WIRELESS COMMUNICATIONS AND MOBILE COMPUTING
Wirel. Commun. Mob. Comput. (2011)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/wcm.1159

RESEARCH ARTICLE

Multichannel medium access control for ad hoc wireless networks[†]

Khaled H. Almotairi and Xuemin (Sherman) Shen*

Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada

ABSTRACT

In this paper, we study the multichannel exposed terminal problem in multihop wireless networks. We propose a multichannel medium access control (MAC) protocol, called multichannel MAC protocol with hopping reservation (MMAC-HR), to resolve the multichannel exposed terminal problem. MMAC-HR uses two radio interfaces; one interface is fixed over the control channel, and the other interface switches dynamically between data channels. The fixed interface supports broadcast information and reserves a data channel for any data transmission. The switchable interface, on other hand, is for data exchanges and follows independent slow hopping without requiring clock synchronization. In addition, the proposed protocol is a distributed one. By using the ns-2 simulator, extensive simulations are performed to demonstrate that MMAC-HR can enhance the network throughput and delay compared with existing multichannel MAC protocol. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS

medium access medium; multiple channels; multichannel exposed terminal problem; ad hoc networks

***Correspondence**

Xuemin (Sherman) Shen, Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada.

E-mail: xshen@bbcr.uwaterloo.ca

1. INTRODUCTION

The capacity of wireless networks is limited because of the interference experienced among nodes [1,2]. With the increasing number of new inventions and applications, wireless media have become more congested. Fortunately, many existing technologies can be used to resolve the congestion and improve the network performance, such as exploiting multiple orthogonal channels. The IEEE standard defines three orthogonal channels in the 2.4-GHz band and 12 channels in the 5-GHz band [3]. Only one common channel is assigned for ad hoc networks, and this assignment does not utilize the other available channels.

There are several design considerations for multichannel medium access control (MAC) protocol. First, a multichannel MAC (MCMAC) protocol should support broadcast because some applications use broadcast information such as routing protocols. In single-channel ad hoc networks, all nodes communicate with each other over the same channel (if omni antennas are employed), thereby supporting broadcast information. In multichannel ad hoc networks, nodes might exist over different channels; as a result, some nodes might not receive broadcast information [4–6]. Not considering broadcast support for designing MCMAC protocols may incur higher delay or network partition [7].

The busy receiver problem is a new issue that occurs only in multichannel networks [8]. When nodes are synchronized and know each other's assigned channels, transmitters cannot find their receivers on a channel where the receivers are supposed to be because the receivers are busy over other channels (either transmitting or receiving). Thus, the busy receiver problem increases the dropping rate of packets and wastes the channel bandwidth.

Moreover, a new problem has been identified as the control saturation problem, which occurs only in multichannel networks by having one dedicated control channel (e.g., dynamic channel assignment (DCA) [9]) or one dedicated control time duration (e.g., multichannel medium access control (MMAC) [10]) to reserve data channels for transmissions [10,11]. The problem occurs when the number of nodes and the network load increase, preventing the data channels from being utilized efficiently; in other words, the control channel becomes the bottleneck.

[†]Parts of this paper have been presented at IEEE Globecom 2010.

Copyright © 2011 John Wiley & Sons, Ltd.

The single-channel hidden terminal problem is a well-known problem that causes collisions. To eliminate this problem, request-to-send (RTS) and clear-to-send (CTS) handshaking is used; however, it does not completely eliminate the single-channel hidden terminal problem. In multichannel environments, the multichannel hidden terminal problem is similar to the single-channel hidden terminal problem [10]. When a transmitter has a packet for a receiver and the receiver is on another channel, the transmitter switches to the receiver's channel. Before sending a packet, the transmitter must detect the channel. The transmitter assumes that the channel is idle because the transmitter is within the transmission range (TR) of the receiver but not within the carrier sensing range (CSR) of the node that is currently transmitting to the receiver. Then, the transmitter sends its packet to the receiver, and therefore, a collision occurs at the receiver and thereby degrading the network performance.

Finally, in single-channel networks, the single-channel exposed terminal problem is a traditional issue, and there is no existing solution to resolve it. This problem is not as serious as the hidden terminal problem because the exposed terminal problem does not cause collisions; the single-channel exposed terminal problem leads to poor channel utilization. In multichannel networks, there is a new type of the exposed terminal problem known as the multichannel exposed terminal problem due to poor channel assignment, which has not been well studied.

In this paper, we focus on the multichannel exposed terminal problem that leads to poor channel utilization over multiple channels. We propose the multichannel MAC protocol with hopping reservation (MMAC-HR) for multihop networks to resolve the multichannel exposed terminal problem. MMAC-HR does not require nodes to monitor the control channel in order to determine whether or not data channels are idle; instead, MMAC-HR employs independent, slow channel hopping without exchanging information, thereby reducing the overhead. In addition, the proposed protocol uses the carrier sensing multiple access with collision avoidance (CSMA/CA) scheme over all channels to determine the channels' condition and avoid collisions. Furthermore, MMAC-HR is distributed, does not require clock synchronization, and supports broadcast information.

The remainder of the paper is organized as follows. Section 2 reviews the related work. In Section 3, the multichannel exposed terminal problem is discussed. We propose a novel multichannel MAC protocol to resolve the multichannel exposed terminal problem in Section 4, and the performance evaluation of the proposed MMAC-HR protocol is presented in Section 5. The conclusion is given in Section 6.

2. RELATED WORK

In the early days, the purpose of using multiple channels was to eliminate the hidden terminal problem. In busy tone multiple access (BTMA) [12], the shared channel is divided into two subchannels; one channel is used as an indicator channel, and the other channel is used for data transmissions. The bandwidth for the indicator channel is much shorter than the bandwidth for the data channel. If a node needs to transmits a packet, the node checks the indictor channel to detect whether or not the data channel is idle. If the indicator channel is idle, the node transmits a busy tone signal over the indicator channel and the data packet over the data channel. BTMA uses only one data channel and does not exploit multiple channels. Now, researchers have proposed MAC protocols to exploit multiple channels [9,13–23].

Some protocols require that nodes have to be equipped with multiple wireless interfaces that are equal to the number of the channels such as [21,22]. In [21], the protocol divides the channel bandwidth into N nonoverlapping channels, similar to the frequency division multiple access scheme. The nodes are able to sense all channels at the same time and transmit over one idle channel randomly. Therefore, it is costly. In this paper, we only require nodes to have two interfaces.

The DCA protocol is proposed for multihop networks [9]. Two interfaces are installed on each node. One interface is fixed on the control channel, and the other interface switches between data channels. The control packets are RTS, CTS and reservation (RES) that are transmitted over the control channel; data and acknowledgment (ACK) packets are transmitted over data channels. All nodes maintain a channel usage list to determine the data channels' activities by overhearing the control channel; thereby, channel assignment is accomplished. However, this channel list causes the multichannel exposed terminal problem as described in Section 3. DCA does not need clock synchronization, so does our protocol. Although our proposed protocol is similar to DCA, there are several key differences between the two protocols. Our protocol (i) uses CSMA/CA over all channels; (ii) does not require nodes to monitor the control channel in order to determine whether data channels are idle or not; (iii) resolves the multichannel exposed terminal problem because MMAC-HR does not use any channel list that causes poor channel utilization; and (iv) utilizes data channels by independent hopping.

