An Adaptive High-Throughput Multi-Channel MAC Protocol for VANETs

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***Abstract*—IEEE 802.11p standard, operating over the 75 MHz spectrum at 5.9 GHz band (1 control channel (CCH) and 6 service channels (SCHs)), has been poised to provide V2X services over vehicular ad hoc networks (VANETs). However, due to the absence of central coordinator and the nature of high vehicular mobility, it is difficult to achieve reliable multi-channel coordination and adaptive resource reservation to make full use of SCHs, resulting in dramatic throughput degradation. To mitigate this, in this paper, we propose an adaptive high-throughput multi-channel medium access control (MAC) protocol, namely, AHT-MAC, which can effectively handle the data transmissions over SCHs. With AHT-MAC, data transmission range is adjusted according to the beacon transmission range over the CCH so that a transmitting node can determine proper communication candidates and prepare available resources for both communication nodes before transmissions. Moreover, the communication coordination is done through a two-way handshake. During the handshake, adaptive resource reservation is realized following the proposed resource sharing mechanism, where nodes first utilize as much resource as possible and then share them with others proactively. To increase the success probability of the communication handshake, a request conflict resolution mechanism is also proposed to nullify improper handshakes. Therefore, AHT-MAC can reduce the resource wastage due to handshake failure and extra overheads for retransmission requests. Our performance analysis shows that AHT-MAC can significantly improve the system throughput and reduce the channel access period.**

***Index Terms*—VANET, MAC, Multi-Channel, Adaptive Resource Reservation.**

I. INTRODUCTION

VEHICULAR ad hoc networks (VANETs) have been evolving into the Internet of Vehicles (IoV) to provide more diverse, ubiquitous, reliable and intelligent services, such as ultra-high-definition (UHD) video, auto-driving, mobile cloud and fog computing, vehicular social networks, etc. [1]–[4]. To support these diverse services, vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications should satisfy the strict quality-of-service (QoS) requirements on transmission rates, reliability and latency to guarantee the delivery of network beacons, safety related messages, as well as application oriented data packets.

The United States Federal Communication Commission (FCC) has authorized a 75 MHz radio spectrum at the 5.9 GHz for VANETs. The resulting standard IEEE 802.11p contains one control channel (CCH) and six service channels (SCHs). How to utilize all these channels is critical for medium access control (MAC) protocols to support high data rate transmissions for various mobile applications. However, it is quite challenging to do so efficiently. One reason is that there is no central coordinator in VANETs. Multi-channel coordination is usually performed in a distributed manner, where communication handshakes frequently encounter failures or suffer from significant increasing beacon overhead for reliability enhancement. Another reason is that high mobility of VANETs results in fast topology changes and rapid node density variations. Hence, to improve the throughput, the success probability of the handshakes should be enhanced and the MAC protocols should be adaptive to accommodate high throughput for various situations.

The official IEEE 1609.4 standard [5] has been adopted into IEEE WAVE (Wireless Access in Vehicular Environments) for multi-channel operations. In this standard, one second is divided into synchronization intervals, each of which contains a CCH interval and an SCH interval. Usually, the radio device stays on the CCH during the CCH interval exchanging control messages and safety related packets. The transmissions over SCHs are coordinated by the control messages. Once the coordination is done, nodes switch to the targeted SCHs to transmit application oriented data. The standard, IEEE 1609.4, provides only a basic multi-channel coordination mechanism with suggested parameter settings, which is proved inadequate to meet various communication requirements [6]. Therefore, many researchers attempt to enhance its design by dynamic adaptation of CCH intervals. According to IEEE 1609.4, there is only one transceiver that can be utilized for communications. Thus, all SCHs are left idle when the single transceiver camps on the CCH to handle beacon exchanges and accomplish resource reservation. Nodes could miss beacons when they are engaged in data transmissions over SCHs, which may in turn harm the subsequent handshakes. As a result, the achievable network throughput will be degraded. This may become worse as the node density increases [7]–[11].

To overcome the limitations of single-transceiver based protocols, two transceivers based MAC protocols were proposed. One transceiver always camps on the CCH to guarantee

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the reliable beacon delivery, while the other transceiver is dedicated to data transmissions over SCHs. This guarantees the reliability of control signaling messages. Although these protocols can offer reliable beaconing, to improve the throughput, the success probability of communication control messages for resource allocation should also be considered. For instance, in time-division-based CCH protocols [12], when a node sends out a request to start a communication handshake, the response cannot be immediately returned from the receiving node due to the absence of a central coordinator. Before this handshake is completed, other nodes may request to utilize the same transmitter or receiver, resulting in contention. In this situation, only one node can successfully establish communication link, while all other nodes will suffer failures, which may further degrade the system throughput. The cluster (or ring) based protocols [13]–[15] may solve the communication coordination effectively in a centralized manner, but require complicated cluster (ring) management which may need intensive beaconing.

To simplify resource reservation process, various techniques have been developed to help channel selection. In [16], it is proposed that nodes select SCHs based on the predefined road segments according to the updated digital maps. In [17], a channel hopping based protocol is proposed to reduce the beaconing overhead for channel coordination. However, it may be difficult for nodes to adapt to rapidly changing environments as they have to strictly follow the hopping sequence.

All these problems have motivated us to develop an adaptive high-throughput multi-channel MAC, namely, AHT-MAC, dedicated to data transmissions over SCHs. In AHT-MAC, the following two issues should be addressed in order to achieve higher throughput:

1. How to determine the mutually available resources between a pair of nodes so that most of the communications can be established by only one two-way handshake?
2. How to enable adaptive resource reservation to achieve high throughput under various node density?

To deal with these two issues, a novel resource management scheme is introduced, where the transmission range over SCHs is adjusted according to that over the CCH. By overhearing the beacons from one-hop neighbors, nodes can directly determine the mutually available resources that can be utilized to communicate with other nodes. Therefore, most of the data transmission requests can establish communication links successfully. To achieve adaptive resource reservation, a resource sharing mechanism is proposed. With this scheme, nodes attempt to utilize an entire SCH to conduct high data rate transmissions when the node density is low, and nodes may share their own SCH resources to support others when the node density is high. Hence, AHT-MAC can dynamically adapt to rapid node density changes. Finally, a conflict resolution mechanism is developed to protect normal handshakes from interference caused by improper data transmission requests. Since the proposed handshake process is reliable, contentions over SCHs can be avoided, which also helps increase the throughput.

The remainder of this paper is organized as follows. The related works are summarized in Section II. In Section III, the basic model of AHT-MAC is introduced. Section IV presents the details of our AHT-MAC protocol, including the resource management scheme, the resource sharing mechanism and the conflict resolution mechanism. In Section V, an analytical model is derived. Section VI provides the experimental results for performance evaluation. Conclusions are drawn in Section VII.

II. RELATED WORK

There are many existing works enhancing the multi-channel operational scheme in IEEE 1609.4 by dynamic adaptation of CCH intervals in order to enhance the reliability of critical messages, increase the throughput of non-safety data or reduce transmission delays. As mentioned in Section I, the achievable network throughput is still unsatisfactory due to the limitations of a single transceiver [7]–[11], which is observed and discussed in the IEEE 802.11 MAC protocol in [18]–[21]. Another single transceiver based protocol, AMCMAC-D (asynchronous multichannel medium access control with a distributed time-division multiple-access mechanism) [22], conducts channel negotiations over the CCH by using RTS/CTS, not fully follow the basic settings and the operational procedures of IEEE 1609.4. To eliminate the hidden terminal problem, nodes are required to listen to the SCH for a short time period before data transmission. Thus, the throughput improvement brought by AMCMAC-D is limited.

To overcome the aforementioned problems, two transceivers based MAC protocols have been proposed. In these protocols, one transceiver always stays on CCH to guarantee reliable beaconing, prevent collisions and solve the hidden/exposed terminal problem beforehand, while the other transceiver switches among SCHs and is dedicated to data transmissions. Based on the collected information, nodes can get the availability of each SCH. However, no strategy is introduced to prevent multiple nodes from accessing the same resource at the same time. Thus nodes may fail in resource reservation when node density is high, and the system throughput may decrease as well. Su *et al.* have proposed a cluster-based protocol [13] where the functions of CCH and SCHs are redefined. Three channels are responsible for inter-cluster control, inter-cluster data and cluster range control, respectively. The rest 4 SCHs are used to support data transmissions within clusters to eliminate inter-cluster interference as in traditional cell systems. The intra-cluster communications are coordinated by the cluster head in a centralized manner. In the multi-channel token ring MAC protocol (MCTRP) [14], the nodes that utilize the same SCH form a ring, that is similar to a cluster. Different SCHs are assigned to adjacent rings to avoid interference. The inter-ring data is delivered over the CCH. The intra-ring data exchange is coordinated by a token based protocol. By dynamically adjusting the token holding time, low channel access delays and load balance can be achieved. The bottleneck of the protocols in [13] and [14] is the complicated cluster (ring) management which often needs intensive beaconing.

