STB-MAC: Staggered Multichannel Traffic Balanced MAC Protocol in Wireless Networks

Chih-Yung Chang, *Member, IEEE*, Chao-Tsun Chang, Tzu-Chia Wang, and Yun-Jung Lu

***Abstract*—Multichannel medium-access-control (MAC) protocols have attracted much attention because they possess the ability to boost the capacity of wireless networks. In the literature, a staggered channel model has been proposed to handle the rendezvous problem and improve the bandwidth usage. However, it might cause a channel traffic unbalance (CTU) problem in which certain channels are busy whereas others are idle. It is a great challenge to balance the traffic of each channel because each station finds it difficult to manage the incoming slots in a distributed manner. To cope with the CTU problem, a novel MAC protocol the staggered multichannel traffic-balanced MAC (STB-MAC) protocol, is proposed, which applies the staggered channel model that migrates traffic from busy channels to idle channels. Performance evaluation reveals that the proposed STB-MAC achieves superior performance in network throughput and packet delay.**

***Index Terms*—Ad hoc networks, channel traffic unbalance (CTU) problem, multichannel medium-access-control (MAC) protocol, staggered multichannel traffic-balanced protocol.**

I. Introduction

MULTICHANNEL medium-access-control (MAC) protocols have received considerable interest from researchers in recent years. When a multichannel MAC protocol is applied, stations can exploit frequency diversity to improve the network throughputs and to reduce the transmission latency. However, the main challenge of developing a multichannel MAC protocol is achieving coordination among stations that possibly operate on different channels. The existing studies can be classified into three approaches: 1) dedicated-control-channel-based (DCCB), 2) hopping-based (HB), and 3) split-phase-based (SB).

The DCCB approaches [1]–[5] divide the frequency into a narrow channel and a group of equal-width channels, which are called the control channel and the data channel, respectively. The sender and the receiver exchange control packets via the control channel to reserve the slot of the data channel for exchanging data packets. The DCCB approaches use a common control channel to provide stations with rendezvous opportunities. However, the channel usage information is not easy to maintain because each station is only equipped with a single antenna. When a station switches to the data channel for data exchange, it cannot further maintain the channel usage information, which can be only obtained by listening to the control channel. As a result, a multichannel hidden terminal problem might occur. To solve the multichannel hidden terminal problem, the stations are equipped with more antennas. One antenna remains on the control channel and maintains the channel usage information, whereas the other antennas are used for data exchange on the data channels. However, using two or more antennas increases the hardware cost.

In HB approaches [6]–[8], each station frequently switches its channel according to its own channel hopping sequences. When two stations meet on the same channel, they are able to exchange and maintain the information of their hopping sequences. Afterward, if a sender intends to exchange data with a receiver, it switches to the receiver's hopping channel. When the sender and receiver meet on the same channel, they conflict with one another in their efforts to obtain a transmission opportunity for data exchange. The advantage of the HB approaches is that they cope with the rendezvous problem. Nevertheless, several occurrences of channel hopping considerably increase the delay and cause redundant energy consumption.

In SB approaches [9]–[14], each node is equipped with a single transceiver. The time of each channel is divided into many beacon intervals, and all channels are synchronized. Each beacon interval consists of an ad hoc traffic indication message (ATIM) window and a data window. In the ATIM window, all stations switch to a predefined channel for rendezvous. During this period, the senders struggle to obtain a transmission opportunity to negotiate with its receiver for reserving available data slots. In the data window, stations exchange packets on the reserved channels. However, substantial contentions and collisions may occur because all transmission pairs compete to exchange control packets in the ATIM window in a predefined channel. Moreover, the bandwidth usage must be still improved because all channels, except the predefined channel, are idle in the ATIM window.

To solve the aforementioned problems, a staggered channel model has been proposed in [15] to arrange the nonoverlapped ATIM windows among multichannel channels. Each ATIM window is shifted to the right of the previous channel's ATIM window and arranged in a staggered manner. The staggered channel model can improve the bandwidth usage. However, it still suffers from the channel traffic unbalance (CTU) problem. If the most popular receivers are assigned to the same home channel, that channel will be busy, but the other channels will

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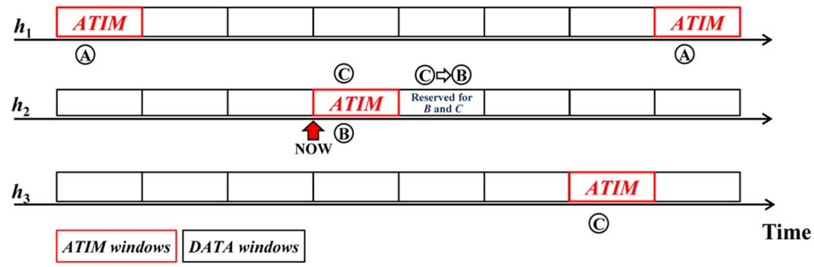

Fig. 1. Example that applies the staggered channel model.

be idle. This occurs because all transmission pairs compete to reserve a few data slots on the same channel.

To cope with the CTU problem, a novel multichannel MAC protocol the staggered multichannel traffic-balanced MAC (STB-MAC) protocol, is proposed, which employs the staggered channel model [15]. The proposed STB-MAC inherits all the benefits of the staggered channel model, including the improvements in channel usage and the competing control packets, and resolves the CTU problem that occurs in the staggered channel model. The main purpose of the proposed STB-MAC is to migrate the traffic from busy to idle channels. The traffic migrations can help reduce the average transmission latencies of the busy channels and increase the usage of idle channels. Therefore, the network throughputs and transmission latency can be considerably improved.

The remainder of this paper is organized as follows. Section II introduces the applied staggered channel model. Section III describes the system model and problem formulation of this paper. The proposed STB-MAC protocol and its performance evaluation are presented in Sections IV and V, respectively. Finally, Section VI concludes this paper.

II. Staggered Channel Model

Assume that m nonoverlapped channels $C = \{h_1, h_2, \ldots, h_m\}$ exist. The timeline of each channel is divided into several beacon intervals, and each interval consists of an ATIM window and a data window. The ATIM window is mainly used for stations to compete in obtaining a transmission opportunity for exchanging control messages, thereby reserving a data slot for data exchange. The data window consists of several data slots that can be reserved by stations for data exchange. The lengths of a data slot and an ATIM window are identical. Each ATIM window is shifted p data slots, i.e., $p \geq 2$, to the end of the previous channel's ATIM window and arranged in a staggered manner. Therefore, the ATIM windows of different channels do not overlap.

Each station is equipped with a single half-duplex transceiver, which allows for either sending or receiving data simultaneously. In addition, each station owns a unique MAC address. The concept of the home channel [15] is applied herein. Each station s_i has the common built-in channel mapping function $f(\cdot)$, which determines its home channel. Expression (1) gives the derivation of the home channel of station s_i, where s_i_MAC.Address represents the MAC address of s_i. Through the exchange of beacons, each station knows the MAC addresses; thus, the home channels of its neighboring stations are as follows:

$$s_i.\text{home} = f(s_i\text{\_MAC.Address}, m). \quad (1)$$

All stations that treat channel h_k as a home channel are called home stations of channel h_k. To cope with the rendezvous problem, each home station s_i participates in the whole ATIM window of its home channel s_i.home. In the ATIM window, station s_i can exchange control packets with potential sender s_j, which must switch to channel s_i.home at the beginning of the ATIM window. Once the transmission pair of stations s_i and s_j obtains the transmission opportunity, they exchange control packets in an effort to reserve one data slot for further data exchange in channel s_i.home.

