RawPEACH: Multiband CSMA/CA-Based Cognitive Radio Networks

Jo Woon Chong, Youngchul Sung, and Dan Keun Sung

Abstract: A new medium access control (MAC) scheme embedding physical channels into multiband carrier sense multiple access/collision avoidance (CSMA/CA) networks is proposed to provide strict quality of service (QoS) guarantee to high priority users. In the proposed scheme, two priority classes of users, primary and secondary users, are supported. For primary users physical channels are provided to ensure strict QoS, whereas secondary users are provided with best-effort service using CSMA/CA modified for multiband operation. The performance of the proposed MAC scheme is investigated using a new multiband CSMA/CA Markov chain model capturing the primary user activity and the operation of secondary users in multiple bands. The throughput of secondary users is obtained as a function of the primary user activity and other CSMA/CA parameters. It is shown that the new MAC scheme yields larger throughput than the conventional single-band CSMA/CA when both schemes use the same bandwidth.

Index Terms: Carrier sense multiple access/collision avoidance (CSMA/CA), cognitive radio, Markov chain, multiband, priority, quality of service (QoS), throughput.

I. INTRODUCTION

Medium access control (MAC) schemes based on random access have been successfully used in many wireless applications since ALOHA was first introduced in early 1970s. Among many MAC protocols based on random access, wireless local area networks (WLANs) [1] in the industrial, scientific and medical (ISM) band adopt carrier sense multiple access/collision avoidance (CSMA/CA) [2]–[5], and provide high-rate wireless data. For the enhancement of WLAN, it is required to provide voice and video services that require strict quality of service (QoS) guarantee for real-time communications. The operation of CSMA/CA protocols is based on the contention among users in the network. However, this contention-based operation of CSMA/CA does not guarantee the QoS required by the above-mentioned real-time traffic users. Several modifications have been proposed to provide higher priority to certain users requiring improved QoS for CSMA/CA based protocols. For example, in IEEE 802.11e [6], QoS is classified according to service class. In this standard, however, the strict guarantee of QoS for higher priority users is not provided still because of its contention-based collision resolution.

In this paper, we propose a new MAC scheme based on CSMA/CA to provide strict QoS guarantee to certain high priority users (called primary users) in the network by embedding channels into a CSMA/CA network (operating in multiple bands) in which low priority users (called secondary users) are operating. Thus, the network has a two-class priority structure with strict QoS guarantee for the primary users and best-effort service for the secondary users. This new MAC scheme can be viewed as a random access protocol with pre-arbitrated channelization (RawPEACH). We investigate the performance of the proposed MAC scheme using a Markov chain capturing the primary user channel activity and the multiband operation.

A. Related Work and Organization

To guarantee QoS in WLAN, reservation schemes have been proposed in MAC layer. IEEE 802.11 point coordination function (PCF) [1] and packet reservation multiple access with dynamic allocation (PRMA-DA) [7] were proposed to reserve time slots for which other users are not allowed to access the medium. In high layers, reservation protocol (RSVP) [8] was proposed based on a flow setup protocol with the aid of network routers. These schemes for QoS guarantee in the MAC and higher layers have disadvantages because the reserved resource can be wasted when it is not used and the packet flows during the reservation procedure increase traffic load in the network. Here, in this paper we focus on an evolution of the conventional CSMA/CA to provide QoS guarantee to certain users in the network by modifying the conventional CSMA/CA in physical and MAC layers to incorporate *multiband operation* and *channelization*. The multiband CSMA/CA operation was also considered by other researchers too [9]. A CSMA/CA protocol using multiple channels and distributed channel selection scheme was described in [10]–[12]. An interface assignment strategy based on IEEE 802.11 was provided in [13]. The idea of priority classification is present in many other studies, especially, in cognitive radio communications [14], [15]. For example, overlay cognitive coexisting radio protocols have primary and secondary users with different QoS [16]–[18]. Also the priority classification is considered in cellular systems including WiMAX and 3G-LTE. For the example of 3G, circuit-switched connections are provided for absolute guarantee of QoS for delay-sensitive voice calls, and packet-switched connections are provided for best-effort services. For these best-effort services, however, typically, a packet scheduler is employed, and this requires complex scheduling algorithms and the complexity increases as the number of best-effort service users increases. RawPEACH also provides QoS guaranteed channels for primary users, which is similar to the case of circuit-switched connections for typical cellular networks. However, RawPEACH does use a random access protocol for secondary users to provide best-effort services, and it does not require packet schedulers and simplifies the network operation. Thus, RawPEACH combines the benefits from both of cellular systems and random access networks: QoS guarantee for primary users based on channelized connection and distributed random access for secondary users that is scalable

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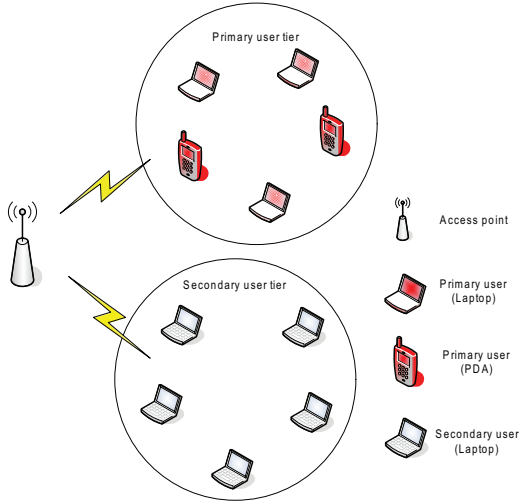
Fig. 1. The network model.

Table 1. Notations.

Parameter	Description
AIFS_p	Arbitrary interframe space for primary users
AIFS_s	Arbitrary interframe space for secondary users
CW	Contention window size
N_{CH}	Number of subbands
N_{FB}	Number of primary user free bands
N_p	Number of primary users
N_s	Number of secondary users
p	Collision probability of a given secondary user when the user transmits
P_b	Probability that all channels are busy by primary users
P_p	Probability that a channel is used by a primary user
P_c	Collision probability
P_i	Idle probability
P_s	Successful transmission probability
RC	Retry counter value
RL (or m)	Retry limit value
S	System throughput
S_{user}	Normalized throughput per user
$T_{f,p}$	Frame length of primary users
$T_{f,s}$	Frame length of secondary users
T_s	System slot interval
W	Contention window size + 1

with the number of secondary users and does not require any scheduler.

The rest of paper is organized as follows. The RawPEACH protocol is proposed in Section II. In Section III, we provide a model for the operation of a secondary user capturing the primary user activity and the operation in multiple bands, and analyze the throughput and delay performance of secondary CSMA/CA users. Numerical results are provided in Section IV. The performance of RawPEACH is also evaluated in multiple overlapped CSMA/CA network environments in Section V, followed by conclusion in Section VI.

II. RAWPEACH: PROTOCOL DESCRIPTION

The network model that we consider is shown in Fig. 1. We have an access point (AP) and multiple secondary users who access the common AP in the uplink direction. Here, the users are classified into two groups: Primary and secondary users. The primary users require the strict guarantee of QoS, whereas the secondary users are satisfied with best-effort services. (Even though the primary and secondary users are shown to be grouped, as shown in Fig. 1, they can be randomly located within the coverage of the network.) We assume that each user identifies its user type (primary or secondary) using the reserved field of association frames. Hence, the AP under the proposed RawPEACH protocol knows the user type in the association procedure at the beginning of the active session of each user. The detailed operation in the network will be described in the following subsections. Before we proceed, we summarize all notations used in this paper in Table I.

