A Stepwise Multichannel MAC Protocol for Improving Bandwidth Utilization in Wireless Ad Hoc Networks

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***Abstract*—Multichannel media access control (MAC) protocols can increase wireless network capacities. The rendezvous problem is the most frequently encountered challenge in developing multichannel MAC protocols. Some studies have assumed that each device is equipped with one additional antenna; however, this increases the hardware cost. Other studies have divided the timeline of each channel into several beacon intervals. All stations are awake simultaneously on a predefined channel to enable rendezvous opportunities; however, this leads to low bandwidth utilization. This paper presents an efficient staggered multichannel MAC protocol (SMC-MAC) for ad hoc networks. By using a single antenna, the proposed SMC-MAC applies a staggered channel model with a home channel concept for exploiting multichannel bandwidth resources. Performance results reveal that the proposed SMC-MAC outperforms existing multichannel MAC protocols in terms of network throughput, control packet collision ratio, packet delay time, packet discarding, packet loss ratio, control overhead, and robustness.**

***Index Terms*—Ad hoc network, hidden terminal problem, multichannel, multichannel medium access control (MAC), rendezvous problem.**

I. Introduction

MULTICHANNEL medium access control (MAC) protocols have attracted considerable attention in recent years because they can increase the capacity of wireless ad hoc networks. Applying multiple frequency channels immensely improves wireless network capacities. Efficient multichannel MAC protocols exploit frequency diversity and utilize network capacity more efficiently than do single-channel MAC protocols. Although the IEEE 802.11b/g and IEEE 802.11a standards [1], [2], respectively, define 3 and 12 nonoverlapping channels that support higher network throughput, the distributed coordination function (DCF) within the commercial MAC protocol of IEEE 802.11 is designed mainly for sharing a single channel between stations. Thus, the IEEE 802.11 DCF cannot function in a multichannel environment. In recent years, a large number of MAC protocols have been developed for exploiting the transmission opportunities in a multichannel environment. This paper proposes a MAC protocol that more efficiently utilizes multichannel resources. Although the 802.11n and 802.11ac protocols increase throughput by using multiple-input–multiple-output technology, which employs multiple antennas at both of the sender and receiver, a large number of stations are still equipped with a single antenna. To exploit the advantages of the single antenna hardware with half-duplex function, several multichannel MAC protocols have been proposed in recent years.

Two main problems are encountered in multichannel MAC protocol design, namely, the *rendezvous problem* and *multichannel hidden terminal problem* [3]. The major challenge in a multichannel environment is the rendezvous problem. To exchange data between the sender and receiver, both must stay on the same channel for reserving the channel and time for data exchange. The antenna can dynamically switch channels, but it can only either transmit data or listen to channel information at the same time. Thus, when stations exchange data on a particular channel, the channel usage information cannot be maintained because such information can only be obtained using another antenna. Consequently, the sender that recently completed a data exchange operation cannot maintain the correct channel usage information and may select a busy channel, thus encountering the hidden terminal problem. Multichannel MAC protocols must overcome the hidden terminal problem [4]–[13], [19]–[23].

As discussed in the subsequent section, several multichannel MAC protocols [4]–[13], [19]–[23] have been proposed for improving throughput by using multiple channels. However, most protocols attempt to ensure efficient data exchange on the basis of one or more of the following assumptions, each of which raises certain disadvantages.

1) *All stations exchange control packets on a dedicated common control channel*. Here, maintaining complete channel usage information at each station by using one antenna is difficult, therefore leading to the multichannel hidden terminal problem.
2) *All stations are equipped with multiple antennas*. These approaches clearly increase the hardware cost, size, and energy consumption.

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3) *The station switches its channel frequently*. A high level of channel switching consumes more energy and induces longer delays.
4) *All stations exchange control packets on a predefined channel during a dedicated control period*. Here, the bandwidth utilization is low because the control periods of all channels except the predefined channel are idle and wasted.

This study aims to exploit parallel transmission opportunities within certain hardware constraints (e.g., single antenna and half-duplex) through the proposed home-channel-based MAC protocol (*SMC-MAC*) designed on the basis of a novel staggered multichannel model. The major objective of this study is to improve spectrum utilization for substantially increasing network throughput. In particular, the main contributions of the proposed SMC-MAC are as follows.

1) ***Improve spectrum utilization***.
The proposed SMC-MAC presents a novel staggered channel model that operates control and data packet transmissions concurrently on different channels, thereby substantially improving spectrum utilization and network throughput.
2) ***Alleviate packet collisions***.
The control overheads and data transmission are distributed over all channels, thereby alleviating contention and collision as well as substantially improving channel utilization.
3) ***Parallel transmissions***.
By applying the staggered channel model with a home channel concept and rendezvous policies, multiple transmission pairs can simultaneously communicate over different channels in a distributed manner.
4) ***Lower control overheads***.
Since the proposed SMC-MAC adapts the reserving-based approach for reserving data transmission, *Request to Send (RTS)/Clear to Send (CTS)* handshaking is unnecessary before data exchange in the data period. Consequently, the proposed SMC-MAC substantially decreases the control overheads and improves network throughput.

The rest of this paper is organized as follows. Section II reviews and compares related literature. Section III presents the assumptions and problem statement. The channel model and frame structure are described in Section IV. Section V introduces the design of the proposed SMC-MAC protocol. Section VI analyzes the performance of the proposed protocol, and Section VII investigates the performance evaluation of the proposed protocol. The conclusion is summarized in Section VIII.

II. Related Works

Several multichannel MAC protocols have been proposed. According to the rendezvous schemes, these protocols can be classified into three categories [3]: split phase based (*SPB*), dedicated control channel based (*DCCB*), and hopping based (*HB*).

A. SPB

SPB approaches [4]–[7], [19] mainly divide the timeline of each channel into several *beacon intervals*, with each beacon interval consisting of two periods: *control* and *data periods*. In the control period, senders compete for transmission opportunities and negotiate with the receivers for data exchange on the data channel. During the data period, a sender–receiver pair switches to the negotiated data channel and competes with the other pairs for data exchange. To overcome the rendezvous problem, each station must switch to the specific channel at the beginning of the control period.

Although SPB methods avoid the rendezvous problem without increasing the hardware cost and frequent channel switching, two factors lead to low spectrum utilization. First, several collisions may occur during the control period because a large number of stations intending to simultaneously exchange control packets are on the same channel, causing poor spectrum utilization during the subsequent data period (i.e., the *control period congestion problem*). Second, all channels except the default channel are idle during each control period because each station must stay on the default channel during each control period to get rendezvous opportunities (i.e., the *control period idle problem*).

B. DCCB

DCCB [8]–[12], [20] protocols divide the frequency into a narrow channel and several equal-width channels, termed the control and data channels, respectively. The control channel primarily provides opportunities for control information exchange. The sender and receiver must first exchange control packets in the common control channel and coordinate the data channel for data exchange.

Although such methods overcome the rendezvous problem, maintaining complete channel usage information at each station remains difficult because stations that stay on the data channel for data exchange cannot maintain information in the control channel, leading to incomplete channel usage information and the multichannel hidden terminal problem.

To avoid the multichannel hidden terminal problem, some studies [9], [12], [20] have assumed that all stations are equipped with two antennas: one stays on the control channel to maintain the channel usage information, and the other stays on the data channel for data exchange. Because all stations can use one antenna to constantly monitor the control channel, they can track the busy status of neighboring stations and channels, thus avoiding the multichannel hidden terminal problem. However, using two or more antennas increases the hardware cost.

C. HB

In HB approaches [13], [21]–[23], each station frequently switches its channel according to the hopping sequence generated to rendezvous its neighbors. When the sender and receiver meet on the same channel, they compete with other transmission pairs for a transmission opportunity for data exchange. The channel hopping sequences are estimated based on either blind, difference-set-based [13], cyclic-based [21], quorum-based [22], or pseudorandom-based [23] approaches. In existing studies, channel planning ensures that all stations rendezvous each other. Therefore, such methods easily solve the rendezvous problem in a multichannel environment. However, the large number of channel hops considerably delays transmissions and consumes more energy.

TABLE I
MAIN CHARACTERISTICS OF THE PROPOSED SMC-MAC AND RELATED PROTOCOLS

Studies	Type	# of antennas	Spectrum utilization	Time sync.	Fairness of channel access	Buffer overflow consideration
[4–6]	Split Phase Based	1	Low	○	×	×
[7]	Split Phase Based	1	Low	○	○	×
[19]	Split Phase Based	1	Medium	○	×	×
[8, 10, 11]	Dedicated Control Channel Based	1	Low	×	×	×
[9, 12]	Dedicated Control Channel Based	2	Medium	×	×	×
[20]	Dedicated Control Channel Based	2	Medium	○	×	×
[13]	Hopping Based	1	Low	×	×	×
[21, 22]	Hopping Based	1	Medium	○	×	×
[23]	Hopping Based	2	Medium	○	×	×
SMC-MAC	**Staggered Multi-channel Model**	**1**	**High**	○	○	○

Table I summarizes the characteristics of the existing protocols and the proposed SMC-MAC. The proposed SMC-MAC presents a home-channel-based MAC protocol on the basis of a novel staggered multichannel model. The proposed staggered channel model concurrently operates the control and data packet transmissions on different channels, thus eliminating the control period idle problem and substantially improving spectrum utilization and network throughput. In addition, control overheads and data transmissions are distributed over all channels, further improving channel utilization and alleviating contention and collision. The design of the proposed SMC-MAC protocol is elaborated in the next section.

