A Novel Distributed Asynchronous Multi-Channel MAC Scheme for Large-Scale Vehicular Ad Hoc Networks

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***Abstract*—This paper proposes a novel distributed asynchronous multi-channel MAC scheme for large-scale Vehicular Ad Hoc Networks, namely, Asynchronous Multi-Channel MAC-Distributed (AMCMAC-D). The proposed scheme supports simultaneous transmissions on different service channels, while allowing rendezvous and broadcast of emergency messages on the control channel. The scheme is distributed, in the sense that it handles access to the shared control channel for different access categories without relying on the beacon frames from roadside units. This eliminates the overhead associated with channel allocation making the proposed scheme suitable for large-scale networks in terms of the number of active nodes. Service differentiation in the proposed scheme is enhanced by allocating different numbers of time slots for different access categories. We compare the performance of the proposed scheme with that of the IEEE 1609.4 standard and Asynchronous Multi-channel Coordination Protocol (AMCP), in terms of throughput, packet delivery rate, collision rate, utilization of service channels, service differentiation, and the penetration rate of non-collided emergency messages. The results show that AMCMAC-D outperforms the IEEE 1609.4 standard and AMCP in terms of system throughput by increasing the utilization of the control channel and service channels. The proposed scheme also demonstrates better performance in terms of packet delivery rate, collision rate on service channel, load balancing, and service differentiation. Finally, AMCMAC-D mitigates the multi-channel hidden terminal and missing receiver problems which occur in asynchronous multi-channel MAC schemes.**

I. INTRODUCTION

A. Scope and Problem Statement

Vehicular Ad hoc Networks (VANETs) [1] enable communications among nearby vehicles and between vehicles and nearby fixed infrastructures. These communication facilities are expected to be used for a variety of applications to improve safety of the future transport systems and provide many industrial and entertainment services [7]-[9]. VANETs enable Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications using Wireless Local Area Network (WLAN) technologies [1]-[6]. In particular, the IEEE 802.11p standard [10] has been proposed with a special physical layer for the highly dynamic propagation environment in VANETs. The MAC layer of 802.11p is also designed to provide different levels of QoS support for different types of Intelligent Transport System (ITS) applications [11]-[14].

Recently, it has been reported that the original IEEE 802.11p standard based MAC sub-layer demonstrates a poor performance in dense VANETs, in provisioning QoS for different categories of applications [15]-[18]. This seems to be a particularly important shortcoming for reliable deployment of safety related applications. Thus, multi-channel extension of the IEEE 802.11p standard, namely, the IEEE 1609.4 standard [19] has been proposed to improve the service differentiation capability of the 802.11p standard. In a typical multi-channel system, there is one Control Channel (CCH) which is used for control messages such as channel negotiations, as well as, the important safety related information. Other applications use multiple Service Channels (SCH) for data communications. Both non-safety and safety related applications could be supported by employing multiple channels. This could improve QoS performance for different types of applications by allocating them different channels.

Although the IEEE 1609.4 standard provides a better QoS support, its MAC sub-layer suffers from a few shortcomings: 1) strict MAC sub-layer synchronisation is required; 2) synchronous MAC sub-layer operation results in inefficient utilization of the control and service channels, i.e., utilization cannot inherently exceed 50%; 3) fixed duration of control and service time intervals prohibits adaptive and intelligent allocation of time intervals in response to variable traffic demands; and 4) there is a possibility of contention in service channels, that may result in inefficiency due to possible collisions. A number of recent publications aim to address these problems. In the following subsection, we provide a comprehensive survey of these related studies and discuss their approaches, contributions, and shortcomings.

B. Existing Related Work

There are a number of studies in the literature to deal with the inherent problems of the IEEE 1609.4 standard as

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discussed in the following. Details of the relevant aspects and design challenges of the IEEE 1609.4 standard are given in Section II-A. Some synchronous split phase multi-channel MAC schemes have been recently proposed ([20]-[23]) to address the aforementioned problems of the IEEE 1609.4 standard. Wang et al. in [20] present a Variable CCH Interval (VCI) approach, which dynamically adjusts the duration of the CCH and the SCH intervals according to the number of active nodes in the network. The dynamic VCI algorithm helps improve the saturation throughput compared to that of the IEEE 1609.4 standard. In this work, it is assumed that the number of nodes and packet size are known by roadside units, which may not be possible in distributed scenarios. In [22], a Distributed Reliable Multi-channel MAC scheme (DR-MMAC) is proposed to provide a contention-free channel access mechanism both on CCH and SCHs. For CCH frames, Reliable Reservation ALOHA (RR-ALOHA) [24] is used by nodes to reserve respective slots to transmit data without collisions. Since this scheme uses RR-ALOHA for the reservation of slots, it may not be suitable for large-scale networks. In addition, pre-determined reservation of time slots may result in poor channel utilization. Finally, synchronization remains a problem in this scheme. In [23], the authors propose a multi-channel MAC scheme to solve the multi-channel hidden terminal problem in a network where each host has only one transceiver. However, in this scheme, all nodes have to synchronize their beacon intervals, which may result in poor utilization of service channels similar to other synchronous multi-channel MAC schemes. Furthermore, during the beacon interval, the data channels all stay idle until the end of each beacon interval, which may limit the system performance with low channel utilization rate.

Different from synchronous split phase multi-channel MAC schemes, there are two other categories of multi-channel MAC schemes [25], namely, Common Hopping ([26], [27]), and Parallel Rendezvous schemes ([28], [29]). These schemes either require tight clock synchronization or demand the source node to know the hopping sequence of the destination node, resulting in excessive signalling overhead. In addition, the hopping time penalty is not negligible in both categories, since the time necessary for switching the channel is comparable with the time consumed on transmitting an RTS packet [25].

Alternatively, asynchronous multi-channel MAC schemes ([30]-[32]) are also proposed in the literature. This category of multi-channel schemes usually requires no strict time synchronization and allows nodes to independently hop among channels to make the best use of channel resource. However, this may lead to a well known and common problem that some nodes may miss emergency broadcast information on the control channel when they are engaged in communications over service channels. Nonetheless, this may not be a big issue for two reasons: 1) emergency messages are rarely generated; 2) they are repeated multiple times by the disseminating nodes. This problem will be analysed more in details in Section VI. As a prime example of asynchronous schemes, the Asynchronous Multi-channel Coordination Protocol (AMCP) [30] uses a dedicated control channel similar to that of the IEEE 1609.4 standard. However, this scheme does not require time synchronization among nodes to operate on data channels. Nonetheless, the channel selection negotiation in this scheme may require a second round negotiation, which results in extra overhead. In addition, the node that returns to CCH after the completion of a transmission on a particular SCH, marks other SCHs busy for a certain period of time in order to avoid the multi-channel hidden terminal problem. In [32], the authors introduce cooperation among neighbours into the multi-channel MAC to assist with more reliable selection of available service channels. However, as concluded in their paper, node mobility can adversely affect the effectiveness of this scheme. In addition, due to the multiple phases in the handshake process, the scheme is not suitable for vehicular networks in which node mobility may be dramatic.

In the urban area, large-scale vehicular networks often form at intersections, or in traffic jams, or in some urban area due to complex road architecture. These situations can result in scalability problems that have been pointed out in [5]. For example, it is reported that large-scale vehicular networks do not perform well due to the high contention level among nodes in the same reference area. Multi-channel MAC schemes can mitigate this problem by allowing more than one pair of nodes to transmit over different channels separated on frequency. However, from simulation results in our previous study [33], large-scale networks with multi-channel MAC schemes still suffer from degradation of network performance as the network size increases. Contention problem can be addressed to some extent by introducing some coordinating nodes. However, the very dynamic nature of vehicular networks prohibits effective deployment of coordination nodes. This problem can be even worse in dense networks due to signalling issues. Saeed et al. in [34]-[36] propose decentralized TDMA assisted MAC schemes for vehicular ad hoc networks. The scheme in these papers rely on the existence of Roadside Units (RSU) to obtain information from beacon messages. In [35] and [36], the STDMA is proposed as a self organized single-channel MAC scheme for communications among ships and Vessel Traffic Service (VTS) stations. Nodes broadcast data messages containing information about their positions periodically. During the initialization phase, a node will listen to the channel activity for a duration of one frame length to determine the slot assignments. However, due to the features of vehicular environments, this scheme is not suitable to be used for VANETs, especially for large-scale vehicular networks. First, it introduces overhead due to the periodical broadcast data messages; second, nodes determine the slots to be used by listening to the channel, where collisions are not avoidable since two or more nodes may choose the same time slot; third, in large-scale vehicular networks, decentralized schemes cannot allocate a unique time slot for each node. In our paper, we introduce a simple but effective sub-layer on the top of the multi-channel MAC scheme to reduce the contention among nodes.

