Stochastic Medium Access for Cognitive Radio Ad Hoc Networks

Xiao Yu Wang, Alexander Wong, and Pin-Han Ho

***Abstract*—In ad hoc cognitive radio (CR) networks, medium access control (MAC) design has been raised as a major challenge due to its highly dynamic nature and strong user diversity, particularly in situations where a dedicated control channel is not reserved among the distributed CR nodes. In this paper, we propose a novel Stochastic Medium Access (SMA) scheme that takes interference constraints into account to improve spectrum sharing efficiency. Specifically, the proposed SMA scheme is developed to serve in a CR network without dedicated control channels, such that the probability of successful channel accesses can be maximized. The formulated optimization problem is then solved by using a dynamic Markov-Chain Monte-Carlo scheme. Moreover, the paper introduces a suite of mechanisms for implementation of the proposed SMA scheme, including segmentation of long packets and contention resolution, which is working on top of power controlled Request-to-Send (RTS) and Clear-to-Send (CTS) exchanges in a multichannel environment. An analytical model is developed on the proposed SMA scheme using an absorbing Markov chain model to evaluate throughput of the secondary user network. Extensive simulation is conducted to study the impact of some important factors on the proposed SMA scheme, such as channel conditions and secondary traffic loads.**

***Index Terms*—Cognitive Radio, Dynamic Spectrum Access, Ad Hoc Networks.**

I. INTRODUCTION

To SOLVE the problem of spectrum resource starvation in wireless communications under the static frequency allocation regime, Cognitive Radio (CR) [1], [2] has been considered as a promising approach by opportunistically accessing the spatiotemporally available licensed bands are not been used by licensed users. The main goal of CR network design is to facilitate efficient utilization of spectrum resources without degrading the performance of licensed user networks. Therefore, with CR, two tiers of wireless users are defined: i) the licensed users on their own spectrum bands, which are known as "primary users", and ii) the unlicensed users that attempt to use spatiotemporally available licensed bands, which are known as "secondary users".

In the context of media access, the secondary users must determine which channels to use for data transmissions in presence of the dynamic and opportunistic nature of wireless environments. This issue is crucial in designing an efficient media access scheme in CR, and is extremely challenging in ad hoc networks where no centralized controller is involved. The conventional way of achieving media access in multichannel ad hoc networks is to pre-define a dedicated control channel, which is used to exchange channel selection information such that channels are available between both secondary transmitter and receiver (defined as commonly available channels) can be identified for data transmission, where channel availability is defined as the fact that a channel is not occupied by the primary users and therefore can be accessed by the secondary users. Thus, the presence of a dedicated control channel in multichannel networks has become a widely accepted assumption by the research community, even in most recently reported MAC protocols for CR networks [3]–[12].

However, dedicated control channels among a group of nodes may not always be present in future CR networks due to the strong network dynamics and user diversity, in which devices of different vendors and even different protocol stacks could be accommodated in a common network domain. Thus, the requirement for a pre-defined dedicated control channel could be harmful to the system flexibility and interoperability. Moreover, we envision that the static use of a dedicated control channel may cause contention and resource starvation of the channel, which not only limits the prevalence and ubiquitousness of CR network development, but also degrades the system performance due to possibly long contention latencies on the dedicated control channel.

In the context of achieving interference-free utilization of primary user spectrum resources, the secondary users must access these channels over the licensed spectrum without degrading the performance of the primary users. There are three main issues associated with interference-free access of the secondary users. First, current spectrum sensing techniques cannot achieve a perfect detection of primary signals with reasonable computational complexity. Second, since spectrum availability is continually changing over time, the design of fast yet precise channel negotiation[1] and access mechanisms is subject to a great challenge. Third, the accuracy of spectrum availability prediction is highly dependent on the selection of the prediction model. Due to these three main issues, interference to the primary users are almost unavoidable because an interference-free access is extremely hard to achieve when secondary users coexist with primary users. Therefore, current research efforts on CR networks have focused on minimizing the harmful interference while leaving the improvement of throughput as the second-tier target.

Motivated by the above observations, this study takes the assumption that dedicated control channels are not available, by

Manuscript received 1 December 2009; revised 30 May 2010.

X. Y. Wang and P.-H. Ho are with Electrical and Computer Engineering, U. of Waterloo, Waterloo, Canada N2L 3G1 (e-mail: {x18wang,p4ho} @engmail.uwaterloo.ca).

A. Wong is with Systems Design Engineering, U. of Waterloo, Waterloo, Canada N2L 3G1 (e-mail: a28wong@engmail.uwaterloo.ca).

Digital Object Identifier 10.1109/JSAC.2011.110409.

[1]Channel negotiation is defined as a process that dynamically sets parameters of communications channels established between communication pairs before data transmission over the channels begins, also known as Request-to-Sent / Clear-to-Send (RTS/CTS) handshake

which a novel media access scheme via an efficient dynamic stochastic approach is developed. The proposed media access scheme is characterized by achieving probabilistic objectives of minimum interference to the primary users through a power control mechanism. The contributions of this paper are as follows:

- By assuming the absence of any pre-defined dedicated control channel, a stochastic media access (SMA) scheme for secondary users in ad hoc CR networks is introduced, in which the problem of channel selection is formulated as an optimization problem for maximizing the probability of channel access.
- The formulated optimization problem is solved via an adaptive Markov-Chain Monte-Carlo (MCMC) approach, given the partial knowledge of channel availability such as imperfect energy detection results. The dynamic MCMC method is incorporated with the proposed SMA scheme for channel access in order to achieve high success rates and short delay of data transmission.
- We develop a power-controlled distributed Request-to-Send and Clear-to-Send (RTS/CTS) exchange mechanism, along with the incorporating collision resolution and data fragmentation strategies, that can best fit into the outlined CR network design premises with an ultimate goal for effectively minimizing the interference on the primary user network.

Simulation results validate the developed analytical model, as well as indicate that the proposed SMA scheme can achieve comparable performance as that achieved by existing approaches assuming dedicated control channels, while achieving noticeably improved performance when compared with the existing approaches without dedicated control channels (i.e., static channel hopping). We expect that the proposed SMA scheme will serve as a value-added complement to the state-of-the-art multi-channel MAC protocols with pre-defined dedicated control channels in distributed and highly dynamic CR networks.

The rest of this paper is organized as follows. Related work is presented in Section II. The system model is described in Section III. The problem formulation is presented in Section IV. The proposed stochastic media access (SMA) scheme is introduced in Section V. Performance analysis is presented in Section VI. Simulation results are provided in Section VII. Finally, conclusions are drawn in Section VIII.

II. Related Work

To our best of our knowledge, most of the reported studies on CR multi-channel networks have taken a common assumption on the presence of one or multiple frequency bands as dedicated control channels [4]–[12]. In [4], a cross-layer opportunistic multi-channel MAC protocol integrated with spectrum sensing at the physical layer and packet scheduling at the MAC layer was proposed. Two collaborative channel spectrum-sensing policies were proposed, in which the channel selection information is exchanged via a dedicated control channel to support the agreement during the channel access process between transmission pairs. In [5], constraints on sensing and transmission were considered in designing a stopping algorithm to realize opportunistic media access with the aid of the dedicated control channel to exchange control messages. In [12], a code-division multiple-access (CDMA) based channel-aware access control (CAAC) algorithm was proposed that adjusted channel access probabilities based on the received SINR and measured interference temperature. The algorithm is then implemented on a CSMA/CA access method where the channel status information is overheard and exchanged over a control channel.

In a traditional multichannel network, some MAC protocols apply channel hopping [13], [14] as an alternative, where each node follows a set of pre-defined multi-channel hopping sequences in an attempt to access channels with any intended receiver without the need for a dedicated control channel. While channel hopping holds a great potential in alleviating the need of dedicated control channels, it is subject to a critical limitation when applied in a CR network. Currently existing channel hopping schemes are based on fixed and static sequences, which are either generated from simple hashing functions [14] or pseudo-random hopping sequences [13]. Without considering the underlying channel availabilities of the network environment, the channel hopping schemes do not account for the highly dynamic wireless channels and user behaviours, which serve as the most important and unique features of CR networks. This will certainly lead to poor performance of CR systems as transmission pairs may not be able to identify commonly available channels in a timely manner due to poor hopping sequences.

There are a few MAC protocols designed for CR networks that try to dance around the need for pre-defined dedicated control channels, but with implicit assumptions on common resources, such as channels, time slots, as well as codes, which can be used to facilitate the media access. In [3], based on an assumption that bidirectional communication links exist between communication pairs enabling coordination and selection of common channels to communicate, the problem of media access is then studied in a two-tier media access game composed of a channel allocation and a multiple access sub-games. In [9], a slotted beaconing period is defined in each MAC super-frame to exchange information and negotiate channel usage. A beacon is signed when a node detects an available channel where no other beacon is present, and other nodes can join the beacon group by sending its own beacon. In this way, a dynamic rendezvous channel is selected by the beacon group, where these nodes can communicate with each other. In [11], an analytical framework for opportunistic spectrum access based on a Partially Observable Markov Decision Process is developed. A simplified suboptimal algorithm that greedily maximizes each-slot throughput is proposed for spectrum sensing and access, and the idea of receiver oriented code assignment is used to facilitate the initial handshake.