In general, all stations are equally distributed to different channels. To cope with the rendezvous problem, each station has to remain on its home channel in the ATIM window of its home channel. A sender switches to the receiver's home channel at the start of the ATIM window and negotiates with its receiver so that a rendezvous between the two can take place. The negotiation between the sender and the receiver mainly tries to reserve a data slot in the data window. After the exchange in the ATIM window, the transmission pair exchanges packets in the reserved data slot. The staggered channel model distributes stations to different home channels. Because the ATIM window of different channels are not overlapped, certain stations exchange control packets in ATIM windows of one particular channel, whereas other stations exchange data packets in data windows of all the other channels simultaneously. Compared with the DCCB and SB channel models, the staggered channel model can reduce the phenomenon of contentions in the ATIM window and improve the channel usage.

Fig. 1 provides an example to illustrate the staggered channel model. Let channels h_1, h_2, and h_3 be the home channels of stations A, B, and C, respectively. Assume that station C intends to send packets to station B. At the start of the ATIM window on h_2, station C must switch to B's home channel h_2 to negotiate with station B. Meanwhile, station B listens to h_2. By contrast, station A possesses no packet to exchange with station B, does not switch to h_2, and turns off its transceiver for energy conservation. After negotiating in the ATIM window, stations B and C reserve the first incoming data slot of channel h_2 for data exchange, and the other stations change the first incoming data slot to a reserved status, as shown in Fig. 1.

The staggered channel model that uses the channel mapping function aims to assign an equal number of stations to each channel. However, if the most popular receivers are assigned to the same home channel, that channel will be busy. This situation leads to two severe problems. First, all transmission pairs compete to reserve a few data slots on the same channel, whereas other channels are idle. Second, all senders compete for transmission opportunities in the same ATIM window, leading to contention among senders. Based on the staggered channel model, this paper attempts to solve the CTU problem by proposing a MAC protocol to migrate the traffic loads of busy channels to the idle channels.

III. System Model and Problem Formulation

A. Motivation

Although the staggered channel model considerably improves channel usage, it might cause CTU problems. Consider time interval T. Let r_k denote the number of data exchanges requested during time interval T on channel h_k. Let a_k denote the available data slots during time interval T on channel h_k. Channel h_k is said to be busy during time interval T if $r_k > a_k$ and is said to be idle if $r_k < a_k$. The CTU problem occurs if busy and if idle channels exist during a given time interval T.

Two major events cause the CTU problem. First, the channel mapping function unevenly maps the stations to multiple channels. As a result, certain channels that are assigned few stations will be idle, whereas the other channels that are assigned many stations will be busy, thus causing the CTU problem. Another reason is the problem of unbalanced traffic. Although each channel has been assigned the same number of stations, some channels may have light traffic loads because no sender intends to exchange data with the stations on that channel. Consequently, these channels will be idle; thus, the CTU problem occurs. Stations on the busy channels increase the average transmission delay, whereas the bandwidth resources of idle channels are wasted. Therefore, the traffic loads must be dispersed into idle channels as soon as the CTU problem occurs.

B. System Model

For clarity, the following provides assumptions under which the proposed multichannel MAC protocol operates. This paper considers n stations s_i in ad hoc networks, where i denotes the station ID from 1 to n. In this paper, it is assumed that all stations are synchronized. To achieve synchronization, all stations apply the multichannel synchronization mechanism [18] while they simultaneously exchange their MAC addresses. The synchronization mechanism is considered an essential aspect of the design of a working implement and thus paves the way for efficient multichannel MAC protocols. Each station is equipped with only a half-duplex transceiver; thus, no station can send and receive data simultaneously. The transceiver is able to switch among multiple channels on demand. Each station listens to and is thus aware of the activities of neighboring stations.

The applied channel model is described as follows. The frequency band is divided into m nonoverlapped channels possessing equal bandwidth. Let h_k represent the kth channel, where k denotes the channel ID from 1 to m. Each station s_i applies the predefined channel mapping function $f(\cdot)$ to identify its home channel, which is denoted by s_i.home. The notation s_i^k represents the fact that the home channel of station s_i is h_k. Let S^k denote the set of all stations that treat channel h_k as their home channel, i.e.,

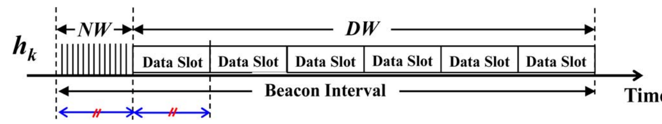

Fig. 2. Frame structure of STB-MAC.

$$S^k = \{s_i | s_i.\text{home} = h_k \quad \forall k \in [1, m]\}.$$

□

The timeline of each available channel is divided into several equal-length beacon intervals, each of which consists of a negotiation window (NW) and a data exchange window (DW). The DW is further divided into $(\rho - 1)$ data slots, and the length of each slot is identical to the length of the NW. In the NW, stations that intend to exchange data with the home stations will compete to reserve a data slot. Fig. 2 display the frame structure of a beacon interval, which consists of one NW and $(\rho - 1) = 6$ data slots.

C. Problem Formulation and Goal

Here, we present the formulation of the investigated CTU problem and outlines the goal of this paper. To measure the busy degree of a given channel, a busy index of channel h_k, which is denoted by I_k^{busy}, represents the ratio of traffic demands to the bandwidth resources supported by channel h_k. Channel h_k is a busy channel if $I_k^{\text{busy}} > 1$. This also indicates that the bandwidth resource cannot satisfy the traffic demands on channel h_k. Let g_k represent the number of packets generated within a beacon interval on channel h_k. Given time period T, the traffic demands on h_k can be measured by $g_k \times \lfloor T/\rho \rfloor$, whereas the bandwidth resources of channel h_k are $T \times (\rho - 1)/\rho$. The aim of this paper is to minimize the maximal busy index, as shown in (2).