To reduce the beaconing overhead for resource reservation, various schemes have been introduced to help channel selection. In Road-Based Multi-Interface MultiChannel Assignment (MIMC-Road) [16], roads are segmented into regions, and each region is associated with an SCH for communications within this region. Then nodes can simply switch their operating channels according to their locations without any beaconing overhead. However, this scheme requires digital up-to-date maps. The channel hopping based protocols ask nodes to switch their operating channels by following a predefined hopping sequence. For instance, Chu *et al.* proposed a prioritized channel allocation scheme [17], where nodes are first categorized into primary providers (PPs) and secondary providers (SPs). The optimal hopping sequence for SPs is determined by a PPs' access probability of each SCH. Thus, the channel coordination overheads can be reduced. However, it may be difficult for nodes to adapt to rapid environment changes as they have to strictly follow the hopping sequence.

There are many other multi-channel MAC protocols that incorporate various techniques to solve channel negotiation problem and boost throughputs. Han *et al.* proposed a cognitive scheme that utilizes TV band to boost network throughputs [23]. FMC-MAC [24] was proposed based on a much more flexible multi-channel resource allocation scheme which allows safety messages to be broadcast over SCHs and non-safety data to be transmitted over the CCH. Lyu *et al.* proposed a mobility-aware time division multiple access (TDMA) MAC [25], MoMAC, in which a channel is allocated according to the network topology and road structure to enhance the reliability. In GAH-MAC [26], game theory is incorporated to handle resource reservation collisions so that wireless resources can be fully utilized.

Beyond VANET environments, separating control signaling and data transmissions that is known as C/U decoupling in centralized wireless systems such as cellular systems, has become an effective approach in distributed multi-channel wireless networks [27], [28]. In the spirit of IEEE 802.11 wireless systems, this idea has also been explored in [18], [19] where a dual-channel MAC protocol, DUCHA, is designed to mitigate severe contention in multi-hop ad hoc networks. However, only two channels, CCH and one single data channel, are considered in the IEEE 802.11 MAC protocol. Besides, the resource allocation is not considered. Motivated by those previous works, we propose AHT-MAC to achieve high throughput data transmissions via fast, reliable and adaptive resource reservation.

III. SYSTEM MODEL

In this paper, according to IEEE 802.11p standard, the entire spectrum is divided into 1 CCH and M SCHs, where $M = 6$. Each vehicle (node) is equipped with two transceivers: a CCH transceiver and an SCH transceiver. The CCH transceiver always operates on CCH to ensure reliable exchanges of network beacons and emergency messages. The SCH transceiver switches among M SCHs to serve data transmissions for various applications. Both CCH and SCH transceivers are half-duplex. Both of them cannot transmit and receive simultaneously at the same frequency band. In addition, each node has a global positioning system (GPS) interface to get its position and attain the strict time synchronization for AHT-MAC.

In AHT-MAC, the transmission power is assumed to be fixed. Two ranges, transmission range (TR) and interference range (IR), are introduced. If the distance between two nodes is less than TR, it is assumed that they can correctly receive the data packets from each other over the same channel. If the distance between the two nodes is longer than TR, it is assumed that they cannot receive any data packet from each other due to the weak signal. Besides, the transmitting node will strongly interfere all the other nodes within its IR, therefore, it is impossible for them to successfully decode the incoming signals from other transmitters in the same frequency band. In AHT-MAC, TR for CCH, denoted by TR_{cch}, is different from the one for SCHs, which is denoted by TR_{sch}. Similarly, the corresponding IRs, namely, IR_{cch} and IR_{sch}, are also different.

The CCH is shared in a time division mode (distributed TDMA) since this scheme has been proved more efficient than the traditional CSMA/CA [12]. Nodes periodically broadcast their basic information, such as ID (MAC address), position, velocity, so that those nodes within TR_{cch}, called one-hop neighbors (or neighbors in short), can know their surrounding network topology. The handshakes for initiating data transmissions over SCHs are conducted over the CCH. It should be noted that AHT-MAC does not rely on a particular CCH MAC protocol. The TDMA-based MAC protocols, such as VeMAC [12], SS-MAC [29], OGCMAC [30], etc., are all compatible with AHT-MAC.

Similar to that as in the IEEE 1609.4 standard [5], SCHs are divided into SCH intervals (SIs). Each SI consists of a guard interval (GI) at the beginning and a payload interval (PI) in succession. The GI is used to account for the radio switching among SCHs. Nodes cannot send or receive data during GIs. The PI is further equally divided into D service resource blocks (SRBs) via time division. Each SRB can be further divided into slots if necessary. All slots in an SRB are shared exclusively by a pair of nodes in the TDMA manner. Thus, in AHT-MAC, SRBs are the basic resource allocation unit over SCHs. The structure of the SI is illustrated in Fig. 1. Since the SI has been introduced, AHT-MAC applies a synchronized switching policy. The beginning of the SIs in different SCHs are aligned and nodes must complete the channel switch operations within the GI.

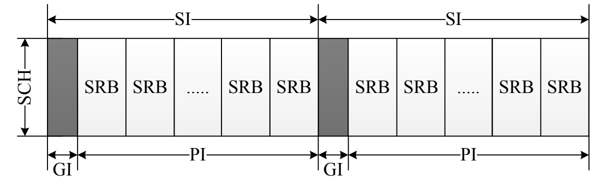

Fig. 1. The structure of the SIs over an SCH. Each SI contains a GI and a PI. The PI is equally divided into SRBs via TDMA.

Before introducing more details, the abbreviations and symbols used this paper are provided in Table I.

IV. AHT-MAC PROTOCOL

A. Protocol Overview

AHT-MAC is a two-transceiver based MAC protocol, where the CCH transceiver always operates over the CCH and

TABLE I
SUMMARY OF IMPORTANT SYMBOLS

Symbol	Definition
CCH	control channel
SCH	service channel
SI	SCH interval
GI	guard interval
PI	payload interval
SRB	service resource block
ESRB	exclusive SRB
SSRB	shareable SRB
TR	transmission range
IR	interference range
ER	exclusive range
DTR	data transmission request
DTA	data transmission acceptance
CTN	conflict notification
TR_{cch}, TR_{sch}	TR over CCH and SCHs
IR_{cch}, IR_{sch}	IR over CCH and SCHs
ER_{sch}	ER over SCHs

the SCH transceiver switches among SCHs on demand. In this paper, we adopt the VeMAC protocol [12] for CCH access procedure while the major design of AHT-MAC is to coordinate the data transmissions over SCHs.

CCH is divided into time frames and each frame is further divided into slots. Each node occupies one slot during a frame so that it can periodically broadcast control and safety related massages. Since the length of the frame is typically shorter than 100 ms, the delay requirement for safety related massages can be satisfied. To get a slot over the CCH, each node initially randomly selects a slot within the frame and sends a beacon over that slot. If no packet collision occurs, the selected slot is uniquely occupied and this node can continue to use this slot in the following frames. If a node encounters a packet collision, the accessed slot will be released because at least two nodes attempt to use it simultaneously and messages cannot be successfully delivered due to collisions. After the collision, each of all the involved nodes should randomly choose a new slot within the frame, send packets, and attempt to seize a slot again.

After a node acquires a slot over the CCH, it can initiate a handshake for data transmissions over SCHs. To do that, the transmitting node first sends out a data transmission request (DTR) over the CCH to a receiving node. The DTR contains the ID of the receiving node and a set of available SRBs of an SCH that the node attempts to transmit. If the SRBs are available at the receiving node site as well on the SCH, the receiving node shall respond with a data transmission acceptance (DTA) over the CCH to reserve those SRBs. Once the DTA is received by the transmitting node, the handshake succeeds. Then, these two nodes will switch to the corresponding SCH and start the data transmission using the reserved resources.

The function of the DTR/DTA handshake is similar to the RTS/CTS handshake in IEEE 802.11. However, RTS/CTS is based on CSMA/CA, and is actually a three-way handshake. Whereas, the DTR/DTA handshake is designed for the TDMA channel, and is a two-way handshake. The major difference is that DTR sent over the CCH cannot be responded by the receiving node immediately due to the use of TDMA over CCH. The receiving node has to wait for its own slot and then sends its DTA out. Hence, before a pair of nodes finish their DTR/DTA handshake, other DTR/DTA handshakes could be initiated and even finished beforehand. Hence, in this scheme, it is vital to find a set of mutually available resources for a pair of nodes and reserve them.

To resolve that issue, an *SRB management scheme* is developed to ensure that every node knows the available resources of its surrounding nodes by overhearing the DTR/DTA packet broadcast in the network. Therefore, a node can always reserve mutually available SRBs together with its receivers. If multiple pairs of nodes intend to utilize the same set of SRBs, *SRB sharing mechanism* in AHT-MAC can help them conveniently share those SRBs. By leveraging this policy, adaptive resource reservation is achieved. Based on the above two polices, *the DTR/DTA routine* is designed to improve the success probability of the communication handshakes. Finally, a *request conflict resolution* mechanism is proposed to reduce the resource wastage caused by unreliable beaconing. As reliable handshakes are guaranteed, contention windows over SCHs are not necessary any more. All SCHs can be operated in the TDMA fashion and dedicated to data transmissions. Consequently, the system throughput can be significantly improved.