C. Contributions

A novel distributed TDMA based asynchronous multi-channel MAC scheme, namely Asynchronous Multi-Channel

MAC with a distributed TDMA mechanism (AMCMAC-D) is proposed in this paper. This scheme supports multiple transmissions simultaneously on different service channels and improves the system performance in large-scale networks. The AMCMAC-D scheme consists of two algorithms, i.e., the AMCMAC and the DTDMA, that can function both together and separately. AMCMAC relies on a single radio which is suitable for most of the existing systems. According to a comparative study of some well known multi-channel MAC schemes in [37], AMCP outperforms the Multi-Channel MAC (MMAC) [23] in the 802.11a scenarios where the number of SCHs is high enough to amortize the signalling overhead. Thus, AMCP is chosen as a benchmark scheme in our performance analysis. Contributions from the AMCMAC scheme are summarized as follows:

1) AMCMAC assures the balance among service channels by adopting the load balancing channel selection mechanism;
2) AMCMAC reduces the collision rate on the control channel by using different post-transmission process comparing to AMCP;
3) AMCMAC tackles the missing receiver problem in a different way comparing to AMCP. As a result, AMCMAC reduces the waiting time for other nodes, and the collision rate on the CCH if the receiver is missing;
4) AMCMAC improves the utilization of the service channels by tackling the multi-channel hidden terminal problem differently from that in AMCP.

In addition, to reduce the high contention level on the control channel in large-scale networks, we propose a fully distributed TDMA-like algorithm that controls the transmission attempts on the control channel, namely, DTDMA scheme. Unlike the centralized TDMA schemes, the DTDMA does not require assistance from Roadside Units, and there is no need for overhead associated with allocation of time slots to stations; hence, DTDMA is more suitable for the large-scale distributed vehicular networks. DTDMA scheme handles the chances of accessing the shared control channel for different access category queues on demand, which means a single time slot does not need to be dedicated to a specific node. Due to the nature of DTDMA algorithm, it can be used on top of any other distributed CSMA contention based MAC scheme. The contention level is reduced by decreasing the effective network size, which refers to the number of competing nodes at each time slot. Mathematical analysis of the adverse impacts of congestion on the control channel, as well as, the impacts of DTDMA on the effective load on each time slot are also given in this paper. Contributions from the DTDMA scheme are summarized as follows:

1) DTDMA is fully distributed so that it does not require assistance from Roadside Units, central controllers or cluster headers, and there is no need for overhead associated with allocation of time slots to stations;
2) DTDMA reduces the high contention level on the control channel in large-scale networks;
3) DTDMA can be used on top of any other distributed CSMA contention based MAC scheme;
4) With DTDMA, service differentiation is enhanced by allocating different numbers of time slots for access categories with different priorities.

Finally, comparisons of the performance of the AMCMAC-D scheme with that of the IEEE 1609.4 standard and the AMCP protocol are given. Obtained results show that the proposed scheme outperforms both of the aforementioned schemes in terms of system throughput (i.e., the total normalized throughput on all service channels), packet delivery rate, collision rate on service channel, load balancing, and service differentiation.

D. Organization of the Paper

The remainder of the paper is organized as follows. Section II provides an overview of the IEEE 1609.4 standard and AMCP schemes. AMCMAC scheme is introduced in Section III. The main idea of DTDMA is discussed in Section IV. Section V gives a rigorous mathematical analysis of the bottleneck impacts of control channel, as well as, the impacts of DTDMA scheme on reduction of contention level. Performance analysis and comparisons of the proposed scheme and the relevant discussions are given in Section VI. Finally, conclusions are given in Section VII.

II. BACKGROUND

In this section, the relevant aspects of the IEEE 1609.4 standard and AMCP are illustrated. Then, several scheme design issues and challenges for asynchronous multi-channel MAC schemes are discussed.

A. The IEEE 1609.4 standard

The IEEE 1609.4 standard is the standard of multi-channel operation for VANETs. In the IEEE 1609.4 standard, as shown in Fig. 1, the channel access time is divided into sync intervals. Each interval contains guard intervals and alternating fixed-length intervals called CCH interval and SCH interval. The duration of CCH and SCH intervals are fixed as 50 ms in [19][1]. During the CCH interval, all nodes monitor the CCH for exchanging safety messages and other control packets. During the SCH interval, nodes transmit potential non-safety application data on SCHs. Guard intervals are used to account for the lack of precise synchronization among different nodes. The value of the guard interval is the sum of SyncTolerance and MaxChSwitchTime, where SyncTolerance is the maximum allowed clock drift; MaxChSwitchTime is the maximum time allowed for a node to switch among channels. Transmissions shall not be permitted during guard intervals.

The current version of the IEEE 1609.4 standard MAC does not provide a high level of QoS guarantee and strict differentiation of services for the potential real time applications in the dense network scenarios. First, the duration of CCH and SCH intervals are fixed in the IEEE 1609.4 standard. In a congested urban areas with dense VANETs, large volume of safety and control messages may need to be delivered in the CCH interval. The fixed length of CCH may not be able

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[1] CCH interval starts every Coordinated Universal Time (UTC) second.

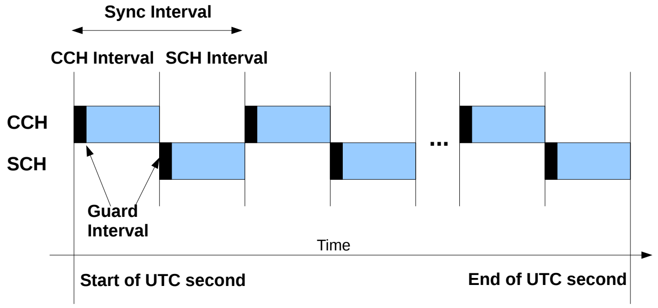

Fig. 1. Sync interval and its components in the IEEE 1609.4 standard.

to provide sufficient bandwidth in these scenarios. This may affect the utilization of service channels as the nodes may not be able to perform negotiations on a highly congested CCH. On the other hand, if the node density is sparse, the CCH interval will may be left idle for significant periods of time.

In addition, since nodes do not specifically determine the starting time of their transmission on service channel during the negotiation process on the control channel, there will be possibilities of collisions on the service channels.

B. AMCP

The AMCP is an asynchronous multi-channel coordination scheme which does not require synchronous hopping from service channels to the control channel and vice versa. Each node in AMCP maintains a channel table with N entries corresponding to N data channels. In the channel negotiation process of AMCP, a sender chooses a preferred channel and sends the information within RTS; if the channel is available for the receiver, a Confirming CTS is sent back. After receiving the Confirming CTS, both nodes switch to the data channel they agree with to start the transmission. However, if the channel chosen by the sender is unavailable for the receiver, a Rejecting CTS containing index 0 and a list of available channels of the receiver will be sent to the sender. Then if one of the available channels in the list is also available for the sender, it retransmits an RTS inserting the new channel. This process may result in a second round of channel negotiation when the preferred channel of the sender is not available for the receiver. This will result in inefficient channel utilization in AMCP.

In addition, nodes may mark many service channels busy for unnecessarily long periods of time in their local tables. If a node does not have a precise status of a specific data channel, it sets the channel unavailable to avoid possible collisions on that channel. This helps to reduce the probability of collisions on data channels; however it also causes other problems: 1) it may unnecessarily waste the opportunities for a node to make successful channel negotiations; and 2) nodes may always use a specific channel since it does not obtain enough information about the status of the other channels.