Minimize the maximum of (I_k^{busy}), where

$$I_k^{\text{busy}} = \left(\frac{g_k \times \lfloor \frac{T}{\rho} \rfloor}{T \times \frac{\rho - 1}{\rho}} \right) \qquad \forall\, k \in [1, m] \tag{2}$$

□

Equations (3)–(6) present several constraints for achieving the goal of this paper. Let Boolean variable $\eta_{k,i}^t$ denote whether station s_i remains on channel h_k at any given time point t, i.e.,

$$\eta_{k,i}^t = \begin{cases} 1, & s_i \text{ stays on } h_k \text{ at time } t \\ 0, & \text{otherwise.} \end{cases}$$

The home channel constraint requests that station s_i remains on the home channel for any time t of the NW

Home Channel Constraint:

$$\eta_{k,i}^t = 1 \text{ if } s_i.\text{home} = h_k \quad \forall t \in \text{NW of } h_k. \tag{3}$$

□

Let $t^{\text{rendezvouz}}_{k,(i,j)}$ denote the time duration that stations s_i and s_j remain on the same channel h_k. Let $t^{\text{exchange}}_{k,(i,j)}$ denote the total time required for exchanging one data packet between stations s_i and s_j on channel h_k. The rendezvous constraint asks that nodes s_i and s_j remain on the same channel for a longer time than required for data exchange, as shown in (4)

Rendezvous Constraint:

$$t^{\text{rendezvouz}}_{k,(i,j)} \geq t^{\text{exchange}}_{k,(i,j)}. \quad (4)$$

□

Because each station is equipped with one transceiver, another constraint, known as the transceiver constraint, guarantees that station s_i remains on one channel at any given time point t

Transceiver Constraint:

$$\sum_{k=1}^{m} \eta^t_{k,i} \leq 1 \qquad \forall t \in T. \quad (5)$$

□

Let $d^q_{k,x}$ denote the qth data slot of the DW in the xth beacon interval on channel h_k. Let $\phi^q_{k,x,(i,j)}$ be a Boolean variable, which denotes that the transmission pair of s_i and s_j possesses reserved channel h_k for data exchange at the data slot $d^q_{k,x}$. Let notation $N(i)$ denote the set of neighboring stations of station s_i. To guarantee the successful data exchange between s_i and s_j, the collision-free constraint requests that all neighboring stations of stations s_i or s_j not exchange data at the reserved data slot $d^q_{k,x}$

Collision-Free Constraint:

$$\phi^q_{k,x,(i,j)} + \sum_{u,\,u' \in N(i)} \phi^q_{k,x,(u,u')} + \sum_{v,v' \in N(j)} \phi^q_{k,x,(v,v')} \leq 1$$
$$\forall i,\ j \in [1,n],\ i \neq j; \quad \forall k \in [1,m]; \quad \forall d^q_{k,x} \in T. \quad (6)$$

□

The goal of this paper is to minimize the maximal busy index, whereas the home channel, rendezvous, transceiver, and collision-free constraints remain satisfied.

IV. Channel Traffic Balanced Medium-Access-Control Protocol

This paper presents the STB-MAC protocol to cope with the CTU problem, which occurs when certain channels possess heavy traffic and other channels are idle. The proposed STB-MAC aims to balance the traffic loads over all channels by migrating the traffic loads from the busy channels to the idle channels.

The following first explains the slot states and defines the slots that are major resources to be assigned to the traffic loads of busy channels. A detailed description of STB-MAC is then presented. The STB-MAC protocol mainly consists of two stages: the negotiation stage and the data exchange stage. A detailed explanation of the negotiation and data exchange stages is presented in Section IV-B.

A. Data Slot State

The proposed STB-MAC protocol attempts to use the data slots that will be overdue soon but are not reserved by any transmission pair. These slots are used to migrate traffic away from busy channels. Let $\text{NW}_{k,x}$ and $\text{DW}_{k,x}$ denote the NW and the DW of the xth beacon interval on channel h_k, respectively. Recall that notation $d^q_{k,x}$ denotes the qth data slot of $\text{DW}_{k,x}$. Each data slot $d^q_{k,x}$ has a state, which is denoted by $d^q_{k,x}$.state, that has four possible values, including "available," "reserved," "idle," and "urgent." At the beginning of $\text{NW}_{k,x}$, the default states of all data slots $d^q_{k,x} \in \text{DW}_{k,x}$ are "available." In $\text{NW}_{k,\,x}$, available data slot $d^q_{k,\,x}$ can be reserved by any transmission pair of s_i and s_j, where receiver s_j treats channel h_k as its home channel. When $\text{NW}_{k,x}$ is terminated, $\text{DW}_{k,x}$ starts, and the states of data slots are maintained as follows. First, the state of any data slot $d^q_{k,x}$ marked as "available" is changed to "idle" because the reservation opportunities cannot be obtained after $\text{NW}_{k,x}$. Second, the states of all the data slots that are marked as "reserved" are not changed.

The last state, which is called the "urgent" state of data slot $d^q_{k,x}$, is much more complicated. In the following, the concepts of an incoming NW and urgent zone based on channel h_k are first introduced. The "urgent" state of data slots is then introduced based on the two concepts. Let the next$(\cdot)$ function return the next incoming NW of $\text{NW}_{k,x}$. The following equation illustrates the derivation of the next incoming NW:

$$next(\text{NW}_{k,x}) = \begin{cases} \text{NW}_{k+1,x} & \text{if } k < m \\ \text{NW}_{(k+1)\bmod m,x+1} & \text{if } k = m. \end{cases}$$

By applying the staggered channel model, the NW of channel h_{k+1} follows but does not overlap with the NW of channel h_k. Consequently, in case $k < m$, the incoming NW of $\text{NW}_{k,x}$ is $\text{NW}_{k+1,x}$. Otherwise, the incoming NW of $\text{NW}_{m,x}$ is $\text{NW}_{(m+1) \bmod m,x+1}$.

To facilitate the presentation of data, let W^0 represent the current NW $\text{NW}_{k,x}$. Let the yth incoming NW of $\text{NW}_{k,x}$ be denoted by W^y, which can be derived by repeatedly applying the next$(\cdot)$ function y times when using $\text{NW}_{k,x}$ as the input. The following derives W^y for a given $\text{NW}_{k,x}$:

$$W^y = \text{next}^y(\text{NW}_{k,x}).$$

Fig. 3 gives an example to illustrate the next$(\cdot)$ function. Three channels, h_1, h_2, and h_3, are considered in this example. The $\text{NW}_{1,2}$, $\text{NW}_{2,2}$, and $\text{NW}_{3,2}$ are the NWs of h_1, h_2, and h_3, respectively. Assume the current time is $\text{NW}_{1,2}$. Therefore, $W^0 = \text{NW}_{1,2}$. The next two incoming NWs can be derived by the following:

$$W^1 = \text{next}^1(\text{NW}_{1,2}) = \text{NW}_{2,2}$$
$$W^2 = \text{next}^2(\text{NW}_{1,2}) = \text{NW}_{3,2}.$$

Next, the concept of an "urgent zone" is introduced. Let t^{start}_l and t^{end}_l denote the start and end time points of W^l, respectively. Let t_i and t_j denote a time interval from time point t_i to time point t_j. An urgent zone of W^l, which is denoted by notation Z^{urgent}_l, refers to the time interval $[t^{\text{end}}_l, t^{\text{end}}_{l+1}]$. The following uses Fig. 3 to explain why zone $[t^{\text{end}}_l, t^{\text{end}}_{l+1}]$

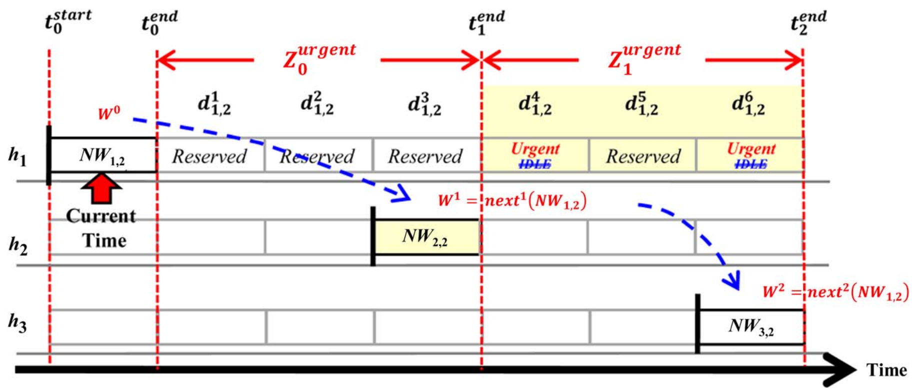

Fig. 3. Example of the next$(\cdot)$ function and urgent zones.