A. Multiband Operation and Primary Users

While conventional CSMA/CA networks such as WLAN[1] use

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[1] In WLAN case, the whole ISM band is divided into multiple frequency allocations (FA's). However, the transmission is not across multiple FA's; single carrier transmission is performed in the selected FA. The division of FA is for interference mitigation between close AP's; neighboring AP's can use different FA's. One can consider the bandwidth B as the bandwidth of one FA for simplicity.
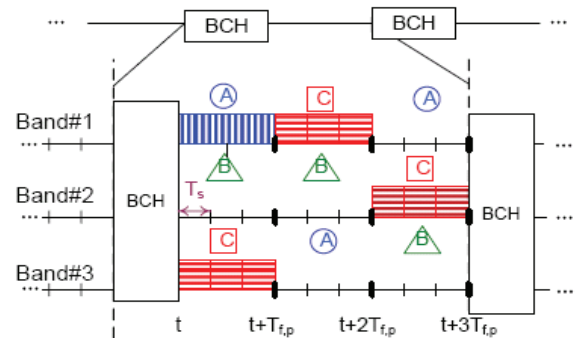

Fig. 2. Operation of primary users in a RawPEACH (A broadcast channel (BCH) is considered for possible downlink control message).

the whole allocated band with bandwidth B using a single carrier transmission, the proposed CSMA/CA system operates on multiple bands. That is, the allocated bandwidth B is divided to N_{CH} subbands, and each subband is divided into time slots with interval T_s. Further, the slot boundaries are synchronized across the subbands. (For example, such a subband division can be implemented using OFDMA at physical layer.)

Fig. 2 shows an example of subband division with $N_{CH} = 3$. In this slotted multiband operation, the AP supports channelization for primary users, and provides a contention-free channel to each primary user. Here, a channel is defined as a sequence $\{B_1, B_2, \cdots, B_n, \cdots\}$ of frequency subbands which is orthogonal to other channels and can be assigned to one primary user. A primary user transmits its data over frequency subband B_i

during the time interval $[t + iT_{f,p}, t + (i + 1)T_{f,p}]$, where $T_{f,p}$ is the frame interval of primary users, and is a multiple of the system slot interval T_s. That is, each primary user transmits its data frame over one primary frame interval $T_{f,p}$, and hops to a different band according to the assigned hopping sequence for the next frame interval. The orthogonality among the primary users is obtained by the synchronization of primary frames and orthogonal hopping sequences. Without loss of generality, we consider the Latin squares system for orthogonal hopping patterns. The reason for hopping across all subbands is to exploit the frequency diversity to avoid channel fading and interference. Fig. 2 illustrates the operation of the primary users for $N_{CH} = 3$ and $T_{f,p} = 3T_s$. Each primary user transmits its data frame according to the assigned hopping pattern when it has frames to transmit while the frame synchronization among the primary users is maintained. In this figure, there are three channels A, B, and C. Here, channel A hops across the bands: B_1(Band#1) from t to $t + T_{f,p}$, B_3 from $t + T_{f,p}$ to $t + 2T_{f,p}$, and B_1 from $t + 2T_{f,p}$ to $t + 3T_{f,p}$. However, the user assigned to channel A transmits only from t to $t + T_{f,p}$ and the channel A is released at $t + T_{f,p}$. On the other hand, channel C hops over bands B_3, B_1, B_2 and the primary user assigned to channel C transmits frames over all the three frame intervals. If the number, N_P, of primary users is larger than N_{CH}, the orthogonality among primary users can not be maintained. Thus, the maximum number of primary users is equal to the number of frequency subbands, and N_{CH} is a design parameter in the proposed protocol. Hence, it is required that the RawPEACH protocol employs an admission control to maintain the orthogonality among the primary users in the network. For example, the RawPEACH may simply reject the request from a user in the network to be associated as a primary user when the primary channels are all occupied. The rejected user can initiate an association as a secondary user.

B. Operation of Secondary Users

As seen in the previous section, the RawPEACH protocol provides orthogonal channels to primary users using multiband operation. The operation of primary users can be considered as typical channelization in the OFDMA-based MAC scheme in cellular systems. The difference lies in the operation of secondary users. Since we consider the RawPEACH in MAC networks with low and medium traffic load, it is likely that the channel resources are not occupied by primary users fully. Thus, there remains available channel resource in frequency and/or time, and this resource is used to provide best-effort services to secondary users. Here, to exploit the benefits of the CSMA/CA protocol over simple ALOHA or p-ALOHA type random access, we elaborate the conventional CSMA/CA protocol for multiband operation with a constraint that the secondary users under the multiband CSMA/CA do not interfere with the operation of primary users in the network. The operation of the multiband CSMA/CA protocol is described as follows.

The first step is channel sensing by secondary users; *all the secondary users sense all N_{CH} frequency subbands* after the arbitrary interframe space for secondary users (AIFS$_s$)[2] from the

[2]AIFS$_s$ is set to be larger than the sum of the primary AIFS and the propagation delay within the network so that the primary transmission can be sensed by all secondary users.
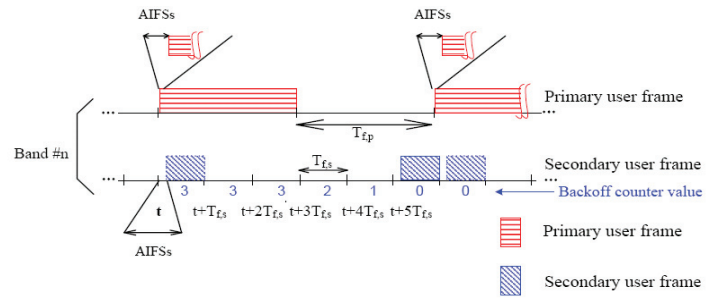

Fig. 3.   Operation of secondary users under the presence of primary users in RawPEACH.

beginning of every secondary time slot with length $T_{f,s}$. For simplicity, we may assume that $T_{f,s} = T_s$, where T_s is the system slot interval defined in the previous section. The secondary frame length $T_{f,s}$ is required to be no larger than the frame length $T_{f,p}$ of primary users. Otherwise, the transmission of primary users can be collided by secondary users, and the QoS for primary users can not be guaranteed. If a particular subband is sensed to be busy, it is certain with a proper choice of AIFS$_s$ that the transmission in that subband is on-going by a primary user and secondary users do not transmit their frames in that subband for the secondary frame interval. Thus, priority is always given to primary users whenever the primary and secondary users contend for channel use simultaneously, and the secondary users do not interfere with the transmission of primary users. The performance of secondary users is controlled by various parameters such as AIFS$_s$, contention window (CW) size, and the frame lengths of primary and secondary users.

An example of the operation of secondary users in the presence of primary users in the proposed protocol is illustrated in Fig. 3. The secondary user generates a frame to transmit at time slot t. Since the primary user also has a frame to transmit and transmits the frame for time interval $[t, t + 3T_{f,s}]$, the secondary user senses the transmission of the primary user, and does not decrease its counter value in its CSMA/CA operation. It starts to decrease its backoff counter value when the channel is not occupied by a primary user at $t + 3T_{f,s}$ and its backoff counter value reaches zero at slot $t + 5T_{f,s}$. Since there is no primary user transmission at slot $t + 5T_{f,s}$, the secondary user transmits its frame successfully at slot $t + 5T_{f,s}$.