III. ASSUMPTIONS AND PROBLEM STATEMENT

This study assumes that there are m independent channels represented by $CH = \{c_1, c_2, \ldots, c_m\}$. Each station is equipped with a single half-duplex antenna, which allows either sending or receiving data at the same time. In addition, each station has a unique MAC address and is aware of its neighbors' MAC addresses. Time synchronization is a basic and essential scheme generally applied in multichannel MAC protocols [3]–[7], [13].

This study aims to develop a multichannel MAC protocol that exploits the multichannel bandwidth resource and overcomes the rendezvous problem and hidden terminal problem. In this section, the notations used to represent the objective and constraints of the multichannel MAC protocol are defined and presented.

Let C_i denote the achievable channel capacity of channel c_i. Herein, the Shannon theorem represented by (1) is used to measure the channel capacity, where B_i, S_{avg}, and N_i represent the bandwidth, average received signal strength, and average noise power of channel c_i, respectively

$$C_i = B_i \cdot \log(1 + S_{\text{avg}}/N_i). \tag{1}$$

To increase the throughput of a multichannel environment, the multichannel MAC protocol must improve bandwidth utilization. Let g_i^T denote the number of packets successfully transmitted on channel c_i during a specific time period T. Let l_{data} denote the packet size. The bandwidth utilization of channel c_i during a specific time period T, denoted by U_i^T, is calculated using

$$U_i^T = \frac{\left(g_i^T \times l_{\text{data}}\right)}{\left(C_i \times T\right)}. \tag{2}$$

In addition, let $S = \{s_1, s_2, \ldots, s_n\}$ denote the set of stations existing in the environment and $N(s_x)$ be the set of stations neighboring to station s_x. The following presents the purposes and constraints for developing an efficient multichannel MAC protocol.

Objective Function

$$\boldsymbol{Maximize} \quad \sum_{i=1}^{m} U_i^T \tag{3}$$

Subject to:

$$\sum_{i=1}^{m} a_x^{t,i} = 1, \quad \forall\, s_x \in S, \text{ where}$$

$$a_x^{t,i} = \begin{cases} 1, & \text{if station } s_x \text{ stays on channel } i \text{ at time } t \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$$x^t_{\text{sending}} + x^t_{\text{receiving}} + x^t_{\text{idle\_listening}} = 1, \quad \forall\, s_x \in S, \text{ where}$$

$$x^t_{\text{sending}} = \begin{cases} 1, & \text{if station } s_x \text{ is sending data at time } t \\ 0, & \text{otherwise} \end{cases}$$

$$x^t_{\text{receiving}} = \begin{cases} 1, & \text{if station } s_x \text{ is receiving data at time } t \\ 0, & \text{otherwise} \end{cases}$$

$$x^t_{\text{idle\_listening}} = \begin{cases} 1, & \text{if station } s_x \text{ is idle listening at time } t \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

$$b_{x,y}^{t,i} - \left(a_x^{t,i} \wedge a_y^{t,i}\right) \le 0, \quad \forall\, s_x, s_y \in S, \quad \forall\, s_y \in N(s_x),\ i \in CH, \text{ where}$$

$$b_{x,y}^{t,i} = \begin{cases} 1, & \text{if sender } s_x \text{ is sending data to receiver } s_y \\ & \quad \text{on channel } c_i \text{ at time } t \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

$$b_{x,y}^{t,i} + \delta_{x,y}^{t,i} \le 1, \quad \forall\, s_x, s_y \in S, \quad \forall\, s_y \in N(s_x), i \in CH, \text{ where}$$

$$\delta_{x,y}^{t,i} = \begin{cases} 1, & \text{if } \sum\limits_{\forall s_z \in N(s_x)-s_y} \left(a_z^{t,i} \wedge z^t_{\text{receiving}}\right) \\ & \quad + \sum\limits_{\forall s_w \in N(s_y)-s_x} \left(a_w^{t,i} \wedge w^t_{\text{sending}}\right) \ge 1 \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

The objective of designing an efficient multichannel MAC protocol is depicted in (3), i.e., to maximize the overall bandwidth utilization for improving network throughput.

Because we assume that the station is equipped with a single half-duplex antenna, (4) constrains that each station can only

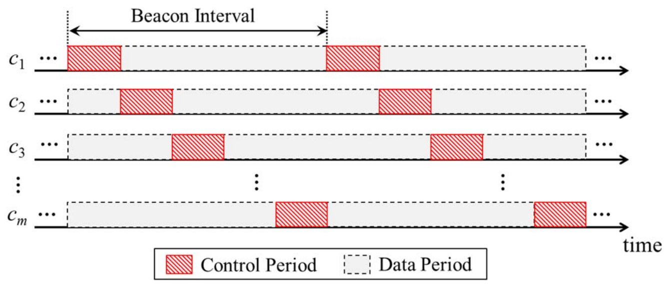

Fig. 1. Proposed staggered channel model.

stay on one of the m channels at any given time point t. Expression (5) further constrains that each station can only be *sending*, *receiving*, or *idle listening* at any given time point t.

Expression (6) identifies the rendezvous constraint wherein the transmission pair must stay on the same channel at the same time. Constraint (7) aims to avoid data collision; the value of $\delta_{x,y}^{t,i}$ is either 0 or 1, representing whether the stations neighboring to the sender s_x and receiver s_y are kept silent or not on channel c_i at time t, respectively. That is, if the sender s_x is sending data to receiver s_y on channel c_i at time t (i.e., $b_{x,y}^{t,i} = 1$), the stations neighboring s_x and s_y must be idle. The subsequent section presents the proposed SMC-MAC protocol and aims to achieve the objective stated as (3) while satisfying constraints (4)–(7).

IV. Proposed Staggered Channel Model and Frame Structure

This section presents the staggered channel model and frame structure applied for overcoming the rendezvous problem in the proposed SMC-MAC protocol.

A. Staggered Channel Model

Each channel is divided into several equal-length beacon intervals, each consisting of a control period and a data period.

As shown in Fig. 1, the staggered channel model arranges control periods at different channels such that the periods do not overlap; the end of the control period in the ith channel is the beginning of the control period in the $(i+1)$th channel. Such nonoverlapping allows the sender to participate in any control period for exchanging control packets with its receiver.

Let t^{CP} and t^{DP} denote the time durations of the control and data periods, respectively. Equation (8) represents the relationship between t^{CP} and t^{DP}, where $k \geq m-1$

$$t^{\mathrm{DP}} = k \times t^{\mathrm{CP}}. \qquad (8)$$

This study assumes that each station s has a common built-in channel mapping function f that determines its home channel s.home. Equation (9) derives the home channel of station s, where s.address represents the MAC address of station s as well as α and β represent two arbitrary parameters

$$s.\mathrm{home} = [(s.\mathrm{address} \times \alpha + \beta)\%m] + 1. \qquad (9)$$

Let *home stations* $H^i = \{s_1^i, s_2^i, \ldots, s_{|H^i|}^i\}$ of channel c_i represent the set of stations whose home channel is c_i, and $|H^i|$ denotes the number of home stations in channel c_i.

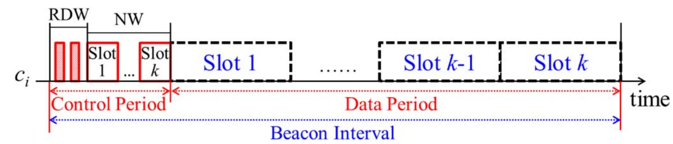

Fig. 2. Frame structure of the SMC-MAC.

B. Frame Structure

The frame structure of the proposed SMC-MAC is illustrated in Fig. 2. The control period is further divided into the *receiver declaration window (RDW)* and *negotiation window (NW)*. In addition, the NW and data period are divided into k slots, called *negotiation slots* and *data slots*, respectively. The RDW is primarily used by home stations to announce their scheduling established before the beacon interval, which is composed of a control period and a data period. The scheduling information ensures that potential senders are aware of the available slots of the receiver. The control period provides opportunities for the sender and receiver to rendezvous and negotiate for reserving a data slot. In the control period, all potential senders compete for a negotiation slot for reserving a data slot with their receivers. During the data period, the sender and receiver exchange data only in the reserved data slot.

The subsequent section presents the proposed SMC-MAC developed on the basis of the aforementioned staggered channel model and frame structure.