Besides the multi-channel hidden terminal and missing receiver problems, there is another common problem for asynchronous multi-channel MAC schemes. In asynchronous multi-channel MAC schemes, when a node attempts to broadcast an emergency message, it broadcasts the packet on the CCH without the RTS/CTS handshake. However, it is important to note that emergency messages will not be received by the nodes that are involved in some ongoing communication on the service channels. It has to be mentioned that in asynchronous multi-channel MAC schemes, the problem of missing emergency messages cannot be completely mitigated. One possible solution can be rebroadcast/forwarding of emergency messages by the nodes which have received the message. Since emergency messages are usually forwarded/disseminated to the neighbours or nodes within a relevant area, the concern of missing emergency messages should not be severe.

As discussed in this section, the aforementioned multi-channel MAC schemes suffer from some shortcomings. Thus, in the following section, we propose a new asynchronous multi-channel MAC scheme, taking into account the requirements for potential VANET applications.

III. ASYNCHRONOUS MULTI-CHANNEL MAC (AMCMAC)

Considering the strength and weakness in the existing solutions, as well as, the specific features of VANETs, an asynchronous multi-channel MAC is proposed in this section. First, an overview of the proposed scheme is provided. Then, the detailed design of the proposed scheme is discussed. Finally, we explain how the multi-channel coordination problems are addressed.

AMCMAC scheme aims to overcome the weaknesses in existing multi-channel schemes such as time synchronization difficulty, hopping time penalty, the missing receiver problem, and the multi-channel hidden terminal problem, and finally improves the performance of multi-channel operation.

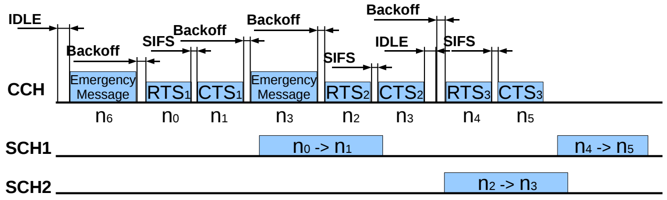

Fig. 2. Proposed asynchronous multi-channel MAC scheme.

Fig. 2 shows the basic channel access mechanism of the proposed MAC scheme. All the nodes, which are not using SCHs to transmit data stay with CCH, and listen to the CCH if they do not have packets to transmit in their queues. The MAC scheme adopted on the CCH is the Enhanced Distributed Channel Access (EDCA) defined in the IEEE 802.11p standard. Each node listens to the CCH and keeps a local SCHs entry table, which records the status of each channel and the time when the channel will be freed.

Once a node needs to broadcast/unicast a packet, it competes with other stations for the access of the CCH. If the channel is sensed idle, after a backoff time the sender broadcasts an RTS packet through CCH. Inside the RTS packet, a list of available SCHs for the sender is added. The destination node obtains the list from the RTS and checks its local SCHs entry table. If the destination finds an available channel which also is available for the sender, it replies a CTS after a period of Short Interframe Space (SIFS) with the channel information that they will use for the transmission. After a successful handshake, the two nodes will switch to the SCH they agreed to finish the data transmission. Transmissions can simultaneously proceed on different service channels.

More specific design aspects of the proposed scheme are given in the following subsections.

A. Time Synchronization

To avoid the synchronization problem that exists in most split phase schemes (e.g., [19]-[23]), an asynchronous multi-channel MAC scheme is designed. The nodes without packets in queues listen to the broadcast emergency messages and channel negotiation information on the CCH. Unlike the IEEE 1609.4 standard [19], nodes do not have to switch among CCH and SCHs every 50 ms, hence not only tight time synchronization is not needed, but also the service channels can be utilized all the time. Thus, the utilization of SCHs and the CCH are increased, which brings performance gain in terms of throughput.

B. Channel Negotiation and Selection Strategy

Taking the weaknesses of channel negotiation process in AMCP into account, the proposed AMCMAC adopts a different channel negotiation mechanism and a different channel selection strategy, aiming to offer more efficient channel negotiations and load balancing.

First, as explained before, the decision of which SCH to be used is made by the destination node; hence, no more renegotiations are needed. While in AMCP, if the preferred SCH is not available for the destination node, a second round of negotiation will be initiated by the destination node. Due to the fast movement of the nodes in VANETs, the shorter a handshake takes, the higher probability of successful transmission will be achieved.

Secondly, in a multi-channel MAC, in some occasions, all the SCHs may seem unavailable for a sender/receiver. On the sender side, it will not send any packet except emergency messages, since it is not possible to make an agreement with other nodes. The sender restarts a backoff procedure to try to access the CCH later if it has packets to transmit. While if all the available SCHs are not available for the receiver, it means that the pair of nodes cannot make any agreement on SCH selection. Hence, on the receiver side, in our MAC scheme, we assume that destination node drops the received RTS packet directly, instead of replying a CTS. This mechanism reduces the time wasted on transmitting a CTS with failure information, hence other nodes may access to the CCH to make possible channel negotiation or to broadcast emergency messages.

In addition, each node updates its local SCHs entry table by listening to the CCH. Once a node becomes a destination, it randomly chooses one of the available service channels in order to offer balanced load on service channels. Considering such scenarios, one of the SCHs is heavily used while other SCHs are seldom chosen for transmissions; load balancing is needed, since not only a higher probability of collisions may occur on the heavy loaded SCH, but also it may become the bottleneck of the network.

C. Multi-channel Hidden Terminal Problem

For a multi-channel MAC, hidden terminal problem is different from that of single-channel MAC. As Fig. 3 illustrates, the multi-channel hidden terminal problem occurs in the following situation. For example, consider a scenario where pair (n_2, n_3) are involved in an ongoing communication on SCH2. If pair (n_0, n_1) misses the corresponding RTS/CTS between pair (n_2, n_3), they may choose the same service channel. This is known as the multi-channel hidden terminal problem. This problem causes collisions on SCHs and degrades the network performance.

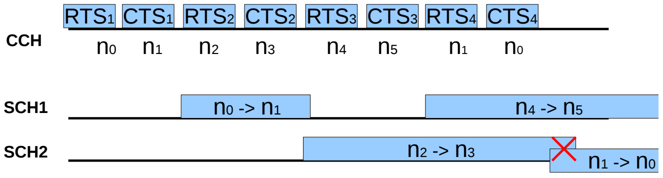

Fig. 3. Multi-channel Hidden Terminal Problem.

The AMCMAC aims to solve this problem: when nodes switch to an SCH, first, they listen to the service channel for a short period of time before transmission. This duration can vary according to the requirements of the system, such as the guard interval for frequency switching and channel condition in specific scenarios. However, it must be larger than 32 ms which is an SIFS duration. During the carrier sensing period, if the channel is not idle, i.e., another pair is currently using that particular channel, the nodes record that SCH as busy for a certain duration (e.g., the time necessary for transmitting a DATA and an ACK) and return to the CCH to renegotiate for another available SCH.

In single hop networks, this measure helps to mitigate the multi-channel hidden terminal problem. In multi-hop networks, one of a pair of nodes remains on the service channel assuming it fails to sense the current SCH's busy status, while its sender/receiver has left the SCH. If the destination node remains on SCH, once it receives any packet from other pair of nodes, the node knows the SCH is occupied by other nodes and returns to CCH. If the remaining node is the sender node, it must be outside the communication range of the transmitting node of the other pair of nodes. If the receiving node of the other pair of nodes is also outside its communication range, there will be no interference even though the sender node without partner transmits a packet on SCH. However, in the worst case, if the node acts like a hidden terminal on the service channel to the other pair of nodes, either employing RTS/CTS mechanism on SCHs or introducing cooperation among nodes on CCH can help to mitigate the problem. These aspects will be analysed in future work.

There is a possibility that some nodes may have incorrect local entry tables due to the multi-channel hidden terminal problem. For instance, in Fig. 3, n_0 and n_1 make a successful channel negotiation to use SCH2. Thus, other nodes which have received the corresponding CTS packet from n_1 will update their local entry tables. However, when the pair (n_0, n_1) sense SCH2 busy and return to CCH to do another channel negotiation, other nodes will still have SCH2 busy in their local tables. Nonetheless, this is not a big problem as the occupied duration will not last more than the time reserved for one data transmission.