If all the subbands are busy because of the transmission from primary users, the secondary users freeze their backoff counters, and wait until at least one of the primary users releases a subband. *If at least one of N_{CH} subbands is sensed to be idle, all the secondary users decrease the value of backoff counters by one.* The secondary users with backoff counter value reaching zero start to transmit their data frames on a randomly selected subband out of the primary user-free subbands (the number of which is at least one). If only one secondary user transmits its data frame on one primary user-free channel, its transmission is regarded as a success. If more than one secondary user transmit their data frames simultaneously on the same primary user-free subband, on the other hand, the transmission of the secondary users on that subband is considered to be collided. After the col-
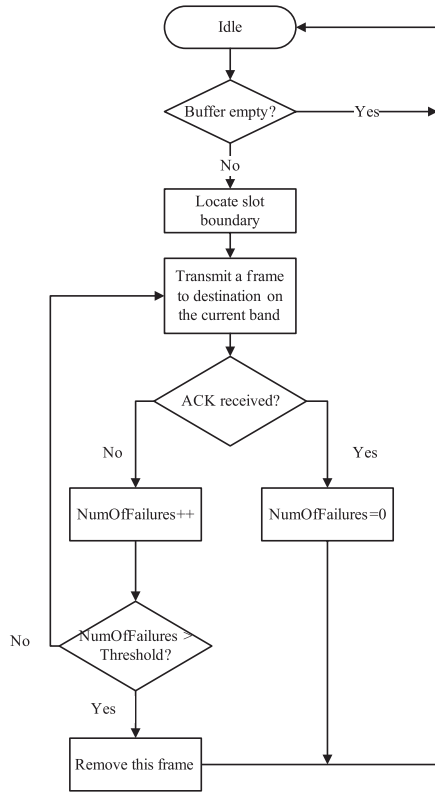
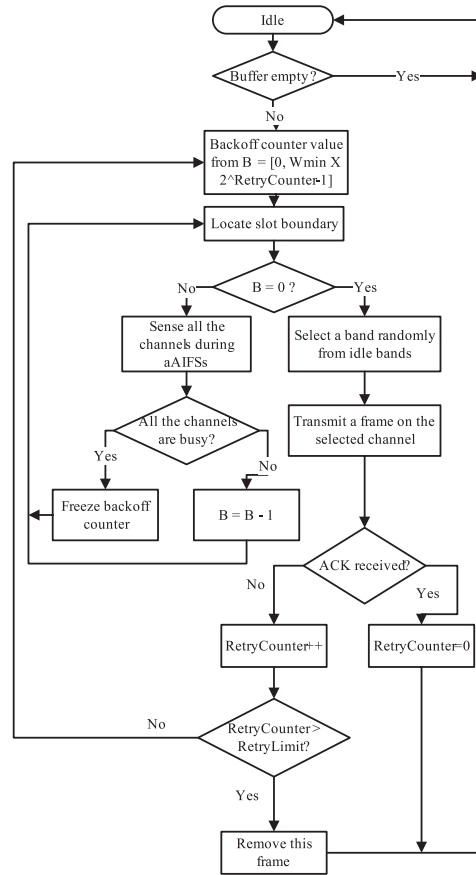Fig. 4. Flow chart at a primary user.

Fig. 5. Flow chart at a secondary user.

lision, the engaged secondary users increase the backoff stage by one, and select their backoff counter values randomly from the corresponding CW in that backoff stage. (Here, we may assume a fast common downlink channel carrying ACK information for all admitted users and the collision among the secondary users is known by the absence of ACK at the end of time slot.)

Summary of the RawPEACH MAC Procedure

The operation of primary users, secondary users and AP's in the RawPEACH protocol is summarized in Figs. 4–6.

Primary user U_p

(1) If a primary user succeeds in associating with an AP, it receives an orthogonal subband hopping sequence from the associated AP.

(2) When the associated primary user has a frame to transmit, it checks its allocated subband for transmitting the frame at the nearest primary frame boundary.

(3) After locating the nearest frame boundary, it transmits its frame from the boundary on the subband obtained in (2) and waits for an acknowledgement from the AP.

(4) If the data transmission time is longer than one primary frame interval, the primary user transmits the data over multiple primary frames according to the assigned hopping sequence.

Secondary user U_s

(1) If a secondary user succeeds in associating with an AP, it receives a set of parameters for the secondary user to configure itself.

(2) When the associated secondary user has a frame to transmit, it randomly selects its backoff counter value form [0, CW]

where CW is the current contention window. It sets CW initially to CW_{min} which is included in the set of parameters received from the associated AP.

(3) After locating the nearest secondary slot boundary, it senses all the frequency subbands from the slot boundary t to $t +$ AIFS$_s$.

(4) If all the channels are sensed to be busy, the secondary user freezes its backoff counter. Otherwise, it decreases its backoff counter value by one.

(5) When the backoff counter value reaches zero, it finds idle frequency subbands and selects one subband among them randomly. Using this subband, the secondary user transmits its data frame.

(6) If the secondary data frame can not be transmitted within one primary frame interval $T_{f,p}$, it fragments its data frame so that each fragment can be transmitted over one $T_{f,p}$.

(7) If the secondary user does not receive an acknowledgement from the associated AP until the AckWaitTimeLimit duration, it considers a collision has occurred and it increases its retry counter value (RC) by *one* and randomly selects its backoff counter value from $[0, W_{min} \times 2^{RC} - 1]$ as 802.11 legacy protocol. If RC exceeds a retry limit (RL), it discards its data frame.

Access point

(1) If an AP receives an association request, it checks the user priority field in the received request.

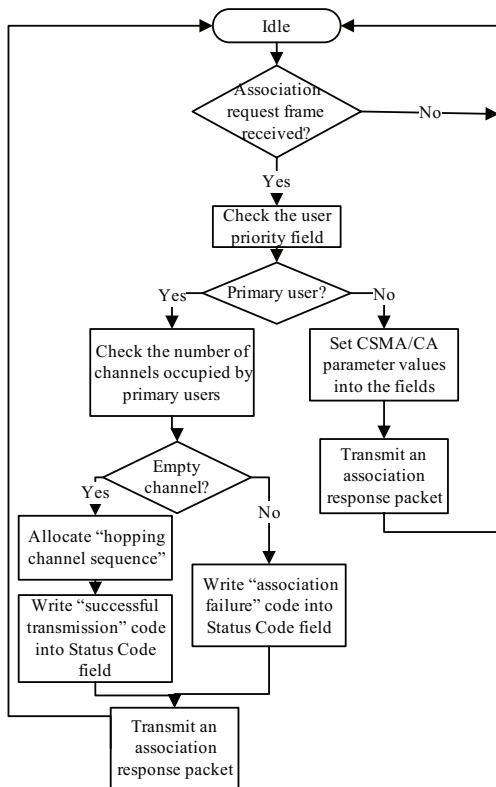(2) In (1), if the user priority field is set to be "0" (primary user

Fig. 6. Flow chart at an AP.

Table 2. Equivalent CSMA/CA configuration of RawPEACH.

	Primary Users	Secondary Users
Frame interval	$T_{f,p}$	$T_{f,s}$
AIFS	$\text{AIFS}_p = 0$	$\text{AIFS}_s \ (> \text{AIFS}_p)$
CW	0	$\text{CW}_{min}2^i, i = 0, 1, \cdots, m$ s.t. $\text{CW}_{min}2^m \leq \text{CW}_{max}$
Band selection	Deterministic (Latin squares)	Random
Sensing	Not required	Required

overall RawPEACH operation can be viewed as a single unified CSMA/CA protocol in which all users in the network sense the subbands after AIFS from their corresponding frame boundary. Here we have two different sets of values for parameters AIFS, CW, and frame length, algorithm to choose subbands for transmission, etc.: One for primary users and the other for secondary users. The conditions, $\text{AIFS}_s > \text{AIFS}_p = 0$ and $T_{f,p} \geq T_{f,s}$, ensure that the primary users occupy the channel always over the secondary users, and the sensing procedure of the primary users is not required. Due to these conditions, the secondary users can even use the subbands that are assigned to the primary users without affecting the primary transmission when the primary users do not transmit continuously in light traffic load.

III. ANALYSIS OF RAWPEACH MAC PROTOCOL

In this section, we analyze the performance of the proposed MAC protocol. In particular, we investigate the saturated throughput of the proposed protocol based on 802.11a physical layer specifications. The analysis can easily be extended to 802.11b/g and later physical layer extensions. Before we analyze the throughput of RawPEACH, we briefly address the complexity of RawPEACH. First, consider the complexity of AP's algorithm for primary users. An AP only needs to perform resource allocation for the primary users when they associate with the AP. Let us consider a simple admission scheme of admitting the same number of primary users as the number of frequency subbands. Once the AP distributes the resource (orthogonal frequency hopping sequence), the AP does not need to perform additional operations for the primary users. Hence, the complexity of AP's algorithm for primary users is not a function of the number of primary users but the number of frequency subbands. However, this complexity is negligible because the admission control is only in the initial association. Next, consider the algorithm complexity for the secondary user group. The AP does not need to perform any operation for secondary users because RawPEACH is a fully distributed random access for secondary users[3].