V. Proposed SMC-MAC Protocol

Because SMC-MAC operates in a multichannel environment, the rendezvous problem must be overcome. In this section, the rendezvous policies are introduced, and the detailed design of the proposed SMC-MAC is presented.

A. Rendezvous Mechanism

To overcome the rendezvous problem, we present two rules: *home rule* and *rendezvous rule*. The home rule constrains a home station to stay on its home channel during the control period, thereby enabling rendezvous opportunities for the senders. For simplicity, let s_x^i and s_y^j represent the station x (sender) and station y (receiver), whose home channels are c_i and c_j, respectively.

Home Rule: Each station s_y^j must stay on its home channel c_j during the control period of every beacon interval. ■

The *rendezvous rule* helps senders switch to the receiver's home channel for reserving the data slot.

Rendezvous Rule: If station s_x^i intends to transmit data to station s_y^j, it must switch to and participate in the control period of channel c_j. ■

By applying the home rule, each station stays on its home channel during the control period of every beacon interval. The sender s_x^i can replace the MAC address of s_y^j with that obtained using the channel mapping function given by (9) to derive the home channel of receiver s_y^j. Next, the sender s_x^i switches to channel c_j and rendezvous the receiver s_y^j. Subsequently, stations s_x^i and s_y^j negotiate during the NW for reserving a data slot.

The main contributions of the rendezvous policies in the proposed SMC-MAC are as follows. 1) Because all stations are distributed on all channels by the home channel's mapping function, the control overheads can be distributed over all channels. Therefore, the control period congestion problem is considerably improved. 2) Control and data packet transmissions are concurrently operated on different channels. Therefore, each channel is fully utilized with no idling at any given time, thus eliminating the control period idle problem. The proposed rendezvous policies thus substantially improve spectrum utilization and network throughput.

B. SMC-MAC Design

This section details the design of the proposed SMC-MAC. The frame structure of the proposed SMC-MAC is illustrated in Fig. 2. The control period is mainly designed for the transmission pairs to reserve a slot for data exchange. As stated earlier, the control period is divided into the RDW and NW. The RDW, NW, and data period utilization is elaborated herein.

Let $t^{i,\mathrm{CP}}$ and $t^{i,\mathrm{DP}}$ represent a control period and the subsequent data period on channel c_i, respectively. In addition, let $t^{i,\mathrm{CP(RDW)}}$ and $t^{i,\mathrm{CP(NW)}}$ denote the RDW and NW of $t^{i,\mathrm{CP}}$, respectively. Let $t_u^{i,\mathrm{CP(NW)}}$ and $t_u^{i,\mathrm{DP}}$ denote the uth negotiation and data slots of channel c_i, respectively.

The following sections detail the RDW, NW, and data period designs.

1) RDW: The RDW is mainly designed for home stations to broadcast their scheduling information, ensuring that potential senders are aware of the available slots.

When station s_y^j intends to send data to s_z^q, it must stay on channel c_q during $t^{q,\mathrm{CP}}$, which implies that station s_y^j cannot receive data on channel c_j during $t^{q,\mathrm{CP}}$. If a sender intends to request station s_y^j for a reservation of the uth data slot $t_u^{j,\mathrm{DP}}$, which is the same time as duration $t^{q,\mathrm{CP}}$, a scheduling collision occurs at station s_y^j. To prevent such collisions, station s_y^j must announce its unavailable data slots by broadcasting its *receiver declaration packet (RDP)* during $t^{j,\mathrm{CP(RDW)}}$.

The RDP of station s_y^j is denoted as RDP_y^j; it contains the *ID* and the *home station bitmap* B_y^j of station s_y^j.

Home Station Bitmap B_y^j: The home station bitmap B_y^j of station s_y^j is a vector of k binary entries. The value of the uth entry $B_y^j[u]$ is either 1 or 0, representing whether the uth data slot $t_u^{j,\mathrm{DP}}$ of station s_y^j is available or unavailable, respectively. That is

$$B_y^j[u] = \begin{cases} 1, & \text{if } t_u^{j,\mathrm{DP}} \text{of } s_y^j \text{ is available} \\ 0, & \text{otherwise} \end{cases}, \quad 1 \le u \le k. \quad (10)$$

■

If $B_y^j[u]$ is 0, station s_y^j leaves its home channel c_j at the uth data slot $t_u^{j,\mathrm{DP}}$; thus, the uth data slot is unavailable for further reservation. Conversely, if $B_y^j[u]$ is 1, s_y^j will stay on its home channel c_j during the uth data slot $t_u^{j,\mathrm{DP}}$, i.e., the uth slot of station s_y^j is available for reservation.

For example, assume that station s_y^4 has negotiated with other stations at time slots t_5 and t_7 on channels c_2 and c_3 during $t^{2,\mathrm{CP}}$ and $t^{3,\mathrm{CP}}$ (i.e., t_2 and t_3), respectively, as shown in Fig. 3. Station s_y^4 announces that the first and third data slots $t_1^{4,\mathrm{DP}}$ and $t_3^{4,\mathrm{DP}}$ (i.e., t_5 and t_7) are unavailable because

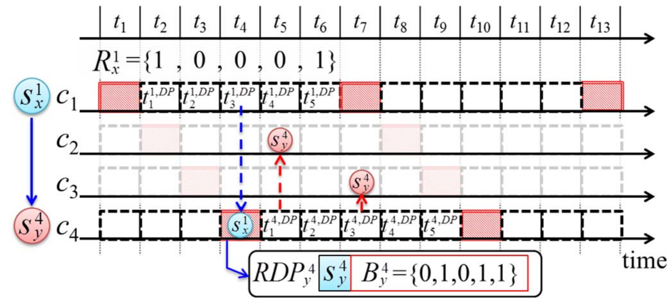

Fig. 3. Illustration of RDP.

it must stay on channels c_2 and c_3 during $t_1^{4,\mathrm{DP}}$ and $t_3^{4,\mathrm{DP}}$ (i.e., t_5 and t_7), respectively. Therefore, $B_y^4[1]$ and $B_y^4[3]$ are set as 0. Consequently, the bitmap announced by station s_y^4 is $B_y^4 = \{0,1,0,1,1\}$.

2) NW: In the NW, sender s_x^i must compete for a transmission opportunity for reserving one data slot with its receiver s_y^j. According to the received RDP_y^j and its available slots, sender s_x^i selects an available data slot, e.g., $t_u^{j,\mathrm{DP}}$, common between sender s_x^i and receiver s_y^j. Therefore, the sender competes for a transmission opportunity at the uth negotiation slot $t_u^{j,\mathrm{CP(NW)}}$ for reserving the corresponding uth data slot $t_u^{j,\mathrm{DP}}$.

a) Data structure of sender station bitmap R_x^i: To calculate the available data slots common between the sender and the receiver, the sender must maintain a bitmap representing its available data slots. The data structure of the *sender station bitmap* R_x^i, which maintains the available data slots of sender s_x^i, is described herein.

Sender Station Bitmap R_x^i: The sender station bitmap R_x^i of station s_x^i is a vector of k binary entries. The value of the uth entry $R_x^i[u]$ is either 1 or 0, representing whether the uth data slot $t_u^{i,\mathrm{DP}}$ of station s_x^i is available or unavailable. That is

$$R_x^i[u] = \begin{cases} 1, & \text{if } t_u^{i,\mathrm{DP}} \text{ of } s_x^i \text{ is available} \\ 0, & \text{otherwise} \end{cases}, \; 1 \le u \le k. \quad (11)$$

■

For example, assume that station s_x^1 intends to send data to receiver s_y^4, as shown in Fig. 3. Assume that station s_x^1 has negotiated with other stations for data exchange at time slots t_3 and t_5. The sender station bitmap R_x^1 maintained by station s_x^1 indicates that the data slots $t_2^{1,\mathrm{DP}}$ and $t_4^{1,\mathrm{DP}}$ (i.e., t_3 and t_5) are unavailable. That is, $R_x^1[2]$ and $R_x^1[4]$ are 0. In the sender station bitmap R_x^1, 1 and 0 represent whether the station s_x^1 is available or unavailable, respectively. In addition, because station s_x^1 intends to send data to the receiver s_y^4, it must stay on channel c_4 during $t_3^{1,\mathrm{DP}}$ (i.e., t_4) to contend for a transmission opportunity. Therefore, $R_x^1[3]$ is set as 0, and the sender station bitmap maintained by station s_x^1 is $R_x^1 = \{1,0,0,0,1\}$.

On receiving the home station bitmap B_y^j announced by receiver s_y^j, sender s_x^i is aware of the available slots of the receiver s_y^j. To select an appropriate negotiation slot, sender s_x^i compares its sender station bitmap R_x^i with the received home station bitmap B_y^j by using a *bitwise logical AND operation* (discussed later) for identifying the available data slots common between sender s_x^i and receiver s_y^j.