D. Missing Receiver Problem

Another problem in asynchronous multi-channel schemes is called missing receiver problem, which occurs if the destination node is absent in a channel negotiation due to participating an ongoing transmission on another service channel, or unavailable in the network. This problem also contributes to inefficient channel utilization as a node may have to wait for a long time to confirm an unsuccessful handshake as happens in the IEEE 802.11a, e, p and the IEEE 1609.4 networks. Nodes have to set their NAV timers for duration of CTS packet plus an SIFS. Before the NAV timer expires, all the nodes except the destination node wait for the response, i.e., the CTS packet. If the destination node is not available any more or currently busy on other SCHs, the other nodes will have to stay in a waiting mode for a long time.

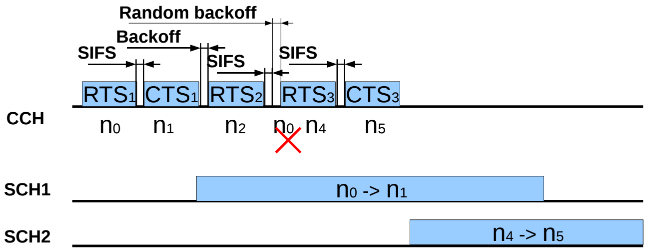

Fig. 4. Missing Receiver Problem.

The proposed solution for missing receiver problem is shown in Fig. 4. A shorter NAV timer is adopted to reduce the channel access time due to the unsuccessful handshakes. Once receiving an RTS packet, nodes on CCH (excluding the sender and destination nodes) set a timeout period, $Timeout_{CTS}$, given by:

$$Timeout_{CTS} = 2\delta + T_{SIFS} + \text{X mod Y}, \tag{1}$$

where δ is the propagation delay, and T_{SIFS} is the duration of a SIFS. After $Timeout_{CTS}$, if the receiver does not send a CTS message, the other nodes could start their own backoff procedures, immediately. The purpose of introducing the last term of (1) is to reduce the chance of having identical $Timeout_{CTS}$ values for different nodes. X and Y here can be configured based on the specific network status. For instance, X can be a unique node ID derived from the MAC address. The value of X can be configured based on the size of the network. We set Y=31 in our analysis. This means that after the first SIFS duration, all the nodes that have packets to transmit on CCH may start their backoff procedure within the next 32 μs. A larger or smaller values may be suitable for large or small scale networks.

IV. DISTRIBUTED TDMA

In Section III, multi-channel MAC scheme is proposed to improve the network performance in vehicular environment. However, in large-scale vehicular networks, contention among nodes on the control channel degrades the whole network performance by reducing chances of making successful channel negotiations ([15], [33]). The term successful channel negotiation means a pair of nodes agree on the service channel to be used for data transmission after a channel negotiation on the CCH. However, it is worthwhile to note that a successful channel negotiation does not assure a successful data transmission on service channel due to the probability of colliding with other pairs of nodes on service channel. Multi-channel MAC sub-layers can help to address this problem to some extent. However, Section VI shows that throughput decreases as the number of nodes in the reference area increases. This degradation of system performance is mainly due to the high contention level among nodes caused by the transmissions of channel negotiation packet. In this section, we propose an algorithm which employs a distributed TDMA in order to enhance the network performance by reducing collision rates on the highly congested control channel.

The concept of the proposed solution is shown in Fig. 5. The proposed scheme divides the time of CCH into intervals of 50 ms. Each interval is further divided into 100 time slots, hence each slot has a duration of 0.5 ms. For different Access Categories (AC) traffic, the numbers of dedicated time slots are configured as a, b, and c, respectively. When a node joins the network, it dedicates a time slots out of the 100 time slots (of the 50 ms interval) to AC1, b time slots to AC2, and c time slots to AC3 (for example, in Fig. 5: a = 6; b = 3; c = 1). We will refer to this as 'a-b-c scheme' throughout this paper. The idea is that the active nodes only attempt to access the channel for transmission of RTS packets for a certain AC at the dedicated time slots. DTDMA can work with any other CSMA contention based scheme without synchronization of the 50 ms operation intervals shown in Fig. 5. In other words, since the selection of slots are random, it does not matter if there is no tight synchronization of the 50 ms time intervals.

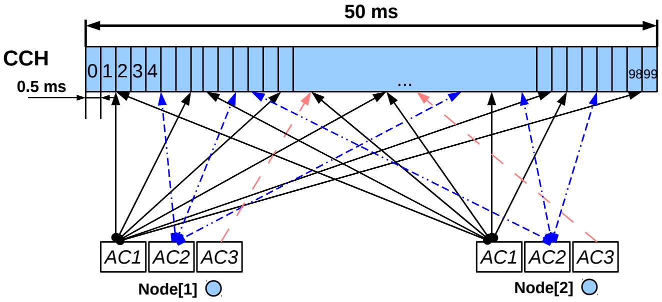

Fig. 5. DTDMA mechanism.

Allocating different time slots to different ACs helps the proposed scheme differentiate QoS for different ACs that have different service priorities. For example, in Fig. 5, AC1 has the largest number of time slots for negotiation packets in each interval. Negotiation packets for AC1 traffic are allowed to be transmitted during 6% of the time on the control channel;

while RTS packets for AC3 are only able to access the channel in 1% time slots. Thus, the chance of making successful channel negotiations of AC1 packets is higher than that of AC3 and AC2.

If two or more nodes select the same time slots on the CCH, they will have to contend on those time slots. However, the level of contention is significantly reduced, as only a subset of the total number of active nodes will contend a particular time slot (an rigorous analysis of this is given in Section V). For example, in 1-1-1 scheme, where each node selects only 1 time slot for each AC, only 3% of the active node will effectively contend for each time slot. There is a trade-off between level of contention and achievable throughput in this scheme, i.e., the achievable system throughput will also be decreased when the level of contention is reduced. In the sparse networks (e.g., 10 nodes in the reference area), the contention is not a severe problem; thus, selecting a small number of time slots produces low channel utilization and results in low system throughput. This issue will be discussed with further quantitative analysis in Section VI.

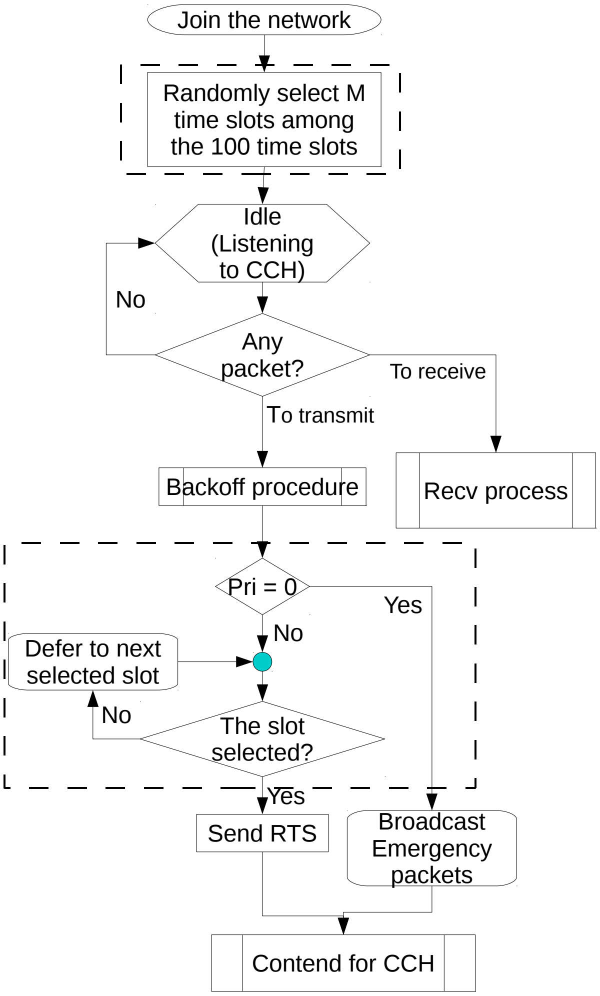

Fig. 6. The transmit process with DTDMA mechanism.