III. System Model

In the study, users with CR capabilities, referred to as secondary users, can utilize spatially and/or temporally available spectrum resources of the primary network to communicate with other CR nodes when their own network does not have sufficient spectrum resources. The secondary users then form an ad-hoc network without a central controller or reserved dedicated control channels. Due to a highly dynamic and heterogeneous networking environment, a dedicated control channel is not pre-defined for exchanging control messages. The notation used in this section is listed in Appendix A.

A. Channel Model

Let the total bandwidth of a licensed spectrum be denoted as W Hz. Assume there are M non-overlapping channels [15] that can be accessed by N_s secondary users who may hunt for spectrum opportunities. Note that the channels are not necessarily equally spaced. Moreover, the radio propagation is assumed to be subject to small scale Rayleigh fading. Such an assumption has been commonly taken to describe the rapid fluctuations of radio signal over a short period of time or transmission distance [16]. Mathematically, given a transmitter-receiver pair and the radio transmitting power P_i on channel i, the corresponding received power X_i follows a chi-square distribution with two degrees of freedom:

$$p(X_i) = \frac{1}{\bar{P}_i}\exp(-\frac{X_i}{\bar{P}_i}) \tag{1}$$

with the mean value $\bar{P}_i = \frac{P_i G_i}{d^\xi}$, where G_i is the antenna gain on channel i, d is the distance between the transmitter and the receiver, and ξ is the path loss component associated with channel i.

B. Spectrum Sensing Model

In the Rayleigh fading channel model, each secondary user detects the presence of primary users independently of other secondary users through energy detection over the entire radio spectrum, which is a fast but relatively inaccurate sensing process. Given the observed signal $x_i(t)$ on channel i and a known one-sided noise power spectral density (PSD) N_0, for $0 \le t \le T$, the test statistics can be expressed as

$$u_i \cong \frac{2}{N_0}\int_T x_i^2(t)dt, \tag{2}$$

which is a random variable with a chi-square (χ^2) distribution. Therefore, the probability density function (PDF) of u_i can be expressed as [17]

$$f(u_i) = \begin{cases} \frac{1}{2^{k/2}\Gamma(k/2)} u_i^{(k/2)-1} e^{-u_i/2}, & H_0 \\ \frac{1}{2} e^{-(u_i/2+\omega_i)}(\frac{u_i}{2\omega_i})^{k/4-0.5} I_{(k/2)-1}(\sqrt{2\omega_i u_i}), & H_1 \end{cases} \tag{3}$$

where k is the degrees of freedom, ω_i is the instantaneous SNR on channel i, Γ denotes the Gamma function, and I denotes a modified Bessel function.

Given a certain probability of false alarm, p_f, the average detection probability can be approximated as [17]

$$\bar{p}_{d,i} = \frac{1}{\bar{\omega}_i}\int_0^\infty \int_{N_0 b(1+\frac{Q^{-1}(p_f)}{\sqrt{k}})}^\infty f(u_i)\exp(-\frac{\omega_i}{\bar{\omega}_i})du_i d\omega_i, \tag{4}$$

where $\bar{\omega}_i$ is the average SNR, b is the signal bandwidth, and $Q(\cdot)$ is the Q function.

Such a narrowband resolution is necessary for reliable wide-band sensing at a secondary user. Thus, a secondary user can sense multi-gigahertz-wide bandwidth simultaneously, which is considered as a physical design issue addressed in [5], [18], [19]. Although multichannel wideband sensing has been gradually accepted as off-the-shelf wireless hardware (e.g., ICS-572 products [20], [21]), sequential sensing is still the major approach taken in the state-of-the-art technologies. Thus in this work, we conservatively assume a sequential sensing approach over M channels one by one to obtain the spectrum sensing results. The imperfection in the channel availability information obtained through the spectrum sensing process may be introduced by factors such as hardware sensitivity as well as time delay in using the sensing results. Moreover, without loss of generality, we assume that the sensing process and the data transmission process cannot take place simultaneously [4], [5], [11], [20], [22]–[25].

C. Interference Model

In the interference model, any secondary transmitter must ensure that its interference power on a particular channel i added to the existing interference power $P^I_{i,(1)}$ at a primary receiver must not exceed the interference power limit. By assuming that the secondary transmitters operate with average power $P_{i,(2)}$, the maximum interference power at the primary receiver $P^{I,\max}_{i,(1)}$ on channel i should be satisfied by [20],

$$P^I_{i,(1)} + \varepsilon_i P_{i,(2)} \le P^{I,\max}_{i,(1)}, \tag{5}$$

where $P^I_{i,(1)}$ is the existing interference power at the primary receiver. The selection of ε_i has been shown to be dependent on the distance d on channel i between the closest primary receiver and the secondary transmitter, and the distribution of the corresponding minimum distance d_{min} is given by [20], [26]

$$p(d_{\min} < d) = 1 - e^{-\alpha_i \eta_i \pi d^2}, \tag{6}$$

where α_i is the probability of primary user transmission, and η_i is the average number of primary users per unit area. Therefore, we can get the ε_i with the interference probability from secondary transmission $\hat{p}$ with distance d under the channel fading model. Accordingly, the maximum allowable transmission power $P^{\max}_{i,(2)}$ at the secondary transmitter is given by

$$P^{\max}_{i,(2)} = \frac{P^{I,\max}_{i,(1)} - P^I_{i,(1)}}{\varepsilon_i}. \tag{7}$$

D. Access Model

For the secondary opportunistic access, as long as the observed test statistics u_i is lower than a specific threshold, which varies from different primary user systems, the secondary users are allowed to access. Orthogonal Frequency Division Multiple Access (OFDMA) is taken as the underlying multiple access technique for data transmission across multiple free channels. A channel is a sub-carrier in the OFDMA system, and the transmission data rate is determined by the SNR of the channel, where a higher SNR leads to a higher transmission rate. Therefore, the multi-rate capacities are supported, and the channel is categorized into γ different modulation schemes with corresponding data transmission rates based on the perceived SNR of the channel. Finally, data transmission can only be initiated on channels after a successful channel negotiation.

IV. Problem Formulation

Due to the imperfect channel availability information in spectrum sensing, it is challenging in selecting channels for access in order to achieve efficient usage of temporally available channels. Channel negotiation acts as the first step of media access and should be designed to efficiently identify and establish commonly available channels between a pair of secondary users. With the commonly available channels determined, channel access can be subsequently initiated between the CR pair.

In the scenario without pre-defined control channels, a fundamental question is how to dynamically and adaptively find commonly available channels between communication pairs. Specifically, our goal is to identify the optimal channel sequence for a secondary transmitter to negotiate with the intended secondary receiver given the limited number of channel negotiation attempts n_{max} that can be performed within a limited time period, such that the probability of successful channel negotiation of the selected channels is maximized.

Let S be a random variable taking on a channel $i, i = 1, 2, ..., M$, and s be the realization of S. Let Y_s be a binary indicator on the results of channel negotiation on s (i.e., a channel $i, i = 1, 2, ..., M$), where $Y_s = 0$ and $Y_s = 1$ indicates a failed and successful channel negotiation, respectively. The problem of selecting channels for negotiation can be formulated as the determination of an optimal sequence of channels, denoted as $\hat{s}_1, \hat{s}_2, ..., \hat{s}_j$, such that the joint probability of successful negotiations on the selected channels is maximized given the limited number of attempts n_{max}. Moreover, the transmission power for channel negotiation at the secondary transmitter should be under the power constraint given by Eq. (7) to limit the interference to the primary user signals. In order to increase the probability of reaching the intended secondary receiver whose position may be unknown to the secondary transmitter, it is also important to select the channels with the highest allowable transmission power. The higher the allowable transmission power, the farther the secondary user can be communicated. Therefore, the problem of determining the optimal sequence of channels for negotiation while meeting the interference power limitation can be formulated as

$$\{\hat{s}_1, ..., \hat{s}_j\} = \underset{s_1,...,s_j}{\arg\max}\{p(Y_{s_1} = 1, ..., Y_{s_j} = 1)\}, \quad (8)$$

subject to:

$$P_{s_k} \leq \max\{P^{\max}_{s_k,(2)}\} \quad (9)$$

where $k = 1, 2, ..., j$ and $j \leq n_{max}$.

A straightforward approach to solving this optimization problem is to identify a sequence of channels sorted according to both channel availability and SNR, and have the system negotiate on channels with higher availability and SNRs first in order to increase the likelihood of successful channel negotiation. However, it is extremely hard, if not impossible, to have sufficient knowledge on the availability of each channel in order to determine an optimal sequence of channels. This is due to the highly dynamic environment of CR networks and the imprecision of the sensing process, and as a result makes it not possible to obtain a close-form solution to this problem.

In this study, we propose a stochastic method to solve the problem via a Markov-Chain Monte-Carlo (MCMC) approach, given the partial knowledge of channel availability such as the imperfect energy detection results. While the proposed method does not guarantee perfect accuracy, it is very efficient and expected to provide feasible solutions in a highly dynamic environment such as CR networks. We will conduct extensive simulations to verify the proposed stochastic scheme.