B. SRB Management Scheme

In order to initiate a communication session successfully, a pair of nodes should search for mutually available resources for both of them. Unlike centralized systems, there is no global coordinator for resource management in VANETs. Nodes have to determine the availability of SRBs by channel sensing or beacon overhearing. However, it is difficult to accurately know the available SRBs of the intended receiver due to the location difference between the transmitter and the intended receiver. In order to find the common set of SRBs, typically at least a three-way handshake between the transmitter and receiver should be carried out. Specifically, the transmitter sends out a control message containing information of its available SRBs to the intended receiver, and the receiver responds with the information of its available SRBs. The transmitter then finds the common SRBs and informs the receiver about the common SRBs to use and initiates data transmission over the common SRBs. This has been done in IEEE 802.11 based multi-channel systems with RTS/CTS exchanges [22], [31]. Unfortunately, in our problem setting, CCH has adopted TDMA due to its more reliable feature, and thus the receiver may not be able to respond immediately as done during the RTS/CTS exchange, and it could only respond at the slot it is assigned. In between, there may be other nodes that may make the same handshakes, which will cause collision if their SRBs overlap. Besides, the delay due to TDMA may invalidate the availability information of SRBs. Thus, we need to find a viable SRB management solution to resolve this issue. One solution is to let the transmitter take full charge of the SRBs so that whenever a transmitter seizes the set of SRBs, it could transmit to any receiver without collision. In the following, we design a scheme.

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The proposed SRB management scheme in AHT-MAC is inspired by traditional cellular systems. Each vehicle (node) is viewed as a moving base station. When a node V announces the reservation of SRB B over an SCH during the lth SI, it virtually establishes a cell during that SI. During the lth SI, any node in this virtual cell cannot use B without the permission of V. To reduce the time in reaching agreement on the use of available common SCHs at both transmitter and receiver, we design the scheme so that the transmitting node of a transmission determines which SCHs to use to ensure success of this transmission, i.e., there is no collision at the intended receiver. Thus, the transmitting node has to ensure that *there is no interference from the receiver's IR to impact the reception*.

The first step is to determine the range of the cell, namely, the exclusive range (ER), which can completely eliminate the interference over SCHs when TR_{sch} is given. In this paper, we derive the minimum of ER_{sch} based on a straight road model as shown in Fig. 2. Without loss of generality, we suppose that V_1 intends to communicate with V_2 at the lth SI using B_1. In general, the distance between V_1 and V_2 should be shorter than TR_{sch}. According to the definition of the IR in Section III, no node is allowed to use B_1 within the IR_{sch} of V_1 except for V_2. Similarly, no node is permitted to utilize B_1 within the IR_{sch} of V_2 except for V_1. Thus, as illustrated in Fig. 2, potential interference can only happen within the union of IR_{sch} of V_1 and V_2 (the gray area covered by the two overlapped medium circles). To completely avoid interference, B_1 should be occupied by V_1 and V_2 exclusively within the gray area. From the perspective of V_1, the minimum radius of its neighborhood that can fully cover the above potential interfering area is $TR_{\text{sch}} + IR_{\text{sch}}$. Hence, we have

$$ER_{\text{sch}} = TR_{\text{sch}} + IR_{\text{sch}}. \tag{1}$$

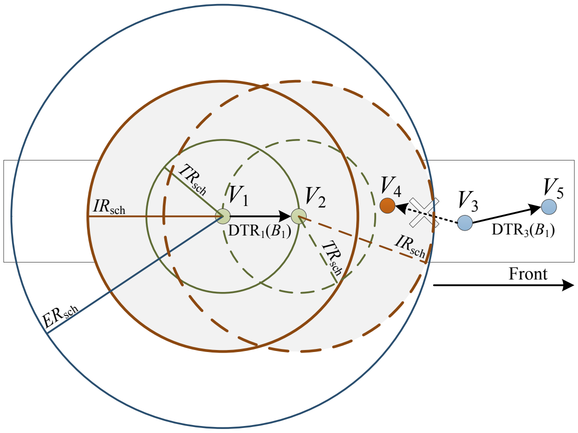

Fig. 2. The derivation of ER_{sch}, which should be shorter than TR_{cch}.

After determining ER_{sch}, the next step is to ensure the neighbors of a node to be aware of its SRBs request so that they will not attempt to request these SRBs. For example, as in Fig. 2, V_1 has announced its occupation of B_1 by including B_1 in its DTR. V_4 should be informed that it cannot use B_1 because the distance between V_1 and V_4 is less than ER_{sch}. V_3 can use B_1 to communicate with V_5, but not with V_4 because V_4 knows that B_1 is not available and will definitely reject this request.

To achieve the above goal, two new rules are introduced. First, *TR_{cch} should be greater than ER_{sch} so that all involved nodes can receive the related beacons*. As described in [18] and [32], IR is proportional to TR. Hence, TR_{sch} should be sufficiently short to satisfy this constraint. Second, *SIs are classified into two categories based on sequence numbers*. During the SIs whose sequence numbers are even (or odd), a node can only communicate with the node in its front (according to the moving direction), while during odd (or even) SIs, a node can only communicate with the node behind it. Apparently, nodes may make incorrect decisions if they have neighbors moving in the opposite direction. This problem can be solved by making them choose the communication targets moving in the same direction with high priority.

As shown in Fig. 2, by applying the above rules, all nodes within the ER_{sch} of V_1 will know that B_1 belongs to V_1 after V_1 broadcasts its DTR. The nodes that cannot receive the beacons from V_1 can use B_1 free of interference. Like V_1, the valid communication targets of V_3 must be in front of itself. Thus, V_3 will not send its DTR to V_4 even if V_3 cannot receive DTR_1. Consequently, the potential collisions are also avoided.

In the proposed SRB management scheme, TR_{cch} is much longer than TR_{sch}. The CCH is responsible for long-range beacon broadcasting, while SCHs are dedicated to short-range high data rate transmissions. It is similar to the control/data separation strategy proposed in [33]. Based on this design, a node knows its mutually available SRBs with its candidate receivers. Both hidden and exposed terminal problems are solved effectively. As a result, AHT-MAC can apply a two-way handshake.

C. SRB Sharing Mechanism

By the SRB management scheme, a node is able to determine the availability of SRBs. However, how many SRBs should be utilized still needs to be addressed carefully. If a node occupies too many SRBs, the transmissions of other nodes will be blocked, especially in high node density scenarios. To solve this problem, an SRB sharing mechanism is proposed. *The basic idea is that nodes are encouraged to utilize as many SRBs as possible initially and then share their owned SRBs generously*. By means of this mechanism, it is expected that SRBs can be fully utilized when the node density is low, while each node obtains its opportunity to send or receive data packets when the node density is high.

To this end, the SRBs in the DTR are divided into two categories: *exclusive SRBs* (ESRBs) and *shareable SRBs* (SSRBs). ESRBs are utilized exclusively by the transmitting and receiving nodes, while SSRBs can be shared among nodes. Whenever a node V_{s} attempts to utilize some SSRBs owned by another node V_{o}, it can directly include those SSRBs into its DTR. Here, the DTR of V_{s} also functions as an SRB sharing request. However, V_{o} does not have to reply to this request, and it just releases the corresponding SSRBs upon the DTR of V_s. The neighbors of V_o also assume that V_o will release those SSRBs according to the protocol. Thus, the occupation of those SSRBs by V_s will be acknowledged by all the nodes that receives the DTR from V_s. The overheads of sending an agreement message can be avoided.

By overhearing DTR/DTA handshakes, every node can know the exact state of each SRB, which can be on one of the following states:

- *Idle*: it is not occupied by any node;
- *Obtainable*: it is an SSRB of a node;
- *Occupied*: it is an ESRB of a node or it has appeared in a DTA to another node;
- *Ready*: it has been successfully reserved by the current node.

The SRBs marked by *Idle* or *Obtainable* can be utilized free of interference. The *Occupied* SRBs are not allowed to use to avoid potential interference. Now, a node V_s can select SRBs as follows:

1. If there are *Idle* SRBs, find the SCH that has most *Idle* SRBs. Then all the *Idle* SRBs of that SCH will be included in the DTR. The number of ESRBs is set to be 1 so that most of the SRBs can be shared. This is specially helpful when the node density is high.
2. If no SRB is in *Idle* state, find out a neighbor V_o that possesses the largest amount of SRBs. We suppose that V_o possesses n SRBs and some of them are SSRBs, $\lfloor n/2 \rfloor$ SRBs of V_o will be shared out. In this way, the node V_s and V_o possess equal amount of SRBs. It helps to distribute SRBs evenly throughout the network.
3. In the worst case that all SRBs are occupied exclusively, V_s cannot start a DTR/DTA handshake due to resource exhaustion.