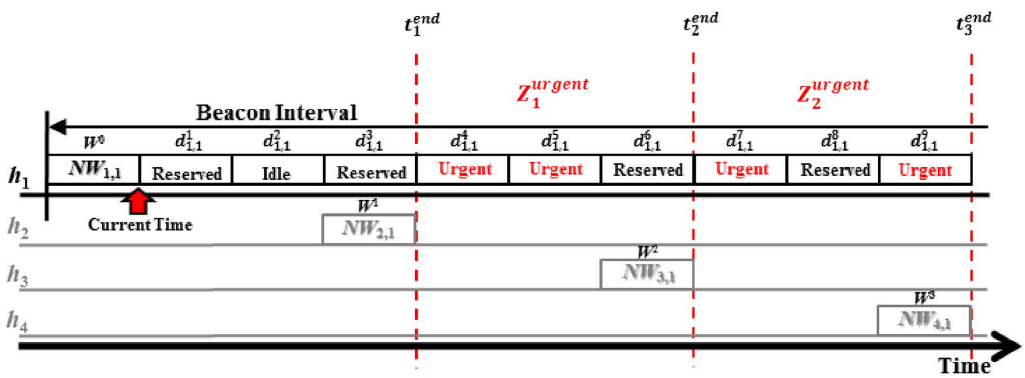

Fig. 4. Example of the concept of the urgent zone.

is critical. Consider zone $Z_1^{\text{urgent}} = [t_1^{\text{end}}, t_2^{\text{end}}]$, as shown in Fig. 3. Assume that the current time point falls into $\text{NW}_{1,2} = [t_0^{\text{start}}, t_0^{\text{end}}]$. The next opportunity for reserving data slots $d_{1,2}^q \in Z_1^{\text{urgent}}$ is the next incoming NW, which is $W^1 = next(\text{NW}_{1,2})$. As soon as W^1 finishes, all the opportunities for reserving data slots $d_{1,2}^q \in Z_1^{\text{urgent}}$ are expired. Therefore, if the "idle" data slot in Z_1^{urgent} on channel h_1 cannot be reserved in W^1, it must be wasted. Therefore, in this paper, $[t_1^{\text{end}}, t_2^{\text{end}}]$ of channel h_1 is called the "urgent zone" of W^1.

To fully use the idle data slots of Z_i^{urgent}, transmission pairs in W^i must take opportunities to reserve the data slots in Z_i^{urgent}. For this reason, the states of these idle slots are changed from "idle" to "urgent." Therefore, consider the example in Fig. 3. After the time point t_0^{end}, $\text{NW}_{1,2}$ has finished. The states of idle slots $d_{1,2}^4$ and $d_{1,2}^6$ are changed to "urgent." Recall that notation s_i^k denotes station s_i, the home channel for which is h_k. During W^1 of channel $h_{(k+1)}$, home station s_i^k that intends to communicate with receiver $s_j^{(k+1)}$ on the channel of W^1 will invite $s_j^{(k+1)}$ to use the urgent slot in Z_1^{urgent} of channel h_k. This results in the traffic loads of channel $h_{(k+1)}$ dispersing to the idle channel h_k.

Before inviting the receiver to fully use the idle slots, home stations s_i^k must maintain a data structure, which is denoted by data slot map $\mathcal{M}_i^k$, to record the $d_{k,x}^q$.state $\forall d_{k,x}^q \in \text{DW}_{k,x}$. More specifically, $\mathcal{M}_i^k$ is a vector $(z_1, \ldots, z_{q-1})$ consisting of $(q-1)$ state variables z_j, where z_j has possible values of "available," "reserved," "idle," or "urgent." When the time point falls in W^l, s_i can easily construct $\mathcal{M}_i^k$. Let U_l^{urgent} denote the set of all urgent slots in Z_l^{urgent}, which is given as follows:

$$U_l^{\text{urgent}} = \left\{ d_{k,x}^q | d_{k,x}^q.\text{state} = \text{“urgent”} \quad \forall q \in \left[t_l^{\text{end}}, t_{l+1}^{\text{end}}\right] \right\}.$$

The home stations s_i^k of channel h_k try to further migrate the traffic loads from other channels to the urgent slots $d_{k,x}^q \in U_l^{\text{urgent}}$ on channel h_k.

Fig. 4 provides an example to illustrate the concept of an urgent zone. The four channels h_1, h_2, h_3, and h_4 are considered in this example. The current time is t_0^{end}, which is at the end time point of $\text{NW}_{1,1}$. Stations s_i on channel h_1 are aware that W^0 is the current window $\text{NW}_{1,1}$. By applying the next function, each station s_i derives W^1, W^2, and W^3 as $\text{NW}_{2,1}$, $\text{NW}_{3,1}$, and $\text{NW}_{4,1}$, respectively. Because the data slots $d_{1,1}^1$, $d_{1,1}^3$, $d_{1,1}^6$, and $d_{1,1}^8$ have been reserved by certain transmission pairs during $\text{NW}_{1,1}$, the states of the remaining data slots are changed to "idle." Based on the concept of an urgent zone, the idle data slots $\{d_{1,1}^4, d_{1,1}^5\}$ and $\{d_{1,1}^7, d_{1,1}^9\}$ are in Z_1^{urgent} and Z_2^{urgent}, respectively. Because $\text{NW}_{1,1}$ has already been passed, stations s_i change the states of these idle slots to "urgent." Therefore, stations s_i treat $\text{NW}_{2,1}$ and $\text{NW}_{3,1}$ as the last NWs that can provide reservation opportunities for urgent slots $\{d_{1,1}^4, d_{1,1}^5\}$ and $\{d_{1,1}^7, d_{1,1}^9\}$, respectively.