The throughput of primary users is easily obtained under the assumption of no sensing error. Once, they are admitted into the network, they just transmit their frames in the assigned channels.

type), which means the user wants to be associated with the AP as a primary user, then the AP checks the number of channels occupied by primary users.

(3) In (2), if there is an available channel sequence, then the AP allocates the corresponding hopping sequence to the primary user in association by sending an association response containing the hopping sequence. If there is no available primary channel sequence, then the AP notifies the primary user of an association failure in the association response.

(4) In (1), if the user priority field is set to be "1" (secondary user type), which means the user wants to be associated with the AP as a secondary user, then the AP sends a set of CSMA/CA related parameters to the secondary user in the association response.

C. Equivalent CSMA/CA Model for Primary Operation

In the previous sections, we described the proposed MAC scheme as a combination of channelization and CSMA/CA random access. One can view the RawPEACH as either a MAC scheme that inserts CSMA/CA secondary users into the white space of an OFDMA-based primary system or a MAC scheme that inserts several frequency hopping orthogonal channels into a multiband CSMA/CA system. Note that without primary users the RawPEACH is an extension of the conventional CSMA/CA protocol with slot interval $T_{f,s}$ to multiband scenario. The second viewpoint is more relevant as we consider the RawPEACH as an evolution of the conventional CSMA/CA-based WLAN protocols for supporting some users with QoS guarantee without interruption from other users based on demand. Indeed, the

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[3]However, each secondary user needs to sense all the frequency subbands of proper operation of RawPEACH which is linear with respect to the number of frequency subbands and this is the main challenge in physical layer for RawPEACH protocol.
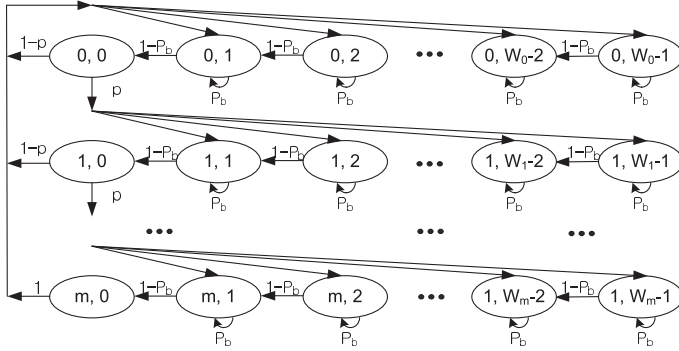
Fig. 7. Markov chain model for a secondary CSMA/CA user in a Raw-PEACH network ($0 \le P_b \le 1$).

Thus, we focus on the analysis of the throughput of secondary users in the network.

A. Throughput of Secondary Users in the Presence of Primary Users

We model the operation of secondary CSMA/CA users in the presence of primary users using a Markov chain in which states are defined by the values of the backoff stage and counter and a state transition occurs every secondary frame interval $T_{f,s}$. For the sake of analysis, we assume that both the primary and secondary frame intervals are the same as the system slot interval, i.e., $T_{f,p} = T_{f,s} = T_s$[4] and there is no sensing error. Our analysis for the evaluation of the overall secondary system throughput is based on the symmetry among the secondary users as exploited in many other CSMA/CA throughput analyses. In this method, the operation of one particular secondary user is tracked considering the impact of all the other users on that user of interest, and the overall system throughput is given by the product of the per-user throughput and the number of secondary users. We choose one secondary user arbitrarily and call this user as the given secondary user.

Fig. 7 shows the Markov chain for the operation of the given secondary CSMA/CA user considering both the operation of primary CSMA/CA users and other secondary users under the multiband CSMA/CA protocol. In this figure, state (i, j) (i.e., the circle in the ith row and jth column in the figure) is defined as secondary user's state having a backoff stage value of $i-1$ and a backoff counter value of $j-1$. Transitions among the states occur as follows. When the secondary user has a positive backoff counter value of j, it decreases its backoff counter value if the channel is not occupied by a primary user with probability $1-P_b$. On the other hand, if the channel is occupied by a primary user with probability P_b, the secondary user maintains its backoff counter value as the same value j. When the backoff counter value of the secondary user reaches 0 and the backoff stage value is smaller than the retry limit m (that is, $i \in [0, m-1]$ and $j = 0$), it transmits its frame. If other secondary users do not transmit simultaneously with probability $1 - p$, then its transmission is successful and the secondary user resets its backoff stage value to 0 and randomly selects its backoff counter value in the range of $[0, W_0-1]$. On the other hand, if at least one other

user transmits its frame, then a collision occurs and transmission fails with probability p. In this failure case, the secondary user increases its backoff stage value from i to $i + 1$, and randomly selects its backoff counter value in the range of $[0, W_{i+1} - 1]$. When the backoff counter value j of the secondary user reaches 0 and the backoff counter stage value reaches retry limit m, the secondary user resets its backoff stage to 0 regardless of the success or failure of transmission, and randomly selects its backoff counter value in the range of $[0, W_0 - 1]$, as shown in Fig. 7.

Since the Latin squares hopping sequence randomizes the probability of a frequency subband's being occupied by a primary user for each secondary frame interval uniformly without *a priori* knowledge of hopping pattern at the given secondary user, we assume that the probability of each frequency subband being busy by the transmission of a primary user is independent and identical, and this probability is denoted by P_p, which is a measure of the primary activity. In case of continuous transmission of N_p primary users, P_p is given by

$$P_p = \frac{N_p}{N_{CH}} \qquad (1)$$

where we have $N_p \le N_{CH}$ by the admission control of primary users. As noted in the previous section, however, the Raw-PEACH secondary users even use the subbands assigned to the primary users when the primary users do not use the assigned subband due to discontinuous transmission. Hence, the P_p can be smaller than the value in (1) with light primary traffic load. As described in Section II, the RawPEACH operates in multiple subbands and each secondary user senses all subbands and selects a transmission subband *randomly and uniformly* among the subbands sensed not to be occupied by primary users. Since the probability P_p of each channel being used by a primary user is assumed to be independent and identical, the probability P_b that all channels are busy by the primary users is given by

$$P_b = P_p^{N_{CH}} \qquad (2)$$

where N_{CH} is the number of subbands. Since the given secondary user freezes its backoff counter only when all the subbands are occupied by primary users, the probability for looping at each state is given by P_b, as shown in Figure 7. (In case of $P_b = 1$, all the subbands are occupied by primary users, and, thus, no secondary user can transmit a data frame in the Raw-PEACH network.) If the given secondary user has a positive backoff counter value, it decreases its current backoff counter value by one when the given secondary user senses that at least one out of N_{CH} channels is idle. (The probability for this event is $1 - P_b$.) Otherwise, the given secondary user freezes its current backoff counter. If at least one other secondary user transmits its data frame simultaneously in the subband that has been chosen by the given secondary user for transmission, the transmission of the given secondary user is collided. The probability for this event is denoted by p, which will be derived shortly. Then, the probability of successful transmission is given by the probability, $1 - p$, that only the given secondary user transmits its data frame in its selected subband. Thus, the transition probabilities for the Markov chain in Fig. 7 are given by

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[4]The analysis can be extended to the case of $T_{f,p} \ge T_{f,s}$.

$$P\{S_{i,j-1}|S_{i,j}\}=1-P_b, \qquad i \in [0,m], j \in [1,W_i-1],$$
$$P\{S_{i,j}|S_{i,j}\}=P_b, \qquad i \in [0,m], j \in [1,W_i-1],$$
$$P\{S_{0,j}|S_{i,0}\}=(1-p)/(W_0-1), \quad i \in [0,m-1], j \in [1,W_i-1],$$
$$P\{S_{i,j}|S_{i-1,0}\}=p/(W_i-1), \qquad i \in [1,m], j \in [1,W_i-1],$$
$$P\{S_{0,j}|S_{m,0}\}=1/(W_m-1), \qquad j \in [1,W_i-1].$$