It is worth mentioning that since the SRB sharing mechanism is implemented via a two-way DTR/DTA handshake, and no extra beacon exchanges or complex computations are needed. Thus, the proposed AHT-MAC can quickly adapt to rapid changes in node density.

D. The DTR/DTA Routine

As mentioned in Section IV-A, in TDMA-based CCH protocols, a DTR cannot be responded immediately by its receiving node. Before a handshake finishes, other nodes may request the same resources or intend to communicate with the same receiving node, which causes resource contention. Eventually, only one pair of nodes can successfully finish their handshake and establish a communication link. The SRBs over SCHs may not be fully utilized. To address this issue, a DTR/DTA handshake routine is proposed. Its goal is to increase the probability that a DTR can be acknowledged with a DTA so that the handshake can initiate data transmission successfully. This probability is referred to handshake success probability (HSP) in this paper.

To increase the HSP, the main principle is not to interfere with any legal DTR so that they can successfully establish communication links. In AHT-MAC, *a DTR is legal if it does not contain any ESRB of other nodes*. With the support of the proposed SRB management scheme, nodes can determine the legality of DTRs by overhearing DTRs from their one-hop neighbors. Nodes must update SRB states based on legal DTRs and attempt to send legal DTRs by choosing *Idle* and *Obtainable* SRBs. The node states should also be updated based on legal DTRs, which could be one of the following:

- *IDLE*: the node has not sent or received any DTR;
- *BUSY*: the node has finished its DTR/DTA handshake;
- *SENDDTR*: the node has sent a DTR;
- *RECVDTR*: the node has received a DTR.

Nodes can only send their DTRs to *IDLE* nodes because the nodes on state *SENDDTR* or *RECVDTR* shall finish the ongoing handshakes and become *BUSY* soon. Based on the above rules, nodes are guided to choose *Idle* and *Obtainable* SRBs to communicate with *IDLE* nodes. The benefits are twofold: 1) potential resource contention is avoided so that the ongoing handshakes will not be disturbed; 2) the nodes that are close to each other tend to utilize different SCHs to communicate with different nodes, which further boosts the throughput.

To reply a DTR, a node should first check whether the SRBs in this DTR are possessed or not by the transmitting node. Only SRBs still occupied by the transmitting node can be utilized and will be included in the DTA. If no SRB matches this criterion, this DTR is treated as invalid and will be discarded.

The DTR/DTA procedure is summarized in Algorithm 1 and 2. When a node is ready to send a beacon, it should send DTR/DTA by following Algorithm 1 below. When a DTR or DTA is received, the node processes it by following Algorithm 2 below. The DTR/DTA packets are transmitted over the CCH, which are sent together with other beacons at a slot via the frame aggregation as defined in IEEE 802.11p [34].

Algorithm 1 The DTR/DTA Sending Routine

```
bSendDTA = false
if the node has received DTRs then
    check the validity of each received DTR
    discard invalid DTRs
    if there is at least one valid DTRs then
        respond to the DTR that is received most early
        bSendDTA = true
    end if
end if
if bSendDTA == false then
    select available SRBs according to Section IV-C

    select a receiver that satisfies:
        1) the receiver is within TR
        2) the receiver is in the allowed transmission direction
        3) the receiver is IDLE
    if the above two steps are successful then
        send a DTR to this receiver
    end if
end if
```

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Algorithm 2 The DTR/DTA Receiving Routine

```
if the received beacon is a DTR then
    if the received DTR is legal then
        set the sender state to SENDDTR
        set the receiver state to RECVDTR
        update the SRB states according to Section IV-C
        if this node is the DTR receiver then
            save this DTR
        end if
    end if
end if
if the received beacon is a DTA then
    set the states of the sender and receiver to BUSY
    if this node is the DTA receiver then
        set the states of all SRBs in the DTA to Ready
    else if this node is in the $IR_{\text{sch}}$ of the DTA sender or the DTA receiver then
        set the states of all SRBs in the DTA to Occupied
    end if
end if
```

The complexity analysis of AHT-MAC is provided in Appendix A. Our analysis shows that neither Algorithm 1 nor 2 requires intensive computations.

E. Request Conflict Resolution

In practice, 100% reliable beacon delivery is prohibitively difficult to achieve. Sometimes, beacons are corrupted due to channel fading or collisions. Nodes may send illegal DTRs which contain the ESRBs of others, which is called request conflict. If the handshake initiated by an illegal DTR succeeds, collisions over SCHs will occur or some other handshakes will be abnormally terminated. Fig. 3 presents a typical scenario of the request conflict caused by the beacon collisions over the CCH. In the figure, V_3 receives a DTR from V_1 (denoted by DTR$_1$), whose intended receiver is V_2. V_3 finds that DTR$_1$ contains the ESRBs of V_4, then V_3 will conclude that DTR$_1$ is illegal. However, the reason of the request conflict is that V_1 has not correctly received the DTR$_4$ due to the collision with the transmission between V_4 and V_5 over the CCH. V_1 is not aware of the occupation of the SRBs in DTR$_4$.

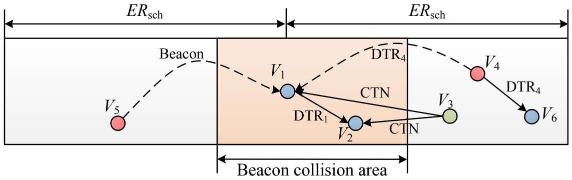

Fig. 3. A typical scenario of the request conflict caused by the beacon collision over the CCH. The beacons sent by V_4 and V_5 collide at V_1. Due to this collision, V_1 sends an illegal DTR to V_2, leading to request conflict.

To address request conflict, the main idea is to nullify those illegal DTRs and protect the legal ones. When a node receives a DTR, it checks the legality of the DTR first. If a node detects request conflict, it refuses to respond with DTA to the illegal DTR and instead generates a conflict notification (CTN). The CTN includes the ID of the transmitting node that has sent the illegal DTR, the index of the related SI as well as the ID and all SRBs of the legal owner. When the node gets the chance to access CCH, CTN is transmitted with other beacons via the frame aggregation defined in IEEE 802.11p [34] if the node has not overheard the same CTN from others.

Upon receiving a CTN, the node will check whether it is the transmitting node that sent the illegal DTR. If yes, it sets all the SRBs listed in the CTN to *Occupied* and aborts its improper handshake. Otherwise, the node only needs to discard the corresponding illegal DTR. Taking Fig. 3 as an example again, if V_3 sends out a CTN in advance, V_4 will not repeat the same CTN to reduce beaconing overheads. V_1 will not use the SRBs possessed by V_4 after the reception of the CTN. Correspondingly, V_2 will discard DTR$_1$. Finally, the problem caused by the illegal DTR$_1$ is solved, and V_4 can finish its handshake as usual.

V. PERFORMANCE ANALYSIS

In this section, we propose an analytical model to derive the average HSP and throughput. Here, a straight road scenario is considered. Since the definition of ER_{sch} implies that 2 nodes can use the same SRBs without any conflict if the distance between the two is longer than ER_{sch}, the HSP and throughput can be estimated within a road segment with the length of ER_{sch}. We assume that there are n nodes uniformly distributed along the road moving in the same direction. Without loss of generality, the number of nodes n is set to be $2c, c \in \mathrm{N}^*$. During an SI, the number of SRBs per SCH is $D = 2^d, d \in \mathrm{N}^*$. Nodes broadcast DTRs one by one to reserve SRBs following the rules given in Section IV-C. Each node is constrained to broadcast only one DTR since a node may not have sufficient time to retransmit its DTR in practice. The unreliability of DTR delivery is taken into account in this model, while the side effects of illegal DTRs and other factors are ignored.

Recall that a DTR can successfully initiate a communication link only if the DTR sender selects mutually available SRBs and chooses an *IDLE* intended receiver. Thus, to derive the HSP, the probability that a node selects available SRBs to send a legal DTR, p_l, and the probability that a node chooses an *IDLE* receiver, p_t, are first analyzed. As introduced in Section IV, the node senses its surrounding by overhearing the DTRs from its neighbors. Therefore, both p_l and p_t highly rely on the number of the previous legal DTRs, r_l, and the number of the received legal DTRs, r_{lr}.

According to Section IV-C, the maximum r_l related to an SI, denoted as r_{lmax}, is $2^d M$ if n is sufficiently large. These DTRs can be classified into $(d+1)$ groups. The 1st group contains M DTRs, each of which reserves an entire SCH. After the DTR of the 1st group, all the M SCHs are occupied. We assume that the 2nd group also contains M DTRs and each of them shares a half of an SCH. After the DTR of the 2nd round, all the M SCHs are partitioned into $2M$ portions and each portion consists of 2^{d-1} SRBs. Similarly, for the DTRs in the 3rd group, there are $2M$ portions of SRBs in total that can be chosen to share with. Thus, the number of

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DTRs in the 3rd group is $2M$. After this group, all SRBs are partitioned into $4M$ portions. This process will continue till each portion contains only one SRB. Fig. 4 illustrates the case when $M = 1, d = 3$.

