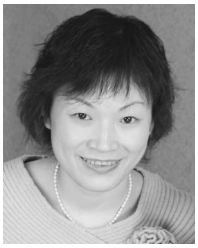

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