However, the time slots indicated in the sender station bitmap R_x^i and home station bitmap B_y^j are asynchronous. For example, as shown in Fig. 3, time slot $t_1^{1,\mathrm{DP}}$ represents time t_2, but $t_1^{4,\mathrm{DP}}$ represents t_5 because the proposed staggered channel model arranges nonoverlapping control periods at different channels; the end of the control period in the ith channel is the beginning of the control period in the $(i+1)$th channel. Therefore, the uth data slots of $t_u^{i,\mathrm{DP}}$ and $t_u^{j,\mathrm{DP}}$ are asynchronous. Therefore, the sender s_x^i must first adjust its sender station bitmap R_x^i by using *bitmap synchronize operations* (discussed later).

The following sections first introduce the bitmap synchronize operations used by sender s_x^i to synchronize R_x^i and B_y^j. Subsequently, the bitwise logical AND operation is applied to identify the available data slots common between the sender and receiver.

b) Bitmap synchronize operations: Let $\Delta_{i,j}$ denote the slot offset between channels c_i and c_j; it$_{,j}$ can be obtained using (12), where $(k+1)$ is the number of slots in a beacon interval

$$\Delta_{i,j} = (j-i)\%(k+1). \quad (12)$$

The bitmap synchronize operations are composed of *bitmap shift* and *bitmap modify* operations. The bitmap shift operation is introduced in the following.

Bitmap Shift Operation LShift$(R_x^i, \Delta_{i,j})$*:* The bitmap shift operation $L\mathrm{Shift}(R_x^i, \Delta_{i,j})$ shifts R_x^i left by $\Delta_{i,j}$ bits, and zeroes replace the discarded bits; the result of $L\mathrm{Shift}(R_x^i, \Delta_{i,j})$ is denoted as $\widetilde{R}_x^{i,j}$

$$\widetilde{R}_x^{i,j}[u] = \begin{cases} R_x^i[u+\Delta_{i,j}], & \text{if } 1 \le u \le (k-\Delta_{i,j}) \\ 0, & \text{otherwise} \end{cases}, 1 \le u \le k. \quad (13)$$

■

Subsequently, the sender s_x^i must modify certain specific bits by using bitmap modify operations. According to the home rule, sender s_x^i must stay on its home channel c_i during the control period $t^{i,\mathrm{CP}}$ which is identical to the duration $t_{k-\Delta_{i,j}+1}^{j,\mathrm{DP}}$ in time domain. Thus, the data slot $t_{k-\Delta_{i,j}+1}^{j,\mathrm{DP}}$ is unavailable for sender s_x^i for further reservation. Therefore, $\widetilde{R}_x^{i,j}[k-\Delta_{i,j}+1]$ is 0. In addition, because the data slots in the next beacon interval in the home channel c_i of sender s_x^i are available, the slots with duration $t_u^{j,\mathrm{DP}}$, where $(k-\Delta_{i,j}+2) \le u \le k$, are available for sender s_x^i for further reservation. Therefore, $\widetilde{R}_x^{i,j}[u]$, where $(k-\Delta_{i,j}+2) \le u \le k$, is 1. The bitmap modify operation is defined in the following.

Bitmap Modify Operation Modify$(\widetilde{R}_x^{i,j}, \Delta_{i,j})$*:* Replace $\widetilde{R}_x^{i,j}[k-\Delta_{i,j}+1]$ with 0 and $\widetilde{R}_x^{i,j}[u]$ with 1, where $(k-\Delta_{i,j}+2) \le u \le k$. That is

$$\widetilde{R}_x^{i,j}[u] = \begin{cases} 0, & \text{if } u = (k-\Delta_{i,j}+1) \\ 1, & \text{if } (k-\Delta_{i,j}+2) \le u \le k \end{cases}, 1 \le u \le k. \quad (14)$$

■

Consequently, the synchronized bitmap $\widetilde{R}_x^{i,j}$, which maintains the available data slots of sender s_x^i, is obtained using

$$\widetilde{R}_x^{i,j} = \mathrm{Modify}\left(L\mathrm{Shift}\left(R_x^i, \Delta_{i,j}\right), \Delta_{i,j}\right). \quad (15)$$

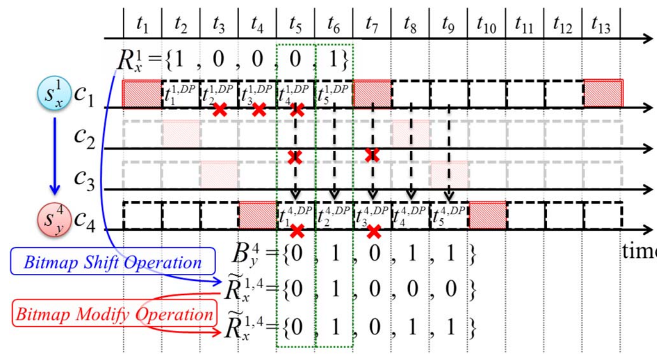

Fig. 4. Illustration of bitmap synchronize operations.

For example, assume that station s_x^1 intends to send data to the receiver s_y^4, as shown in Fig. 4, and assume that the sender station bitmap R_x^1 is {1, 0, 0, 0, 1}. By using (12), slot offset $\Delta_{1,4}$ is obtained as 3. To synchronize R_x^1 with B_y^4, sender s_x^1 applies the bitmap shift operation $L\mathrm{Shift}(R_x^1, \Delta_{1,4})$ and obtains $\widetilde{R}_x^{1,4} = \{0,1,0,0,0\}$. Thus, the time slots indicated by $\widetilde{R}_x^{1,4}[1]$ and $B_y^4[1]$ are both at t_5. Subsequently, sender s_x^1 modifies certain specific bits by using the bitmap modify operation $\mathrm{Modify}(\widetilde{R}_x^{1,4}, \Delta_{1,4})$. Consequently, sender s_x^1 obtains $\widetilde{R}_x^{1,4} = \{0,1,0,1,1\}$ and $\widetilde{R}_x^{1,4}[3] = 0$ because the sender s_x^1 must stay on its home channel c_1 during the control period $t^{1,\mathrm{CP}}$ (i.e., time t_7). Thus, data slot $t_3^{4,\mathrm{DP}}$ is unavailable for sender s_x^1 for further reservation. In addition, $\widetilde{R}_x^{1,4}[4]$ and $\widetilde{R}_x^{1,4}[5]$ are updated to 1 because the data slots in the subsequent beacon interval are available. Therefore, data slots $t_4^{4,\mathrm{DP}}$ and $t_5^{4,\mathrm{DP}}$ (i.e., t_8 and t_9) are available for sender s_x^1.

c) Bitwise logical AND *operation:* To reserve an appropriate data slot for data transmission, sender s_x^i executes the bitwise logical AND operation in the next step to identify the available data slots common between sender s_x^i and receiver s_y^j. The bitwise logical AND operation is defined in the following.

Bitwise Logical AND *Operation:* The binary operator of two bitmap vectors $\widetilde{R}_x^{i,j}$ and B_y^j, denoted by $\mathrm{AND}(\widetilde{R}_x^{i,j}, B_y^j)$, is defined by executing the logical AND operation on the corresponding bits of vectors $\widetilde{R}_x^{i,j}$ and B_y^j. The resultant vector by applying $\mathrm{AND}(\widetilde{R}_x^{i,j}, B_y^j)$ can be obtained by

$$\mathrm{AND}\left(\widetilde{R}_x^{i,j}[u], B_y^j[u]\right) = \begin{cases} 1, & \text{if } \widetilde{R}_x^{i,j}[u] = B_y^j[u] = 1 \\ 0, & \text{otherwise} \end{cases}, 1 \le u \le k. \quad (16)$$

■

Let notation $A_{x,y}^{i,j}$ denote the set of the common available data slots between sender s_x^i and receiver s_y^j. That is

$$A_{x,y}^{i,j} = \left\{ u | \mathrm{AND}\left(\widetilde{R}_x^{i,j}[u], B_y^j[u]\right) = 1, 1 \le u \le k \right\}. \quad (17)$$

For example, as shown in Fig. 5, assume that station s_x^1 intends to send data to receiver s_y^4 and that bitmaps $\widetilde{R}_x^{1,4}$ and B_y^4 are {0, 1, 0, 1, 1} and {0, 1, 1, 0, 1}, respectively. $\mathrm{AND}(\widetilde{R}_x^{1,4}, B_y^4)$ yields $\{0,1,0,0,1\}$. Thus, the set of available data slots common between sender s_x^1 and receiver s_y^4 is $A_{x,y}^{1,4} = \{2,5\}$, indicating that the sender s_x^1 can exchange data with the receiver s_y^4 at $t_2^{4,\mathrm{DP}}$ and $t_5^{4,\mathrm{DP}}$.

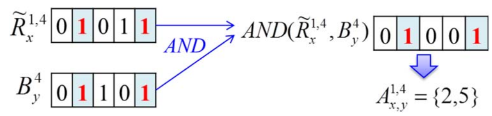

Fig. 5. Illustration of the bitwise logical AND operation.