Using multiple channels with transmission power control will increase the network capacity [20,24]. An extension of DCA is called the DCA with the power control (DCA-PC) protocol [20]. Nodes transmit at the maximum power over the control channel and determine the minimum power for each transmission on data channels.

Channel-hopping multiple access (CHMA) is proposed to exploit the available channels [25]. This protocol is based on common hopping, meaning that all nodes must follow a common hopping sequence. The dwell time is the time needed for a handshake (e.g., RTS), and during the dwell time, no carrier sensing or code assignment is needed. CHMA requires too many switchings between frequencies. Hop-reservation multiple access for ad hoc networks [26] is similar to CHMA. Both protocols require tight clock synchronization. Our proposed protocol does not need any synchronization. Another issue that occurs in these protocols is the busy receiver problem [8]. For example, while node A is transmitting to node B on a specific channel, node C transmits to node D on another channel. Nodes A and B are unaware of the negotiation between nodes C and D. Therefore, if node A has a packet for node C, the busy receiver problem occurs because node A does not know over which channel node C exists.

A new direction to use multiple channels is based on splitting phases (similar to the time division multiple access scheme), for example, the MMAC protocol [10]. The time is divided into beacons. The beacons consist of two windows: ad hoc traffic messages (ATIM) and data. At the beginning of the ATIM window, wireless nodes tune their radios into the known channel. A pair of nodes selects a channel by exchanging ATIM, ATIM-ACK and ATIM-RES packets during the ATIM window. After the ATIM window, the successful pairs switch their radios to their agreed channels. Then source nodes start competing using the IEEE 802.11 MAC standard. MMAC solves multichannel hidden terminal problems by synchronization, which is difficult to achieve in multihop networks.

A new technique to improve the network performance is to use parallel rendezvous such as the slotted seeded channel hopping (SSCH) [15] and McMAC [14] protocols, which require only one radio interface. SSCH and McMAC are based on the prime module and linear congruential generator, respectively. A sender needs to synchronize with a receiver to transmit a packet so that the sender might deviate from its default hopping sequence; as a result, the busy receiver problem occurs [8]. In addition, they also require clock synchronization.

A recent comparison between MCMAC protocols is given in [8]. [17] and [4] provide certain multichannel issues and present some existing MCMAC protocols.

3. MULTICHANNEL EXPOSED TERMINAL PROBLEM

In this section, we study the multichannel exposed terminal problem. We first describe the single-channel exposed terminal problem, and this problem leads to poor channel utilization because it defers transmissions of other nodes that are within the CSR of the sending nodes, but they are not within the CSR of the receiving nodes.

As shown in Figures 1(a) and 1(b), while node B is transmitting to node A, node C wants to transmit a packet to node D. Node C senses the channel, and it finds that the channel is busy and thus must defer its transmission. Therefore, node C is called an exposed terminal because node C is not within the range of node A but within the CSR of node B [27]. However, node E is clearly able to either transmit or receive because node E is not within the CSR of node B.

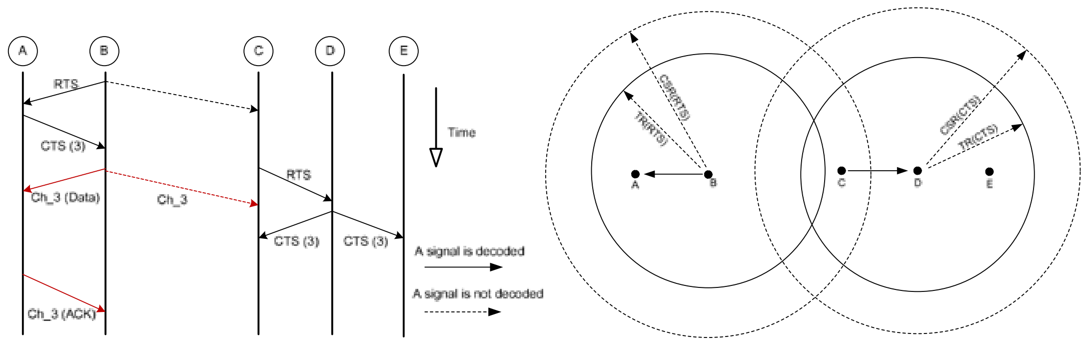
To describe the multichannel exposed terminal problem, we introduce a simple MCMAC protocol, which is similar to the DCA protocol [9] where the multichannel exposed terminal problem has not been addressed. [28–30] are other examples. Each node has two interfaces; one interface is fixed over the control channel, and the second interface is switchable between data channels. In addition, each node maintains a local *channel list* updated by overhearing control packets over the dedicated control channel. The channel list indicates whether a data channel is busy or not, and thus, the nodes select an idle data channel from the channel list for their transmissions. In other words, channel assignment is accomplished through the channel list. Another list also used and known as a free channel list is generated from the channel list and attached into RTS packets by transmitters. The free channel list determines which channels are idle, and therefore, the transmitters are able to use it for transmission.

Nodes use RTS and CTS packets for channel negotiations over the control channel and use CSMA/CA over all channels before transmitting data packets to avoid collisions. Notice that the DCA protocol does not use carrier sensing over data channels; as a result, collisions occur.

Figures 1(a) and 1(b) illustrate the multichannel exposed terminal problem. There are five nodes: A, B, C, D, and E. Node C is not within the TR of node B (i.e., node C cannot decode any packet that is transmitted by node B), and node E is within the TR of node D. Moreover, node B has a packet for node A, and node C has a packet for node D. Therefore, nodes B and C must compete over the control channel. If node B transmits to node A an RTS packet that includes node B's free channel list, node C must defer its transmission. Node C is not able to decode the RTS packet. Therefore, node C is unaware of the channel negation between nodes B and A because node C is not within the TR of node B. After node A receives the RTS packet correctly, node A selects a data channel that must be idle not only for node A but also for node B. Then node A replies to node B with a CTS packet, which includes a selected data channel (e.g., Channel 3) and switches its transceiver to Channel 3. Upon receiving the CTS packet correctly, node B turns its switchable transceiver to the selected data channel. Node B must sense Channel 3 for a certain amount of time (e.g., the distributed interframe space (DIFS) period) to avoid collisions. If Channel 3 is idle, node B starts transmitting its data packet to node A over Channel 3. After the short interframe space (SIFS) period, node B transmits an ACK packet to node A over the same channel if the packet is received correctly.

As soon as the control channel becomes idle for a period of time (e.g., the DIFS period), node C transmits an RTS packet that includes node C's free channel list and indicates Channel 3 as being free, to node D. When node D receives the CTS packet successfully, node D selects an idle data channel and replies to node C with a CTS packet, which includes a selected channel (e.g., Channel 3). Both nodes C and E receive the CTS packet because they are within the TR of node D. Node E updates its channel list indicating

Color Online, B&W in Print



(a) Packets exchange

(b) The top view of Figure 1a showing different ranges of different nodes.