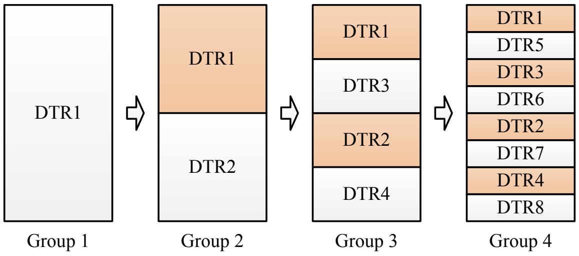

Fig. 4. The evolution of the resource partition of the SRB sharing mechanism when $M = 1, d = 3$.

From the above description, the number of the legal DTRs r_l ($r_l \geq M$) that have been broadcasted can be decomposed as follows:

$$\begin{aligned} r_l =& M + M + 2M + \cdots + 2^{k-2}M + r_{cl} \\ =& 2^{k-1}M + r_{cl}, \end{aligned} \tag{2}$$

where $2^{k-1}M$ is the number of the DTRs in the past k groups and r_{cl} is the number of the DTRs in the current group. The parameter k can be obtained by

$$k = \left\lfloor \log_2(\frac{r_l}{M}) \right\rfloor + 1. \tag{3}$$

Then, we have

$$\begin{aligned} r_{cl} =& r_l - 2^{k-1}M \\ =& r_l - 2^{\lfloor \log_2(\frac{r_l}{M}) \rfloor} M. \end{aligned} \tag{4}$$

To simplify, three new functions are introduced:

$$g(r_l) = \begin{cases} \lfloor \log_2(\frac{r_l}{M}) \rfloor + 1 & r_l \geq M \\ 0 & r_l < M \end{cases}, \tag{5}$$

$$g_c(r_l) = \begin{cases} r_l - 2^{\lfloor \log_2(\frac{r_l}{M}) \rfloor} M & r_l \geq M \\ r_l & r_l < M \end{cases}, \tag{6}$$

$$g_m(r_l) = \begin{cases} 2^{\lfloor \log_2(\frac{r_l}{M}) \rfloor} M & r_l \geq M \\ M & r_l < M \end{cases}. \tag{7}$$

Given r_l and r_{lr}, the next DTR from node V should be in the $(g(r_l) + 1)$th group, in which there are $g_m(r_l)$ candidate portions of SRBs in total. $g_c(r_l)$ is the number of the occupied portions of SRBs in this group. Then, the number of the available SRB portions for V should be $g_m(r_l) - g_c(r_l)$. In fact, V has received r_{lr} ($r_{lr} \leq r_l$) DTRs. From the perspective of V, its DTR is in the $(g(r_{lr}) + 1)$th group, and it should choose an SRB portion from the remaining $g_m(r_{lr}) - g_c(r_{lr})$ portions. If $g(r_{lr}) = g(r_l)$, V may choose a portion that has already been occupied. However, if $g(r_{lr}) < g(r_l)$, V's choice will be definitely illegal because the resources in the previous groups are occupied. Then the probability that a legal DTR is broadcast by V can be expressed as

$$h_l(r_l, r_{lr}) = \begin{cases} \frac{g_m(r_l) - g_c(r_l)}{g_m(r_{lr}) - g_c(r_{lr})} & g(r_{lr}) = g(r_l) \\ 0 & \text{otherwise} \end{cases}, \tag{8}$$

when V receives r_{lr} legal DTRs out of a total of r_l ones. More elaboration on (8) can be found in Appendix B.

As mentioned in Section IV-D, to guarantee the success of a DTR/DTA handshake, V must choose an *IDLE* receiver. The corresponding probability is denoted by $h_t(r_l, r_{lr})$ when V receives r_{lr} legal DTRs out of a total of r_l ones. Under this condition, the other $(n-1)$ nodes are categorized into 2 groups, one is for $n_u = 2r_l$ unavailable nodes, and the other is for $n_a = n - 2r_l - 1$ available nodes. Similarly, V may miss several legal DTRs due to the unreliable beaconing. Thus for V, there are $n_{hu} = 2(r_l - r_{lr})$ hidden unavailable nodes. Since the DTR receiver must be in the TR_{sch} ahead or behind of V, which is called a target area in this section. So only the states of the nodes in the target area influence the DTR target selection. Let X be the number of unavailable nodes in the target area and n_{ta} be the number of nodes in the target area, the probability distribution of X can be written as [1]

$$P\{X = x\} = \frac{\binom{n-n_{ta}}{2r_l - x}\binom{n_{ta}}{x}}{\binom{n}{2r_l}}. \tag{9}$$

Given $X = x$ unavailable nodes in the target area and n_u total unavailable nodes, the probability that Y out of n_{hu} hidden unavailable nodes are from the target area can be calculated by

$$P\{Y = y \mid X = x\} = \frac{\binom{x}{y}\binom{n_u - x}{n_{hu} - y}}{\binom{n_u}{n_{hu}}}. \tag{10}$$

Together with (9) and (10), $h_t(r_l, r_{lr})$ can be expressed as

$$\begin{aligned} h_t(r_l, r_{lr}) =& \sum_{x=0}^{n_{ta}} \sum_{y=0}^{\min(n_{hu}, x)} \frac{n_{ta} - x - 1}{n_{ta} - x - 1 + y} \\ & \times P\{Y = y \mid X = x\} P\{X = x\}. \end{aligned} \tag{11}$$

To model the entire SRB sharing process, the state (r_b, r_l) is introduced, where r_b is the number of the broadcasted DTRs and r_l is the number of legal DTRs. $a(r_b, r_l)$ stands for the probability that r_b DTRs have been broadcasted, among which there are r_l legal ones. When a new DTR is broadcasted, the system state will transfer from (r_b, r_l) to $(r_b + 1, r_l + 1)$ at a probability of $p_l(r_b, r_l)$ if the new DTR is legal. Otherwise, it will transfer to $(r_b + 1, r_l)$ at a probability of $1 - p_l(r_b, r_l)$. $p_l(r_b, r_l)$ stands for the legal probability of the new DTR at the state (r_b, r_l). This process is depicted in Fig. 5.

Since the first DTR is always legal, the initial state $(0, 0)$ will change to $(1, 1)$ at a probability $p_l(0, 0) = 1$. Thus, $a(r_b, r_l)$ can be calculated iteratively from state $(1, 1)$. $p_l(r_b, r_l)$ can be expressed as

$$p_l(r_b, r_l) = \sum_{i=1}^{r_b} \sum_{j=0}^{\min(i, r_l)} h_l(r_l, j) \frac{\binom{r_l}{j}\binom{r_b - r_l}{i-j}}{\binom{r_b}{i}} f(i, r_b). \tag{12}$$

The variable i denotes the number of DTRs the new DTR sender has received, and j denotes the number of the legal DTRs it has received accordingly. $h_l(r_l, j)$ represents the probability that the new DTR is legal. The rest part of (12)

---

[1] This is similar to the calculation of the probability that x balls are from a target area when selecting $2r_l$ balls randomly from an area where there are n balls in total.

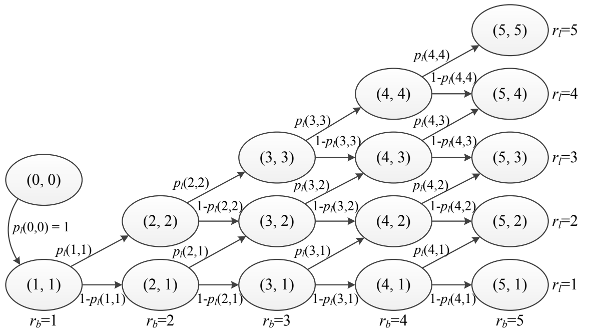

Fig. 5. The state transition diagram of the SRB sharing process when the number of nodes $n = 5$.

is the occurrence probability of the event (r_b, r_l, i, j), where $f(i, r_b)$ is the probability that a node successfully receives i beacons out of r_b. Given a beaconing reliability over the CCH $p_b = 1 - PER_{\text{cch}}$, $f(i, r_b)$ is calculated by

$$f(i, r_b) = \binom{r_b}{i} p_b^i (1 - p_b)^{r_b - i}. \tag{13}$$

Then, the iterative formula of $a(r_b, r_l)$ can be written as

$$\begin{aligned} a(r_b, r_l) =& [1 - p_l(r_b - 1, r_l)]a(r_b - 1, r_l) + \\ & p_l(r_b - 1, r_l - 1)a(r_b - 1, r_l - 1). \end{aligned} \tag{14}$$

Similar to $p_l(r_b, r_l)$, the success probability of the handshake initiated by the DTR at the state (r_b, r_l), denoted by $p_s(r_b, r_l)$, is expressed as

$$\begin{aligned} p_s(r_b, r_l) =& \sum_{i=1}^{r_b} \sum_{j=0}^{\min(i, r_l)} h_l(r_l, j) h_t(r_l, j) \\ & \times \frac{\binom{r_l}{j}\binom{r_b - r_l}{i - j}}{\binom{r_b}{i}} f(i, r_b). \end{aligned} \tag{15}$$

In (15), the term $h_l(r_l, j)h_t(r_l, j)$ means that the DTR is legal and its intended receiver is an *IDLE* node. The average HSP, p_s, can be approximated as

$$p_s = \frac{1}{c}\big[1 + \sum_{r_b=1}^{c-1} \sum_{r_l=1}^{r_b} p_s(r_b, r_l) a(r_b, r_l)\big] p_b. \tag{16}$$

In (16), the maximum number of DTRs during the entire process is set to be a constant c, and the factor $\frac{1}{c}$ is introduced to get the average HSP. The sum in the square brackets denotes the success probabilities of c DTRs, and each of the success probability is calculated via total probability formula except for the first DTR. $p_b = 1 - PER_{\text{cch}}$ is the beaconing reliability, which stands for the probability that the DTR is successfully received by the receiving node.