The sender s_x^i calculates set $A_{x,y}^{i,j}$ on receiving bitmap B_y^j from receiver s_y^j during $t^{j,\mathrm{CP(RDW)}}$ and subsequently selects the uth negotiation slot $t_u^{j,\mathrm{CP(NW)}}$, where $u \in A_{x,y}^{i,j}$ for reserving the uth data slot $t_u^{j,\mathrm{DP}}$. During $t_u^{j,\mathrm{CP(NW)}}$, sender s_x^i and receiver s_y^j should exchange RTS/CTS packets for reserving the uth data slot $t_u^{j,\mathrm{DP}}$. If the result of applying the bitwise logical AND operation is $A_{x,y}^{i,j} = \text{null}$, it indicates that no proper data slot exists for data transmission in the current beacon interval. In this situation, the sender must stay silent during the remaining control period and attempt to reserve a data slot with the receiver in the next beacon interval.

3) Data Period Design: During the data period, each transmission pair can exchange data only in the reserved data slot. The reservation-based approach adapted in the proposed SMC-MAC for allocating data slots avoids packet collisions. Therefore, the RTS/CTS handshake is unnecessary before data packet transmission in the reserved data slot, thereby considerably reducing the control overheads and improving throughput.

VI. Performance Analysis

This section analyzes the spectrum usage performance of the proposed SMC-MAC and an existing SPB scheme [4] during a specific time period ξ. Assume that there are m channels and that the time durations of the control periods in the SMC-MAC and SPB approaches are identical. For simplicity, we define the *pair* as a sender–receiver pair. The proposed home-based policy efficiently improves the control period congestion problem and hence the spectrum usage.

Fig. 6 illustrates the scenarios considered in this analysis. Fig. 6(a) illustrates the SPB scenario. Assume that channel c_1 is the default channel, that all stations must switch to channel c_1 during each control period, and that there is only one control period within the given time period ξ. Fig. 6(b) presents the proposed SMC-MAC scenario. Assume that there are q control periods distributed over q different channels within the given time period ξ, where $q \leq n$.

Let t_p denote the time required for a pair to complete control packet exchanges without interference or collision. Let k denote the maximal number of slots for successfully exchanging control packets during each control period, which is given by

$$k = \left\lfloor \frac{t^{\mathrm{CP}}}{t_p} \right\rfloor. \tag{18}$$

Consider n transmission pairs intending to exchange control packets during ξ, which consists of k slots. From [18], the number of sender–receiver combinations of n transmission pairs is equal to the number of available integer solutions that satisfy the equation $x_1+x_2+\cdots+x_k=n$, where $x_i \geq 0$ and $1 \leq i \leq k$. That is, the number of combinations is $C(k+n-1, n)$. Let $P_k(n,i)$ denote the probability that i pairs from the n pairs successfully exchange control packets on a channel during a control period containing k slots. Theorem 1 calculates $P_k(n,i)$.

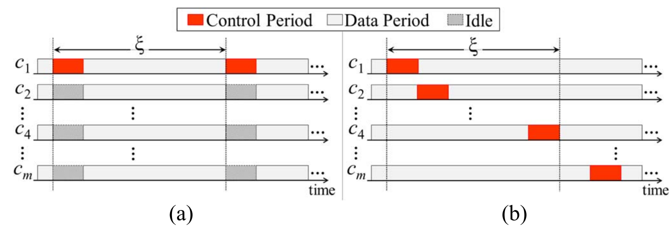

Fig. 6. Performance analysis scenarios. (a) SPB. (b) SMC-MAC.

Theorem 1: $P_k(n,i)$ is evaluated using

$$P_k(n,i) = \frac{(p_1 \times p_2)}{C(k+n-1,n)}; \text{ where} \tag{19}$$

$$p_1 = C(k,i); \text{ and} \tag{20}$$

$$\begin{aligned} p_2 &= \sum_{j=0}^{k-i}\left(C\binom{k-1}{j} \times C\binom{(k-i-j)+(n-i-2(k-i-j))-1}{n-i-2(k-i-j)}\right) \\ &= \sum_{j=0}^{k-i}\left(C\binom{k-1}{j} \times C\binom{n-k+j-1}{n-2k+i+2j}\right). \end{aligned} \tag{21}$$

■

Proof: In Theorem 1, p_1 represents the number of combinations satisfying i pairs that successfully exchange control packets in i of k slots, as shown in (20). This is because only one pair uses a slot to exchange control packets. p_2 describes the number of combinations for the remaining $k-i$ slots in which 1) no pair competes for the slot or 2) two or more pairs compete for the slot. Consider the case wherein no pair competes for using j slots of the $k-i$ slots. The number of combinations in this case is $C(k-i,j)$, which is the first term in (21). This case also indicates that more than one of $n-i$ pairs may compete for each of the remaining $k-i-j$ slots. According to [18], the number of combinations of which each of the $k-i-j$ slots is used by more than one pair out of $n-i$ pairs is equivalent to the available integer solutions that satisfy the equation $x'_1+x'_2+\cdots+x'_{k-i-j}=n-i$, where $x'_u \geq 2$ and $1 \leq u \leq k-i-j$. Consequently, the number of combinations is $C(n-k+j-1, n-2k+i+2j)$, which is the second term in (21). Because j ranges from 0 to $k-i$, (21) depicts the number of combinations of p_2. Consequently, $P_k(n,i)$ can be obtained by evaluating p_1 and p_2, as shown in (19). ■

To accurately estimate the probability depicted in Theorem 1, the random backoff mechanism is considered in the following analysis. Let $R_k(n,i)$ denote the probability of i pairs out of n pairs successfully exchanging control packets on a channel through the random backoff mechanism during a control period containing k slots. Theorem 2 calculates the probability of $R_k(n,i)$.

Theorem 2: $R_k(n,i)$ is evaluated using

$$R_k(n,i) = \sum_{\alpha=0}^{i} \left(P_k(n,\alpha) \times P_{k-\alpha}(n-\alpha, i-\alpha)\right). \quad (22)$$

■

Proof: Expression (22) reveals that $R_k(n,i)$ is derived by summing all chances of obtaining $P_k(n,i)$. Consider the case in which each chance competes for using i of the k slots through the random backoff mechanism. $P_k(n,\alpha)$ describes the probability of α out of n pairs successfully exchanging control packets during the control period containing k slots. Similarly, the probability of $i-\alpha$ out of $n-\alpha$ pairs competing to exchange control packets in the remaining $k-\alpha$ slots is derived using $P_{k-\alpha}(n-\alpha, i-\alpha)$. $P_k(n,\alpha)$ and $P_{k-\alpha}(n-\alpha, i-\alpha)$ represent the probabilities obtained in the *carrier sense multiple access* and random backoff mechanisms for each chance to determine $P_k(n,i)$, respectively. Consequently, $R_k(n,i)$ is derived using $P_k(n,\alpha)$ and $P_{k-\alpha}(n-\alpha, i-\alpha)$ for each $0 \le \alpha \le i$, as shown in (22). ■

With these theorems and assumptions, the spectrum usage performances of the proposed SMC-MAC and the existing SPB scheme [4] are estimated on m channels for the given time period ξ.

For any channel with k slots during ξ, let $b_\xi^A(n,i)$ denote the probability of i out of n pairs successfully exchanging control packets on m channels by using scheme A, where scheme A is either an SPB or an SMC-MAC. Because only one control period is present during ξ, $b_\xi^{\mathrm{SPB}}(n,i)$ is evaluated using (23), where $0 \le i \le k$

$$b_\xi^{\mathrm{SPB}}(n,i) = R_k(n,i). \quad (23)$$

For $A = $ SMC-MAC, assume that n transmission pairs are equally distributed over q channels. In other words, $\lceil n/q \rceil$ pairs intend to exchange control packets on each channel during ξ. Let σ represent $\lceil n/q \rceil$. Similar to (23), $b_\xi^{\mathrm{SMC}}(\sigma,i)$ is calculated using (24), where $0 \le i \le k$

$$b_\xi^{\mathrm{SMC}}(\sigma,i) = R_k(\sigma,i). \quad (24)$$

Let E_{suc}^A denote the expected number of pairs that successfully exchange control packets by using A during ξ. A high E_{suc}^A indicates high spectrum usage. $E_{\mathrm{suc}}^{\mathrm{SPB}}$ is given by

$$E_{\mathrm{suc}}^{\mathrm{SPB}}(n) = \sum_{i=0}^{k} \left(i \times b_\xi^{\mathrm{SPB}}(n,i)\right). \quad (25)$$

Similarly, (26) estimates the $E_{\mathrm{suc}}^{\mathrm{SMC}}$, considering that q control periods are present during ξ

$$E_{\mathrm{suc}}^{\mathrm{SMC}}(n) = q \times \left(\sum_{i=0}^{k} \left(i \times b_\xi^{\mathrm{SMC}}(\sigma,i)\right)\right). \quad (26)$$