The flow chart in Fig. 6 illustrates the DTDMA scheme and how it fits into the transmission procedure of distributed CSMA contention based MAC schemes. The parts surrounded by dash line frames represent the added sub-layer on top of distributed CSMA contention based MAC schemes. After joining the network, a node needs to randomly select a/b/c time slots for AC1, AC2 and AC3 queues. When the backoff timer counts down to 0, the node starts its transmission procedure. Since emergency messages are critical to the safety of drivers, their access to CCH are not restrained within any time slot. For traffic from other AC queues, the node checks the current time slot to find out whether the time slot is selected for the specific AC. If so, RTS packets from the AC queue are allowed to transmit on the CCH. In addition, different configuration schemes can be applied as the selection rules for the numbers of selected time slots and allocation of selected slots for different ACs, according to the concern of the network performance (e.g., either to pursue high throughput, or low contention level, or better service differentiation).

V. ANALYSIS OF THE PROPOSED SCHEMES

In this section, we use a rigorous mathematical analysis to discuss some important aspects of AMCMAC and DTDMA schemes. A summary of major notations which are used in this section is given in Table. I.

TABLE I
NOTATIONS USED IN THE ANALYSIS

Notation	Definition
N_S	Number of service channels
Ω	Random number of successful channel negotiations during T_{DATA}
Ω_{max}	Maximum value of Ω
T_C	Random contention period
$\dot{T}_C$	Minimum contention period
r_s	Data rates for the SCHs
r_c	Data rate for the CCH
N_n	Actual number of active nodes in the reference area (i.e., actual scale of the network)
M_s	Number of time slots (equal to 100 for a 50 ms time interval)
$M(i)$	Number of time slots allocated for node i in each M_s time slots
p	The probability that a node selects a given time slot
π_i	The probability that i nodes are allowed to access the channel in a given time slot
$\mu(M)$	Expected value of the effective network scale

Most multi-channel MAC schemes suffer from under-utilization of service channels. This is often associated to the fact that the control channel becomes a serious bottleneck for processing of demand in multi-channel systems [25]. In this subsection, we aim to discuss this problem for the proposed AMCMAC scheme. Our objective is to elaborate on the parameters which will affect utilization of service channels.

For the sake of analysis in this subsection, we consider a network in saturated traffic condition. The duration of the interval necessary for DATA and ACK transmission is assumed to be fixed. There is a single CCH that is used by the nodes for channel negotiations and emergency message broadcasting. In addition, there are N_S service channels that can be used for other non-safety related applications.

Let Ω represent the random number of successful channel negotiations made on the CCH during the transmission of a data frame on the service channel. If Ω is too small the utilization of service channels will be poor. Thus, it is important to design a multi-channel MAC scheme that ensures a large Ω such that the service channels do not remain idle when there is unserved demands in the network. In a saturated network when there are always requests for transmissions, intuitively, it is desired to have large Ω to achieve high utilization of service channels.

First, we derive a formula for Ω. We define T_{DATA}, T_{ACK}, T_{RTS}, and T_{CTS} to be the deterministic durations of transmissions of DATA, ACK, RTS, and CTS packets, respectively. Denote by T_E the random duration of broadcasting emergency messages within the duration of a data frame transmission. Also, denote by T_{SIFS} the duration of a SIFS, and by T_C the random contention period spent for each channel negotiation on the CCH. Hence, the random number of successful channel negotiations during the data transmission is upper bounded by

$$\Omega = \left[\frac{T_{DATA}+T_{SIFS}+T_{ACK}-T_E}{T_C+T_{RTS}+T_{SIFS}+T_{CTS}}\right], \tag{2}$$

where $[\cdot]$ is the *integer part* function. We can see from (2) that several parameters affect the number of successful negotiations on CCH. For instance, a larger packet size and/or shorter contention period will allow more successful negotiations to take place.

There is an inherent limitation of the number of successful negotiations that can be made on CCH, as we show in the following. The maximum number of negotiations happens when there is no collision and emergency broadcast during that period. Hence,

$$\Omega_{max} = \left[\frac{T_{DATA}+T_{SIFS}+T_{ACK}}{\dot{T}_C+T_{RTS}+T_{SIFS}+T_{CTS}}\right], \tag{3}$$

where $\dot{T}_C$ is the minimum contention period.

The following typical example, for a system with 6 service channels, illustrates the significance of the Ω_{max}, and explains why the number of achievable successful negotiations can become a bottleneck for multi-channel MAC schemes. Consider a typical network with the packet sizes of DATA, ACK, RTS and CTS which equal to 1024 bytes, 29 bytes, 36 bytes, and 30 bytes, respectively. Let the minimum contention period be equal to $AIFS[1]$ [2] Hence,

$$\Omega_{max} = \left[\frac{\frac{1024\times 8}{r_s}+T_{SIFS}+\frac{29\times 8}{r_s}}{T_{SIFS}+AIFS[1]+\frac{36\times 8}{r_c}+\frac{30\times 8}{r_c}}\right], \tag{4}$$

where r_s and r_c are the data rates for SCH and CCH, respectively. Fig. 7 shows how the data rates of CCH and SCHs affect the maximum number of successful channel negotiations according to (4). It can be seen from this figure that the number of successful negotiations that can be made on the CCH will become a bottleneck that hinders utilization of SCHs. For instance, when the service channel can support more than 9 Mbps, the maximum number of successful negotiations, Ω_{max}, is below the number of service channels, N_S, as shown in Fig. 7. This problem will be in practice exacerbated as the actual number of successful negotiations will be fewer than Ω_{max}, due to the collisions on the control channel and occasional broadcast of emergency messages. Hence, This analysis suggests that proper combination of data rates for CCH and SCHs will be an important factor in high utilization of SCHs. Particularly, this problem will be more important in large-scale networks where the average contention period is relatively longer. In the large-scale networks, the contention among nodes becomes the main reason of resulting in low utilization of service channels; hence, alternative schemes need to be devised to improve the system performance. As we will show in the following, the proposed DTDMA scheme helps to significantly mitigate this problem in large-scale networks.

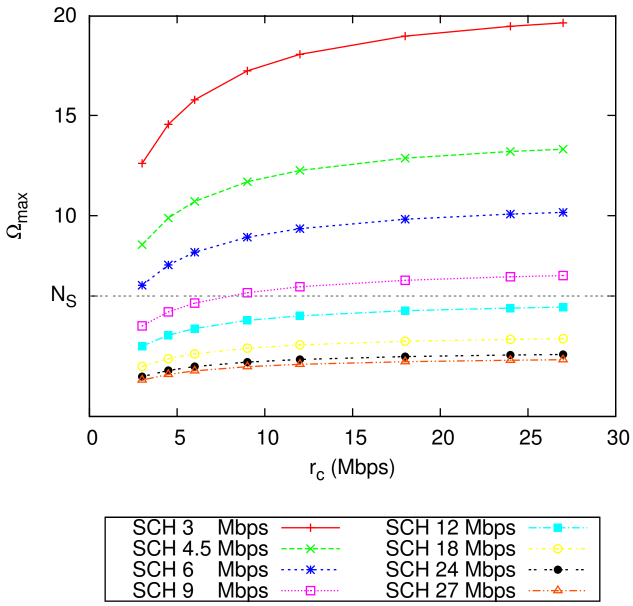

Fig. 7. Ω_{max} v.s. the data rate of CCH.

Consider a reference area with N_n nodes. Let divide the time on CCH into intervals of 50 ms which consists of M_s time slots. Without the DTDMA scheme, N_n nodes are able to access the control channel during each time slot. In the DTDMA scheme, node i randomly selects $M(i)$ time slots in every M_s time slots, where $M(i) \in [1, M_s]$. Hence, that particular node i is only allowed to access the shared channel in $M(i)/M_s$ of the time slots. This will effectively reduce the level of the contention as we will show in the following.

Let p be the probability that a node selects a given time slot in DTDMA. Let π_i be the probability that i nodes are allowed to access the channel in a given time slot. Then, the expected value of the number of nodes that can access a given time slot (i.e., the effective network scale), which depends on the value

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[2] Arbitration Inter Frame Spacing (AIFS) is a time interval between frames being transmitted under the IEEE 802.11p EDCA MAC, which prioritizes one Access Class (AC) over the others, such as giving voice or video traffic priority over email transmission in wireless local area network communications. AIFS[·] is the AIFS for AC[·].