To approximate the average throughput S, the number of successful DTRs, say Z, is analyzed. Given a final state (c, r_l), the conditional expectation $\mathbb{E}[Z \mid r_l]$ can be written as

$$\mathbb{E}[Z \mid r_l] = \big[1 + \sum_{i=2}^{r_l} p_{as}(i)\big] p_b, \tag{17}$$

where $p_{as}(i)$ denotes the average success probability of the ith legal DTR. As shown in Fig. 5, the ith legal DTR can be generated at the states $(j, i-1), \quad j = i-1, \cdots (c-(r_l-i+1))$. Then, we have

$$p_{as}(i) = \frac{\sum_{j=i-1}^{c-(r_l-i+1)} p_s(j, i-1) a(j, i-1)}{\sum_{j=i-1}^{c-(r_l-i+1)} a(j, i-1)}. \tag{18}$$

When $r_l \leq M$, the number of the SRBs in each DTR is D. Then, the conditional expectation of the throughput $\mathbb{E}[S \mid r_l]$ can be expressed as

$$\mathbb{E}[S \mid r_l] = \frac{\mathbb{E}[Z \mid r_l] R_{data}}{c}, \quad r_l \leq M, \tag{19}$$

where R_{data} is the achievable data rate on an SCH. For $r_l > M$, all the SRBs of the M SCHs have been requested. The number of the overall utilized SRBs can be approximated as $\frac{\mathbb{E}[Z|r_l]}{r_l} MD$. Then, we have

$$\mathbb{E}[S \mid r_l] = \frac{\mathbb{E}[Z \mid r_l] M R_{data}}{c r_l}, \quad r_l > M. \tag{20}$$

By the law of total expectation, S can be written as

$$S = \sum_{r_l=1}^{c} \mathbb{E}[S \mid r_l] a(c, r_l). \tag{21}$$

VI. EXPERIMENTAL RESULTS

To evaluate the performance of the proposed AHT-MAC, experiments are conducted by using ns-3 [35] and SUMO [36]. Since AHT-MAC is an SCH dedicated MAC, the evaluation will focus on the performance comparison of data transmissions over SCHs. VeMAC is chosen as a baseline, which is also a two-transceiver based MAC protocol. Another baseline is the modified VeMAC, namely VeMAC-802.11, which adopts the RTS-CTS-ACK procedure defined in IEEE 802.11 for the communication coordination for SCHs. Since the CCH access procedure in AHT-MAC also follows VeMAC, the performances of all the evaluated MAC protocols over the CCH are identical. Thus, the performances over SCHs can be fairly compared.

VeMAC coordinates data transmissions via a three-way handshake over the CCH. For a pair of transmitting and receiving nodes, V_{s} and V_{d}, V_{s} first broadcasts a beacon which contains an *AnS* field. The *AnS* field indicates the available resources at the transmitting node. Upon receiving an *AnS*, V_{d} will choose the available resources to receive the data from V_{s} and include information indicating the chosen resource in the *AcS* field of the broadcast beacon. In addition, V_{d} also embeds a new *AnS* field indicating the available resources at the receiving node. After receiving the beacon back from V_{d}, V_{s} can determine the resources for sending data packets by parsing the *AcS* field. Similarly, V_{s} chooses the available resources from the *AnS* field to receive data from V_{d} and include the information of the chosen resources in the *AcS* field of the broadcast beacon. After those beacon exchanges, the two nodes will switch to the chosen SCH to transmit data. It can be seen that the three-way handshake in VeMAC is composed of two overlapped two-way handshakes, each of which coordinates a unidirectional link. The handshake in VeMAC-802.11 follows the RTS/CTS procedure defined in

IEEE 802.11. The difference is that the receiving node has to wait for its own slot, and then broadcasts the CTS.

The parameters of the simulated MAC protocols are listed in Table II. In order to get the saturated throughput of the simulated protocols, it is assumed that all nodes always have packets to transmit. The channel condition is also assumed to be perfectly known without errors in order to focus on the MAC layer. According to [18] and [32], the relationship between TR and IR is set to be IR = 1.78TR in AHT-MAC.

TABLE II
PARAMETERS OF MAC PROTOCOLS

Parameter		VeMAC	VeMAC-802.11	AHT-MAC
CCH	Frame Duration	40 ms		
	Slots/Frame	100		
	Slot Duration	0.4 ms		
	Data Rate	12 Mbps		
	Max Beacon Size	512 B		
	TR_{cch}	150 m		
SCH	SCHs	6		
	GI Duration	4 ms		
	Data Rate	12 Mbps		
	TR_{sch}	150 m	150 m	50 m
	Slot Duration	1 ms	1 ms	1 ms
	SI Duration	-	-	20 ms
	SRBs/SI/SCH	-	-	8

Two scenarios are considered when conducting the simulations. A ring shape road with sufficiently large radius (approximated by a decagon) is adopted to evaluate the performance of those protocols under the straight road environment. All vehicles are restricted to move in the same direction. Since the analytical model is also derived based on the straight road environment where all nodes move in the same direction, the analytical model can be verified in this simulation scenario. To further show the generality of the proposed AHT-MAC, an intersection scenario is also simulated, which is the typical pattern in urban environments. As vehicles may move forth, turn left or right at the intersection, most of the topology change features can be generated in such a scenario. It is assumed that there is no traffic light at the intersection, so that the effects caused by the imbalanced traffics can be eliminated. When a vehicle arrives at the border of the map, it will turn around and move on. The maps and the parameters of the considered scenarios are shown in Fig. 6 and Table III, respectively. It should be mentioned that the "Vehicles / ER_{sch}" in Table III is the average number of nodes in a straight road segment length of ER_{sch}. Consequently, the node density doubles near the intersection. Thus, in the intersection scenario, the node density varies considerably.

TABLE III
PARAMETERS OF THE SIMULATION SCENARIOS

Parameter	The ring shape Road	Intersection
Total Road Length	1000 m (100 m × 10)	2000 m (500 m × 4)
Bi-directional Road	False	True
Lanes / Direction	8	4
Speed	50 km/h	50 km/h
Vehicles / ER_{sch}	14 to 30, step = 2	14 to 30, step = 2
Number of vehicles	87 to 193 step ≈ 13	177 to 378 step ≈ 25

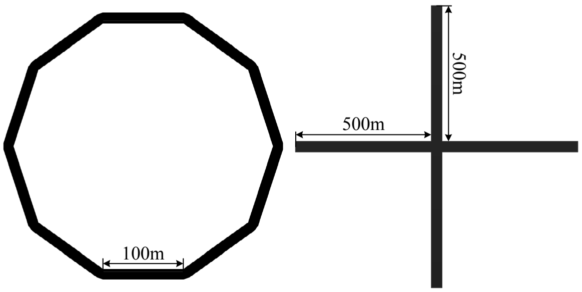

Fig. 6. The ring shape road scenario (left) and the intersection scenario (right).

A. The Ring Shape Road Scenario

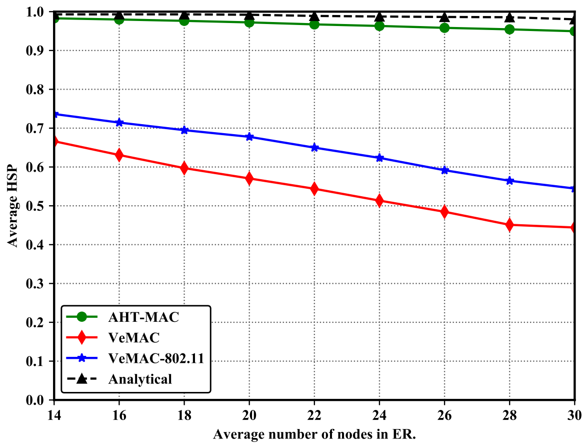

Fig. 7. The average HSP of the simulated protocols in the circular road scenario.