B. Design of the Negotiation and Data Exchange Stages

The following provides a detailed description of the negotiation and data exchange stages in the proposed STB-MAC

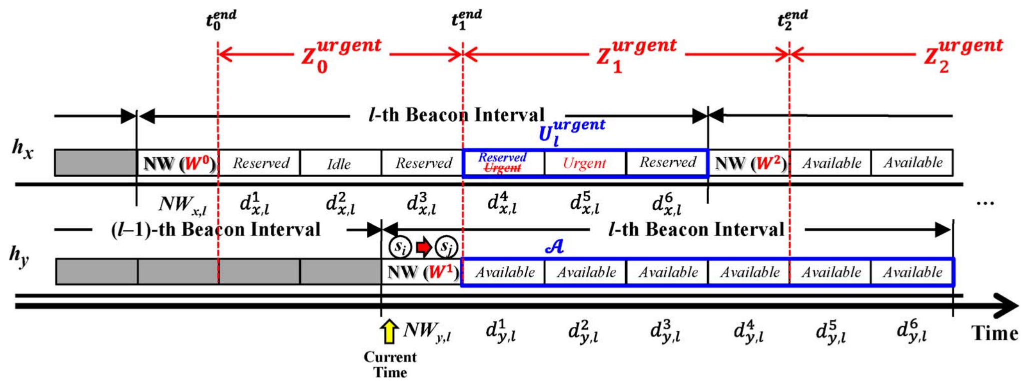

Fig. 5. Example of the negotiation and date exchange stages.

protocol. To facilitate the presentation without loss of generality, the following notations are used. Let sender s_i intend to exchange data with receiver s_j in the lth beacon interval and let their home channels be h_x and h_y, respectively. Fig. 5 provides an example to illustrate the negotiation and data exchange stages.

1) Negotiation Stage: Following the staggered channel model, station s_i remains on its home channel h_x during the NW of h_x. In $\mathrm{NW}_{x,l}$, sender s_i maintains its own data slot map in $\mathcal{M}_i^l$, which records the states of all data slots in the beacon interval. In the $\mathrm{NW}_{y,l}$, sender s_i switches to channel h_y and competes to negotiate with receiver s_j for reserving an urgent slot on channel h_x or an available slot on h_y by applying the following data slot selection approach.

In the data slot selection approach, s_i sends s_j an ATIM packet that includes: 1) the receiver's MAC address; 2) the sender's MAC address; 3) the size of the data packet; and 4) the set of preferable data slots $\mathcal{P}_i = U_l^{\mathrm{urgent}} + \mathcal{A}$, where U_l^{urgent} denotes the urgent slots on h_x, and $\mathcal{A}$ denotes the available data slots on h_y, as shown in Fig. 5. After receiving the ATIM packet, s_j replies to s_i with an ATIM acknowledgment (ATIM-ACK) packet containing the reserved data slot, which is selected from set $\mathcal{P}_i$. To migrate the traffic loads to the idle channel h_x, s_j selects an urgent slot $d_{x,l}^4 \in \mathcal{P}_i$ on h_x prior to selecting available slots in $\mathcal{A}$ on h_y. All home stations of h_y in $N(s_j)$ update their own data slot map accordingly by marking the selected slot $d_{x,l}^4$ as "reserved." This action aims to prevent additional transmission pairs on h_y from attempting to reserve the same urgent slot of h_x. After receiving the ATIM-ACK, sender s_i broadcasts the ATIM response (ATIM-RESPONSE) to notify its neighboring stations that the urgent slot $d_{x,l}^4$ has been reserved. The neighboring stations of s_i also update their data slot maps. Therefore, the transmission pair of s_i and s_j reserves an urgent slot through the three-way handshaking in the negotiation stage. In the event that all the urgent slots provided by s_i are marked "reserved," station s_j selects one available slot on h_y for receiving the sender's data.

2) Data Exchange Stage: In the data exchange stage, stations s_i and s_j exchange data at the reserved common data slot. In the event that the reserved slot is an "urgent slot," stations s_i and s_j switch to channel h_x for data exchange. Similar to the IEEE 802.11 MAC standard, s_i and s_j perform carrier-sense multiple access and random backoff

The Proposed *STB-MAC* Protocol

1. **if** station s_i intends to exchange data with station s_j **then** {
2. s_i switches to s_j's home channel h_y at the beginning of $NW_{y,l}$;
3. s_i sets $W^e = NW_{y,l}$;
4. s_i sets $\mathcal{P}_i = U_e^{urgent} + \mathcal{A}$;
5. **if** h_y is idle **then** { // *applying 802.11 CSMA*
6. s_i sends *ATIM* packet ;
7. on receiving s_i*'s ATIM*, s_j selects $d_{x,l}^q$ or $d_{y,l}^{q'} \in \mathcal{P}_i$;
8. s_j sends *ATIM-ACK* packet to s_i ;
9. station s_b (neighbors to s_j) changes the state of the selected $d_{x,l}^q$ or $d_{y,l}^{q'}$ in $\mathcal{M}_b^l$ to be "*reserved*" ;
10. s_i sends *ATIM-RESPONSE* packet ;
11. station s_c (neighbors to s_i) updates the state of the selected $d_{x,l}^q$ or $d_{y,l}^{q'}$ in $\mathcal{M}_c^l$ to be "*reserved*" ;
12. }
13. **else** {
14. s_i executes the *random back-off mechanism* ;
15. **execute** steps 6 to 11 ;
16. }
17. At the beginning of the reserved data slot, s_i and s_j switch to the reserved channel h_x or stay on h_y ;
18. **if** the reserved channel is idle **then** {
19. s_i and s_j exchange *RTS/CTS/DATA/ACK* packets ;
20. }
21. **else** {
22. s_i executes the *random back-off mechanism* ;
23. **execute** steps 17 to 18 ;
24. }
25. }

Fig. 6. Procedure of the STB-MAC protocol.

mechanisms and exchange Request-to-Send (RTS)/Clear-to-Send (CTS)/DATA/ACK packets to prevent the data collision problem.

3) STB-MAC Algorithm: Stations that apply the proposed STB-MAC can manage their operations by applying the proposed STB-MAC protocol, which is shown in Fig. 6. Let stations s_i and s_j be the sender and the receiver, respectively. Let home channels of stations s_i and s_j be channels h_x and h_y, respectively. In Steps 1 and 2, station s_i switches to h_y, i.e., the home channel of s_j, and competes for opportunities to negotiate with s_j. Steps 3–15 present the operations designed in the negotiation stage. In the event that h_y is idle, s_i and s_j exchange ATIM, ATIM-ACK, and ATIM-RESPONSE packets. Otherwise, sender s_i executes the random backoff mechanism in Step 13. The data exchange stage is implemented in Steps 17–24. In the event that the reserved channel is "idle," s_i and s_j exchange RTS, CTS, DATA, and ACK packets.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Number of channels	3, 6, 9
Communication pairs	20~80
Transmission range	250 m
Transmission rate	11 Mbps
Data packet size	512 bytes
Length of beacon Interval	180 ms
Control period / Data slot size	20 ms
Negotiation slot size	2.5 ms
Number of data slots	8
SIFS	10 µs
DIFS	50 µs
Offered traffic to each pair (packets/sec)	1~11
Dimension of the topography	1000 m×1000 m
Simulation time	500 seconds
Simulation repetitions	1000 times

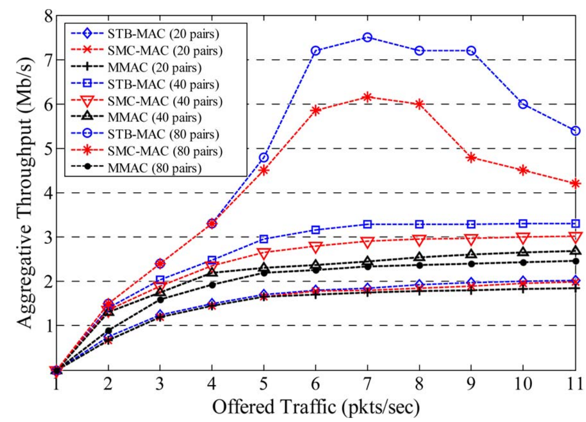

Fig. 7. Comparison of MMAC, SMC-MAC, and STB-MAC in terms of network throughput by varying the offered traffic loads.