V. Proposed Stochastic Media Access Scheme

A. Markov-Chain Monte-Carlo Method for Channel Selection

MCMC is a meta-heuristic approach designed to draw a set of samples that follows a target distribution $p(S)$ in a stochastic manner. When it is applied to solve the problem formulated in Eq. (8), the target distribution becomes the real profile of channel availability over the licensed spectrum, and a set of channels for negotiation are drawn based on this target distribution. As discussed in the previous section, it is very challenging to model channel availability accurately in a highly dynamic radio environment with network states rapidly fluctuated. Taking an alternative approach, the channel availability (i.e., the target distribution) may be well approximated using the energy detection results in Eq. (4) despite of the imperfect channel information. The benefits of using the MCMC approach is that it can better account for uncertainties introduced by the system components, such as channel fading effect, energy detection error, and unpredictable primary user usage.

Let $p(S)$ denote the probability of channel availability relative to that of all M channels across the spectrum being considered, and it can be taken as the best approximation of probability mass function by following relationship:

$$p(S = s) = \bar{p}_{d,s}/\mathrm{Z}, \quad (10)$$

where Z is a normalizing constant to ensure $\sum_{s=1}^{M} p(S = s) = 1$, $\bar{p}_{d,s}$ is the average detection probability of channel s defined by Eq. (4).

Note that $p(S)$ is based on energy detection, and could be an arbitrary probability distribution instead of any reported parametric model. It is difficult to sample from an arbitrary probability distribution $p(S)$, particularly given that it can change for each energy detection process over the spectrum. One possible approach to sampling from an arbitrary probability distribution function (PDF) is to first sample from a uniform distribution and map the samples using its cumulative distribution function (CDF). However, it is too computationally complex given changes in $p(S)$ over time. Therefore, a more effective approach to sampling from $p(S)$ is to use an MCMC approach [27]. The Metropolis-Hastings [28] MCMC scheme, which is used in the proposed solution, takes advantage of an acceptance-rejection sampling process according to a proposal density function $Q(s'_k|s_{k-1})$. Specifically, $p(S)$ is taken as a dominating function over the target density, and a set of channels $\{s_1, ..., s_j\}$ is randomly drawn from the proposal probability distribution $Q(\cdot)$.

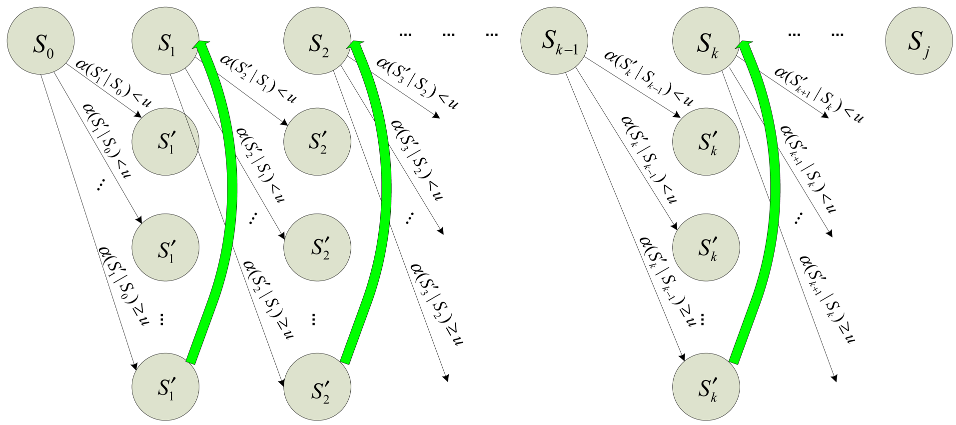


Fig. 1. An overview of the acceptance-rejection channel selection

An overview is shown in Fig. 1, where the k^{th} channel for negotiation is selected through a way where a proposal channel s'_k is first drawn from a proposal probability distribution $Q(s'_k|s_{k-1})$. The probability of the proposal channel s'_k being selected for channel negotiation based on the previous selected channel s_{k-1}, denoted as $\alpha(s'_k|s_{k-1})$, can be defined as

$$\alpha\left(s'_k|s_{k-1}\right) = \min\left\{1, \frac{p(S=s'_k)\cdot Q(s_{k-1}|s'_k)}{p(S=s_{k-1})\cdot Q(s'_k|s_{k-1})}\right\}. \quad (11)$$

Using a symmetric proposal probability distribution such as a Gaussian distribution, where $Q(s'_k|s_{k-1}) = Q(s_{k-1}|s'_k)$, the $Q(\cdot)$ functions cancel each other out on both the numerator and denominator. Also, by substituting Eq. (10) into Eq. (11), the normalizing constant Z from the numerator and denominator cancel each other out, thus Eq. (11) can be rewritten as

$$\alpha\left(s'_k|s_{k-1}\right) = \min\left\{1, \frac{\bar{p}_{d,s'_k}}{\bar{p}_{d,s_{k-1}}}\right\}. \quad (12)$$

Based on Eq. (12), if the following criteria are satisfied, the proposal channel s'_k is accepted as a channel for negotiation, denoted as s_k:

$$\alpha\left(s'_k|s_{k-1}\right) \geq u, \quad (13)$$

where a random number u is drawn from a uniform distribution $U(0,1)$, and

$$s'_k \notin \{s_1, \cdots, s_{k-1}\}. \quad (14)$$

This approach generates a Markov chain as shown in Fig. 1.

This channel selection process is repeated until the desired set of channels to negotiate on channels $\{s_1, s_2, \cdots, s_j\}$ is determined. Moreover, amongst the selected set of channels, the higher the maximum allowable transmission power, the higher probability of reaching the intended secondary receivers that are located at farther distances. Therefore, by incorporating the power control information, we sort the set of drawn channels based on $P^{\max}_{s_k,(2)}$ to get a set of channels $\{\hat{s}_1, \hat{s}_2, \cdots, \hat{s}_j\}$ denoted as Θ.

Finally, channel negotiation is performed between the transmission pairs based on the above sequence of channels and terminated when either the requested number of mutually available channels n_{req} or maximum allowed attempts n_{max} has been reached. The pseudo code of the proposed dynamic MCMC channel selection method is shown in Algorithm. 1.

Algorithm 1 Dynamic MCMC Channel Selection

```
(Upon each data transmission request)
Set an initial channel s_0 as the channel recently negotiated;
for k = 1; k < n_max; k++ do
    Generate a candidate channel s'_k from Q(·) and a value u from U(0,1);
    while u > α(s'_k|s_{k-1}) and s'_k ∉ {s_1, ···, s_{k-1}} do
        Reject the candidate channel s'_k;
        Generate a new candidate channel s'_k from Q(·) and a new value u from U(0,1);
    end while
    Accept the candidate channel s_k ← s'_k;
end for
Obtain the set of channels {s_1, s_2, ···, s_j}.
Sort according to P^max_{s_k,(2)} to obtain Θ = {ŝ_1, ŝ_2, ···, ŝ_j}.
```

B. SMA Scheme

The proposed SMA scheme defines a suite of distributed and asynchronous media access mechanisms for CR multichannel ad hoc networks that enables the secondary CR nodes to agree on a set of channels for negotiation and access. This mechanism also ensures that with interference probability from the secondary transmission $\hat{p}$, the data transmission will not disturb in the vicinities of primary users.

With SMA, a secondary user that initially enters the primary user network performs spectrum sensing via energy detection on the licensed spectrum. As soon as the secondary user finds possibly available channels, it switches its operating central frequency on these channels to further identify the presence of faded primary signals, which is called channel tuning. After identifying the availability of the channels, the secondary user stays on any of these available channels (i.e., residing channel, denoted as s_0) until it either detects any primary user signal or identifies any on-going transmission between other secondary users. Fig. 2 shows an exemplary state diagram

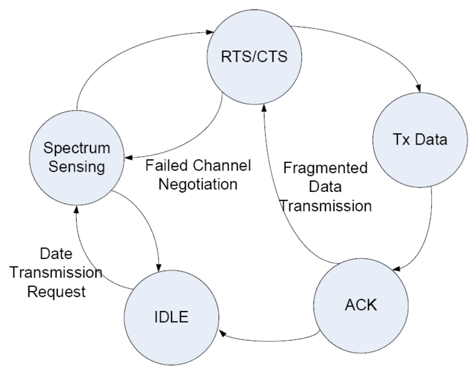


Fig. 2. State Diagram of SMA.

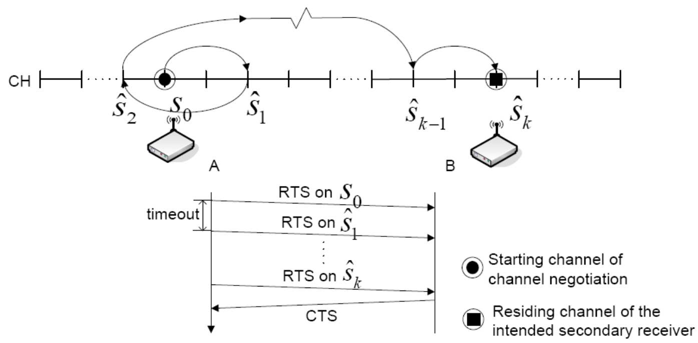


Fig. 3. Overview of RTS/CTS exchange.

of the proposed SMA scheme. The detailed explanation is provided in following subsections.