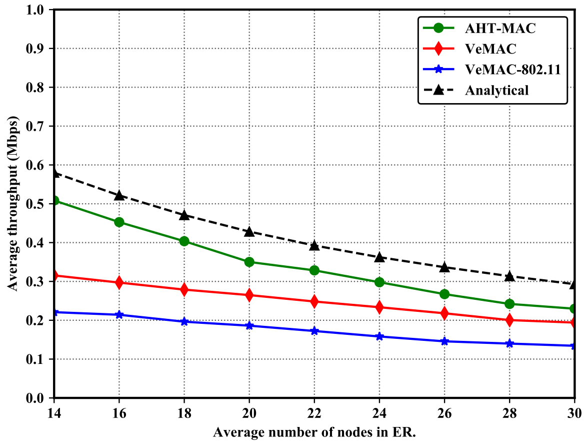

Fig. 8. The average throughput of the simulated protocols in the circular road scenario.

In this scenario, the beacon exchange is reliable. The PER over the CCH, PER_{cch}, is lower than 0.02. The beaconing reliability $p_b = 1 - PER_{\text{cch}}$ is higher than 0.98. Thus in this benchmark, the side effects of the CCH MAC protocol can be excluded. The HSP curves of the simulated protocols are shown in Fig. 7. Simulation results show that both VeMAC and VeMAC-802.11 have lower HSPs than AHT-MAC. The reasons are twofold: 1) the TRs for the CCH and SCHs are equal in VeMAC and VeMAC-802.11. Based on this setup, the information directly collected from those one-hop neighbors is insufficient for a node to discern the resource availability or figure out the behavior of the nodes nearby. Consequently, the resources listed in the *AnS* and RTS could be probably unavailable or the receivers of the *AnS* and RTS tend to be busy. The communication requests will probably be rejected. 2) nodes update the resource state only according to *AcS* (CTS). Thus, multiple nodes will attempt to access the same resource, but only one of them could succeed. In the case that the data traffic load is heavy, e.g., nodes always have packets to transmit, and all the nodes are doing their best to acquire possible available resources, the HSP will deteriorate much more severely. In contrast, the above issues are carefully addressed in the proposed AHT-MAC, which is why it can achieve higher HSP.

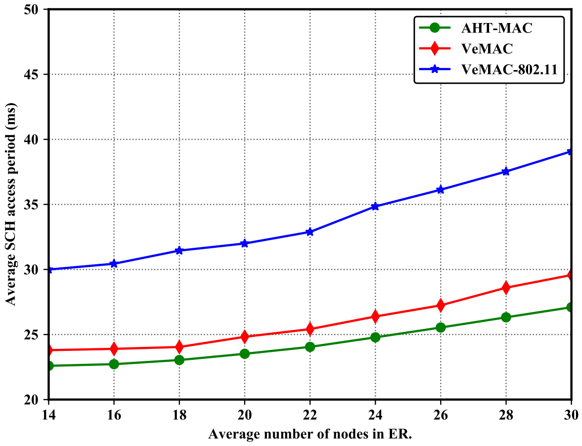

Fig. 9. The average SCH access periods of the simulated protocols in the ring shape road scenario.

Fig. 9 provides the average SCH access periods of all the simulated protocols. As expected, AHT-MAC maintains lower access periods than others because it performs two-way handshakes with higher HSP. For VeMAC and VeMAC-802.11, nodes have to wait longer to obtain the next channel access opportunities. As a consequence, AHT-MAC gains higher throughputs than VeMAC as shown in Fig. 8. Additionally, the DTR/DTA handshake in AHT-MAC enables nodes to use different resources to communicate with different nodes, resulting in a full utilization of all SCHs and thereby can boost the throughput.

The analytical HSP and throughput for AHT-MAC are also illustrated in Fig. 7 and Fig. 8, respectively. It can be seen that the analytical HSP fits the simulation results well. There is a gap between the simulated and analytical average throughput, because the analytical model only takes unreliable beaconing into account. In fact, some other factors, e.g., illegal DTRs, DTR receiver selection, and node mobility, will also influence the average throughput. To further verify the analytical model, additional simulations have been carried out by setting the number of vehicles per ER_{sch} to be 22 (a mean value) and letting p_b vary from 0.84 to 1 at a step size of 0.02. Simulation results are shown in Fig. 10 and Fig. 11, respectively. For HSP, the analytical curve still fits the simulated curve well. This implies that HSP is dominated by the beaconing reliability. When p_b is high, the analytical average throughput is higher due to the same reason explained above. When p_b is low, the HSP drops dramatically. Nodes severely suffer from frequent handshake failures. The low HSP becomes the primary factor of the throughput degradation under this condition. Thus, the analytical curve fits the simulation result. In summary, the simulation results are consistent with those analytical ones.

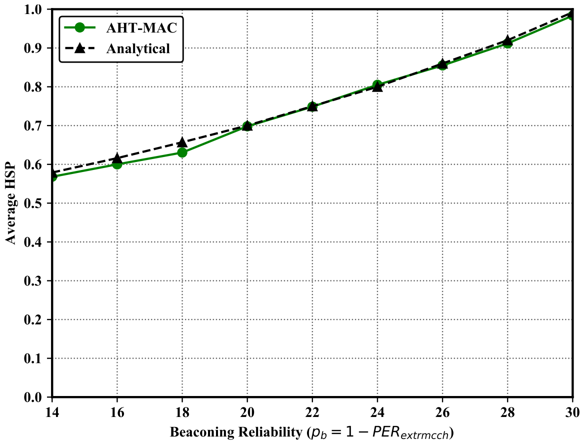

Fig. 10. The average HSP of AHT-MAC in the ring shape road scenario when the beaconing reliability p_b ($p_b = 1 - PER_{\mathrm{cch}}$) changes from 0.84 to 1.

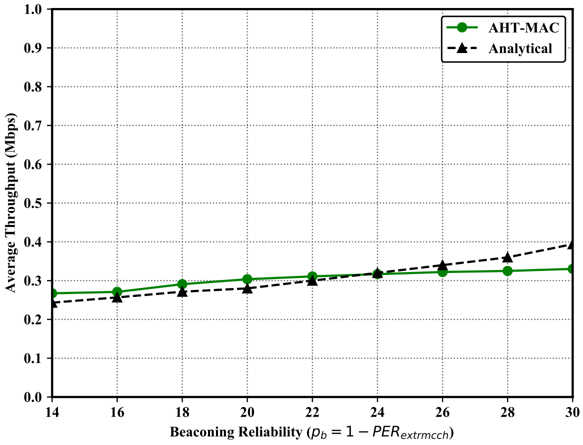

Fig. 11. The average throughput of AHT-MAC in the ring shape road scenario when the beaconing reliability p_b ($p_b = 1 - PER_{\mathrm{cch}}$) changes from 0.84 to 1.

B. The Intersection Scenario

In this scenario, the beacon delivery over the CCH is not always reliable because the node density may exceed the capability for VeMAC near the intersection. Fig. 12 shows the curves of beaconing reliability p_b ($p_b = 1 - PER_{\mathrm{cch}}$) for those simulated protocols. It can be seen that p_b drops considerably when the number of vehicles per ER_{sch} exceeds 24.

More results are shown in Fig. 13, Fig. 14 and Fig. 15. Compared with the other two protocols, AHT-MAC can maintain higher HSP, lower channel access periods as well as higher throughput. Specially, the proposed SRB sharing

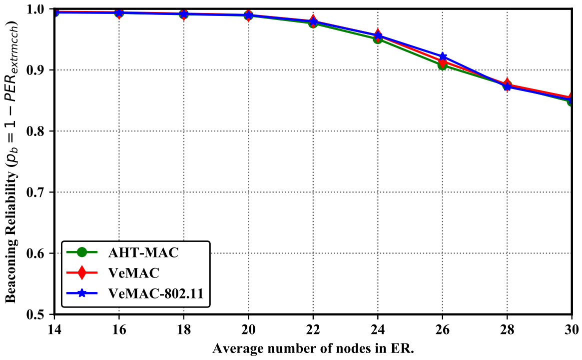

Fig. 12. The beaconing reliability p_b ($p_b = 1 - PER_{\mathrm{cch}}$) of the simulated protocols in the intersection scenario.

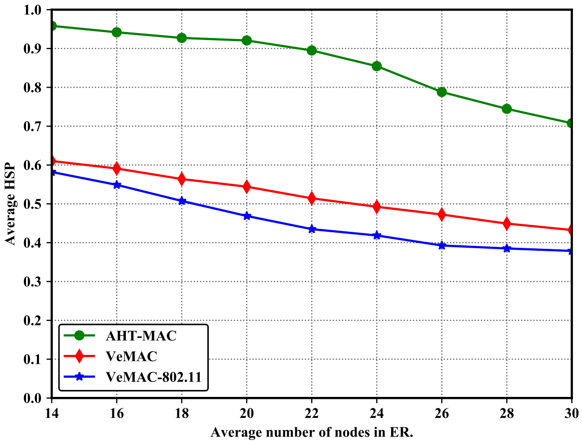

Fig. 13. The average HSP of the simulated protocols in the intersection scenario.