Figure 1. An illustration of the exposed terminal problem in multichannel networks. RTS, request-to-send; CTS, clear-to-send; CSR, carrier sensing range; TR, transmission range.

that Channel 3 is busy. Node C switches to Channel 3, and then node C must sense Channel 3 before transmitting to avoid collisions. However, Channel 3 is sensed as being busy, and thus, node C cannot transmit because node C is within the CSR of node B. Therefore, node C is an exposed terminal. Recall that node E has already updated its channel list indicating that Channel 3 is being used. Inadvertently, node E is also an exposed terminal because node E cannot use Channel 3 for any transmission resulting in poor network performance. Nonetheless, node E can use Channel 3 without causing collisions with nodes A and B.

In summary, node C is an exposed terminal in both single-channel and multichannel networks. However, node E is an exposed terminal only in multichannel networks because it uses a channel list to indicate whether a channel is busy or not. Node E is known as *a multichannel exposed terminal* because it occurs only in multichannel networks. Note that node E cannot cause any collision with nodes B and A. Thus, the multichannel exposed terminal problem is more severe than the single-channel exposed terminal problem because the multichannel exposed terminal problem leads to poor channel utilization (due to poor channel assignment) more than the single-channel exposed terminal problem. In this paper, we propose a new protocol to resolve the multichannel exposed terminal problem.

4. MULTICHANNEL MEDIUM ACCESS CONTROL WITH HOPPING RESERVATION

In this section, we propose the MMAC-HR to eliminate the multichannel exposed terminal problem. Our approach uses a dedicated control channel without any channel assignment; however, channel hopping is employed to maximize the utilization of multiple channels. In MMAC-HR, because nodes do not know which data channel is idle, they must sense data channels (using carrier sensing) to determine the channels' conditions and avoid collisions. Our system model is as follows:

- The network has M channels. One channel is known as a dedicated control channel, and the rest $M-1$ channels are data channels. All channels have equal bandwidths and are able to transport information.
- Each node has two interfaces. One interface is fixed on the dedicated control channel, and the other interface is switchable between data channels. The two interfaces do not interfere with each other, and each interface is a half-duplex transceiver.
- Nodes transmit at the maximum power, $P_{\max}$, over all channels.
- Broadcast and control packets are transmitted over the control channel.

The switchable interface hops between channels and hopping is accomplished randomly between data channels without exchanging information. The dwell time should be large enough to allow multiple data transmissions. When the dwell time expires and a node is idle, the node selects the next data channel randomly. Then the node tunes its switchable interface to the next selected channel. Moreover, we maintain two separated contention window (CW) sizes, one for each interface (e.g., CW^s is designated for the switchable interface, and CW^f is designated for the fixed interface). Each node retains a new integer variable, $nrsv$, to track the number of reservation nodes. If $nrsv$ is equal to zero, then a node is idle and able to transmit a packet. Algorithms 1 and 2 present the pseudo codes of the source and destination nodes.

The control packets used in our proposed protocol are RTS and CTS packets. The RTS packets in our proposed protocol are similar to the RTS packets in the IEEE 802.11 distributed coordination function (DCF) MAC protocol, but the CTS packets have three additional fields: Ch_i (the current channel i of a receiver), Wt (the waiting time,

Algorithm 1 Source node

1: $nrsv$: the number of reservation nodes
2: **if** the control channel is idle $\wedge\ nrsv = 0$ **then**
3: backoff
4: **else**
5: Transmit an RTS packet on the control channel following the 802.11 DCF MAC protocol
6: **if** a CTS (Ch_i,Wt,Rt) packet receives **then**
7: $CW^f \leftarrow CW_{\min}$
8: $WR \leftarrow Wt - T_{\text{CTS}} - St - \tau$
9: $timer \leftarrow Rt$
10: Start decrementing $timer$
11: **if** the switching interface is not on Ch_i **then**
12: Switch to Ch_i
13: **if** $WR > 0$ **then**
14: Listen to Ch_i for WR before attempting
15: **end if**
16: **end if**
17: Transmit the packet over Ch_i following the 802.11 DCF MAC protocol without RTS/CTS packets
18: **if** an ACK packet receives **then**
19: $CW^s \leftarrow CW_{\min}$
20: Reset the number of retrials
21: **else**
22: Double the contention window CW^s
23: Increase the number of retrials
24: **if** the number of retrials = the maximum of trials **then**
25: $CW^s \leftarrow CW_{\min}$
26: Drop the packet
27: Reset the number of retrials
28: **else**
29: Go back to Line 17
30: **end if**
31: **end if**
32: **if** $timer = 0$ **then**
33: $CW^s \leftarrow CW_{\min}$
34: Increase the number of retrials
35: **if** the number of retrials = the maximum of trials **then**
36: $CW^s \leftarrow CW_{\min}$
37: Drop the packet
38: Reset the number of retrials
39: **else**
40: Go back to Line 2
41: **end if**
42: **end if**
43: **else**
44: Double the contention window CW^f
45: Increase the number of retrials
46: **if** the number of retrials = the maximum of trials **then**
47: $CW^f \leftarrow CW_{\min}$
48: Drop the packet
49: **else**
50: Go back to Line 2
51: **end if**
52: **end if**
53: **end if**
54: Continue hopping

Algorithm 2 Destination Node

1: $T_{\max}$: the maximum packet duration in the network
2: Ch_i: the current channel of the switchable interface
3: **if** an RTS packet receives correctly over the control channel **then**
4: **if** Ch_i is not idle **then**
5: $Wt \leftarrow T_{\max}$
6: **else**
7: $Wt \leftarrow 0$
8: **end if**
9: Attach Ch_i, Wt, and Rt to a CTS packet
10: $timer \leftarrow Rt$
11: Start decrementing $timer$
12: Transmit the CTS (Ch_i, Wt, Rt) packet over the control channel after the SIFS period
13: $nrsv \leftarrow nrsv + 1$
14: **end if**
15: Wait for the packet
16: **if** the packet receives correctly **then**
17: Transmit an ACK packet to the source node over Ch_i
18: $nrsv \leftarrow nrsv - 1$
19: **end if**
20: **if** $timer = 0\ \wedge$ Channel Ch_i is idle **then**
21: $nrsv \leftarrow 0$
22: **else**
23: Go to Line 15
24: **end if**
25: Continue hopping

which is the time to hold for a transmitter before attempting), and Rt (the reservation time before releasing the switchable interface). The Wt field is the amount of time indicating the channel condition of the current data channel, Ch_i, which is idle or busy. This field is computed just before transmitting the CTS packet and is used to eliminate the multichannel hidden terminal problem. The Rt field is a committed time from the receiver to be on the current channel, Ch_i, and can be adaptive.

In order to better understand how our protocol resolves the multichannel exposed terminal problem, we use Figure 1(a) for illustration. Whenever node C has a packet for node D, two conditions must be satisfied: (i) node C is not busy, which means node C does not commit to receive, and (ii) the control channel is idle for DIFS, following the IEEE 802.11 MAC standard. If the two conditions are satisfied, node C transmits an RTS packet to node D over the control channel as shown in Figure 2. If the RTS packet collides, node C doubles the contention window size of the fixed interface, CW^f, and increases the number of retrials. If the number of retrials reaches the retry limit, node C drops the packet and resets the contention window size, CW^f. If the RTS packet is received correctly by node D, node D replies with a CTS (Ch_i,Wt,Rt) packet to node C. If the current channel, Ch_i, of node D is busy, Wt is set to be the maximum packet duration (T_{max}) in the network.