*1) **RTS/CTS Exchange**:* Suppose that a secondary transmitter A has data to transmit to a secondary receiver B. The secondary transmitter A performs sensing over the licensed spectrum through energy detection and selects a set of channels $\Theta = \{\hat{s}_1, \hat{s}_2, \cdots, \hat{s}_j\}$ based on the proposed dynamic MCMC approach with power constraints described in Section V-A. The secondary transmitter A attempts to find a set of channels among Θ where the secondary receiver B can possibly be reached.

An overview of the RTS/CTS exchange procedure is shown in Fig 3. Secondary transmitter A sends a RTS message at the basic rate R_0 on its residing channel s_0 at the maximum allowable transmission power $P_{s_0,A}^{\max}$ (computed according to Eq. (7)). The RTS message not only includes the MAC address of the secondary transmitter, intended secondary receiver, and the duration value required to transmit the pending data transmission at the basic rate, but also piggy-backs the channel sequence Θ and maximum allowable transmission power $P_{s_0,A}^{\max}, P_{\hat{s}_1,A}^{\max}, ..., P_{s_j,A}^{\max}$, which can be used to aid secondary receiver B in determining better common available channels. Note that the channel sequence indicates a set of available channels at the secondary transmitter side, while the maximum allowable transmission power information indicates the closest primary user locations with probability $\hat{p}$.

If the secondary receiver B is not on channel s_0, it is unable to receive the RTS message so that no Clear-to-Send (CTS) message will be responded. Therefore, A tunes to channels $\hat{s}_1, \hat{s}_2, ..., \hat{s}_j$ one by one after each timeout and repeats sending the same RTS message. If the secondary receiver B is reached via channel s_k, it performs fast scans on the set of channels Θ upon receiving the RTS message, and determines the feasible set of common available channels $\Theta' \in \Theta$ as well as the noise level on those selected channels. Consequently, the secondary receiver B responds the RTS by launching a CTS message back to A on all of its selected common available channels Θ', which contains the duration and corresponding noise level for intending data transmission. The CTS message implicitly instructs the secondary transmitter A to meet the maximum allowable transmission power constraint, as well as instructs the intending data transmission on the channels Θ' to the other secondary neighbors.

The proposed stochastic approach of channel selection can alleviate serious collisions amongst the secondary users by stochastically distributing access attempts on different channels even if these secondary users identify similar sets of available channels at the same time. Moreover, a classical issue that needs to be dealt with in the design of a media access scheme is the hidden terminal problem, which can be mitigated by applying state-of-the-art strategies such as inserting busy tones [22], [23]. In this study, the major effort and focus is on the minimization of interference to the primary user transmission, and not on solving the hidden terminal problem, which is beyond the scope of this study.

*2) **Data Packet Fragmentation and Transmission**:* After completing the RTS/CTS exchange, the data transmission from A to B takes place on the agreed common available channel set $\Theta' \in \Theta$. For transmission of a long data packet, fragmentation is necessary to improve the performance due to the following reasons. First, a longer data packet takes longer transmission time, during which the transmission may more likely be subject to loss of channel availability and spectrum opportunity. Second, a user launching a longer data packet will likely occupy the channel for a longer period of time and prevent other users from fairly accessing the same media, which raises an issue on temporal fairness [24]. The above two situations become critical in the dynamic environment of CR networks.

To address the problem, the proposed SMA scheme defines segmentation of long data packets, and imposes a parameter on the maximum length on data fragment, denoted as L_{fr}. Here, $L_{fr} = R_0 \cdot CMT$, where R_0 is the basic transmission rate, and CMT is the channel move time defined in IEEE 802.22 [29]. Note that CMT can be interpreted as the longest allowable time period that the CR system can possibly stay on a channel that has just been identified as occupied by any primary user.

The data transmission rates in the proposed scheme are determined based on the channel condition obtained from RTS/CTS message exchange. This allows a higher quality channel to achieve a higher rate of data transmission, which in turn can deliver more data packets within T_{max}. Fig 4 illustrates the proposed mechanism in transmitting fragmented data packets. In the case where the transmission of a packet at A is less than L_{fr}, B sends an ACK message to acknowledge a successful reception at the channel where B was originally found. On the other hand, in the case where a data fragment

Fig. 4. Illustration of data fragmentation time line.

(DF) is transmitted at a high data transmission rate, additional DFs may be transmitted within T_{max}, and an ACK message is returned by B after each transmission of a DF, which acts as a virtual RTS message. Upon receiving this ACK message from B, the secondary receiver A performs the same process as if it had received a real RTS message.

C. Collision Solution

With access efficiency and interference reduction in mind when designing a media access scheme for secondary users, we realize that the characteristics and behavior of the spectrum resources in the secondary user network are significantly distinguished from that in the primary user network. In the proposed SMA scheme, the collision resolution mechanism, which is one of the most important functions in a MAC protocol, will be substantially different from that in current IEEE 802.11 in order to fit into the CR dynamic environment.

Instead of employing the popular random backoff algorithm, the proposed SMA simply retransmits a collided packet so as to minimize the interference on the primary network. Note that the imprecision of primary user identification is the main cause of interference from secondary users, which can be much more frequently encountered if there is possibly a long backoff delay in sending each packet. The problem due to imprecision of primary user identification certainly becomes more serious when the period of backoff for each packet is getting longer. The retransmission of collided packets instead of backoff is expected to effectively solve this problem at the expense of increased secondary network access overhead. Our proposed design is based on the theorem provided in Appendix B.

In the retransmission of a collided packet, the proposed SMA has to conduct a new round of spectrum sensing and RTS/CTS exchange, which results in additional access overhead and serves as the expense on the reduced interference on primary users. Such a tradeoff between primary user interference and access overhead will be justified in the simulations.

VI. Performance Analysis

In this section, we present a performance analysis of the proposed scheme in terms of throughput. In the situation where primary and secondary user networks coexist in the area of interest, the status of a single channel alternates between idle and busy, where the busy period can be occupied by primary users or/and secondary users. We assume the primary user network and the secondary user network are independent to simplify the analysis for the secondary user network as the primary user network does not change its behavior according to the secondary access. Based on this assumption, the secondary transmission cycle consists of a busy period (its expectation is denoted as $\bar{B}_i$) plus the following idle period (its expectation is denoted as $\bar{I}_i$), and underlays the idle period of the primary user network on channel s_i. Therefore, the channel utilization on channel s_i for the secondary user network can be given using renewal theory as [22]

$$\rho_i = \frac{\bar{U}_i}{\bar{B}_i + \bar{I}_i}, \tag{15}$$

where $\bar{U}_i$ is the average utilization time for successful data transmission. The average duration of an idle period is

$$\bar{I}_i = 1/(\lambda_{p,i} + \Lambda_i), \tag{16}$$

where $\lambda_{p,i}$, and Λ_i denotes the arrival rate of new and rescheduled primary, and secondary packets on channel s_i, respectively.

A successful data transmission is established by a successful RTS/CTS exchange. A RTS message generated from any secondary transmitter (e.g., secondary user A) is successfully transmitted after the channel is sensed idle. Any other messages that are transmitted during the vulnerable period τ cause collision due to that fact that the channel is still sensed as unused. Therefore, the probability of a successful transmission of the RTS message is given by

$$p_{rts,i} = (1 - p_f)e^{-\tau\Lambda_i}. \tag{17}$$

When the RTS message is received at the intended secondary receiver (e.g., secondary user B), the channel negotiation succeeds. Therefore, a successful channel negotiation process consists of $t-1$ number of failed channel negotiation attempts and one successful channel negotiation attempt, which follows an absorbing finite Markov chain [30] with transition states $\{\hat{s}_1, ..., \hat{s}_j\}$ and absorbing state $\hat{s}_t$. Assume each secondary user has a probability of residing on channel s_i with a probability mass function as $p(s_i)$; the resultant transition probability $\mathbf{P}$ is formulated as

$$\mathbf{P} = \begin{array}{c} \\ s_0 \\ \vdots \\ s_j \\ \Re_1 \\ \vdots \\ \Re_j \end{array} \overset{\qquad\text{Transient States}\qquad\qquad\text{Absorbing States}}{\begin{array}{cccc|ccc} s_0 & & & s_j & \Re_1 & \cdots & \Re_j \\ 0 & p_{0,1} & \cdots & 0 & p_{1,1^{\Re}} & & 0 \\ & & \ddots & p_{j-1,j} & & \ddots & \\ 0 & & & 0 & 0 & & p_{j,j^{\Re}} \\ 0 & & & 0 & 1 & & 0 \\ & & \ddots & & & \ddots & \\ 0 & & & 0 & 0 & & 1 \end{array}} \tag{18}$$

Therefore, the probability of a successful channel negotiation, which is also the absorbing probability, can be estimated as

$$p_{cn} \triangleq p_{rts,s_t} p(s_t) \prod_{i=1}^{t-1} [1 - p_{rts,s_i} p(s_i)]. \tag{19}$$

The successful channel negotiation process is generally followed by successful data transmissions in the cases that hidden problem has been mitigated by applying start-of-the-arts strategies [22], [23], [31], as well as the lack of returning primary users. Let p_{re} be the probability that there is no primary user returning to the channel s_i within the secondary data transmission time T_{max}, and can be expressed as $p_{re} = e^{-\lambda_{p,i}T_{max}}$. Therefore, the probability of successful data transmission can be estimated as

$$p_{s,i} \triangleq p_{cn} p_{re}, \tag{20}$$

and the average lower bound utilization time, which is estimated based on the basic rate R_0, can be determined as

$$\bar{U}_i \triangleq p_{s,i} L_{fr}/R_0. \tag{21}$$

Hence, the throughput we obtain is a lower bound.