V. PERFORMANCE EVALUATION

A. Evaluation Environment

Here, we examine the performance improvement of the proposed scheme against the related works on MMAC [10] and SMC-MAC [15] in terms of aggregative throughput, delay, and channel usage. In this paper, the ns-2.34 simulator [16] was used, combined with modified multichannel modules supported in [17] to incorporate multichannel carrier sensing, channel corruption effects, packet capture, and RTS/CTS operations. The simulated network is composed of 20–80 communication pairs, which are deployed randomly within a 1000×1000 m^2 square region. The simulation parameters in Table I are used, unless otherwise specified. Each performance result was obtained from the average results of 1000 experiments. The 95% confidence interval is always smaller than 5% of the reported values.

The remainder of this section is organized as follows. First, the performance results of the MMAC, SMC-MAC, and proposed STB-MAC protocols in terms of network throughput are examined. Through a review of Figs. 7–9, several factors that impact the performance of network throughput are analyzed. These factors include offered traffic loads and the numbers of transmission pairs and channels. Figs. 10–13 are then used to investigate the parameters that affect the performance of channel usage. These parameters include offered traffic loads, which are not balanced for each channel or station, the number of channels, and the applied staggered channel model exhibiting different p values. Finally, Figs. 14–17 reveal the performance of control overhead, channel balance ratio, packet delay, and packet drop ratio that are influenced by the number of one-hop neighbors, station traffic balance index, offered traffic loads, and delay bound, respectively.

B. Evaluation Results

Fig. 7 identifies the performance results of MMAC, SMC-MAC, and proposed STB-MAC protocols regarding the aggregative throughput. The numbers of transmission pairs are set to 20, 40, or 80 and the offered traffic loads of each transmission pair are dynamically varied from 1 to 11 packets/s. As shown in Fig. 7, the results of three schemes with 20 pairs are similar because no heavy contentions occur in the ATIM windows. However, when the number of transmission pairs is set to 40, the throughput of MMAC slowly increases because the ATIM window of the dedicated channel cannot afford more control packets. Conversely, the SMC-MAC distributes the ATIM windows to multiple channels without overlapping. Therefore, the SMC-MAC avoids heavy contentions and produces a more satisfactory performance than MMAC does regarding aggregative throughput. Furthermore, the proposed STB-MAC provides more reliable performance than SMC-MAC, particularly when the offered traffic is larger than 2 packets/s. This occurs because the idle slots can be used when heavy contentions occur in certain channels. However, when the number of transmission pairs is set to 80, the throughput of MMAC, SMC-MAC, and STB-MAC generally increase with the offered traffic loads. The throughput of MMAC slowly increases because the ATIM window of MMAC cannot afford more control packets. A higher contention of control packets generally degrades the performance of MMAC, particularly when 80 transmission pairs exist. In contrast to the MMAC protocol, SMC-MAC and STB-MAC protocols apply the staggered channel model, which distributes the control packets over multiple channels. Consequently, the throughputs increase with the offered traffic loads. When the traffic load approaches 6 packets/s, the throughput results tend to be stable because the contention on each channel reaches the limitation of the NW. The proposed STB-MAC outperforms the SMC-MAC regarding network throughput because it further migrates traffic loads to the idle channel and thus avoids the traffic stick on the busy channel.

Fig. 8 shows the network throughputs of the three compared MAC protocols. The considered numbers of channels are set to three, six, and nine. The numbers of transmission pairs are set to 20, 40, and 80, and the offered traffic loads of each transmission pair are dynamically varied from 1 to 11 packets/s. As shown in Fig. 8, the throughputs of the MMAC, SMC-MAC, and proposed STB-MAC protocols generally increase with the increment of offered traffic loads or number of channels. When the number of transmission pairs increases, STB-MAC exhibits more reliable performance than SMC-MAC and MMAC do because STB-MAC applies the staggered channel model and further migrates traffic from busy to idle channels. When the

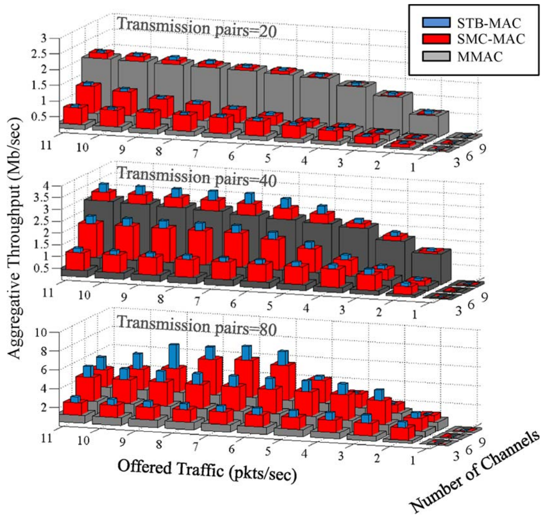

Fig. 8. Comparison of MMAC, SMC-MAC, and STB-MAC in terms of throughput by varying the offered traffic loads and number of channels.

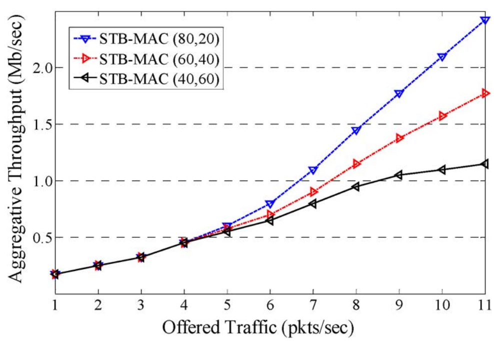

Fig. 9. Comparison of network throughput by varying the offered traffic loads.

number of channels increases, STB-MAC achieves a greater performance gain than SMC-MAC and MMAC. This occurs because the STB-MAC can use more idle slots for data exchange.