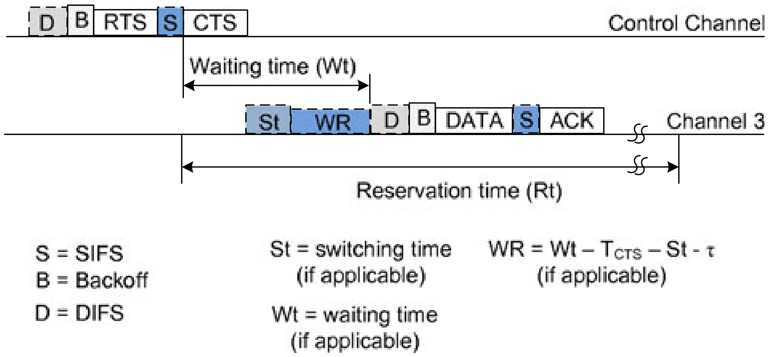


Figure 2. A successful transmission of multichannel medium access control protocol with hopping reservation (MMAC-HR).

However, if the current channel is idle, Wt is set to be zero. To avoid the multichannel exposed terminal problem, node E can decode the CTS packet, but node E will simply ignore the CTS packet. If node C receives the CTS packet successfully, node C checks whether its switchable interface is over Ch_i or not. If yes, node C then starts competing the data channel, similar to the IEEE 802.11 MAC standard, because node C knows the channel condition of the current channel. If no, node C switches to the channel Ch_i. Node C first computes WR if Wt is not equal to zero:

$$WR = Wt - T_{\text{CTS}} - St - \tau$$

where St is the switching delay, τ is the maximum propagation delay, and T_{CTS} is the transmission time of the CTS packet. Then node C listens to Ch_i for Wt. After WR expires, node C starts competing the data channel, Ch_i, following the IEEE 802.11 MAC standard. If the data packet is received correctly by node D, node D replies with an ACK packet over the same channel after SIFS. If a collision occurs, node C doubles the contention window size of the switchable interface (CW^s) and increases the number of retrials. Node C retransmits the data packet over Ch_i. If Rt expires, node C resets CW^s, starts the procedure again, and increases the number of retrials. If the number of retrials reaches the maximum number of retrials, node C drops the packet. If Rt expires, node D first checks whether the current channel is idle or busy; If the channel is busy, node D waits until the current channel becomes idle and then check whether the current transmission is for node D itself or not. If it is idle, node D continues hopping.

5. PERFORMANCE EVALUATION

In this section, we evaluate our proposed protocol and compare it with the DCA and IEEE 802.11 DCF MAC protocols. Recall that MMAC-HR and DCA use a dedicated control channel, but MMAC-HR employs channel hopping and DCA uses channel assignment through a channel list. Two performance metrics are considered as follows:

(1) *Average aggregate throughput*. Ideally, when the number of channels is M, the throughput should be M-folder over a single channel. The M-folder throughput can be achieved if each node has M interfaces, which is unpractical. Our protocol has only two interfaces per node, and the objective is to maximize the utilization of all channels.

(2) *Average packet delay*. The packet delay is the duration of time for a packet to be received correctly by its destination. The delay occurs because of queueing, backoff, propagation, access, switching, and transmission times. The MAC queueing size of each node is 50 packets. We do not take into account the dropped packets. This metric is important for real-time applications.

5.1. Simulation model

For simulations, we have used the ns-2 simulator (ns-2.30) [31] to evaluate the proposed protocol with the simulation parameters in Table I. The two-ray path loss model is adopted in the simulations. Transmitting at the maximum power, the TR is 250 m, and the CSR is 550 m. The constant bit rate traffic model is used for all flows.

Table I. Parameters used in the simulations.

Parameters	Values
Carrier sense threshold	$1.56 * 10^{-8}$ mW
Receiver sensitivity	$3.65 * 10^{-7}$ mW
Maximum transmission power ($P_{\max}$)	281.8 mW
Transmission rate for data channels	2 Mbps
Transmission rate for the control channel	1 Mbps
$CW_{\min}$	32
$CW_{\max}$	1024
Retry limit	7
DIFS	50 μs
SIFS	10 μs
Slot time	20 μs
Dwell time	100 ms
Maximum propagation delay (τ)	1 μs
Switching delay time (St)	100 μs
Reservation time (Rt)	10 ms

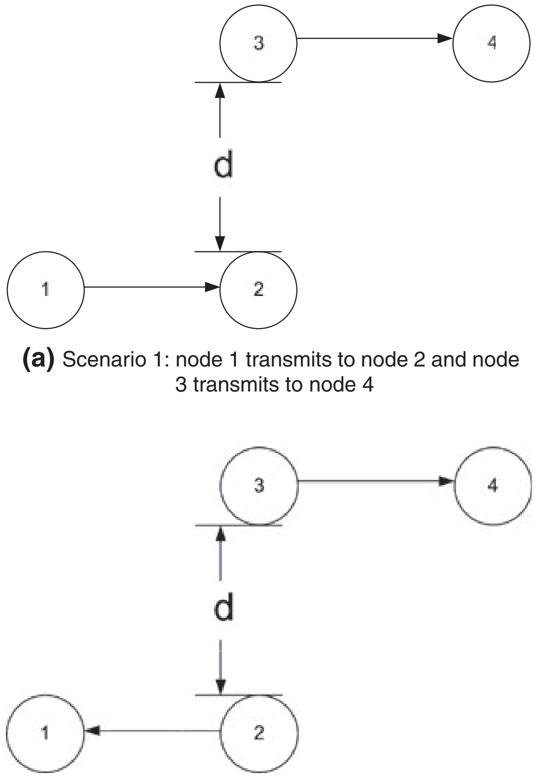
We assume that the switching delay time is 100 μs, and the switching delay can be decreased to 40–80 μs for IEEE 802.11a cards [15]. The simulation results are the average of 50 different scenarios, and each simulation scenario lasts 100 s.

5.2. Simulation topology

We consider three different network topologies: single-hop network, small-scale multihop network, and large-scale multihop network. For the single-hop and small-scale multihop networks, we use the network throughput as the network metric. For the large-scale network, we consider both the average aggregate throughput and packet delay to be the performance metrics.

5.2.1. Single-hop network.

In this network, all nodes are within the TRs of each other. Hence, the single-hop network is limited to a single collision domain, and thus, the multichannel's hidden and exposed terminal problems do not occur. The rationale behind simulating this network is to investigate the control saturation problem [10,30]. The number of nodes is 50, 100, and 200 nodes, and the number of flows is 25, 50, and 100, respectively, because the flows are disjointed. In other words, half the nodes are transmitters, and the others are receivers. Joint flows are not studied in the single-hop ad hoc network but are studied in the multihop network. The payload size is 1024 bytes, and the numbers of channels are 3, 6, and 9.



(a) Scenario 1: node 1 transmits to node 2 and node 3 transmits to node 4

(b) Scenario 2: node 2 transmits to node 1 and node 3 transmits to node 4.