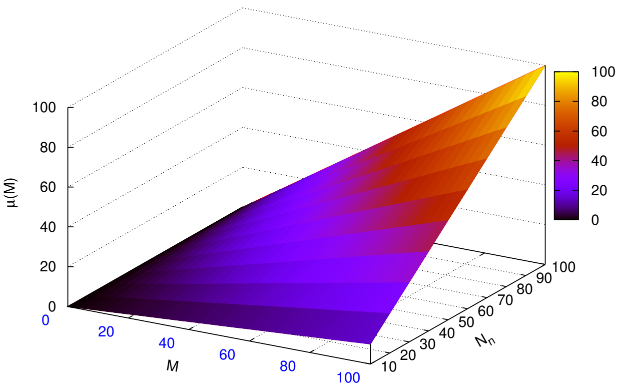


Fig. 8. Effective scale v.s. numbers of selected slots v.s. actual scale.

of M, can be calculated as follows:

$$\mu(M) = pN_n. \tag{5}$$

The derivation of the equation (5) is in the Appendix.

If nodes make random selection of the M_s time slots to access the CCH with the same number of slots M, (5) becomes,

$$\mu(M) = \frac{MN_n}{M_s}. \tag{6}$$

Otherwise, nodes may select different numbers of time slots themselves due to the detection of network status in an adaptive DTDMA scheme or selfish behaviour for instance. Therefore, in the general scenario, (5) writes as,

$$\mu(M) = \frac{\sum_{i=1}^{N_n} M(i)}{M_s}. \tag{7}$$

To get an insight into the results of (6), we plot $\mu(M)$ against M and N_n in Fig. 8. It can be seen that, the contention level $\mu(M)$ increases as the number of selected time slots M. In other words, the effective scale of network is reduced by $1 - M/M_s$. Low contention level helps avoid collisions on the control channel; however, the cost is that each node selects fewer time slots, which may result in poor utilization of the CCH. As a result, if a fixed M is adopted for the network, parameters such as the traffic load of each access category, the most common size of the network, and the main concern of the network performance have to be considered.

VI. PERFORMANCE EVALUATION

We evaluate the proposed multi-channel MAC schemes using NS-2 [38], from Lawrence Berkeley National Laboratory. The simulation scenario considers a multiple hop reference area, where nodes may send messages to the nodes within several hops. The multiple hop scenario comprises a 500 m×1500 m area with Manhattan Grid pattern traffic, where nodes travel along the grids (i.e., representing lanes). We use Bonnmotion [39], which is a scenario generation and analysis tool, to define the mobility patterns in our Manhattan Grid and export it to ns-2 environment. The mobility model allows nodes to travel along the grids, change speed, stop for a while, and turn at the intersection, which is similar to mobility models in SUMO [40]. The maximum speed of vehicles is set to be 15 m/s. The communication range of the radios is set to 500 m. Changing the number of nodes in the range of [10, 90], we vary the density of vehicles per area in our simulations. Communications among the nodes take place over multi-hop communications paths. Nodes collect location information from the info embedded in the packet header. Then, a node may choose a specific node as the destination node for information exchange. If the destination node is outside the sender nodes 1-hop range, the sender tries to find a proper relay node to help forward the packet to the destination. To enable forwarding, we have adopted basic location based routing algorithm in our simulation scenario. If the destination node is not in the communication range of the first chosen relay node, the relay node choose the next RSU along the way to the destination node. We consider scenarios with emergency messages generated in low frequency (i.e., 1 packet/second). The frequency of AC0 flow is configured at a low level since emergency messages do not frequently occur in the network. Based on the analytical results in Section V, many sets of data rates for CCH and SCHs (e.g. (3 Mbps, 3 Mbps), (4.5 Mbps, 4.5 Mbps), (6 Mbps, 6 Mbps), and etc.) can be used for simulations. Meanwhile, according to the finding in [41], 6 Mbps data rate is the best selection for various intended ranges and safety message sizes in most cases. Hence, the data rate for SCHs is set 6 Mbps, and the data rate for CCH is set 12 Mbps just to provide enough load for service channels. The rest of the major simulation parameters are chosen from the IEEE 1609.4 standard as listed in Table. II. The 'AMCMAC-D' in this section means the AMCMAC-D with 15-10-5 scheme without other annotation. Normalized throughput of each service channel is calculated by dividing the aggregate throughput (i.e., the total non-normalized throughput on each service channel) with the data rate of service channel.

TABLE II
SIMULATION PARAMETERS

Slot time	13 μs	Propagation delay δ	2 μs
SIFS	32 μs	DIFS	58 μs
DataRate for SCHs	6 Mbps	BasicRate for CCH	12 Mbps
AIFS[0]	2	AC0: CW(min, max)	(3, 7) time slots
AIFS[1]	3	AC1: CW(min, max)	(3, 15) time slots
AIFS[2]	6	AC2: CW(min, max)	(7, 1023) time slots
AIFS[3]	9	AC3: CW(min, max)	(15, 1023) time slots

In the following, we will analyse system throughput, packet delivery rate, collision rate on SCHs, utilization of CCH, load balancing, impacts of parameter setting and features in DTDMA scheme, and the penetration rate of successfully broadcast emergency messages.

A. *System Throughput*

Fig. 9 shows the average normalized throughput against the number of nodes, i.e., the actual scale of the network. From this figure, we can see that AMCMAC-D, AMCMAC and AMCP all outperform the IEEE 1609.4 standard in terms of system throughput for different network scales. AMCMAC

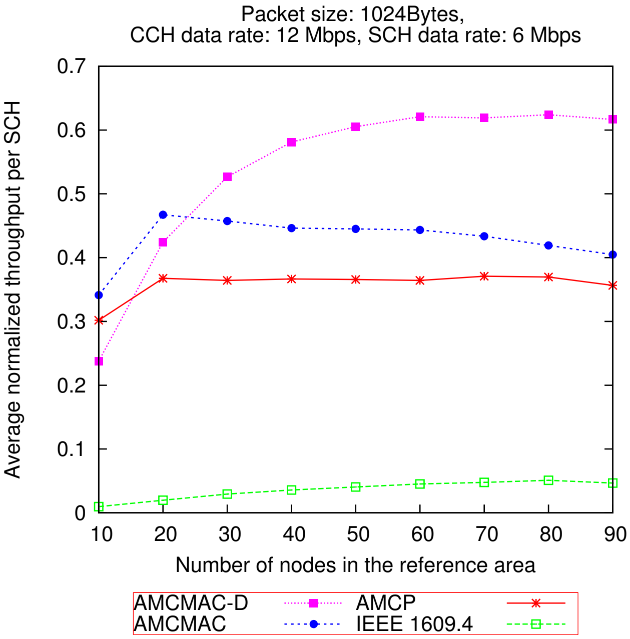
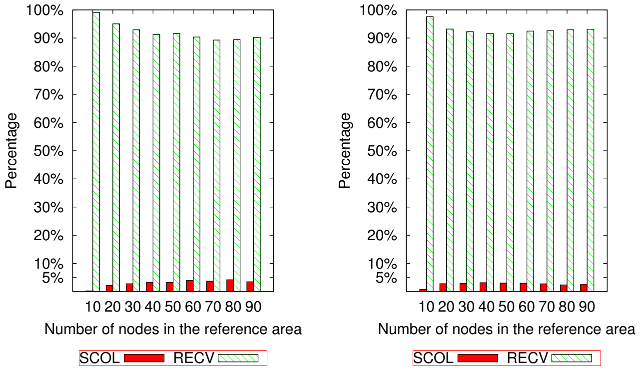
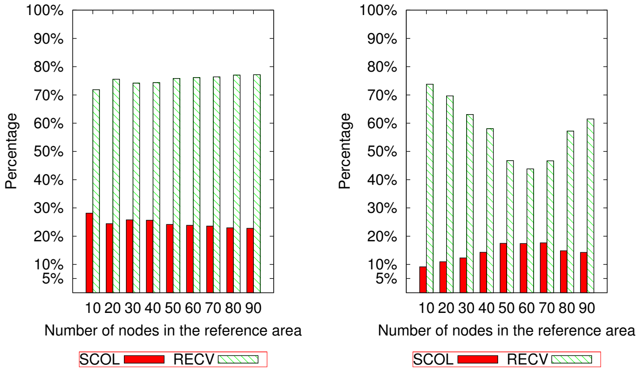