The unique stationary distribution for this ergodic Markov chain is obtained form the above transition probabilities, and given by

$$b_{i,j} = \begin{cases} \frac{W_i-j}{(1-P_b)(W_i-1)} \times \\ \{(1-p)\sum_{k=0}^{m-1} b_{k,0} + b_{m,0}\}, & i=0, 1 \le j \le W_i-1, \\ ((1-p)\sum_{k=0}^{m-1} b_{k,0} + b_{m,0}), & i=0, j=0, \\ \frac{W_i-j}{(1-P_b)(W_i-1)} p b_{i-1,0}, & 1 \le i \le m, 1 \le j \le W_i-1, \\ (1-P_b) b_{i,j+1}, & 1 \le i \le m, j=0, \\ p b_{i-1,0}, & 1 \le i \le m, j=0. \end{cases}$$

The first and second equations represent the relationship among states in the first row in Fig. 7. Since the second equation can also be expressed as $b_{0,0} = (1-p)\sum_{k=0}^{m-1} b_{k,0} + b_{m,0}$, the first equation is expressed as $b_{0,j} = \frac{b_{0,0}}{(1-P_b)}\frac{W_0-j}{(W_0-1)}$ where $j \in [1, W_0-1]$. Similarly, we obtain $b_{i,j} = \frac{b_{i,0}}{(1-P_b)}\frac{W_i-j}{(W_i-1)}$ where $i \in [1,m]$ and $j \in [1, W_0-1]$ by substituting the fifth equation into the third. From these obtained equations, we simplify the above two equations and obtain the following.

$$b_{i,j}=\frac{b_{i,0}}{(1-P_b)}\frac{W_i-j}{W_i-1}, \quad i \in [0,m], \quad j \in [1, W_i-1] \quad (3)$$

where $b_{i,j}$ denotes the stationary probability for state (i,j). The normalization condition for the stationary distribution is given by

$$1 = \sum_{i=0}^{m}\sum_{j=0}^{W_i-1} b_{i,j} = \sum_{i=0}^{m} b_{i,0} + \sum_{i=0}^{m} \frac{b_{i,0}}{1-P_b}\sum_{j=1}^{W_i-1}\frac{W_i-j}{W_i-1}$$
$$= \sum_{i=0}^{m} b_{i,0}\left(\frac{W_i+2-2P_b}{2(1-P_b)}\right). \quad (4)$$

Assuming that $m \le \log_2(\frac{W_{max}}{W_{min}})$, where $W_{max} = CW_{max}+1$ and $W_{min} = CW_{min}+1$, and denoting W_0 as W, we compute the stationary probability $b_{0,0}$ for state $(0,0)$ as a function of P_b, p, m and, W from the above equations, and $b_{0,0}$ is given by

$$b_{0,0} = \frac{2(1-P_b)(1-2p)(1-p)}{W(1-(2p)^{m+1})(1-p) + 2(1-2p)(1-p^{m+1})(1-P_b)}. \quad (5)$$

Based on the stationary distribution, we obtain the probability τ that the given secondary user transmits a data frame at each secondary frame interval with length $T_{f,s}$, and τ is given by

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{1-p^{m+1}}{1-p} b_{0,0}. \quad (6)$$

Here, note that the frequency subband chosen by the given secondary user for transmission can be any of the channels sensed to be idle by the given secondary user.

We now compute p as a function of CSMA/CA parameters. p is the probability that the transmission of the given secondary user is collided when the backoff counter value of the given secondary user reaches zero and it initiates a transmission. A collision occurs because of the simultaneous transmission of other secondary users on the subband chosen by the given secondary user, and the collision probability p is given by

$$p = \sum_{k=1}^{N_s-1}\binom{N_s-1}{k}\tau^k(1-\tau)^{N_s-1-k}\left(1-\left(\frac{N_{FB}-1}{N_{FB}}\right)^k\right) \quad (7)$$

where N_{FB} is the number of primary user free subbands. Each term in (7) is explained as follows. Here, the condition is that the given secondary user transmits at the secondary slot interval, say $T'_{f,s}$. Under this condition, a collision occurs if (1) k other secondary users among N_s-1 secondary users other than the given user also transmit for that $T'_{f,s}$, and (2) at least one of these k secondary users selects the subband chosen by the given secondary user for transmission. The probability for the first event is given by $\binom{N_s-1}{k}\tau^k(1-\tau)^{N_s-1-k}$ and that for the second event is given by $1-\left(\frac{N_{FB}-1}{N_{FB}}\right)^k$. The second probability is obtained by the uniform random subband selection. The overall collision probability p is the sum of the product of the two probability over $k = 1, 2, \cdots, N_s-1$. In case of continuous primary transmission, we have a deterministic value

$$N_{FB} = N_{CH} - N_p$$
$$= N_{CH}\left(1 - \frac{N_p}{N_{FB}}\right) = N_{CH}(1-P_p). \quad (8)$$

For discontinuous primary transmission, we substitute N_{FB} in (7) by the average value $\bar{N}_{FB} = N_{CH}(1-P_p)$ for the sake of simple analysis.

A.1 Normalized throughput S per subband and access delay D

We evaluate the saturation throughput of the RawPEACH network. Our approach to calculate the total system throughput is based on the per-user throughput and the symmetry among the secondary users. For each secondary user, the successful transmission, collision, and idle probabilities, denoted by P_s, P_c, and P_i, respectively, are given by

$$P_s = \tau(1-p), \quad (9)$$
$$P_c = \tau p, \quad (10)$$
$$P_i = 1-\tau = 1-P_s-P_c \quad (11)$$

where the slot transmission probability τ and the slot collision probability p conditioned on transmission are given in the previous section. The normalized throughput S_{user} per user is given by

$$S_{user} = \frac{P_s}{P_i+P_s+P_c}, \quad (12)$$

and the overall system throughput is finally given by

$$S = N_s S_{user} = N_s \tau(1-p). \quad (13)$$

To illustrate the above equation, we provide an example of $N_{CH} = 2$ and $N_s = 3$ with no primary user, as shown in Fig.

Table 3. Parameters used in simulation.

Parameter (Description)	Value
$\{CW_{min}, CW_{max}, m\}$ ({Min. CW size, Max CW size, Retry limit})	$\{15, 31, 1\}, \{31, 63, 1\}, \{31, 127, 2\}$
$T_{f,p}$ (Hopping interval of primary users)	1000 us
$T_{f,s}$ (Transmission unit interval of secondary users)	1000 us
T_s (System slot interval)	1000 us
T_{ack} (ACK duration)	60 us
$t\text{AIFS}_p$ (AIFS for primary users)	15 us
$t\text{AIFS}_s$ (AIFS for secondary users)	20 us
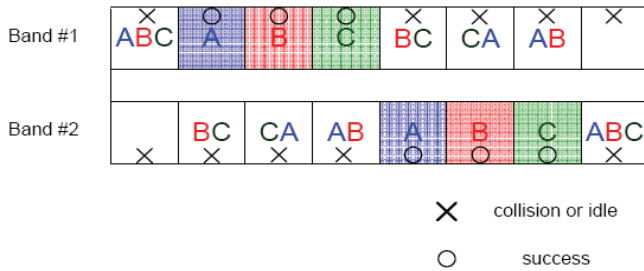
Fig. 8. Possible channel selection cases (N_{CH}=2, $N_s = 3$).

8. Here, we have two subbands (band#1 and band#2) and three secondary users (A, B, and C) with no primary users so that $N_{CH} = N_{FB}$. For simplicity, we assume that every secondary user always transmits, i.e., $\tau = 1$ (it transmits every slot), and randomly and uniformly selects one subband for transmission. Except for the two time slots (the first and last slots) in which all three secondary users select the same channel, only one channel is used by one user for successful transmission. Thus, the collision probability p for each secondary user is $6/8$, and the slot throughput is $6/8$, which is the same as $N_s\tau(1-p) = 3(1-6/8)$.