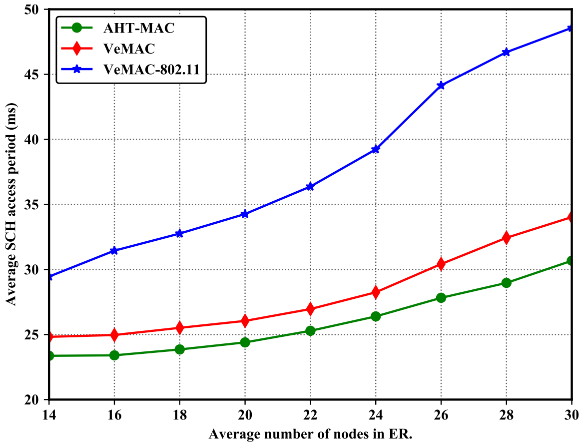

Fig. 14. The average SCH access periods of the simulated protocols in the intersection scenario.

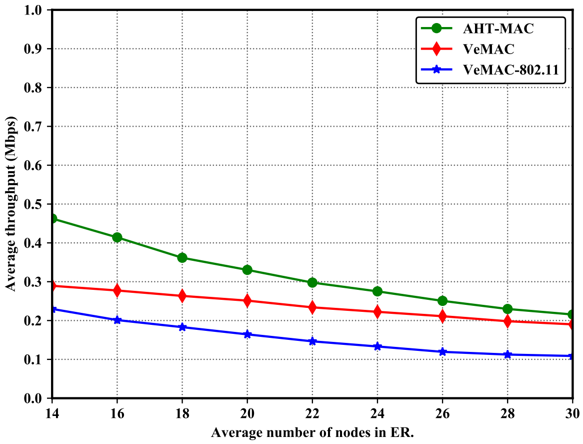

Fig. 15. The average throughput of VeMAC and AHT-MAC in the intersection scenario.

mechanism enables nodes share resources during the two-way DTR/DTA handshakes. Due to this mechanism, nodes can quickly adapt to rapid node density changes. Thus, higher throughputs can be achieved. However, compared with the results in the ring shape road scenario, AHT-MAC offers lower HSP and throughput. That is because AHT-MAC is designed for the straight line model. When a node is approaching the intersection, it probably makes wrong decisions following the rules in AHT-MAC, e.g., generates illegal DTRs or selects improper communication targets, and the illegal DTRs will in turn interfere more nodes near the intersection.

VII. CONCLUSIONS

In this paper, we have proposed a high throughput and adaptive multi-channel medium access control protocol (AHT-MAC) to support data transmissions over service channels (SCHs) in vehicular ad hoc networks (VANETs). In the proposed AHT-MAC, the resource allocation and communication coordination schemes for SCHs are carefully addressed. The service resource block (SRB) management scheme enables nodes to determine the mutually available SRBs based on the directly collected information from the beacons received over the control channel (CCH). The proposed SRB sharing mechanism helps nodes share more proper amount of resources so that all SCHs can be fully utilized in various node density conditions. Based on the above setup, the coordination of transmissions is conducted via a two-way data transmission request/data transmission acceptance (DTR/DTA) handshake. This handshake process is further protected by a request conflict resolution mechanism. The proposed AHT-MAC can achieve higher handshake success probability. Moreover, contention time can be removed from SCHs to further increase throughput. The simulation results and the extensive studies show that the proposed AHT-MAC can maintain lower SCH access periods and hence achieve significantly higher network throughput.

APPENDIX A
COMPLEXITY ANALYSIS OF THE PROPOSED ALGORITHMS

In AHT-MAC, neither Algorithm 1 nor Algorithm 2 involves intensive computations. The majority operations are the state check and update that occur during the traversal of the SRB list, neighbor list and the received DTR list. Thus, the complexity can be measured by the number of the processed items on the lists during the traversal.

For better demonstration, three new variables, l_{s}, l_{n}, l_{r} are introduced to denote the lengths of the SRB list, the neighbor list and the received DTR list, respectively.

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In Algorithm 1, a node can either reply to a received DTR or send a new DTR. To reply to a DTR, each received DTR should be checked for SRB validity, which needs a traversal of the SRB list. This step requires $l_s \cdot l_r$ times for list item check. To send a new DTR, the SRB list and neighbor list should be searched to find proper SRBs and a receiving node, requiring $l_s + l_n$ list item checks. Therefore, the complexity of Algorithm 1 is $O(\max(l_s \cdot l_r, l_s + l_n))$.

As for Algorithm 2, only the state codes of nodes and SRBs indicated by the received DTR/DTA should be updated and no list traversal is required. The total number of actions is no more than $D + 2$ list item checks (the state update for the sender and receiver plus at most D SRBs in the DTR or DTA). Thus, the complexity of Algorithm 2 is $O(D)$.

In practice, the complexity of Algorithm 1 and 2 can be bounded by a constant due to the following facts:

- l_s is bounded. $l_s = MD$, where M is the number of SCHs and D is the number of SRBs in an SCH interval. Both M and D are predefined constants. M is typically 6 following IEEE 1609.4 standard [5]. D should not be too large so that the duration of the SRB is long enough to transmit a packet.
- l_r is small since AHT-MAC does not allow nodes to send DTRs to their neighbors that have already sent or received DTRs/DTAs. Besides, invalid DTRs will be removed from the list upon Algorithm 1.
- l_n is usually less than 100 as mentioned in [12]. After all, there cannot be too many neighboring nodes in VANETs due to the inevitable space occupation by vehicles.

APPENDIX B
EXTENDED EXPLANATION ON (8)

To further explain the derivation of the conditional probability that V broadcasts a legal DTR, an example is presented in this appendix. We suppose that $r_l = 6$, which means 6 DTRs have been broadcasted as shown in Fig. 16(a). The new DTR sent by node V falls in group 4 (by eq (5), $g(6) + 1 = 4$). In this group, there are $g_m(6) = 4$ portions of SRBs in total. Currently, $g_c(6) = 2$ DTRs have been broadcasted in this group (DTR$_5$ and DTR$_6$) and occupied 2 portions of SRBs. Only 2 (=$g_m(6) - g_c(6)$) portions of SRBs remain available. Node V should share a portion of SRBs from V_2 or V_4, provided that V has correctly received all $r_{lr} = 6$ DTRs.

In practice, V may miss DTRs, as shown in Fig. 16(b), where DTR$_6$ has not been received by V. From the perspective of V, it has received 5 DTRs, where $r_{lr} = 5$. Its new DTR falls in group 4 (=$g(5) + 1$), which is correct. However, the SRBs possessed by V_6 is erroneously marked as *Obtainable*, which still belongs to V_3. Thus, V will attempt to share a portion of SRBs with V_3, V_2 or V_4, instead of V_2 or V_4. The probability that V makes a correct choice is

$$h_l(6,5) = \frac{g_m(6) - g_c(6)}{g_m(5) - g_c(5)} = \frac{2}{3}. \tag{22}$$

The situation could be even worse. As shown in Fig. 16(c), V only correctly receives DTR$_1$, DTR$_2$ and DTR$_3$, where $r_{lr} = 3$. Based on the perception of V, its new DTR falls in group 3 (=$g(6) + 1$). V should share SRBs with V_2 that currently possesses the most amount of SRBs. However, all portions of SRBs in group 3 have been exhausted. Hence, when $g(r_l) \neq g(r_{lr})$, V will definitely send an illegal DTR and we have $h_l(6,3) = 0$.

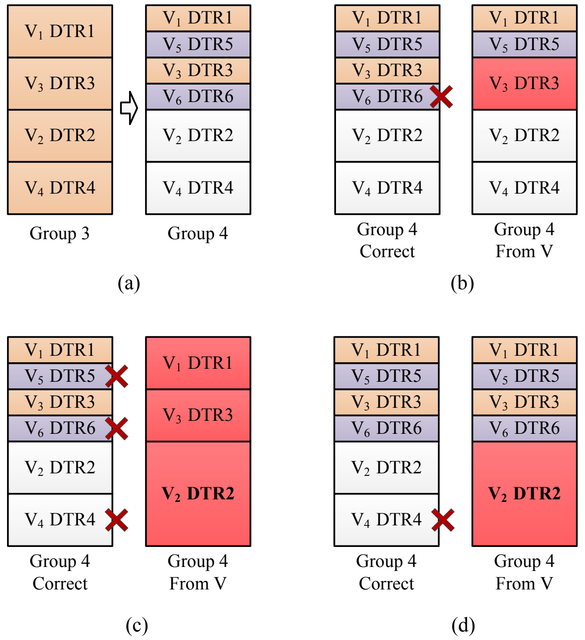

Fig. 16. An example on the derivation for the probability that V broadcasts a legal DTR.

For a special case that DTRs in the previous groups are missed by V as shown in Fig. 16(d), the DTR loss can be detected since the newly received DTR shares a small portion of SRBs instead of the largest portion. Under this condition, extra mechanism should be developed to avoid the broadcast of illegal DTRs. However, such mechanism is too complicated to be discussed here in this paper and will be presented in our future work. It is not considered neither in the protocol design nor in the analytical model.

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