To find the average busy period in the secondary network, we adopt the method proposed in [25], where the busy period is considered as the time the channel is sensed as busy due to a successful transmission on channel or due to collision. The average duration of a successful transmission on the residing channel of the intended receiver, which contains RTS/CTS exchange, is determined by

$$T_s^{rts} \triangleq 3\delta + 4\tau L_{fr}/R_0, \tag{22}$$

where δ is the transmission time of control message, i.e., RTS, CTS, and ACK. The average duration of a successful transmission on other commonly available channel, which does not involve addition RTS/CTS exchange, is determined by

$$T_s^{bas} \triangleq L_{fr}/R_0 + \tau. \tag{23}$$

Since a secondary user resides on channel s_i with probability $p(s_i)$, the average successful busy period can be estimated as

$$\bar{T}_{s,i} \triangleq T_s^{rts} p(s_i) + T_s^{bas}[1 - p(s_i)]. \tag{24}$$

The failed busy period in the multichannel environment may consist of: 1) one RTS message on a channel that is not the residing channel of the intended secondary receiver, which then times out due to not reaching the intended secondary receiver; 2) more than one RTS message which arrives during the vulnerable period. Therefore, the average failed busy period of the two cases can be estimated as:

$$\begin{cases} T_{f,i}^{rts} \triangleq \delta + \tau \\ T_{f,i}^{c} \triangleq (\tau + 1/\Lambda_i)e^{-\Lambda_i \tau} - 1/\Lambda_i + \delta + \tau \end{cases}, \tag{25}$$

where the second equation in Eq. (25) accounts for the average time of the arrival RTS messages during the vulnerable period and a RTS transmission time. Since the first case happens on the channel that is not the residing channel of the intended receiver, while the second case can happen on any channel, the average failed busy period can be estimated as

$$\bar{T}_{f,i} \triangleq T_{f,i}^{rts}[1 - p(s_i)] + T_{f,i}^{c}. \tag{26}$$

Therefore, by substituting Eq. (20), (24) and (26) into Eq. (15), we can obtain the average busy period as

$$\bar{B}_i \triangleq p_{s,i}\bar{T}_{s,i} + (1 - p_{s,i})\bar{T}_{f,i}. \tag{27}$$

Finally, the throughput lower bound of a single channel s_i can be estimated as

$$\rho_i \triangleq \frac{p_{cn} e^{-\lambda_{p,i} T_{\max}} L_{fr}/R_0}{T_s^{rts} p(s_i) + T_s^{bas}[1 - p(s_i)] + p_s \bar{T}_{s,i} + (1 - p_s)\bar{T}_{f,i}}, \tag{28}$$

and thus the network wide normalized throughput lower bound can be estimated as

$$\rho \triangleq \frac{1}{M} \sum_{i}^{M} \rho_i \tag{29}$$

VII. Performance Evaluation

In this section, we present simulation results for the SMA scheme to evaluate its efficiency and effectiveness. An object-oriented modular discrete event-driven simulation model using OMNeT++ [32] is developed, where a $300m \times 300m$ network area uniformly distributed with N_p primary users and N_s secondary users is considered. In the primary user network, we assume a stable state with $\lambda_p/\mu_p = 0.4$ which approximates the corresponding throughput [22], where λ_p and μ_p is the packet arrival rate and service rate in the primary user network, respectively. The size of a primary user packet is uniformly distributed within the range of 0 to 2048 bits. In the secondary network, each secondary user has a radio transmission range radius of $R = 200m$ forming a non fully-connected topology, where not all secondary users are within the transmission range of each other. According to IEEE 802.22, for each attempt of media access, the energy detection time for each channel is set as $0.05ms$, the time elapsed for tuning channels is $1\mu s$ [15], and the basic transmission rate is $1Mbps$. The CMT is set to $0.5ms$ instead of $2ms$ in [29] to further limit the interference caused by collision, which results in a collision window with double the transmission time. Therefore, the maximum length of data packet fragmentation is $L_{fr} = 0.5Kbits$ with regarding of the basic transmission rate. The other available transmission rates are set to $2Mbps, 6Mbps, 12Mbps, 36Mbps, 54Mbps$ [15]. For each transmission, a sender is randomly chosen and then the intended receiver is selected randomly among its neighbors. We conducted the simulation for $t_{sim} = 5000s$ for each trial.

In the simulation, we first study the channel negotiation procedure that will fundamentally affect the performance of SMA. In the second set of simulations, we look into the performance of SMA and study its effects on the performance of the primary user network. The performance measurements are defined as follows:

- Access failure rate R_f: the ratio of the number of failed channel accesses to the number of attempts.
- Access overhead o: the time consumed on access attempts for a data transmission (ms).
- Throughput, ρ: the fraction of time the channels are used to successfully transmit payload bits [25].
- Packet delay, t_d: the average time duration before a successful data transmission.

A. Evaluation of channel negotiation scheme

1) Access Failure Rate: The impact of using the proposed channel negotiation scheme on the performance of SMA is studied and compared with a number of previously reported approaches, such as the dedicated control channel approach and the channel hopping approach [13]. Fig. 5(a) illustrates the average access failure rates $\bar{R}_f$ versus different primary user traffic scenarios. It can be seen that under a light primary user traffic, i.e., $10^{-3} - 10^{-1}$ (arrivals/second), the proposed SMA achieves better performance than the dedicated control channel scheme due to more frequent collisions on the dedicated control channel, which is in terms due to the lack of capacity of the dedicated channel. Note that the fixed control channel could be subject to interference of primary user signals and deep fading of channel condition that seriously impair its capacity. On the other hand, since SMA dynamically selects the channel for control signaling, it can adaptively fit to the environment of frequently changing channel status and channel condition fluctuations. Under medium primary user traffic, i.e., $10^{-1} - 10^{1}$ (arrivals/second), the proposed scheme performs comparably to the dedicated control channel method while significantly outperforming the channel hopping method. Finally, under heavy primary user traffic beyond 10^1, the proposed scheme is outperformed by that with a dedicated control channel because of the frequent changes of channel usage status.

Fig. 5(b) shows the average access failure rate with respect to secondary user traffic under medium primary user traffic (i.e.,0.1 arrivals/second). The increase in the secondary user traffic significantly degrades the performance in the case of using a dedicated control channel due to the fact that collisions on the dedicated control channel results in the lack of the capacity of the dedicated control channel. This situation is alleviated in the proposed channel negotiation approach, thereby achieving much smaller access failure rates.

Fig. 5(c) shows the access failure rate with respect to the maximum number of access attempts n_{max}. The average access failure rate by the proposed SMA scheme decreases noticeably with increasing n_{max} due to the strong diversity gain. On the other hand, the average failure rate of using a dedicated control channel decreases more slowly primarily due to the collisions on the dedicated control channel. We also evaluate the access failure rates of the proposed SMA scheme and compare it with the channel hopping approach by changing the number of channels M. Note that, intuitively, changing M should have no impact on the dedicated control channel approach with fixed primary and secondary traffic; therefore, we omitted this comparison for the sake of brevity. As shown in Fig. 5(d), the access failure rate increases noticeably in the case of channel hopping when M is increasing due to the fact that it does not consider the highly dynamic nature of CR networks and as such the selection of channels for negotiation becomes less reliable as M increases. The proposed SMA scheme, on the other hand, provides consistently lower access failure rates irrespective of M. Moreover, as expected, there is unnoticeable impact on the number of channels of the dedicated control channel approach in this set of simulations.

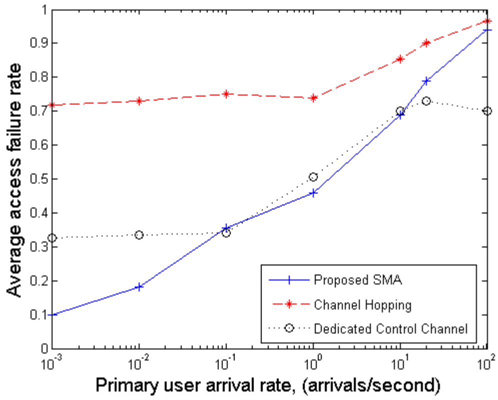
2) Access overhead: To provide a good indication of media access efficiency, we evaluate the access overhead o associated with the proposed SMA. For comparison purposes, the time consumed on energy detection is not included in the access overhead, but will be taken into account in the measurement of package delay in the later subsection. As shown in Fig. 6(a), compared with the dedicated control channel approach, the proposed SMA scheme can achieve comparably lower average access overhead especially under light primary traffic, achieve similar overhead under medium primary traffic, while being outperformed in the case with heavy primary traffic. This meets our expectation because SMA is designed to adaptively distribute channel negotiation attempts over different channels, which can effectively resolve the traffic jamming problem as well as improve overall performance. However, SMA is affected by difficulties in identifying residing channels due to primary traffic, which results in the need for further re-negotiation.