Figure 3. Selected topology scenarios for the small-scale multihop network.

5.2.2. Small-scale multihop network.

We have four nodes and only two flows. In addition, the data rate of the flows is 1 Mbps, and the packet size is 1024 bytes. Two scenarios are selected to demonstrate the network throughput. As shown in Figure 3(a), the first scenario is that node 1 has packets for node 2 and node 3 has packets for node 4. The second scenario is the same as the first except that node 2 is transmitting to node 1, as shown in Figure 3(b). The distance between nodes 1 and 2 is the same as the distance between nodes 3 and 4, which is 200 m.

We compare DCA and MMAC-HR with the IEEE 802.11 DCF MAC protocol. The DCA and MMAC-HR protocols have two channels, one of which is a dedicated control channel and the other is a data channel; the IEEE 802.11 DCF protocol has only a single channel. The throughput of the 802.11 DCF MAC and MMAC-HR protocols is expected to be the same as the throughput of the DCA protocol.

5.2.3. Large-scale multihop network.

We have 100 nodes placed randomly in a 500×500 m^2 flat area, and there are 45 flows in the network. A source node randomly chooses its destination node, and a node may be a destination for multiple source nodes. The packet size is 1024 bytes unless otherwise mentioned.

5.3. Simulation results

This subsection presents and discusses the simulation results. We show the results of the single-hop networks and the multihop networks.

5.3.1. Single-hop network.

Figure 4 shows the aggregate throughput of the single-hop networks. “MMAC-HR-3” indicates that three channels are available for the MMAC-HR protocol, and “DCA-6” indicates that six channels are available for the DCA protocol. The throughput of the IEEE 802.11 MAC protocol using only a single channel is also shown in the figures for comparison. Figures 4(a) and 4(b) present the throughput for the DCA and MMAC-HR protocols, respectively, with 50 nodes. When the data rate increases, the throughput of all protocols increases. However, when the number of channels increases, the throughput of DCA decreases. This behavior is also observed in [10]. The

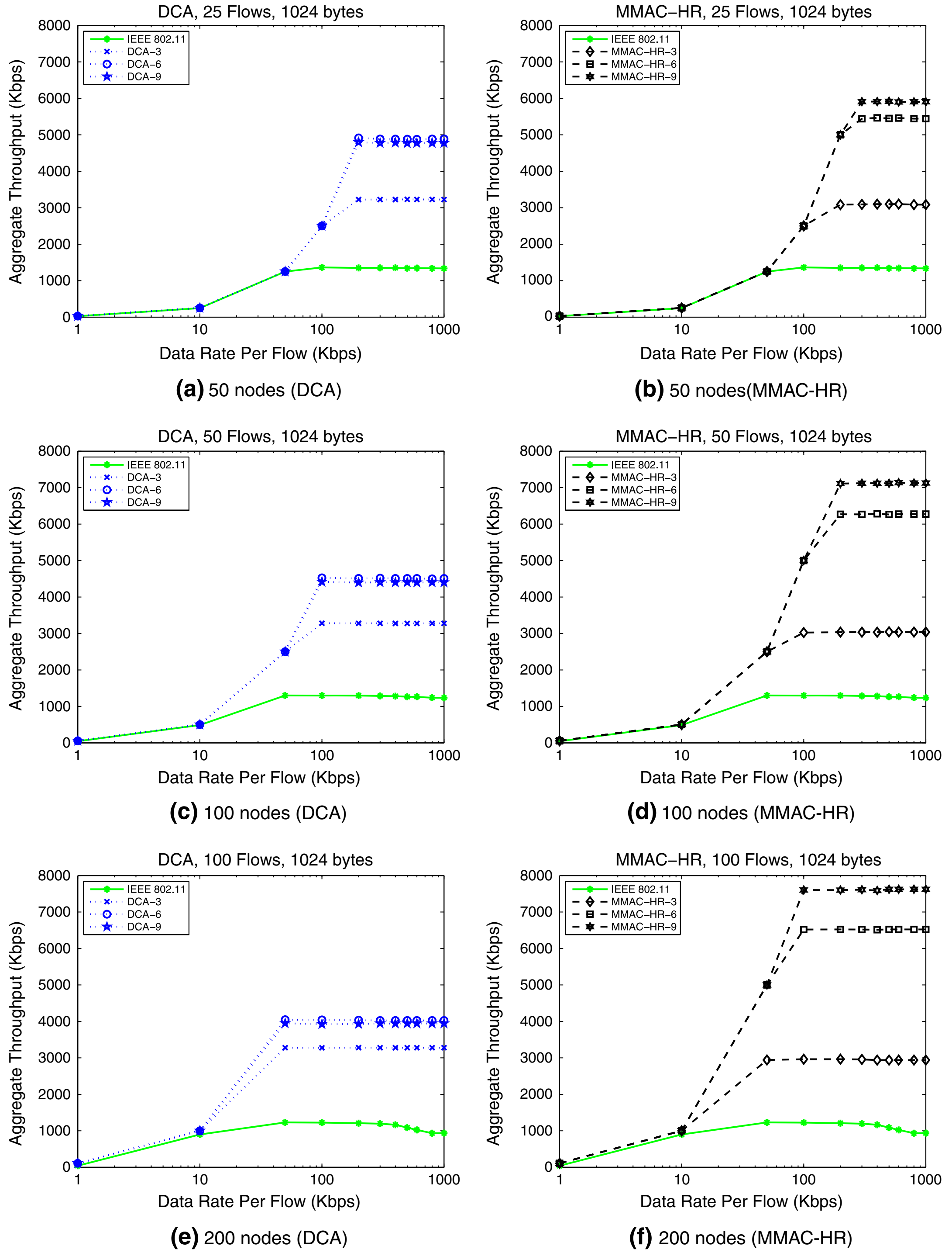


Figure 4. The aggregate throughput of the single-hop networks for various numbers of nodes and network loads. The graphs on the left side are the throughput of dynamic channel assignment (DCA), and the graphs on the right side are the throughput of multichannel medium access control protocol with hopping reservation (MMAC-HR).

reason that the throughput of DCA decreases when the number of channels increases is that all idle transmitters, which have ready packets to send, must wait on the control channel when all data channels are busy. As soon as any data channel becomes idle, all the idle transmitters compete over the control channel. Thus, the collision probability increases over the control channel, and consequently, the data channels are not unitized efficiently.

Unlike DCA, the throughput of MMAC-HR increases when the number of channels increases. In MMAC-HR, whenever a transmitter has a packet, the transmitter sends its RTS packet over the control channel to a receiver regardless of all data channels being busy. Upon receiving the RTS packet, the receiver responds with a CTS packet to the transmitter. Then the transmitter waits for the receiver's data channel; thus, the congestion of the control channel is avoided.

When the number of nodes increases, the aggregate throughput of DCA decreases (as shown in Figure 4(c), when the number of nodes is 100, and in Figure 4(e), when the number of nodes is 200). However, in MMAC-HR, the throughput increases as the number of nodes increases (as illustrated in Figure 4(d), when the number of nodes is 100 and in Figure 4(f), when the number of nodes is 200).