The delay can easily be obtained by the Little's law. Let D be the average access delay, defined as the time elapsing from the instant on which the frame is put into service – i.e., it becomes the head-of-line (HOL) – to the instant on which the data frame is completed with a successful transmission. D is given, using the Little's law, by [3]

$$D = \frac{E[n]}{S/E[P]} \qquad (14)$$

where P is the payload length (i.e., the secondary frame interval in this case), the numerator $E[n]$ represents the average number of competing secondary users which will successfully transmit their HOL frame, and the denominator $S/E[P]$ represents the frame delivery rate (i.e., the throughput measured in frames/seconds).

IV. NUMERICAL RESULTS

In this section, we evaluate the throughput of secondary users as a function of the primary user activity, the number of orthog-
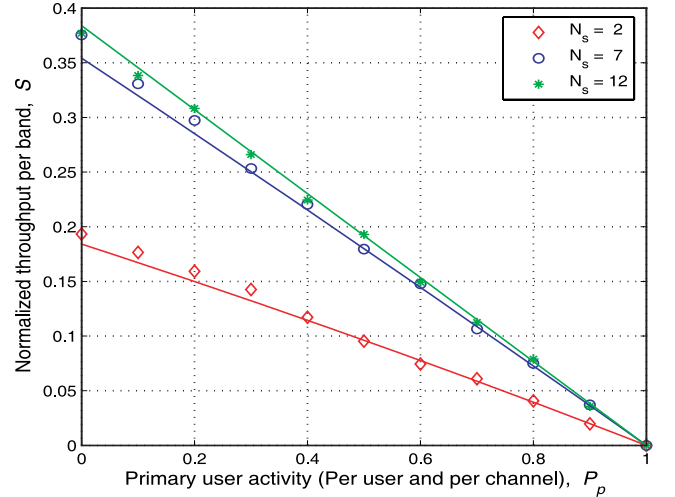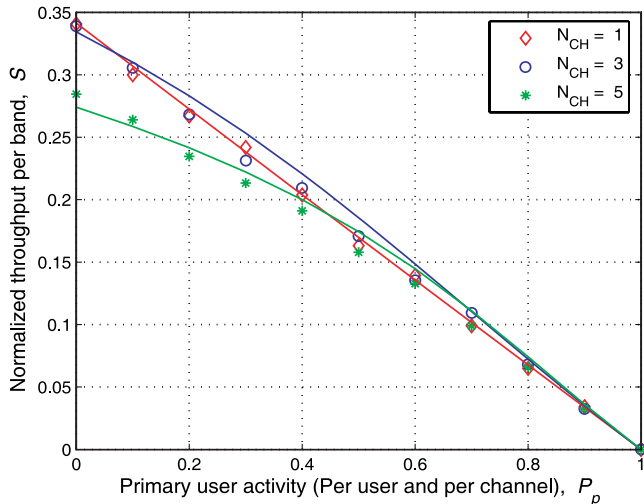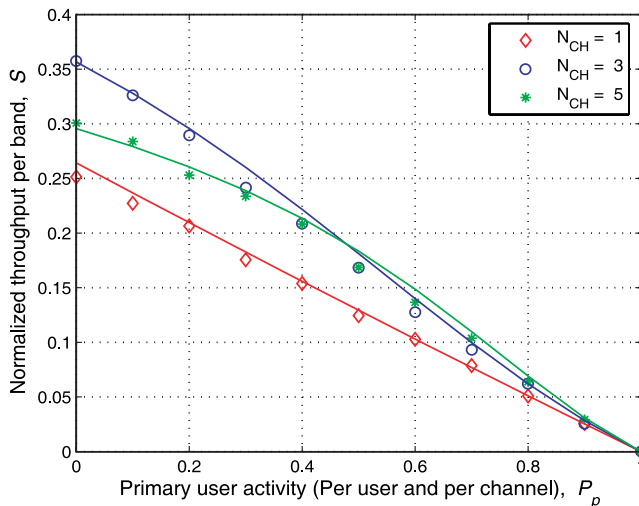

(a)
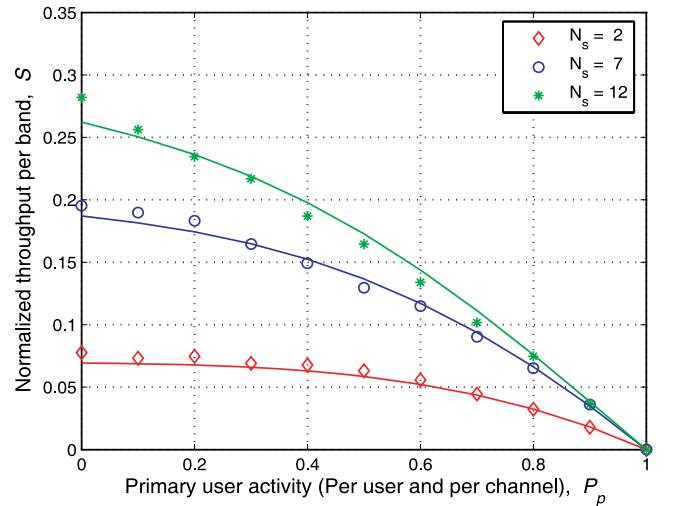
(b)

Fig. 9. Throughput per bandwidth with respect to primary user activity P_p: (a) $N_{CH} = 1$ and (b) $N_{CH} = 3$ ($W_0 = 16, W_m = 32, CW_{min} = 31,$ and $CW_{max} = 63$ Analysis – solid line and simulation – marks).

onal primary channels and the number of secondary users. We assume that the secondary users always have frames to transmit. The CSMA/CA related parameters in our analysis and simulation are shown in Table III. The analytical results are obtained based on the expressions in Section III. Simulation is performed based on the RawPEACH protocol described in Section II, and the simulation results were obtained using OPNET simulation.

Figs. 9(a) and 9(b) show the normalized throughput S versus the primary user activity P_p when the number N_{CH} of frequency subbands is one and three, respectively. While the number of primary users is equal to N_{CH}, the number of secondary users is increased from 2 to 12 in both figures. The solid lines represent the analysis based on our analytical model, whereas the simulation results are shown with the marks. It is observed that the simulation matches the analysis in the previous section well. The throughput decreases as the primary user activ-

(a)

(b)

Fig. 10. Throughput per bandwidth with respect to primary user activity P_p: (a) $CW_{max} = 127$ and (b) $CW_{max} = 63$ ($CW_{min} = 31$ and $N_s = 50$ Analysis – solid line and simulation – marks).

Fig. 11. Throughput per bandwidth: Solid line – $N_P = N_{CH}$ and dashed line – $N_P < N_{CH}$ ($W_0 = 32, W_m = 64$, and $N_s = 50$ Analysis – line and simulation – marks).

ity increases as we expect. Comparing the $N_{CH} = 1$ case with $N_{CH} = 3$, the throughput decreases steeply when N_{CH} is equal to one. This is because the channel is in a heavier contention state and, hence, a small increase in the primary user activity results in a large throughput decrease. If the number of channels is large as in $N_{CH} = 3$ case, on the other hand, an increase in the primary user activity results in a small throughput decrease initially. As the primary user channel activity further increases, however, the throughput decreases rapidly in the end.