The proposed STB-MAC aims to migrate the traffic loads of the busy channels to the idle channels. However, the traffic migration is constrained because the busy and idle channels are the home channels of the receiver and the sender, respectively. In the event that the sender and the receiver reside in the same home channel, the traffic migration of STB-MAC fails. A close observation of the network throughput of the STB-MAC by varying the traffic source is presented in Fig. 9. Two types of traffic source exist. The "interchannel" type refers to the type wherein the home channels of the sender and the receiver differ, whereas the "intrachannel" type refers to the type wherein the home channels of the sender and the receiver are identical. In Fig. 9, notation (X, Y) represents the ratios of "interchannel" and "intrachannel" traffic loads, which are X and Y, respectively. The average network throughput of STB-MAC generally increases with the offered traffic loads. Moreover, the ratio of (80, 20) has more reliable network throughput than the ratios of (60, 40) and (40, 60) when the offered traffic loads are larger than 6 packets/s. This occurs because STB-MAC cannot migrate traffic loads from the receiver's home channel to the sender's home channel when the major traffic belongs to the "intrachannel" type.

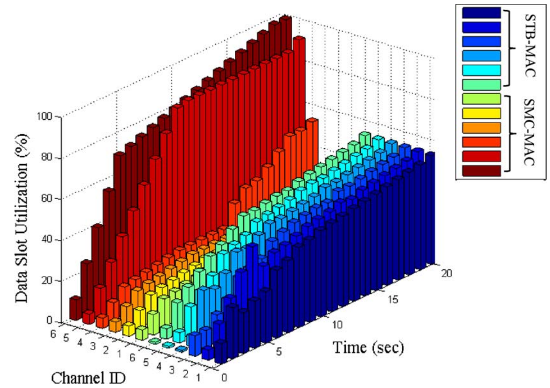

Fig. 10. Utilization of each channel.

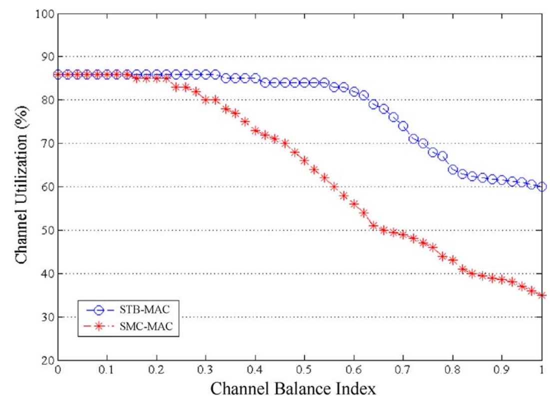

Fig. 11. Comparison of SMC-MAC and STB-MAC in terms of channel utilization by varying channel balance index.

Fig. 10 shows the traffic migrating performance of the STB-MAC and SMC-MAC protocols regarding data slot usage. The experiment arranges six available channels, and most of the traffic loads are generated in channels 5 and 6. As shown in Fig. 10, SMC-MAC exhibits low channel usage when the offered traffic loads are unbalanced on each channel. Applying the SMC-MAC protocol, the channel usage of channels 5 and 6 achieves 80%–100%, whereas the usage of the other channels is approximately 20%. This occurs because the SMC-MAC protocol only dispatches the traffic to the data slots on the receiver's home channel. In contrast to SMC-MAC, the proposed STB-MAC migrates the traffic loads from channels 5 and 6 to the urgent slots of idle channels. As a result, the data slot usage of the six channels is similar, although certain channels possess heavy traffic loads.

Fig. 11 further compares the channel usage of the MMAC, SMC-MAC, and STB-MAC protocols by varying the value of the channel balance index, which is normalized between zero and one. The index represents the levels of balance of the offered traffic loads on each channel. The value of the channel balance index approaching one indicates that most traffic loads are offered to one particular channel. The channel usage of MMAC cannot be simulated in this experiment because the concept of the home channel does not apply to MMAC. When MMAC protocol is applied, each pair that successfully completes the negotiation can dynamically select the channel for data exchange. Therefore, the simulator cannot assign the traffic loads of each channel. In Fig. 11, the channel usage of

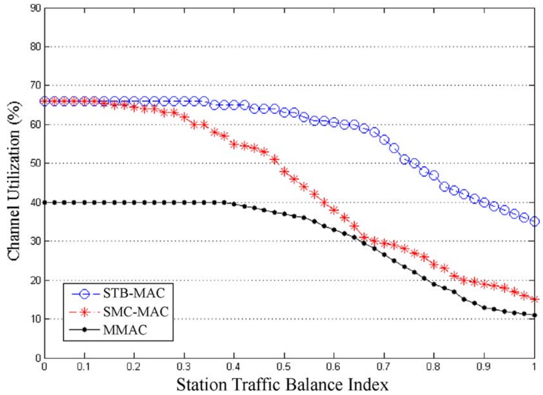

Fig. 12. Comparison of channel utilization by varying station traffic balance index.

SMC-MAC is dropped when the offered traffic loads are unbalanced on each channel. When the index is larger than 0.2, certain channels are busy; thus, the curve of the SMC-MAC drops substantially. The channel usage of STB-MAC drops when the index is larger than 0.6. The STB-MAC outperforms the SMC-MAC protocol because it migrates the traffic loads from busy to idle channels.

Fig. 12 compares the MMAC, SMC-MAC, and STB-MAC protocols regarding channel usage by varying the value of the station traffic balance index, which is normalized between zero and one. The index represents the levels of balance of the offered traffic loads on each station. The value of the station balance index approaching one indicates that most traffic loads are offered to one particular station. The channel usages of the three protocols decrease with the station traffic balance index. When the index is greater than 0.4, the channel usage of MMAC falls in the range of 10%–40%. This occurs because all stations compete to send the control packets in the same ATIM window. The channel usages of SMC-MAC and STB-MAC generally decrease with the index. That is, the channel usage decreases when the offered traffic loads are unbalanced on each station. Observe the performance results of SMC-MAC. When the station traffic index approaches one, the stations with high traffic loads can use all data slots on their channels, but the stations with low traffic loads leave many idle slots unused on their channels, thus exacerbating the CTU problem. Compared with the SMC-MAC, the proposed STB-MAC protocol has higher channel usage because the communication pairs that apply the proposed STB-MAC can use the idle data slots of multichannels.

Fig. 13 compares the SMC-MAC and STB-MAC protocols regarding channel usage by varying the value of p. The channel usage is measured using the volume of data that is successfully exchanged between the sender and the receiver to the maximal capacity in the simulation time of 500 s. In the experiment, three scenarios are considered by setting the numbers of channels to three, six, and nine. The traffic loads offered in each scenario increase with the number of channels. Recall that parameter p represents the number of data slots that are shifted between two consecutive channels. Certain observations from the experiment are shown in Fig. 13. In the SMC-MAC protocol, the channel usage decreases with the number of available channels because

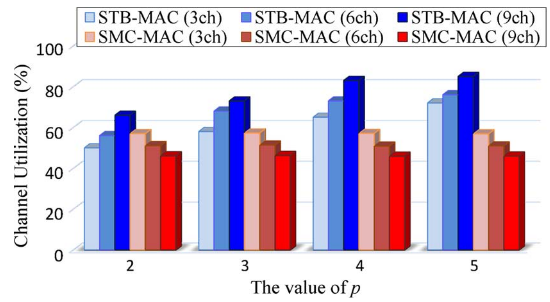

Fig. 13. Comparison of SMC-MAC and STB-MAC in terms of channel usage by varying the value of p.