Recall that t^{CP} and t^{DP} denote the time durations required for a pair to complete control and data packet exchanges, respectively. Z_{SPB} and Z_{SMC} denote the spectrum usage of the SPB and SMC-MAC approaches during ξ, respectively, and are calculated using (27) and (28), respectively

$$Z_{\mathrm{SPB}}(n) = \frac{\left[E_{\mathrm{suc}}^{\mathrm{SPB}}(n) \times (t^{\mathrm{CP}} + t^{\mathrm{DP}})\right]}{(m \times \xi)} \quad (27)$$

$$Z_{\mathrm{SMC}}(n) = \frac{\left[E_{\mathrm{suc}}^{\mathrm{SMC}}(n) \times (t^{\mathrm{CP}} + t^{\mathrm{DP}})\right]}{(m \times \xi)}. \quad (28)$$

Let $I(n)$, derived using (29), denote the ratio of $Z_{\mathrm{SMC}}(n)$ to $Z_{\mathrm{SPB}}(n)$. Given $n > 0$, $I(n) > 1$ indicates that SMC-MAC has higher spectrum usage than does the SPB approach

$$I(n) = \frac{Z_{\mathrm{SMC}}(n)}{Z_{\mathrm{SPB}}(n)} = \frac{E_{\mathrm{suc}}^{\mathrm{SMC}}(n)}{E_{\mathrm{suc}}^{\mathrm{SPB}}(n)} = \frac{q \times \left(\sum_{i=0}^{k} \left(i \times b_\xi^{\mathrm{SMC}}(\sigma,i)\right)\right)}{\sum_{i=0}^{k} \left(i \times b_\xi^{\mathrm{SPB}}(n,i)\right)}. \quad (29)$$

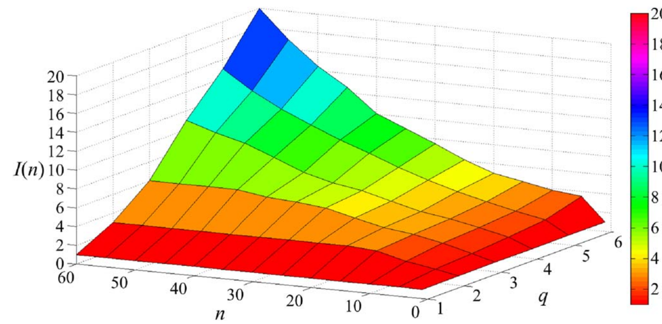

Fig. 7. Analysis of the performance improvement $I(n)$ of SMC-MAC compared with the SPB approach.

Fig. 7 depicts the network throughput improvement $I(n)$ of SMC-MAC compared with the SPB approach by using $k = 6$. The parameters n and q vary and range from 1 to 60 and 1 to 6, respectively. This figure reveals that SMC-MAC substantially outperforms the SPB approach in spectrum utilization when the communication pairs are equally distributed over the channels. Two reasons explain these results. First, SMC-MAC includes more control periods than the SPB approach does, providing more opportunities for control packet exchange on the channels. Second, SMC-MAC equally distributes the communication pairs over the channels, reducing the collision rate. Hence, SMC-MAC exhibits a higher expected number of communication pairs than does the SPB approach when the number of communication pairs or channels increases.

VII. Performance Evaluation

This section examines and compares the performance improvement of the proposed SMC-MAC with current multichannel MAC protocols in terms of network throughput, control packet collision ratio, packet delay time, packet discarding, packet loss ratio, control overhead, and robustness. The SMC-MAC approach is compared with MMAC [4], TMMAC [5], WiFlex [7], CAMMAC [8], and DSP [23]. In addition, by assuming that there is a central controller that knows complete information about the network, including channel condition, offered traffic, traffic arrival time, and location of each station,

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Simulation Tool	NS-2 version 2.35
Propagation Model	Two-ray-ground, Shadowing, Nakagami
Number of Channels	3, 6
Communication Pairs	10~60
Transmission Range	250 m
Transmission Rate	2 Mbps/channel
Data Packet Size	1024 bytes
Length of Beacon Interval	200 ms
Control Period Duration	20 ms
Negotiation Slot Duration	2 ms
Data Slot Duration	20 ms
Total Offered Traffic	50-1250 packets/s
Buffer Size	100 KB
Dimension of the Topography	800m × 800m
Simulation Time	500 seconds
Simulation Repetitions	1500 times

the exhaustive search can be used to obtain the optimal network performance which is treated as the benchmark and is denoted by *OPT*.

A. Evaluation Environment

To simulate a realistic environment, we employ Network Simulator (NS-2; Ver. 2.35) [14], which has been widely used in simulating realistic and expandable networks. In addition, we modify multichannel modules as described in [15] to incorporate multichannel carrier sensing. The simulation parameters are listed in Table II. According to the MMAC analysis results [4], the optimal performance is obtained when the data packet size and control period duration are 1024 B and 20 ms, respectively; hence, these values were adopted in the simulation. In addition, for implementing SMC-MAC, the duration of each data slot is equal to that of the control period. Channel switching delay is brief (80 μs according to [10]) and hence ignored.

Each performance result is the average of 1500 experiments. Here, 95% confidence interval is always smaller than 5% for all reported values.

B. Evaluation Results

1) Network Throughput: Because path loss arises from many factors, such as path variation, obstacles, terrain, and atmospheric conditions, propagation models usually focus on path loss realization through the auxiliary task of predicting signal distribution over different regions. Fig. 8 presents the influence of three propagation models—*two-ray ground*, *shadowing*, and *Nakagami*—on the throughput of the proposed SMC-MAC. The number of channels is 3, and the offered traffic is maintained at 1250 packets/s. The number of communication pairs varies from 10 to 60. As revealed in Fig. 8, network throughput decreases in the shadowing and Nakagami propagation models, primarily because of the variation in the received signal strength.

Because most wireless network studies use the two-ray ground model, the channel model two-ray ground is applied in our subsequent simulations; it considers a ground-reflected propagation path between the transmitter and receiver in addition to the line-of-sight path.

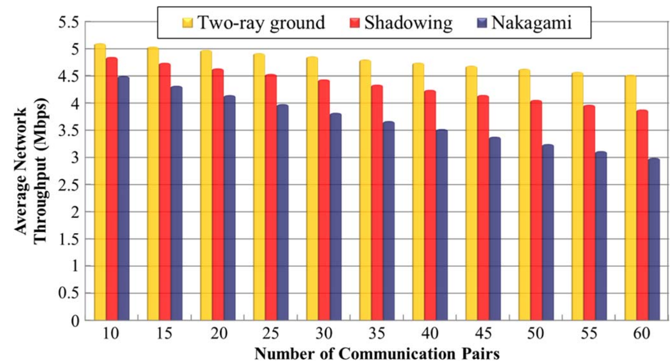

Fig. 8. Influence of propagation models on the network throughput of SMC-MAC.

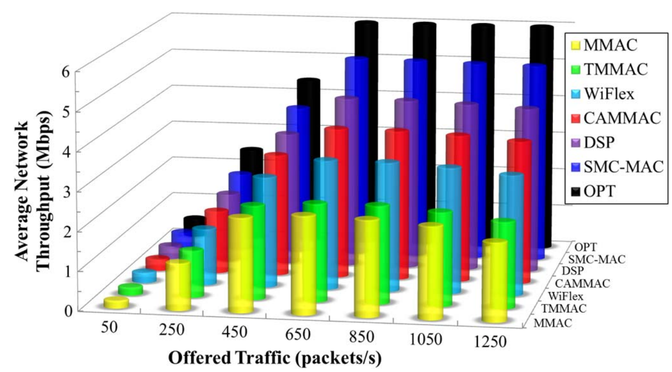

Fig. 9. Average network throughputs of SMC-MAC and existing MAC protocols.

Fig. 9 illustrates the average network throughput performance of MMAC, TMMAC, WiFlex, CAMMAC, DSP, OPT, and the proposed SMC-MAC protocols. The number of channels is 3, with the offered traffic varying from 50 to 1250 packets/s. As seen in the figure, SMC-MAC obtains higher network throughput compared with the existing protocols because the transmission pairs applying the MMAC, TMMAC, WiFlex, and CAMMAC approaches can exchange control packets only on the specific channel, leading to more control packet collisions and fewer transmission pairs successfully exchanging control packets. On the other hand, the DSP approach achieves high network throughput by using more than one antenna; however, this increases the hardware cost. As shown in Fig. 9, the proposed SMC-MAC is closer to the optimal solution (OPT), as compared with the other five compared algorithms.

Furthermore, the ratio of the durations of control and data periods affects the network throughput of SPB-class MAC protocols. Let C/D represent the aforementioned ratio. Fig. 10 reports the influence of C/D on average network throughput. The number of channels is 3, with the offered traffic and C/D varying from 50 to 1250 packets/s and 0.1 to 0.4, respectively.