Fig. 9. Average normalised throughput per service channel as the number of stations varies.

achieves more than 10 times of the normalized throughput of that of the IEEE 1609.4 standard. It can also be seen that AMCMAC achieve higher normalized throughput than the AMCP. However, this advantage reduces as the number of nodes increases. Moreover, with the DTDMA access control, AMCMAC-D demonstrates significant improvement of network throughput for large-scale networks. It should be noted less aggressive scheme (e.g., AMCMAC-D) achieves lower system throughput in small-scale network due to the limitation of accessing time slots. In an IEEE 1609.4 network, the average throughput per service channel is relatively low. Within each 50 ms SCH interval, there are only a few transmissions; thus, service channels are not well utilized. Hence, the throughput on service channels with the IEEE 1609.4 is much lower than those achievable with the other three asynchronous multi-channel MAC proposals. This poor performance in terms of throughput obtained with the IEEE 1609.4 MAC reflects the weakness of adopting fixed CCH and SCH intervals. For small scale networks, insufficient successful channel negotiations are made for the service channels; while in large-scale networks, contention level on CCH is too high, which reduces the number of successful channel negotiations.



(a) AMCMAC-D (b) AMCMAC



(c) AMCP (d) IEEE 1609.4

Fig. 10. Packet delivery rate and collision rate on SCHs in different network scales.

B. Packet Delivery Rate and Collision Rate

Fig. 10 compares the packet delivery rates (RECV) and collision rates on service channels (SCOL). The proposed schemes (i.e., AMCMAC and AMCMAC-D) outperform the other two multi-channel MAC schemes in terms of both packet delivery rate and the collision rate on service channels. For different network scales from 10 nodes to 100 nodes, AMCMAC and AMCMAC-D show higher and more stable PDRs on service channels than AMCP and the IEEE 1609.4 standard. As for the collision rate on service channels, AMCP has about 5 times higher collision rate than that of the proposed schemes; while in Fig. 10(d), the collision rate of the IEEE 1609.4 standard is around 15%. The escalation of the collision rate on SCHs in the IEEE 1609.4 standard stems from the fact that the start time of transmission is not decided in the CCH interval. Thus, once more than one node simultaneously switch to a particular SCH they will contend on the SCHs again for data transmissions.

C. Utilization of CCH

Next, we analyse the utilization of the control channel for the four multi-channel MAC schemes that we discussed earlier. Fig. 11 shows the percentage of the CCH time used by the nodes for RTS/CTS and Emergency messages transmission. From this figure, we can see that the utilization of CCH in systems with AMCMAC, AMCMAC-D, and AMCP is much higher than that of the IEEE 1609.4 standard. Taking into account the contention (i.e., AIFS + backoff timer) and collision periods, the utilization of CCH in asynchronous multi-channel systems is quite high. In the network with AMCMAC-D with 15-10-5 slot allocation scheme, nodes are only allowed to access the CCH in 30% of the time slots; hence, for small scale networks, the utilization rate of CCH is lower than the other two asynchronous multi-channel MAC schemes. As the number of nodes in the reference area increases, the utilization gradually increases to high level which is much higher than that of AMCMAC. From Fig. 11, we can see that although

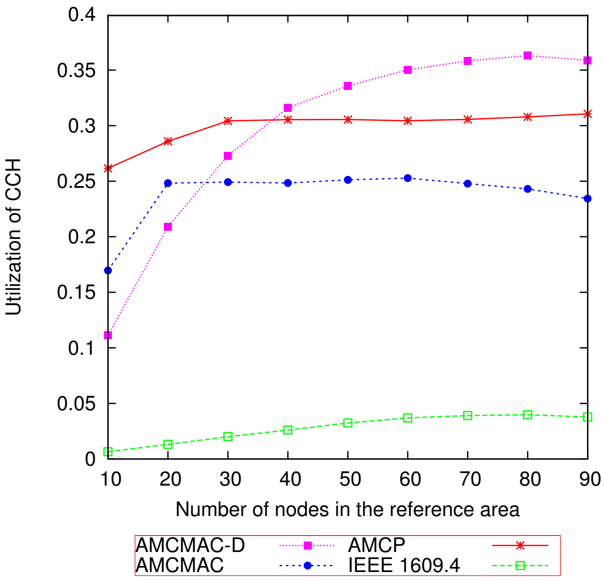


Fig. 11. Utilization of CCH v.s. the network scale.

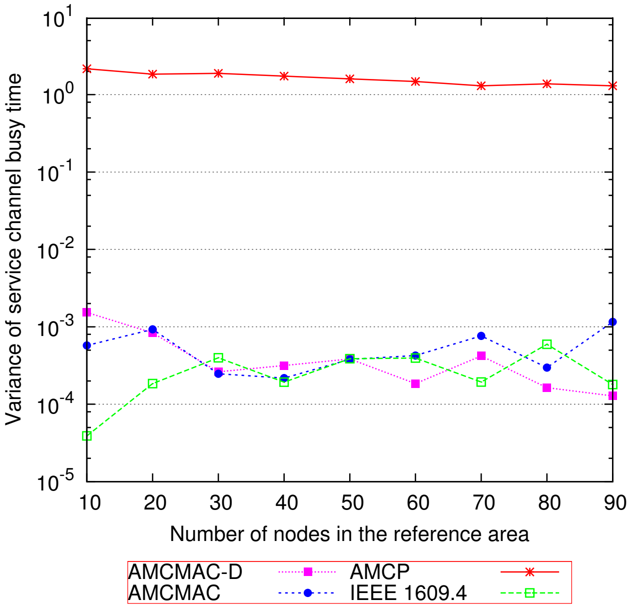


Fig. 12. Variance of service channel busy time as the number of stations varies.

AMCP has the high utilization of CCH, it fails to make as many successful channel negotiations as the proposed schemes AMCMAC and AMCMAC-D in the high density networks as shown in Fig. 9. This is due to the unnecessary second round of channel negotiation algorithm in AMCP. While in AMCMAC-D, both utilization on CCH and the number of successful negotiations are high due to the reduction of the contention level.

D. Load Balancing

To evaluate the load balancing among service channels, first, we assess the busy time of each service channel, and then calculate the variance of the channel busy time for each multi-channel MAC discussed in this paper. Fig. 12 shows the variance of service channel utilization in log scale as the number of stations varies. Comparing to the other two schemes, AMCP has a relatively high variance of channel utilization on the service channels, which may lead to congestion on some of the service channels and underutilization of the others. The IEEE 1609.4 standard and the proposed schemes have a low variance of channel utilization as the number of nodes in the reference area increases, and demonstrate a stable load balancing.

E. Performance of DTDMA Scheme

In this subsection, we analyse how the configuration of slot allocation scheme in DTDMA scheme affects the network performance, in terms of throughput and service differentiation. First, we investigate the impacts of different slot allocation schemes on the performance of AMCMAC-D in terms of throughput per service channel. As defined in Section IV ‘a-b-c scheme’ means that each active node randomly chooses a time slots for AC1 traffic transmissions; b time slots for AC2; and c time slots for AC3 traffic. In ‘15-10-5 scheme’, a, b and c are configured with different values in order to enhance the service differentiation. Fig. 13 illustrates the average system throughput per service channel for different slot allocation schemes in AMCMAC-D. It can be seen that for less aggressive allocation schemes (e.g., 1-1-1 and 2-2-2 schemes), the throughput is lower. More aggressive slot allocation schemes increase the throughput up to certain network sizes. However, further increase in network size will result in more collisions which will adversely affect the throughput. When the M increases to 90 (e.g., in the 30-30-30 scheme), the throughput is worse then 10-10-10 scheme for a large-scale network due to higher contention level per time slot.