Fig. 6(b) shows that the average access overhead by the proposed SMA scheme is lower than that by the other two methods of channel negotiation under the heavy secondary traffic, but is outperformed by that of using dedicated control channel in the case of lower secondary traffic. The heavy secondary traffic increases the chances of jamming and packet collision on the dedicated control channel, which in turn leads to more re-negotiation processes and therefore degrades its performance. This malicious effect can be mitigated in SMA by spreading the negotiation attempts across the whole frequency spectrum. On the other hand, since the lighter secondary traffic causes less collision on the dedicated control channel, the malicious effect due to jamming and packet collision is not obvious; thus SMA is subject to larger overhead since SMA may need to on-line scan for finding the residing channel in case the original residing channel is no longer available. Furthermore, an interesting observation that can be made about SMA is that the access failure rate for SMA is relatively flat until 10^0 packets/second. This is due to the fact that the access failure rate is jointly determined by the primary traffic and secondary traffic. When the secondary traffic is small enough, the failure access rate is almost completely dominated by the primary traffic; and that is why both SMA and dedicated control channel scheme are both insensitive to the change of the secondary traffic when the secondary user traffic is light. But as the secondary traffic increases up to a turning point, the failure rate becomes sensitive to the secondary traffic, and is boosted by the increase of secondary traffic. In our simulation result, it can be clearly observed that the turning point of SMA occurs later than that for the dedicated control channel scheme as the secondary traffic increases. This also demonstrates the superiority of the proposed SMA scheme.

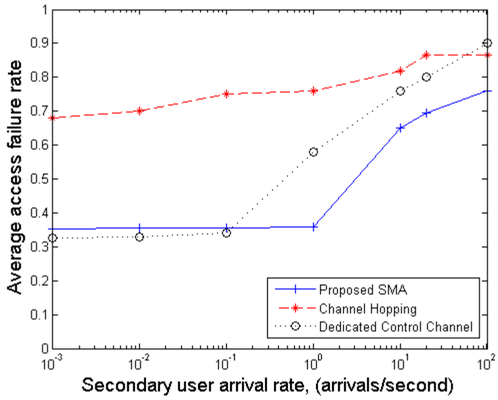
In Fig. 6(c), it can be generally observed that there is a slower and more stable average access overhead versus the increasing of M. These simulation results demonstrate the effectiveness the proposed SMA scheme in providing improved media access efficiency.

B. Throughput of SMA

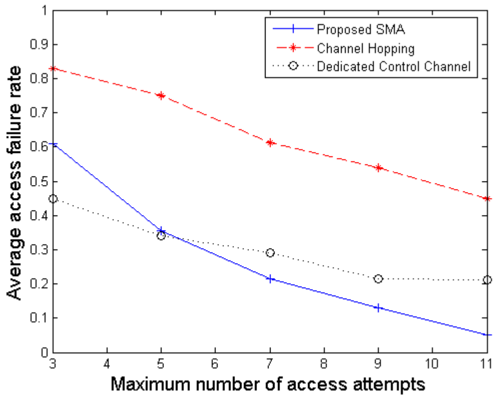
Now we investigate the throughput of proposed scheme in terms of average throughput, as well as validate the proposed analytical model. Fig. 7 plots the average throughput lower bound $\bar{\rho}$ of secondary user network with $\lambda_p = 10$ arrivals/second versus different number of channel negotiation



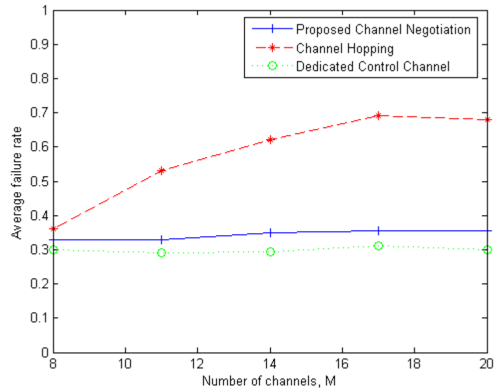
(a) With respect to primary user traffic.



(b) With respect to secondary user traffic.



(c) With respect to maximum number of access attempts n_{max}.



(d) With respect to number of channels M.

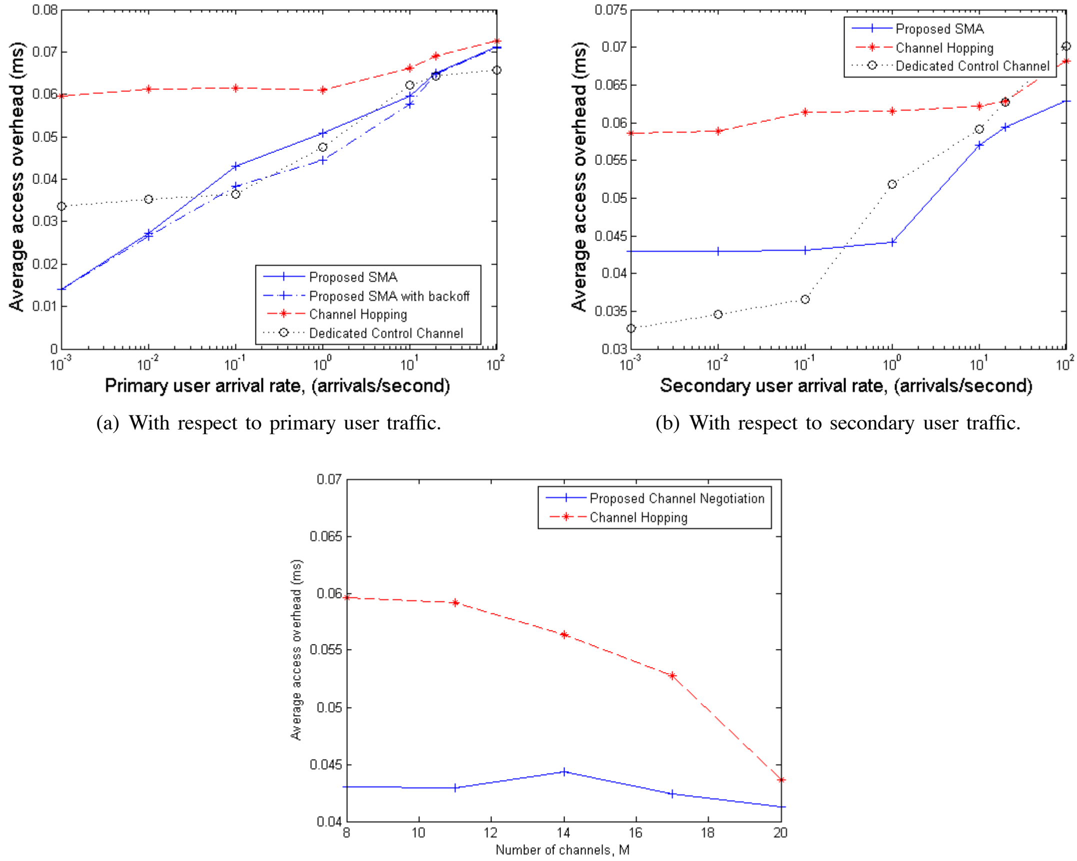
Fig. 5. Average access failure rate.

attempts t associated with normalized $\hat{p}(s_t) = 0.5/M$. All results are within 95% confidence interval. It can be seen that there are high peaks as secondary user arrival rate reaches 10^1, which indicates more collisions in the secondary user network occurring after this point. Note that this situation is in line with the results of most MAC setups. In Fig. 8, the secondary user arrival rate is fixed at the saturation point, and the average throughput lower bound of the secondary user network in the low traffic volume scenario with $\lambda_p = 10^{-2}$ arrivals/second as well as the high traffic volume scenario with $\lambda_p = 10^2$ arrivals/second versus different normalized $p(s_t)$ are shown. A number of observations can be made. Firstly, with a low primary traffic volume, the average throughput lower bound decreases with the increasing of channel negotiation attempts t due to the fact that the failed channel negotiation has a noticeable impact on the average busy period. Secondly, under a light primary traffic volume, the performance is stable due to the fact that the average throughput of secondary user network is saturated and dominated by the secondary traffic volume. Finally, as expected, a higher primary traffic volume results in lower average throughput lower bound of secondary users.

C. Packet Delay of SMA

We analyzed packet delay of the proposed SMA scheme with different primary traffic volumes. As shown in Fig. 9, the average packet delay of secondary users increases as the traffic volume increases. The increased packet delay is mainly contributed by the collisions that occur due to the secondary traffic. Moreover, when taking the same secondary traffic volume, the average packet delay of secondary users increases with the increasing primary traffic volume. It is clear that a higher primary traffic volume results in a longer process time on channel sensing and negotiation.

multiple frequency bands as dedicated control channels [4]-[12]. In [4], a cross-layer opportunistic multi-channel MAC protocol integrated with spectrum sensing at the physical layer and packet scheduling at the MAC layer was proposed. Two collaborative channel spectrum-sensing policies were proposed, in which the channel selection information is exchanged via a dedicated control channel to support the agreement during the channel access process between transmission pairs. In [5], constraints on sensing and transmission were considered in designing a stopping algorithm to realize opportunistic media access with the aid of the dedicated control channel to exchange control messages. In [12], a code-division multiple-access (CDMA) based channel-aware access control (CAAC) algorithm was proposed that adjusted channel access probabilities based on the received SINR and measured interference temperature. The algorithm is then implemented on a CSMA/CA access method where the channel status information is overheard and exchanged over a control channel. set



(a) With respect to primary user traffic. (b) With respect to secondary user traffic.