As shown in Fig. 10, the proposed SMC-MAC obtains higher network throughput than the existing protocols do. The simulation results reveal that the optimal network throughput of SMC-MAC is obtained when C/D is 0.1, whereas MMAC, TMMAC, and WiFlex exhibit the optimal network throughput when C/D is 0.2. These results demonstrate that SMC-MAC

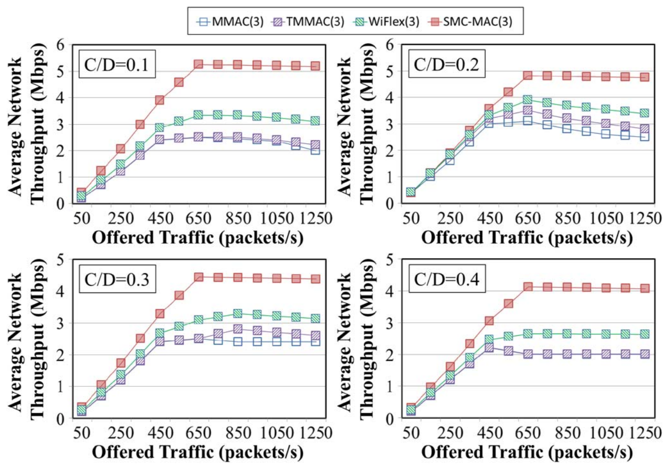

Fig. 10. Network throughputs of SMC-MAC and existing MAC protocols.

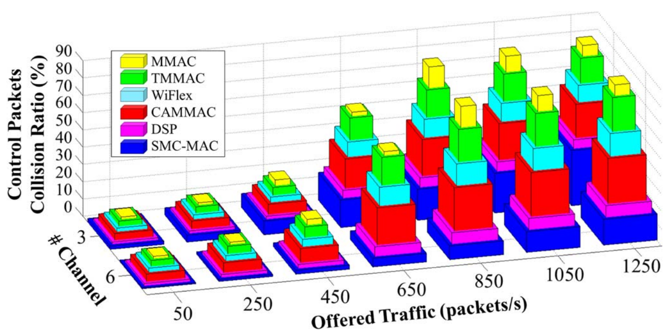

Fig. 11. Control packet collision ratios of SMC-MAC and existing MAC protocols.

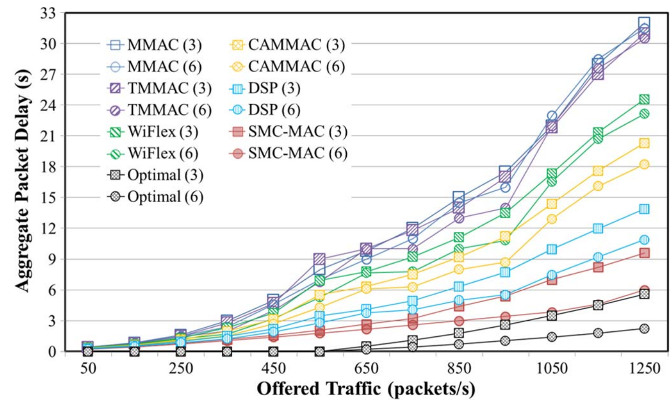

Fig. 12. Average packet delays of SMC-MAC and existing MAC protocols.

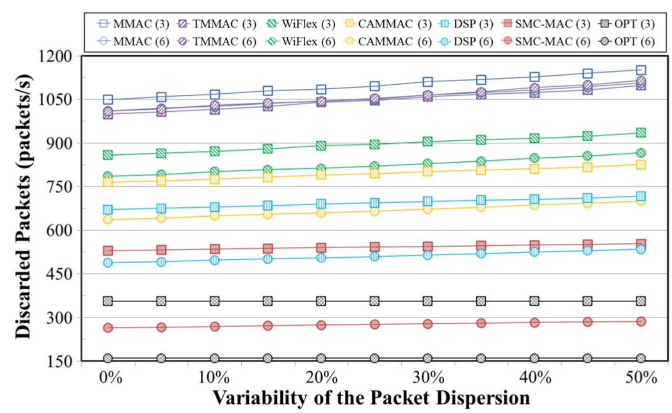

Fig. 13. Packet discarding characteristics of SMC-MAC and existing MAC protocols.

efficiently alleviates contention and collisions and considerably improves network throughput.

2) Control Packet Collision Ratio: Fig. 11 compares the control packet collision ratio of the proposed SMC-MAC with those of the existing protocols. The number of channels is either 3 or 6, with the offered traffic varying from 50 to 1250 packets/s. As shown in the figure, the control packet collision ratio of the proposed SMC-MAC is the lowest in all cases. By contrast, the control packet collision ratios of the existing protocols are less than 25% only when the offered traffic is less than 450 packets/s; when offered traffic exceeds 450 packets/s, the ratio disproportionately increases. At a traffic of 1250 packets/s, the control packet collision ratios of the MMAC, TMMAC, WiFlex, CAMMAC, and DSP protocols are 85.9%, 80.2%, 65.6%, 56%, and 36.8%, respectively, whereas those of the proposed SMC-MAC are 31.6% and 14.8% for 3 and 6 channels, respectively. Moreover, for traffic less than 450 packets/s, the collision ratios of the proposed SMC-MAC are less than 7.9% and 2.3% for 3 and 6 channels, respectively.

3) Packet Delay: Fig. 12 compares the average packet delay of the proposed SMC-MAC with those of existing protocols; the offered traffic varies from 50 to 1250 packets/s, and the number of channels is either 3 or 6. There are two major causes of packet delay. The first is that control overheads increase with traffic and also lead to the packet delay. The second is that the transmission opportunities are fixed, so heavy traffic means that most packets should wait for transmission opportunities; hence, the packet delays are increased. As shown in Fig. 12, the packet delays of all mechanisms increase with the offered traffic.

In the MMAC, TMMAC, and WiFlex approaches, transmission pairs exchange control packets only on the specific channel during the control period. In CAMMAC, the transmission pairs exchange control packets only on the specific channel. This leads to more control packet collisions during heavy traffic loads, causing fewer transmission pairs that successfully exchange control packets. The SMC-MAC design can efficiently reduce the occurrence of control packet collisions, primarily because all communication pairs are likely to be distributed over all channels. Thus, the network throughput can be increased, and hence, the transmission delay of data packets is substantially reduced. As shown in Fig. 12, the proposed SMC-MAC is closer to the optimal solution (OPT) than the other compared algorithms. As shown in Fig. 12, the proposed SMC-MAC restricts packet delays to less than 10 s and outperforms MMAC, TMMAC, WiFlex, CAMMAC, and DSP in all cases.

4) Packet Discarding: Fig. 13 compares the packet discarding characteristics of the proposed SMC-MAC with those of existing protocols. When the packet buffer is completely filled with the captured packets, the station discards older packets and stores newer packets. Packet dispersion variation affects the number of packets discarded in MAC protocols [16], [17]. The *coefficient of variation (CoV)* is a normalized measure

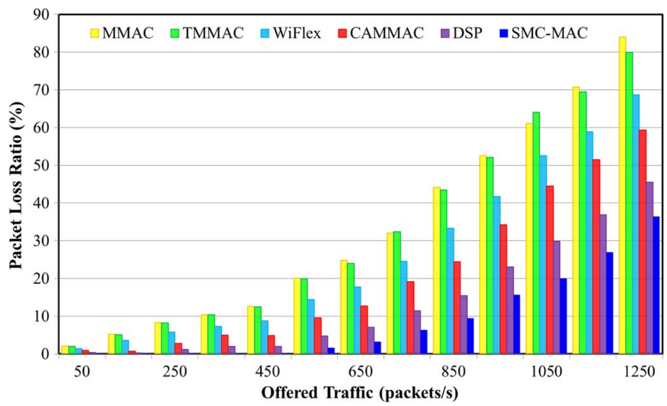

Fig. 14. Packet loss ratios of SMC-MAC and existing MAC protocols.

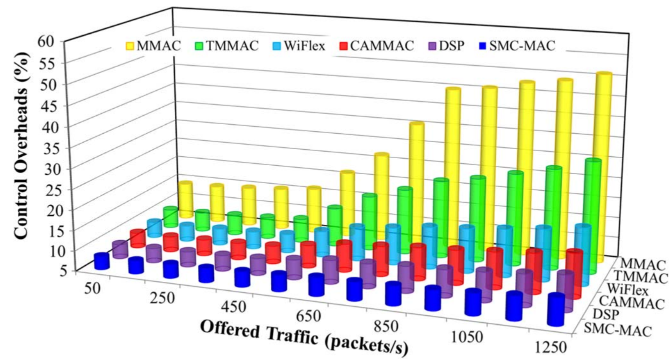

Fig. 15. Control overheads of SMC-MAC and existing MAC protocols.

of the variability of frequency distribution. In (30), the CoV of packet dispersion is used to estimate the degree of packet dispersion variation. CoV is defined as the ratio of the standard deviation σ to the mean μ of packets offered between stations

$$\text{CoV} = \left(\frac{\sigma}{\mu}\right) \times 100\%. \tag{30}$$

The mean μ and standard deviation σ of the packets can be determined using (31) and (32), respectively, where $|H^i|$, q_x^i, and m denote the number of home stations in channel c_i, packets offered to station s_x^i, and channels, respectively

$$\mu = \frac{\left(\sum_{i=1}^{m}\sum_{x=1}^{|H^i|} q_x^i\right)}{\left(\sum_{i=1}^{m}|H^i|\right)} \tag{31}$$

$$\sigma = \sqrt{\frac{\left(\sum_{i=1}^{m}\sum_{x=1}^{|H^i|}(q_x^i-\mu)^2\right)}{\left[\left(\sum_{i=1}^{m}|H^i|\right)-1\right]}}. \tag{32}$$

Fig. 13 reports the influence of CoV on packet discarding. The number of channels is either 3 or 6, and the offered traffic is 1250 packets/s. CoV varies from 0% to 50%. As shown in Fig. 13, the number of packets discarded in MMAC, TMMAC, WiFlex, CAMMAC, and DSP increases with packet dispersion variation. By contrast, SMC-MAC maintains a near-constant value of packet discarding, even with increasing packet dispersion variability, primarily because SMC-MAC efficiently improves the network throughput. Consequently, SMC-MAC efficiently alleviates packet discarding induced by buffer overflow. As shown in Fig. 13, the proposed SMC-MAC is closer to the optimal solution (OPT) than the other compared algorithms.