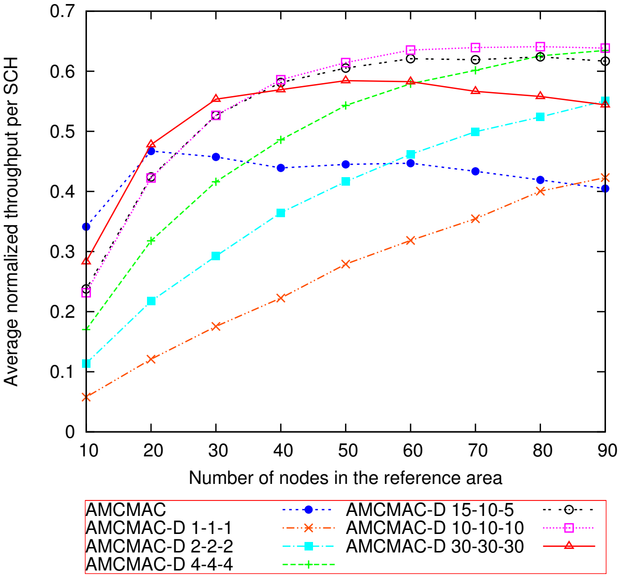
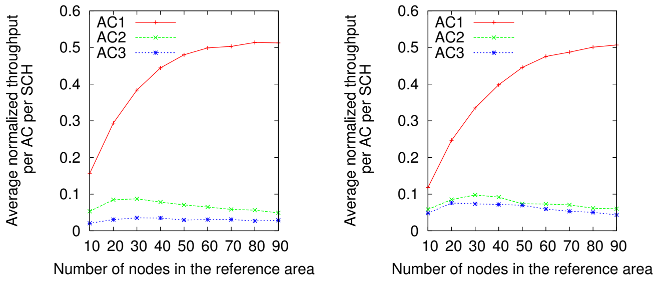


Fig. 13. Average normalised throughput per service channel as the number of stations varies.

From the figure, we can see that DTDMA achieves poor performance for low density networks. In addition, less aggressive slot allocation schemes can achieve higher throughput for dense networks. This figure can be plugged into the models that we developed in Section V in order to obtain values of M and M_s that help achieve high throughput. If nodes can learn the information about the number of active nodes from the broadcast CAM messages, they can optimize the parameters of DTDMA to improve system throughput.

In terms of service differentiation capabilities, the 15-10-5 and 10-10-10 perform best with highest overall throughput as we can see in Fig. 13. However, as shown in Fig. 14, 15-10-5 allocation scheme offers better service differentiation than scheme 10-10-10. Considering the trade-off between service differentiation and throughput improvement, DTDMA with 15-10-5 slot allocation scheme is more suitable if service differentiation is required.



(a) AMCMAC-D 15-10-5 scheme (b) AMCMAC-D 10-10-10 scheme

Fig. 14. Average throughput of each AC per service channel as the number of nodes in the reference area varies.

F. Penetration Rate of Successful Emergency Broadcasts

Finally, as mentioned in Section I, there is a common problem for asynchronous multi-channel MAC schemes, i.e., emergency messages can not be received by all nodes. This is due to the fact that some nodes may be busy transmitting data on service channels during some emergency broadcast periods. We present another set of simulations to compare the penetration rate of emergency messages in terms of the percentage of the nodes that successfully receive a non-collided emergency message. As it can seen in Fig. 15 that, the penetration rate of successfully broadcast emergency messages in the proposed schemes varies between 82%-96% for the networks larger than 20 nodes. The penetration rate of successfully broadcast emergency messages in all the asynchronous multi-channel MAC schemes is almost as good as that of the IEEE 1609.4 standard. Hence, although there are some nodes that miss emergency messages due to the absence on CCH, the emergency messages are disseminated to most of the vehicles in the reference area. If rebroadcast/forwarding is taken into account, the reception of emergency messages can be higher in practice.

VII. CONCLUSION

An asynchronous MAC scheme that employs a distributed TDMA mechanism, namely AMCMAC-D, is proposed and analysed in this paper. By allowing simultaneous transmissions on multiple service channels, the proposed scheme offers a superior performance in dense networks. AMCMAC scheme uses asynchronous multi-channel operation in order to improve the system performance in terms of throughput and QoS metrics. In addition, AMCMAC mitigates two important problems of asynchronous multi-channel MAC operation, namely, the multi-channel hidden terminal problem and the missing receiver problem. Meanwhile, the DTDMA scheme, which can be implemented on top of any decentralized contention based CSMA MAC scheme, helps decrease contention level by reducing the effective network scale per time slot. The results of our performance analysis demonstrate that the AMCMAC-D (i.e., the combination of AMCMAC and DTDMA) outperforms the IEEE 1609.4 standard and another benchmark asynchronous multi-channel scheme AMCP in terms of system throughput, packet delivery rate, collision rate on service channel, load balancing, and service differentiation for large-scale vehicular networks.

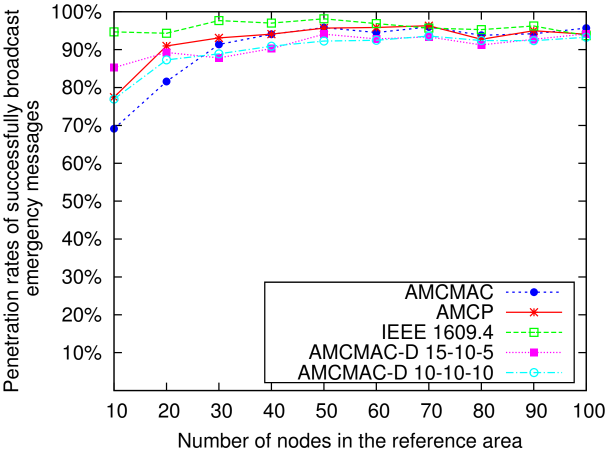


Fig. 15. The penetration rates of successfully broadcast emergency messages as the number of stations varies.

APPENDIX A
THE DERIVATION OF THE EXPECTATION VALUE OF EFFECTIVE SCALE OF NETWORKS.

The expected value of the number of nodes that can access a given time slot (i.e., the effective network scale), which depends on the value of M, can be calculated as follows:

$$\begin{aligned}\mu(M) &= \sum_{i=0}^{N_n} i \times \pi_i = \sum_{i=0}^{N_n} i \binom{N_n}{i} p^i (1-p)^{N_n - i} \\ &= 0\binom{N_n}{0} p^0 (1-p)^{N_n} + 1 \times \binom{N_n}{1} p^1 (1-p)^{N_n - 1} \\ &\quad + \cdots + N_n \times \binom{N_n}{N_n} p^{N_n} (1-p)^0 \\ &= p\left[\binom{N_n}{1}(1-p)^{N_n-1} + 2\binom{N_n}{2} p (1-p)^{N_n-2}\right. \\ &\quad \left. + \cdots + N_n \binom{N_n}{N_n} p^{N_{node}-1}\right]. \qquad (8)\end{aligned}$$

We know that,

$$\begin{cases} \binom{N_n}{1} = N_n = N_n \binom{N_n - 1}{0}; \\ 2 \times \binom{N_n}{2} = 2 \times \dfrac{N_n(N_n-1)}{2} = N_n \binom{N_n - 1}{1}; \\ \vdots \\ N_n \times \binom{N_n}{N_n} = N_n \times 1 = N_n \binom{N_n - 1}{N_n - 1}. \end{cases} \quad (9)$$

Thus, the coefficients in (8) can be replaced as follows.

$$\mu(M) = pN_n \Big[\tbinom{N_n-1}{0}(1-p)^{N_n-1} + \tbinom{N_n-1}{1}p(1-p)^{N_n-2} + \cdots + \tbinom{N_n-1}{N_n-1}p^{N_n-1} \Big]. \quad (10)$$

Based on the definition of the Binomial expansion,

$$(x+y)^{\eta} = \sum_{\kappa=0}^{\eta} \binom{\eta}{\kappa} x^{\eta-\kappa} y^{\kappa}. \quad (11)$$

From (10) and (11),

$$\mu(M) \;=\; pN_n \Big[p + (1-p) \Big]^{N_n-1} = pN_n. \quad (12)$$

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