5.3.2. Multihop network: small scale.

Figure 5(a) illustrates the network throughput of the first scenario with respect to the distance denoted as d between nodes 2 and 3. As shown in the figure, the throughput of the MMAC-HR and IEEE 802.11 DCF MAC protocols is the same.

However, for DCA, when the distance between nodes 2 and 3 is between 5 and 250 m, nodes 2 and 3 update their channel lists because they are within the TR of each other. Consequently, the throughput of DCA is comparable with the throughput of MMAC-HR and DCF. However, as the distance d is more than 250 m up to a limited range (interference range), nodes 2 and 3 are unaware of the channel negotiations of each other; as a result, collisions occur over only the data channel within the interference range because DCA does not employ carrier sensing over data channels. Consequently, the throughput of DCA drops significantly compared with MMAC-HR and IEEE 802.11 DCF MAC. More than the interference range, the nodes do not interfere with each other, and thus, the throughput of DCA is the same as MMAC-HR and IEEE 802.11 DCF MAC and reaches to the maximum (the sum of the two flows). Figure 5(b) shows the throughput of the second scenario, and the observations from the second scenario are the same as in the first scenario.

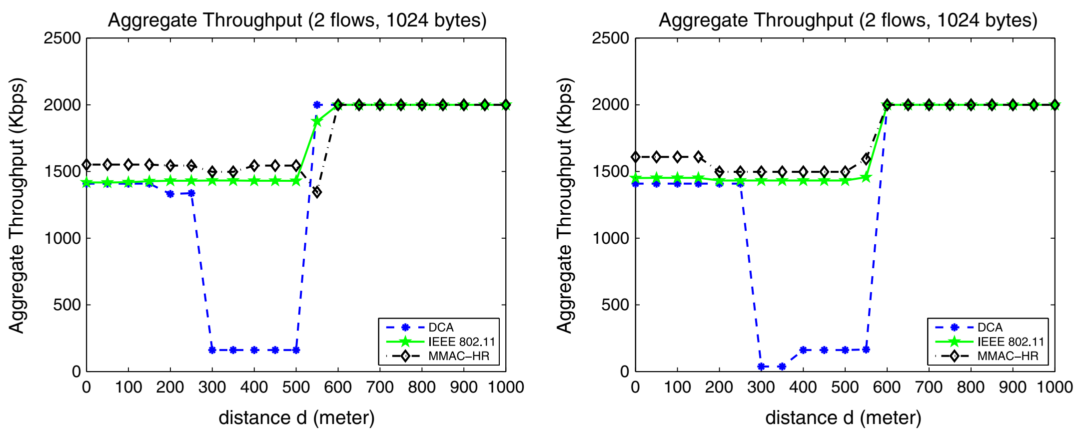
Therefore, a channel list does not have complete information about the data channels. Moreover, if DCA employs carrier sensing, then the multichannel exposed terminal problem will occur in multichannel wireless network as described in Section 3. Hence, our proposed protocol does not use a channel list to determine if a data channel is idle; instead, MMAC-HR employs both channel hopping and carrier sensing to utilize the available channels.

5.3.3. Multihop network: large scale.

Figure 6 shows the throughput of the multihop network with four channels. Admitting higher data-rate flows will result in increasing the throughput of the protocols. However, MMAC-HR outperforms the other protocols (the packet size is 512 bytes in Figure 6(a) and 1024 bytes in Figure 6(b)). The throughput degradation of DCA is the result of the multichannel exposed terminal problem leading to poor channel assignment presented in Section 3. The MMAC-HR protocol does not depend on channel assignment but depends on channel hopping done randomly and independently.

Figure 7 shows the average packet delay of all flows in the network when the number of channels is 4. MMAC-HR achieves less delay than the other protocols as shown in Figure 7(a) and in Figure 7(b).

Figure 8 shows the network throughput for different numbers of channels with 1 Mbps data rate for each flow. When the number of channel increases, the network throughput increases for MMAC-HR and DCA. However, MMAC-HR has higher throughput than DCA because as the number of channels increases, the number of nodes



(a) Aggregate throughput of Scenario 1 **(b)** Aggregate throughput of Scenario 2

Figure 5. Aggregate throughput versus the distance d between node 2 and node 3 as shown in Figure 3.

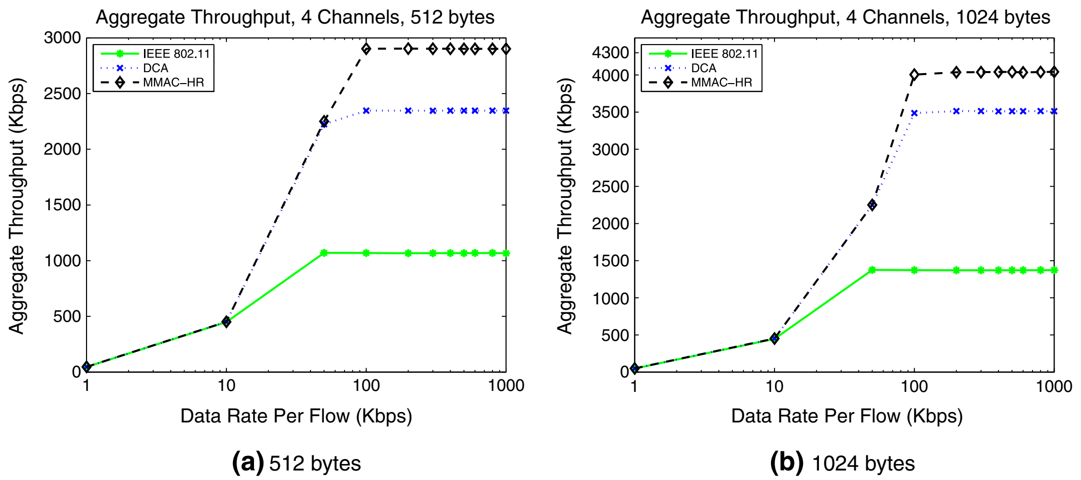


Figure 6. Aggregate throughput versus different network loads when the number of channels is 4 in the multihop network.

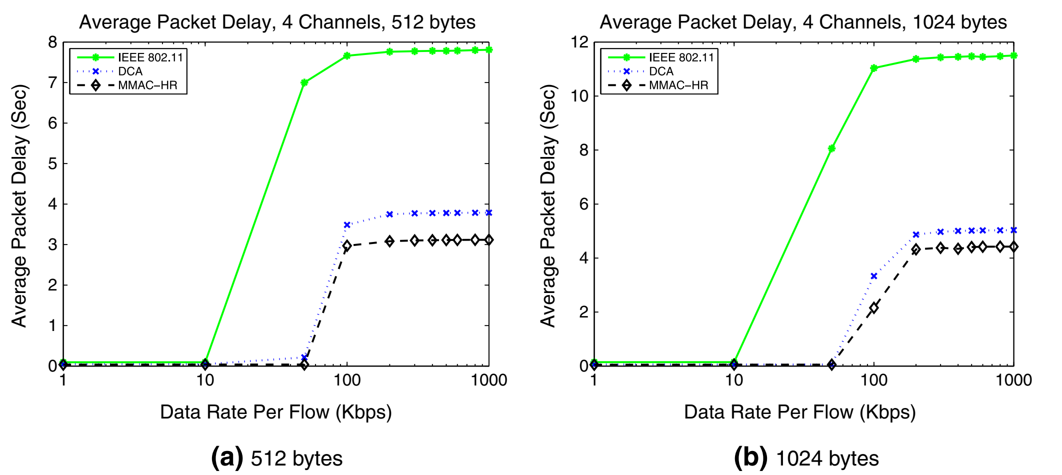


Figure 7. Average packet delay versus different network loads when the number of channels is 4 in the multihop network.

that compete a data channel decreases. Moreover, the DCA protocol reaches its saturation point when the number of channel is 5. The data channels are spatially reused through channel assignment. As mentioned in Section 3, nodes using DCA select data channels through their channel lists resulting in poor channel selection. We can see the effect of the multichannel exposed terminal problem on DCA when the number of channel is more than 5.