5) Packet Loss Ratio: Fig. 14 compares the packet loss ratios of the proposed SMC-MAC and the existing protocols. The simulation parameters are similar to those used in Fig. 13. Packet loss arises from a number of factors, including signal degradation over the network medium because of multipath fading, packet collision, buffer overflow, signal interference, and channel congestion. Buffer overflow is not addressed in the MMAC, TMMAC, WiFlex, CAMMAC, and DSP approaches, leading to high packet drops during heavy traffic. As shown in Fig. 14, the packet loss ratios of MMAC, TMMAC, WiFlex, CAMMAC, and DSP increase considerably with the increased traffic, whereas that of SMC-MAC increases slowly, primarily because SMC-MAC uses the home and rendezvous rules that efficiently distribute all stations on different channels. Such data traffic distribution alleviates contention and collision. The proposed SMC-MAC restricts the packet loss ratio to less than 10% when traffic is less than 650 packets/s.

6) Control Overheads: Fig. 15 compares the control overheads of the proposed SMC-MAC and existing protocols. The offered traffic varies from 50 to 1250 packets/s, and the number of channels is 3. In MMAC and TMMAC, each transmission pair must exchange ATIM/ATIM-ACK/ATIM-RES control packets on a specific channel during the control period. For the MMAC approach, RTS/CTS handshakes are mandatory before data exchange during the data period, leading to high control overheads. In the WiFlex, CAMMAC, DSP, and SMC-MAC approaches, each transmission pair only requires an RTS/CTS handshake before data exchange.

As shown in Fig. 15, the control overheads of MMAC and TMMAC increase substantially with traffic, whereas those of WiFlex, CAMMAC, DSP, and SMC-MAC increase slowly. Although SMC-MAC has additional RDP control packets, the RDP packets ensure that potential senders are aware of the available slots of home stations. SMC-MAC restricts the control overheads to less than 11.5% and outperforms the other protocols in all cases, primarily because SMC-MAC distributes home stations over all channels, efficiently preventing RTS/CTS control packet collisions. The SMC-MAC design reduces the number of retransmissions of control packets, thus substantially lowering the control overheads.

VIII. Conclusion

This paper has presented an efficient SMC-MAC that applies a staggered channel model and exploits multichannel bandwidth resources. Control and data packet transmissions are operated concurrently on different channels. In addition, the proposed home and rendezvous rules efficiently distribute all stations, and thus the control overheads, on different channels, alleviating contention and collision and further improving network throughput. Performance results reveal that the proposed SMC-MAC outperforms existing multichannel MAC protocols in the network throughput, control packet collision ratio, packet delay time, packet discarding, packet loss ratio, control overhead, and robustness.

REFERENCES

[1] *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band*, IEEE Std. 802.11b-1999, 1999.

[2] *Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Std 802.11-1999, Aug. 1999.

[3] J. Mo, H. S. W. So, and J. Walrand, "Comparison of multichannel MAC protocols," *IEEE Trans. Mobile Comput.*, vol. 7, no. 1, pp. 50–65, Jan. 2008.

[4] J. So and N. Vaidya, "Multi-channel MAC for ad hoc networks: Handling multi-channel hidden terminals using a single transceiver," in *Proc. ACM MobiHoc*, Tokyo, Japan, May 2004, pp. 222–233.

[5] J. Zhang, G. Zhou, C. Huang, S. H. Son, and J. A. Stankovic, "TMMAC: An energy efficient multi-channel MAC protocol for ad hoc networks," in *Proc. IEEE ICC*, Glasgow, Scotland, Jun. 2007, pp.3554–3561.

[6] W. T. Chen, J. C. Liu, T. K. Huang, and Y. C. Chang, "TAMMAC: An adaptive multi-channel MAC protocol for MANETs," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4541–4545, Nov. 2008.

[7] J. Lee, J. Mo, T. M. Trung, J. Walrand, and H. S. W. So, "Design and analysis of a cooperative multichannel MAC protocol for heterogeneous networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 7, pp. 3536–3548, Sep. 2010.

[8] S. R. Singh and M. Motani, "Cooperative multi-channel access for 802.11 mesh networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 9, pp. 1684–1693, Oct. 2012.

[9] A. Jeng, R. Jan, C. Li, and C. Chen, "Release-time-based multichannel MAC protocol for wireless mesh networks," *Comput. Netw.*, vol. 55, no. 23, pp. 2176–2195, Jun. 2011.

[10] T. Luo, M. Motani, and V. Srinivasan, "Energy-efficient strategies for cooperative multichannel MAC protocols," *IEEE Trans. Mobile Comput.*, vol. 11, no. 4, pp. 553–566, Apr. 2012.

[11] Z. Zhou, Z. Peng, J. H. Cui, and Z. Jiang, "Handling triple hidden terminal problems for multichannel MAC in long-delay underwater sensor networks," *IEEE Trans. Mobile Comput.*, vol. 11, no. 1, pp. 139–154, Jan. 2012.

[12] Y. Liu, L. X. Cai, and X. Shen, "Spectrum-aware opportunistic routing in multi-hop cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 30, no. 10, pp. 1958–1968, Nov. 2012.

[13] F. Hou, L. X. Cai, X. S. Shen, and J. Huang, "Asynchronous multichannel MAC design with difference-set-based hopping sequences," *IEEE Trans. Veh. Technol.*, vol. 60, no. 4, pp. 1728–1739, May 2011.

[14] VINT Group, UCB/LBNL/VINT Network Simulator NS (Version 2). [Online]. Available: http://www.isi.edu/nsnam/ns

[15] MW-Node Path for NS2 to Support Multiple Interfaces & Multiple Channels. [Online]. Available: http://www.q2s.ntnu.no/~paquerea/ns.php

[16] R. Gusella, "Characterizing the variability of arrival processes with indexes of dispersion," *IEEE J. Sel. Areas Commun.*, vol. 9, no. 2, pp. 203–211, Feb. 1991.

[17] C. Dovrolis, P. Ramanathan, and D. Moore, "Packet-dispersion techniques and a capacity-estimation methodology," *IEEE/ACM Trans. Netw.*, vol. 12, no. 6, pp. 963–977, Dec. 2004.

[18] S. S. Epp, *Discrete Mathematics With Applications*. Pacific Grove, CA, USA: Brooks/Cole, Dec. 2003.

[19] D. N. M. Dang, C. S. Hong, and S. Lee, "A hybrid multi-channel MAC protocol for wireless ad hoc networks," *Wireless Netw.*, vol. 21, no. 2, pp. 387–404, Feb. 2015.

[20] S. Debroy, S. De, and M. Chatterjee, "Contention based multichannel MAC protocol for distributed cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 12, pp. 2749–2762, Dec. 2014.

[21] G. Y. Chang, W. H. Teng, H. Y. Chen, and J. P. Sheu, "Novel channel-hopping schemes for cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 13, no. 2, pp. 407–421, Feb. 2014.

[22] C. M. Chao and H. C. Tsai, "A channel-hopping multichannel MAC protocol for mobile ad hoc networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 9, pp. 4464–4475, Nov. 2014.

[23] K. H. Almotairi and X. S. Shen, "A distributed multi-channel MAC protocol for ad hoc wireless networks," *IEEE Trans. Mobile Comput.*, vol. 14, no. 1, pp. 1–13, Jan. 2015.

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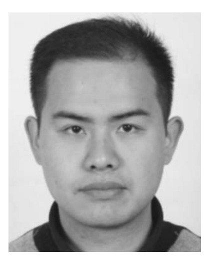

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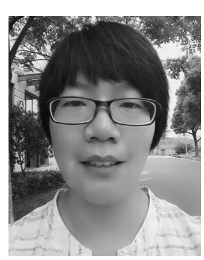

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