(c) With respect to number of channels M.

Fig. 6. Average access overhead.

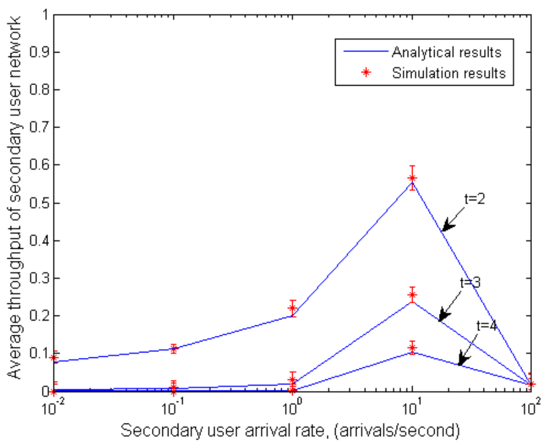


Fig. 7. Average throughput lower bound of secondary users network with different number of channel negotiation attempts t vs. different secondary arrival rates of the proposed SMA.

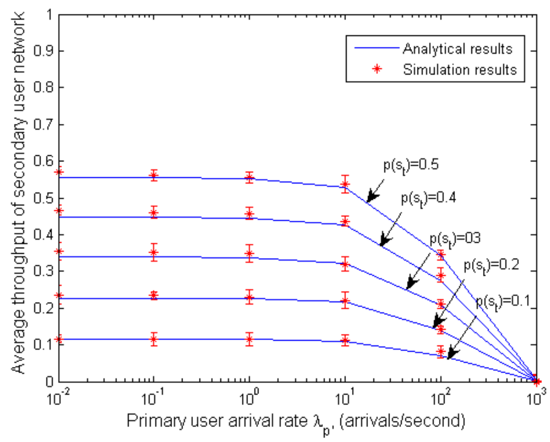


Fig. 8. Average throughput lower bound of secondary users network with different $p(s_t)$ vs. different primary traffic arrival rates λ_p of the proposed SMA.

of pre-defined multi-channel hopping sequences in an attempt to access channels with any intended receiver without the need for a dedicated control channel. While channel hopping holds a great potential in alleviating the need of dedicated control channels, it is subject to a critical limitation when applied in a CR network. functions [14] or pseudo-random hopping sequences [13]. Without considering the underlying channel availabilities of the network environment, the channel hopping schemes do not account for the highly dynamic wireless channels and user behaviours, which serve as the most important and unique features of CR networks. This will certainly lead to poor performance of CR systems as transmission pairs may not be able to identify commonly available channels in a timely manner due to poor hopping sequences. assumptions

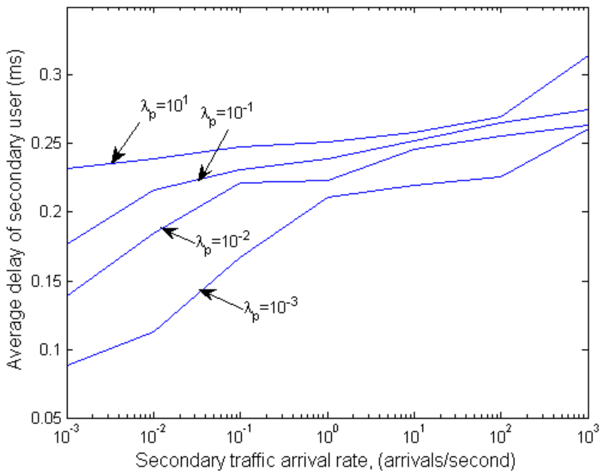


Fig. 9. Average delay of secondary users with different secondary traffic arrival rate vs. different primary traffic arrival rate.

on common resources, such as channels, time slots, as well as codes, which can be used to facilitate the media access. In [3], based on an assumption that bidirectional communication links exist between communication pairs enabling coordination and selection of common channels to communicate, the problem of media access is then studied in a two-tier media access game composed of a channel allocation and a multiple access sub-games. In [9], a slotted beaconing period is defined in each MAC super-frame to exchange information and negotiate channel usage. A beacon is signed when a node detects an available channel where no other beacon is present, and other nodes can join the beacon group by sending its own beacon. In this way, a dynamic rendezvous channel is selected by the beacon group, where these nodes can communicate with each other. simplified suboptimal algorithm that greedily maximizes each-slot throughput is proposed for spectrum sensing and access, and the idea of receiver oriented code assignment is used to facilitate the initial handshake.

VIII. Conclusions

In this paper, a stochastic media access (SMA) scheme is proposed for efficient media access for Cognitive Radios (CR) in ad hoc wireless networks. By assuming the absence of a dedicated control channel, we formulate the channel selection process as an optimization problem to maximize the probability of successful channel accesses. The RTS/CTS exchange is then performed on the selected channel for channel negotiation. The lengthy data fragmentation issue is also addressed by taking into account the interference from miscalculated transmission power and false access attempts to the primary user network. The collision in the secondary user network is simply resolved by retransmission of the collided packets instead of via a commonly used backoff mechanism that will lead to longer delay. Such a design is to better fit the proposed scheme into the dynamic and opportunistic environment of CR networks, where the minimization of primary network interference is set as the ultimate goal.

We have conducted extensive simulations to analyze the proposed SMA scheme, and compare it with other two other channel negotiation approaches by examining the access failure rate and access overhead. The simulation results show that the proposed SMA scheme achieves comparable performance when compared to the dedicated control channel approach, which verified its effectiveness and efficiency. The simulation also examined the overall performance of the proposed SMA scheme working under different primary traffic volumes and compared with previously reported counterparts, which further demonstrated its superiority. Furthermore, the analytical model presented is validated.

Appendix A
Table of Notation

TABLE I
Table of notation in Section III

Notation	Definition
M	number of non-overlapping channels.
N_s	number of secondary users.
P_i, $\bar{P}_i$	radio transmitting power on channel i, and its mean.
X_i	received power.
G_i	antenna gain on channel i.
d, d_{min}	distance between the transmitter and receiver, and its minimum value.
ξ	path loss component associated with channel i.
$x_i(t)$	received bandpass waveform on channel i.
N_0	one-side power spectral density.
u_i	test statistics.
Γ, k	Gamma function, and degrees of freedom.
ω_i, $\bar{\omega}_i$	SNR on channel i, and its average value.
I	Bessel function.
p_f, $\bar{p}_{d,i}$	probability of false alarm, and average detection probability.
b	signal bandwidth.
$P_{i,(2)}$	secondary transmitting power on channel i.
$P^I_{i,(1)}$, $P^{I,max}_{i,(1)}$	interference power at the primary receiver, and its maximum value.
$P_{i,(2)}$, $P^{max}_{i,(1)}$	secondary transmission power, and the maximum value.
ε_i	coefficient of received interference power.
α_i	probability of primary users transmission.
η_i	average number of primary users per unit area.
$\hat{p}$	probability of interference caused by secondary transmission.
γ	number of different modulation schemes.

Appendix B
Theorem of the Collision Solution

Theorem B.1: An increase of backoff time of the secondary users results in an increase in the probability of interference to the primary user networks.

Proof: Let the backoff time of secondary users be denoted as $\tilde{t}_b$, which is a random variable with a probability density function $f_{\tilde{t}_b}(t)$. Let the probability distribution of primary traffic arrival be denoted as $F_{\tilde{t}}(t;\lambda_p)$ with an arrival rate λ_p on each channel. The probability of no primary traffic arrival during $\tilde{t} < t_b$ on channel i can be determined as $p_i(\tilde{t} > t_b)$, thus the probability of any primary traffic arrival during a given backoff period of the secondary users is given by

$$1 - p(\tilde{t} > t_b) = F_{\tilde{t}}(t_b;\lambda_p). \tag{30}$$

In other words, $F_{\tilde{t}}(t_b;\lambda_p)$ is the probability of the interference to the primary user on each channel given the backoff period t_b. The average probability of interference $I(\lambda_p)$ to the primary user using a backoff scheme on each channel is given

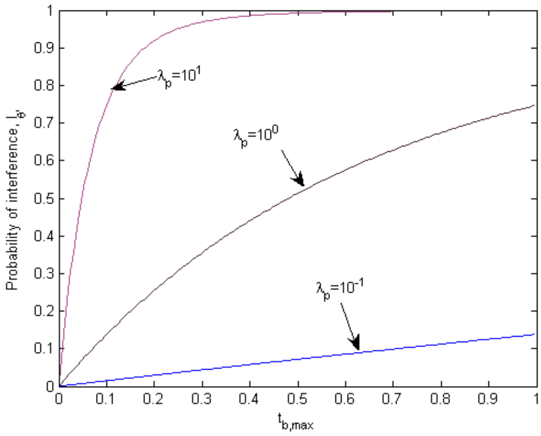


Fig. 10. Probability of interference increases with increasing of $t_{b,max}$ vs. different primary traffic arrival rates λ_p, given $|\Theta'| = 3$.

by

$$I(\lambda_p) = \int_0^{t_{b,max}} F_{\tilde{t}}(t_b; \lambda_p) f_{\tilde{t}_b}(t_b) dt_{t_b}, \tag{31}$$

where $t_{b,max}$ is the maximum backoff time. Therefore, amongst $|\Theta'|$ number of selected channels, the probability of interference is determined by the first arrival of primary traffic, i.e., the earliest interference from the secondary user introduced by the backoff scheme, which can be given according to order statistics analysis [33] as

$$I_{\Theta'} = \sum_{k=1}^{|\Theta'|} \binom{|\Theta'|}{k} (I(\lambda_p))^k (1 - I(\lambda_p))^{|\Theta'|-k}. \tag{32}$$

For example, if we assume $f_{\tilde{t}_b}(t) = 1/t_{b,max}$ to be unformly distributed within time window $[0, t_{b,max}]$, as well as $F_{\tilde{t}}(t; \lambda_p) = 1 - e^{-\lambda_p t}$, Eq. (32) can be written as in (33). The plot of Eq. (33) for different $t_{b,max}$ and different primary traffic arrival volumes is shown in Fig. 10. As we can see, the probability of interference increases rapidly as $t_{b,max}$ increases under heavier primary traffic volumes. ■

REFERENCES

[1] J. Miltola, "Cognitive radio: making software radios more personal", *IEEE Pers. Commun.*, vol.6, no. 4, pp. 13 - 18, Aug. 1999.