In Figure 9, we examine the average packet delay of all flows. As the number of channels increases, the average delay decreases for MMAC-HR and DCA. The DCA protocol encounters higher delay than MMAC-HR because DCA does not utilize data channels efficiently.

So far, the value of the reservation time (Rt) has been 10 ms, and this value has been used in both the single-hop and multihop networks. Figure 10 shows the aggregate throughput of the multihop network and how different Rt values can affect the MMAC-HR protocol. From the figure, "MMAC-HR-256," "MMAC-HR-512," and "MMAC-HR-1024" indicate that the packet sizes are 256, 512, and 1024 bytes, respectively. As the Rt value increases, the throughput of MMAC-HR increases and then the throughput of MMAC-HR decreases, particularly when the packet size is large. This pattern occurs because of two reasons. First, a receiver may have a packet to transmit, but the receiver cannot switch from its current channels because the flows in the network are jointed. Second, if a data channel is busy, a transmitter holds its attempt for Wt, which is set to the maximum packet transmission time in the network; consequently, the Wt value wastes most of the reservation time. In general, the best Rt value depends on the network density and traffic, but it can adapt to obtain the achievable throughput because receivers always send CTS packets including the Rt value.

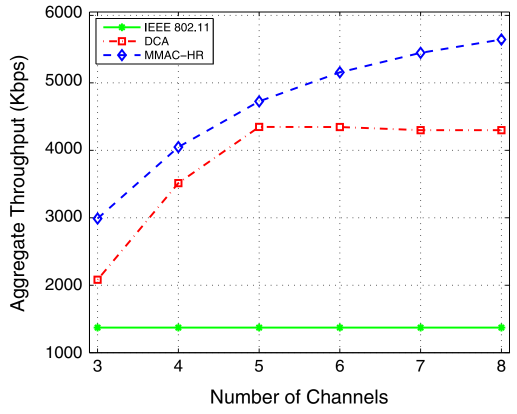


Figure 8. Aggregate throughput versus different numbers of channels in the multihop network.

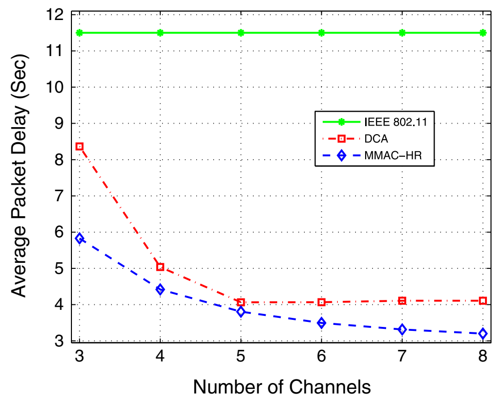


Figure 9. Average packet delay versus different numbers of channels in the multihop network.

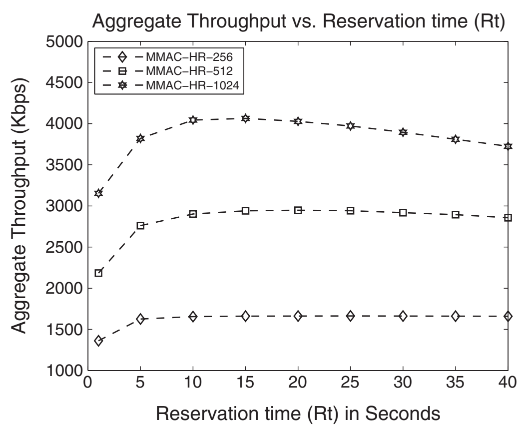


Figure 10. Average aggregate throughput versus reservation time (*Rt*) when the number of channels is 4 in the multihop network.

6. CONCLUSION AND FUTURE WORK

In this paper, we have proposed the MMAC-HR to resolve the multichannel exposed terminal problem, which leads to poor channel utilization. MMAC-HR uses carrier sensing over all channels and does not use a channel list. Therefore, nodes do not need to sense the control channel to determine if any data channel is idle. In addition, the proposed protocol employs an independent and slow hopping strategy to utilize the multiple channels without exchanging information. Moreover, MMAC-HR is a distributed protocol and does not require synchronization. By using ns-2, the simulation results show that MMAC-HR achieves higher throughput and lower delay than DCA.

For our future work, we will develop an intelligent channel selection for MMAC-HR so that the network load is balanced over multiple channels, thereby enhancing the network performance.

REFERENCES

1. Skalli H, Ghosh S, Das S, Lenzini L, Conti M. Channel assignment strategies for multiradio wireless mesh networks: issues and solutions. *IEEE Communications Magazine* 2007; **45**(11): 86–95.
2. Cheng H, Zhuang W. Joint power-frequency-time resource allocation in clustered wireless mesh networks. *IEEE Network* 2008; **22**(1): 45–51.
3. IEEE Standard 80211. Wireless LAN Medium Access Control (MAC) and Physical layer (PHY) specifications, August 1999.
4. Kyasanur P, So J, Chereddi C, Vaidya N. Multichannel mesh networks: challenges and protocols. *IEEE Wireless Communications* 2006; **13**(2): 30–36.
5. Bi Y, Cai LX, Shen X, Zhao H. Efficient and reliable broadcast in intervehicle communication networks: a cross-layer approach. *IEEE Transactions on Vehicular Technology* 2010; **59**(5): 2404–2417.
6. Almotairi KH, Shen X. Fast and slow hopping mac protocol for single-hop ad hoc wireless networks. *Proceedings of IEEE ICC*, Kyoto, Japan, 2011.
7. Draves R, Padhye J, Zill B. Routing in multi-radio, multi-hop wireless mesh networks. In *Proceedings of the 10th Annual International COnference on Mobile Computing and Networking*. ACM: New York, NY, 2004; 114–128.
8. Mo J, So HS, Walrand J. Comparison of multichannel MAC protocols. *IEEE Transactions on Mobile Computing* 2008; **7**(1): 50–65.
9. Wu SL, Lin CY, Tseng YC, Sheu JL. A new multi-channel MAC protocol with on-demand channel assignment for multi-hop mobile ad hoc networks. In *Proceedings of the 2000 International Symposium*