Figs. 10(a) and 10(b) show the normalized throughput versus the primary user activity when CW_{min} is fixed to 31 and the CW_{max} values are set to 127 and 63, respectively. The number N_s of secondary users is fixed to 50. Fig. 10(a) shows the throughput when the channel is not in a heavy contention state. Hence, the throughput per bandwidth does not increase when one more frequency subband can be used additionally. When the
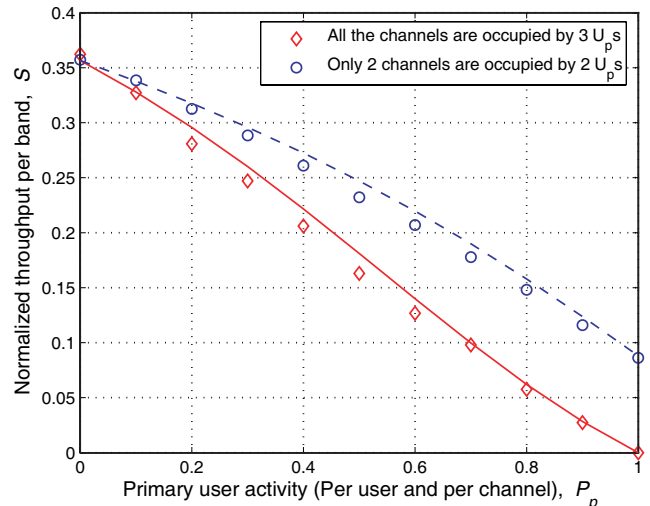
number of secondary users and the maximum contention window size are equal to 50 and 63, respectively, on the contrary, the channel is in a heavy contention state and one additional subband can increase the throughput per subband significantly, as in shown Fig. 10(b).

Fig. 11 shows the throughput of RawPEACH with respect to the primary user activity. We considered two cases: One is that the number of primary users is equal to the number of channels, and the other is that the number of primary users is smaller than the number of channels. As shown in the figure, if at least one channel is not allocated to primary users, the throughput of secondary users is not zero even though the P_p is one.

We now consider the packet transmission delay. The access delay is defined in the previous section. For fair comparison of RawPEACH, multiband CSMA/CA with full band sensing without priority discrimination, and legacy CSMA/CA, the primary user activity P_p is determined by the inverse value of $1/2 \times CW_{min}$ for each system since each user in the multiband and legacy CSMA/CA MAC randomly selects its backoff counter value from $[0, CW_{min}]$. CW_{min}, CW_{max}, m, and other CSMA/CA related parameters in the legacy CSMA/CA system are set according to the IEEE 802.11a specifications [1]. Moreover, the $T_{f,p}$ and $T_{f,s}$ of the RawPEACH system are equally set to $50 us$ and other CSMA/CA related parameters of the RawPEACH system are equally set to those of the legacy CSMA/CA system. Fig. 12 shows the cumulative distribution function for access delay when the number of total users is 58. It is shown that the access delay of the secondary users of the RawPEACH is substantially lower than that of the legacy CSMA/CA protocol [1] due to multiband operation. The access delay for the primary users of the RawPEACH MAC is always smaller than one $T_{f,s}$ and this delay can not be attained by the legacy 802.11 MAC. The delay for secondary users of the RawPEACH is slightly increased, compared with that of the multiband CSMA/CA with full band sensing without user prioritization, at the expense of strict delay guarantee for the primary
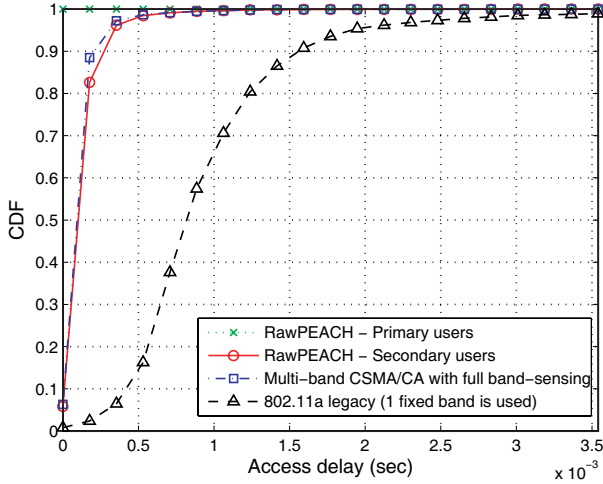
Fig. 12. Cumulative distribution for access delay. (IEEE 802.11a delay performance ($N_P + N_S = 58, N_{CH} = 8, N_P = 8$, and $P_p = 0.125$)).
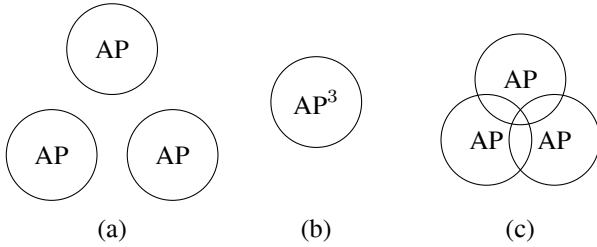

Fig. 13. An example of multiple CSMA/CA networks with 3 AP's where γ a overlapping factor: (a) $\gamma = 0$, (b) $\gamma = 1$, and (c) $0 < \gamma < 1$.

users.

V. MULTIPLE CSMA/CA NETWORKS

In the previous section, we investigated the performance of RawPEACH in a single AP scenario. To evaluate the performance of RawPEACH in a more practical deployment situation, in this section, we consider the RawPEACH in a multiple AP scenario and compare its performance with the conventional CSMA/CA protocol (legacy WLAN systems) in this case. Handling multicell environment is a complicated problem since many APs can be randomly located and interference among cells depends on the location of APs. Moreover, the Latin square frequency hopping pattern does not guarantee orthogonality among the primary users associated with different APs just as inter-cell interference in OFDM-based cellular system with a frequency reuse factor of one. To simplify the problem and gain insights, we consider simple three deployment scenarios here: totally separated, entirely overlapped, and partially overlapped, as shown in Fig. 13(a), 13(b), and 13(c), respectively.

With some coverage overlap, a transmitting user in one AP experiences the contention and/or collision from the users in the adjacent AP's in addition to those from the users in the same AP. To avoid this additional interference from neighboring AP's, the legacy WLAN systems are provided with multi-

ple available frequency allocation (FA) bands[5], and choose one operating band from these multiple available FA's[6]. Using this FA selection method, the frequency reuse factor of the legacy WLAN is not one. However, the RawPEACH protocol aims at multiband operation, and thus the aggregation of all available FA's is a reasonable choice for the RawPEACH. From physical layer perspective, it is much easier to operate a wide spectrum using multiband operation than using a single band or a single carrier transmission. Under the assumption of RawPEACH operation over the aggregated band, the comparison between the legacy WLAN and the RawPEACH is not fair for the entirely separated or partially overlapped case, as shown in Figs. 13(a) and 13(c). In these cases, the same amount of frequency spectrum for the same area is not allocated to the legacy WLAN since the frequency reuse factor is larger than one for the legacy FA allocation. To quantify the amount of the effect of band overlapping, we first define the *overlapping factor* γ_i of an AP as

$$\gamma_i = \frac{A_i^{overlapped}}{A_i} \tag{15}$$

where A_i and $A_{overlapped}$ denote the communication area of the ith AP and the area which is overlapped with the communication area of other APs using the same band. Average overlapping factor $\bar{\gamma}$ in the area served by N_{AP} APs can be calculated as

$$\bar{\gamma} = \frac{\sum_{i=0}^{N_{AP}} \gamma_i}{N_{AP}}. \tag{16}$$

We consider the situation in which each network has the same number of users and the same traffic load, i.e., saturation mode. Moreover, we assume that each AP in the legacy CSMA/CA system selects a different frequency band. In the following, we compare the operation of RawPEACH and legacy CSMA/CA in multiple network environment for different overlapping factor. The performance of the general partially overlapping case should be between the other two extreme cases of which performance is analyzed. This provides some intuition for the general partially overlapping case. [7]

A. No Overlap Case ($\bar{\gamma} = 0$)

Fig. 13(a) shows the no overlap case ($\bar{\gamma} = 0$) in which APs are sufficiently separated and their communication range do not overlap. The aggregated throughput S_{agg}^{legacy} of the legacy CSMA/CA is calculated as the product of the number N_{AP} of APs and the throughput S of one CSMA/CA network. The aggregated throughput $S_{tot}^{RawPEACH}$ of RawPEACH MAC is similarly derived. S_{tot}^{legacy} and $S_{agg}^{RawPEACH}$ are expressed as follows:

$$S_{tot}^{legacy} = S_{1AP}^{legacy} \times N_{AP}, \quad \text{if } \bar{\gamma} = 0 \tag{17}$$

$$S_{tot}^{RawPEACH} = S_{1AP}^{RawPEACH} \times N_{AP}, \quad \text{if } \bar{\gamma} = 0. \tag{18}$$

[5]For example, 802.11b/g have 11 FA's with bandwidth of 22 MHz in the ISM band. Among the 11 FA's, three FA's can be selected without any band overlap. 802.11a has 8 non-overlapping FA's in 5 GHz unlicensed national information infrastructure (U-NII) radio band

[6]If the adjacency relationship among AP's is given, the minimum number of FA's to avoid inter-AP interference is easily calculated.