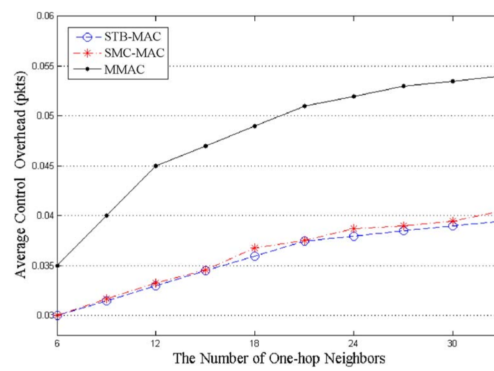

Fig. 14. Comparison of MMAC, SMC-MAC, and STB-MAC in terms of average control overhead by varying number of one-hop neighbors.

the SMC-MAC copes with the CTU problem. The proposed STB-MAC outperforms SMC-MAC in all cases because STB-MAC migrates the data from busy channels to the urgent slots in the idle channels such that channel usage is improved. Furthermore, the channel usage of STB-MAC increases with the incremented value of p because a high value of p enlarges the size of the urgent zone, which causes the traffic loads to be dispersed over all channels.

Fig. 14 compares the MMAC, SMC-MAC, and STB-MAC protocols regarding average control overheads when the number of one-hop neighbors varies from 6 to 40. The evaluation metric, i.e., the control overhead, represents the number of control packets per data exchange. As shown in Fig. 14, the average control overhead increases generally with the number of one-hop neighbors. This occurs because the number of contentions increases with the number of neighbors; thus, the retransmissions of control packets are required. When the MMAC is applied, all stations competing for the exchange of control packets remain on the same channel in the ATIM window. Consequently, the MMAC creates heavy contentions in the ATIM window. The SMC-MAC and STB-MAC protocols exhibit superior performance compared with the MMAC protocol regarding average control overhead. In contrast to the MMAC protocol, the SMC-MAC and STB-MAC protocols apply the staggered channel model to dispatch stations to different channels. Consequently, the control overheads of STB-MAC and SMC-MAC are similar but can be considerably reduced, as compared with MMAC.

Fig. 15 compares the MMAC, SMC-MAC, and STB-MAC protocols regarding the channel balance ratio by varying the station traffic balance index. The channel balance ratio represents the degrees of balance of the offered traffic loads in multiple

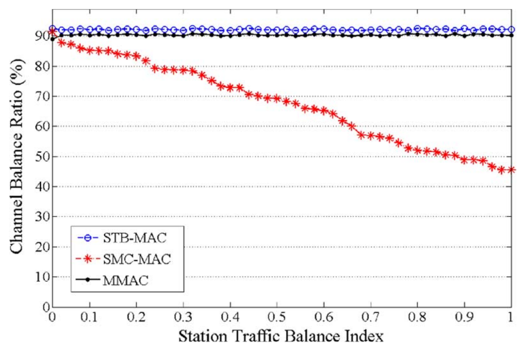

Fig. 15. Comparison of the channel balance ratio by varying the station traffic balance index.

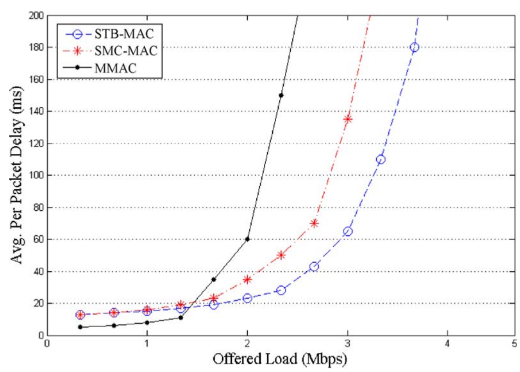

Fig. 16. Comparison of MMAC, SMC-MAC, and STB-MAC in terms of average packet delay by varying offered traffic loads.

channels. The value of the channel balance ratio approaching one indicates that the traffic loads can be evenly dispersed among multiple channels. Fig. 15 shows that, in the application of the SMC-MAC protocol, each pair that successfully completes the negotiation on one channel can select only that channel for data exchange. As a result, the performance of SMC-MAC degrades with the increase in the station traffic balance index. Conversely, when the MMAC or the proposed STB-MAC is applied, all pairs can select one idle data slot from multiple channels for data exchange. This causes the channel balance ratios of the MMAC and the proposed STB-MAC to be higher than that of the SMC-MAC. By comparison, the MMAC possesses lower channel balance ratios than the STB-MAC does because the control packets and data packets are exchanged on the same channel, which constrains the opportunities for using the idle slots in the other channels.

Fig. 16 compares the MMAC, SMC-MAC, and STB-MAC protocols regarding the average packet delay by varying the offered traffic loads from 0.2 to 5 Mb/s. The packet delay is measured according to the duration from the time of packet arrival to the time of successful packet transmission. The proposed SMC-MAC and STB-MAC outperform MMAC because they apply the staggered channel model, which helps reduce the contentions and collisions in the NW. Moreover, the STB-MAC outperforms SMC-MAC in all cases because the STB-MAC further migrates the traffic loads from busy to idle channels.

Fig. 17 shows the performance of STB-MAC regarding the packet drop ratio by varying the delay bound from 40 to 170 ms. The packet drop ratio is measured according to the

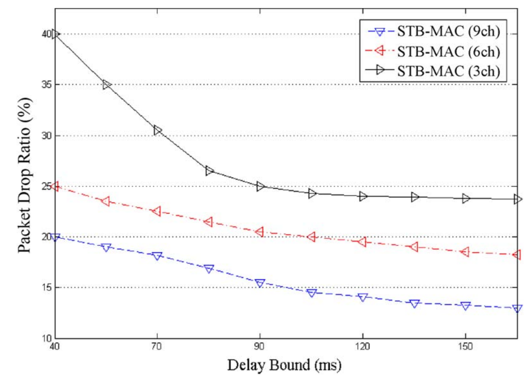

Fig. 17. Comparison of the packet drop ratio by varying the delay bound.

ratio of the number of dropped packets to the total number of arrived packets in senders. As shown in Fig. 17, the results of the packet drop ratio generally decrease with the delay bound. When the number of available channels is three, each channel possesses heavy traffic loads; thus, the STB-MAC performs poorly because of contentions and collisions. When the delay bound approaches 90 ms, the performance of STB-MAC slowly degrades in all cases because many traffic loads can be migrated from busy to idle channels.

VI. Conclusion

This paper has presented a new multichannel MAC protocol, i.e., STB-MAC, which is designed to address the CTU problem. Based on the existing staggered channel model, the STB-MAC consists of negotiation and data exchange stages. In the negotiation stage, each station maintains a data slot map that records the state of all data slots in a beacon interval. The sender that fails to reserve data slots in the NW identifies the urgent zone and attempts to migrate the traffic loads from the receiver's home channel to the urgent zone of its own home channel. Experimental results reveal that the proposed STB-MAC considerably reduces the phenomenon of traffic imbalance and therefore outperforms the MMAC and SMC-MAC protocols in terms of network throughput and packet delay.

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