on Parallel Architectures, Algorithms and Networks. IEEE Computer Society: Washington, DC, 2000; 232–237.
10. So J, Vaidya NH. Multi-channel MAC for ad hoc networks: handling multi-channel hidden terminals using a single transceiver. In *Proceedings of the 5th ACM International Symposium on Mobile Ad Hoc Networking and Computing*. ACM: New York, NY, 2004; 222–233.
11. Huang R, Zhai H, Zhang C, Fang Y. SAM-MAC: an efficient channel assignment scheme for multi-channel ad hoc networks. *Computer Networks* 2008; **52**(8): 1634–1646.
12. Tobagi F, Kleinrock L. Packet switching in radio channels: Part II—The hidden terminal problem in carrier sense multiple-access and the busy-tone solution. *IEEE Transactions on Communications* 1975; **23**(12): 1417–1433.
13. Raniwala A, Chiueh TC. Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network. *Proceedings of the 24th Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 3, 2005; 2223–2234.
14. So HSW, Walrand J, Mo J. McMAC: a parallel rendezvous multi-channel mac protocol, 2007. *Proceedings of the IEEE Wireless Communications and Networking Conference*, 2007; 334–339.
15. Bahl P, Chandra R, Dunagan J. SSCH: slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks. In *Proceedings of the 10th Annual International Conference on Mobile Computing and Networking*. ACM: New York, NY, 2004; 216–230.
16. Bi Y, Liu KH, Cai LX, Shen X, Zhao H. A multichannel token ring protocol for qos provisioning in inter-vehicle communications. *IEEE Transactions on Wireless Communications* 2009; **8**(11): 5621–5631.
17. Crichigno J, Wu MY, Shu W. Protocols and architectures for channel assignment in wireless mesh networks. *Ad Hoc Networks* 2008; **6**(7): 1051–1077.
18. Bahl P, Adya A, Padhye J, Walman A. Reconsidering wireless systems with multiple radios. *ACM SIGCOMM Computer Communication Review* 2004; **34**(5): 39–46.
19. Kyasanur P, Vaidya N. Routing and interface assignment in multi-channel multi-interface wireless networks. *Proceedings of the IEEE Wireless Communications and Networking Conference*, 2005; 2051–2056.
20. Wu SL, Tseng YC, Lin CY, Sheu JP. A multi-channel MAC protocol with power control for multi-hop mobile ad hoc networks. *The Computer Journal* 2002; **45**(1): 101–110.
21. Nasipuri A, Zhuang J, Das S. A multichannel CSMA MAC protocol for multihop wireless networks. *Proceedings of IEEE Wireless Communications and Networking Conference*, 1999; 1402–1406.
22. Adya A, Bahl P, Padhye J, Wolman A, Zhou L. A multi-radio unification protocol for IEEE 802.11 wireless networks, 2004. *Proceedings of the 1st International Conference on Broaband Networks*, 2004; 344–354.
23. Omar H, Zhuang W, Li L. VeMAC: a novel multichannel MAC protocol for vehicular ad hoc networks, 2011. *Proceedings of IEEE INFOCOM—Workshop on Mobility Management in the Networks of Future World*, Shanghai, China, 2011.
24. Almotairi KH, Shen X. Symmetrical power control for multi-channel multi-hop wireless networks, 2010. *Proceedings of the IEEE Global Telecommunications Conference*, Miami, FL, 2010.
25. Tzamaloukas A, Garcia-Luna-Aceves JJ. Channel-hopping multiple access, 2000. *Proceedings of the IEEE International Conference on Communications*, vol. 1, 2000; 415–419.
26. Yang Z, Garcia-Luna-Aceves J. Hop-reservation multiple access (HRMA) for ad-hoc networks, 1999. *Proceedings of the 18th Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 1, 1999; 194–201.
27. Bharghavan V, Demers A, Shenker S, Zhang L. MACAW: a media access protocol for wireless LAN's. In *Proceedings of the Conference on Communications Architectures*. ACM: New York, NY, 1994; 212–225.
28. Felice MD, Zhu M, Bononi L. Future channel reservation medium access control (FCR-MAC) protocol for multi-radio multi-channel wireless mesh networks. In *Proceedings of the 5th ACm Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks*. ACM: New York, NY, 2008; 71–79.
29. Shi J, Salonidis T, Knightly EW. Starvation mitigation through multi-channel coordination in CSMA multihop wireless networks. In *Proceedings of the 7th ACM International Symposium on Mobile Ad Hoc Networking and Computing*. ACM: New York, NY, 2006; 214–225.
30. Wu PJ, Lee CN. Connection-oriented multi-channel MAC protocol for ad-hoc networks. *Computer Communications* 2009; **32**(1): 169–178.
31. The Network Simulator ns-2. http://www.isi.edu/nsnam/ns [Accessed on 1 July 2008].

AUTHORS' BIOGRAPHIES

Khaled H. Almotairi received the BSc degree from King Abdulaziz University, Jeddah, Saudi Arabia, in 2004 and the MSc degree from the University of Waterloo, Waterloo, ON, Canada, in 2007, both in Electrical and Computer Engineering. He is currently working towards the PhD degree at the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. From 2004 to 2005, he worked as a full-time Instructor in the College of Telecommunication and Electronics, Jeddah, Saudi Arabia. His research interests include channel allocation, performance analysis and evaluation, protocol design, transmission power control, and ad hoc networking.

Xuemin (Sherman) Shen received the BSc(1982) degree from Dalian Maritime University (China) and the MSc (1987) and PhD degrees (1990) from Rutgers University, NJ, USA, all in Electrical Engineering. He is a Professor and the University Research Chair in the Department of Electrical and Computer Engineering in the University of Waterloo, Canada. Dr. Shen's research focuses on resource management in interconnected wireless/wired networks, UWB wireless communications networks, wireless network security, wireless body area networks, and vehicular ad hoc and sensor networks. He is a co-author of three books and has published more than 400 papers and book chapters in wireless communications and networks, control and filtering. Dr. Shen served as the Technical Program Committee Chair for IEEE VTC'10, the Symposia Chair for IEEE ICC'10, the Tutorial Chair for IEEE ICC'08, the Technical Program Committee Chair for IEEE Globecom'07, the General Co-Chair for Chinacom'07 and QShine'06, the Founding Chair for IEEE Communications Society Technical Committee on P2P Communications and Networking. He also served as a Founding Area Editor for IEEE Transactions on Wireless Communications, Editor-in-Chief for Peer-to-Peer Networking and Application, Associate Editor for IEEE Transactions on Vehicular Technology, Computer Networks, and ACM/Wireless Networks, and so on, and the Guest Editor for IEEE JSAC, IEEE Wireless Communications, IEEE Communications Magazine, and ACM Mobile Networks and Applications, and so on. Dr. Shen received the Excellent Graduate Supervision Award in 2006 and the Outstanding Performance Award in 2004 and 2008 from the University of Waterloo, the Premier's Research Excellence Award (PREA) in 2003 from the Province of Ontario, Canada, and the Distinguished Performance Award in 2002 and 2007 from the Faculty of Engineering, University of Waterloo. Dr. Shen is a registered Professional Engineer of Ontario, Canada, an IEEE Fellow, an Engineering Institute of Canada fellow, and a Distinguished Lecturer of IEEE Communications Society.