[7]The analysis of general multicell environments with random AP location is beyond scope of this paper and may be considered for future work.
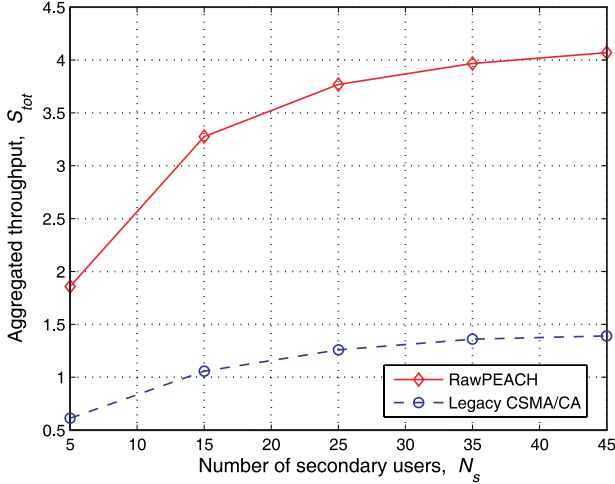
Fig. 14. Aggregated throughput when networks are not overlapped at all ($\bar{\gamma} = 0, W_0 = 16, W_m = 1024, N_{CH} = 3$, and $N_{AP} = 4$).

Fig. 15. Aggregated throughput for $N_{CH} = N_{AP} = 3$ with complete overlapping ($\bar{\gamma} = 1, W_0 = 16$, and $W_m = 1024$).

$S_{1AP}^{RawPEACH}$ is larger than S_{1AP}^{legacy} since 1 AP of RawPEACH can use 3 bands while 1 AP of the legacy MAC can use only 1 band. Hence, the aggregated throughput $S_{tot}^{RawPEACH}$ of Raw-PEACH is expected to be larger than that of legacy CSMA/CA, and $S_{1AP}^{RawPEACH}$ can be obtained from (13).

Fig. 14 compares the aggregated throughput of the Raw-PEACH MAC protocol with that of the legacy CSMA/CA in a multi-cell network of 4 APs with frequency reuse factor of 3. As we expected, it is shown in Fig. 14 that the aggregated throughput of RawPEACH is much larger than that of legacy CSMA/CA when $\bar{\gamma}$ is equal to 0.

B. Completely Overlapping ($\bar{\gamma} = 1$) and Partially Overlapping ($0 < \bar{\gamma} < 1$) Cases

We consider the entire coverage overlapping case, as shown in Fig. 13(b). We assume that we have N_{CH} bands and N_{CH} AP's which are entirely overlapped. A different band is assigned to each AP in the legacy WLAN scheme so that all N_{CH} AP's in the legacy WLAN also use all the spectra in the area as the RawPEACH does. Note that we have N_{CH} AP's with each AP operating in one band in the legacy WLAN scheme whereas one RawPEACH AP is operating in the aggregated N_{CH} bands.

We assume that each scheme has the same number n of users and the same traffic load, and the network is operated in saturation mode. Then, the total throughput for the legacy scheme is given by

$$S_{tot}^{Legacy} = \sum_{k=1}^{N_{CH}} S_{1CH}(n(k)) \tag{19}$$

where $n(k)$ is the number of users at band k such that $\sum_{k=1}^{N_{CH}} n(k) = n$, and $S_{1CH}(n(k))$ is the throughput of AP k under the single band CSMA/CA operation.

On the other hand, the throughput $S_{tot}^{RawPEACH}$ of the Raw-PEACH scheme is given by
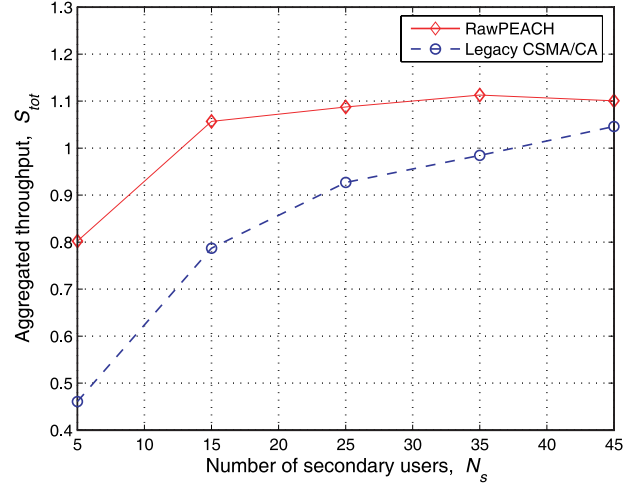
$$S_{tot}^{RawPEACH} = S_{NCH}^{RawPEACH}(n) \tag{20}$$

where $S_{NCH}^{RawPEACH}(n)$ is the throughput of the RawPEACH with n users operating over N_{CH} bands. Fig. 15 shows the total throughput of the two schemes when both N_{AP} and N_{CH} are three. Here, the number of primary users is set to three and the primary activity factor $P_p = 0.0625$ so that the effect of the primary user activity is negligible and the resource is used mostly by the secondary users. It is seen that the total throughput of the RawPEACH is larger than that of the legacy frequency allocation scheme, as expected. This is because in the RawPEACH case the three bands are aggregated and used by all users and thus statistical multiplexing gain is attained, whereas in the legacy WLAN with the legacy frequency allocation the frequency bands are divided and no statistical multiplexing occurs across the multiple bands. Here, the multiband operation of the RawPEACH is considered in a multiple FA environment. However, a single FA can be divided into multiple subbands using physical layer techniques such as OFDMA and the RawPEACH can be applied to this single FA with frequency subdivision. In any case, this multiband CSMA/CA operation is more suitable to cover a wide available spectrum than the conventional CSMA/CA based on single band transmission.

Now consider the partially overlapping case, as shown in Fig. 13. In the legacy CSMA/CA, we can categorize users into two groups: users in the overlapped region or non-overlapped region. In the non-overlapped region, the users compete with other users in the same network. In the overlapped region, on the contrary, the users compete with the users in the adjacent network as well as those in the same network. The performance of the partially overlapping case should be between the other two extreme cases of which performance is analyzed.

VI. CONCLUSION

In this paper, we have proposed a new MAC scheme, called RawPEACH (Random Access With PrE-Arbitrated CHannelization), based on multiband CSMA/CA operation in which the QoS for primary users is guaranteed by embedding orthogo-

nal channels into CSMA/CA-based random access modified to operate in multiple bands. We have evaluated the throughput and delay performance of the proposed scheme using a Markov chain widely used for the analysis of CSMA/CA protocols. The multiband CSMA/CA operation is more relevant to adding orthogonal channels and yields statistical multiplexing gain over the conventional single band CSMA/CA. The proposed MAC protocol is suitable in case that a few users in a CSMA/CA network require uninterrupted service for QoS-sensitive applications like real-time audio or video traffic while most other users are satisfied with best-effort services as in conventional WLAN networks. The proposed multiband operation can be implemented using physical-layer transmission techniques such as the orthogonal frequency division multiplexing/ multiple access (OFDM/OFDMA).
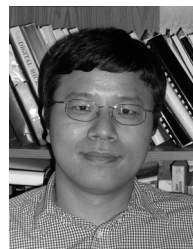
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