[2] S. Haykin,"Cognitive radio: brain-empowered wireless communication", *IEEE J. Sel. Areas Commun.*, vol. 23, no. 2, pp. 201 - 220, 2005.

[3] M. Felegyhazi, M. Cagalj, and J.-P. Hubaux, "Efficient MAC in cognitive radio systems: A game-theoretic approach", *IEEE Trans. Wireless Commun.*, vol. 8, pp. 1984 - 1995, Apr. 2009.

[4] H. Su, and X. Zhang, "Cross-Layer Based Opportunistic MAC Protocols for QoS Provisionings Over Cognitive Radio Wireless Networks", *IEEE J. Sel. Areas Commun.*, vol. 26, pp. 118 - 129, Jan. 2008.

[5] J. Jia, Q. Zhang, and X. Shen, "HC-MAC: A Hardware-Constrained Cognitive MAC for Efficient Spectrum Management", *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 106 - 117, Jan. 2008.

[6] C. Peng, H. Zheng, B. Y. Zhao, "Utilization and Fairness in Spectrum Assignment for Opportunistic Spectrum Access", *ACM Mobile Networks and Applications*, vol. 11, pp. 555 - 576, Aug. 2006.

[7] P. Pawelczak, R. V. Prasad, L. Xia, and I. G. M. M. Niemegeers, "Cognitive Radio Emergency Networks - Requirements and Design", *Proc. IEEE DySPAN*, pp. 601 - 606, Nov. 2005.

[8] A. C. Hsu, D.S. L. Weiy and C.-C. J. Kuo, "A Cognitive MAC Protocol Using Statistical Channel Allocation for Wireless Ad-hoc Networks", *Proc. IEEE WCNC*, pp. 105 - 110, Mar. 2007.

[9] C. Cordeiro, and K. Challapali,"C-MAC: A Cognitive MAC Protocol for Multi-Channel Wireless Networks", *Proc. IEEE DySPAN*, pp. 147 - 157, Apr. 2007.

[10] L. Ma, X. Han, and C.-C. Shen, "Dynamic Open Spectrum Sharing MAC Protocol for Wireless Ad Hoc Networks", *Proc. IEEE DySPAN*, pp. 203 - 213, Nov. 2005.

[11] Q. Zhao, L. Tong, A. Swami, and Y. Chen"Decentralized Cognitive MAC for Dynamic Spectrum Access in Ad Hoc Networks: A POMDP Framework" *IEEE J. Selected Areas on Communications*, vol. 25, no. 3, pp. 589 - 600, Apr. 2007.

[12] B. Yang, G. Feng, Y. Shen, C. Long, and X. Guan, "Channel-Aware Access for Cognitive Radio Networks", *IEEE Trans. Veh. Technol.*, vol. 58, no. 7, pp. 3726 - 3737, Sept. 2009.

[13] R. Rozovsky and P. Kumar, "SEEDEX: A MAC protocol for Ad Hoc Networks", *Proc. ACM MobiHoc*, pp. 67 - 75, Oct. 2001.

[14] P. Bahl, R. Chandra, and J. Dunagan, "SSCH: Slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks", *Proc. ACM Mobicom*, pp. 216 - 230, Sept. 2004.

[15] A. Sabharwal, A. Khoshnevis, and E. Knightly, "Opportunisitc Spectral Usage: bounds and a Multi-Band CSMA/CA Protocoal", *IEEE/ACM Trans. Netw.*, vol. 15, pp. 533 - 545, Jun. 2007.

[16] T. S. Rappaport, Wireless Communications: Priciples & Practice, Prentice-Hall, 1996.

[17] F. Digham, M. -S. Alouini, and M. K. Simon, "On the Energy Detection of Unknown Signals over fading Channels", *IEEE Trans. Commun.*, vol. 55, pp. 21 - 24, Jan. 2007.

[18] D. Cabirc, S. M. Mishar, R. W. Brodersen, "Implementation Issue in Spectrum Sensing for Cognitive Radios", IEEE, Signals, Systems and Computers, Conference Record of the Thirty-Eighth Asilomar Conference, pp. 772 - 776, Nov. 2004.

[19] X. Wang, A. Wong, and Pin-Han Ho, "Extended Knowledge-Based Reasoning Approach to Spectrum Sensing for Cognitive Radio", *IEEE Trans. Mobile Comput.*, vol. 9, pp. 465 - 478, Apr. 2009.

[20] H. A. B. Salameh, M. M. Krunz, and O. Younis,"MAC Protocol for Opportunistic Cognitive Radio Networks with Soft Guarantees", *IEEE Trans. Mobile Comput.*, vol. 8, pp. 1339 - 1352, Oct. 2009.

[21] Application Note (AN-SR-7) "Building a Versatile Low Latency Cognitive Radio for Multi-Mission Applications with the ICS-572", technical report, GE Fanuc Intelligent Platforms, https://www.gefanucembedded.com/news-events/whitepapers/3067, Sept. 2003.

[22] F. A. Tobagi and L. Kleinrock, "Packet Switching in Radio Channels: Part II-The Hidden Terminal Problem in Carrier Sense Multiple-Access and the Busy-Tone Solution", *IEEE Trans. Commun.*, vol.23, pp. 1417 - 1433, Dec. 1975.

[23] J. Deng and Z.J. Hass, "Dual Busy Tone Multiple Access (DBTMA) — A Multiple Access Control Scheme for Ad Hoc Networks", *IEEE Trans. Commun.*, vol.50, pp.975 - 985, Jun. 2002.

[24] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, "Opportunisitic Media Access for Multirate Ad Hoc Networks", *Proc. IEEE Mobicom*, pp. 24 - 35, Sep. 2002.

[25] G. Bianchi,"Performance Analysis of the IEEE 802.11 Distributed Coordination Function",*IEEE J. Sel. Areas Commun.*,vol. 18, no. 3, pp. 535 - 547, Mar. 2000.

[26] T. C. Clancy, "Achievable Capacity Under the Interference Temperatur Model", *Proc. IEEE INFOCOM*, pp. 794 - 802, May. 2007.

[27] A. Gelman and D. Rubin, "Inference from Iterative Simulation using Multiple Sequences", Statistical Science, vol. 7, 1992.

[28] W. Hastings, "Monte Carlo Sampling Methods Using Markov Chains and Their Applications", *Biometrika*, vol. 57, no. 1, 1970.

[29] C. R. Stevenson, C. Cordeiro, E. Sofer, and G. Chouinard, *Functional Requirement for the 802.22 WRAN Standard*,IEEE 802.22-05/0007r48, Nov. 2006.

[30] J. G. Kemeny and J. L. Snell, *Denumerable Markov Chains*, Springer-Verlag, 1976.

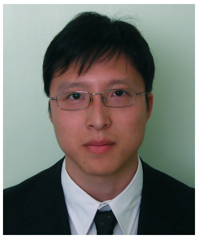
[31] P. Pawelczak, S. Pollin, H.-S. W. So, A. R. S. Bahai, R. V. Prasad, and R. Hekmat, "Performance Analysis of Multichannel Medium Access Control Algorithms for Opportunistic Spectrum Access", *IEEE Trans. Veh. Technol.*, vol.58, no.6, pp. 3014 - 3031, Jul. 2009.

[32] http://www.omnetpp.org/

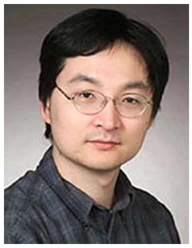
[33] S. M. Ross, *Introduction to Probability Models*, San Diego, CA, Elsevier, 2006.

$$I_{\Theta'} = \sum_{k=1}^{|\Theta'|} \binom{|\Theta'|}{k} (1 + \frac{1}{\lambda_p t_{b,\max}}(e^{-\lambda_p t_{b,\max}} - 1))^k (\frac{1}{\lambda_p t_{b,\max}}(e^{-\lambda_p t_{b,\max}} - 1))^{|\Theta'|-k} \quad (33)$$

Xiao Yu Wang received the M.A.Sc. degree in Electrical Engineering from Concordia University, Montreal, Canada, in 2006. Since 2006, she has been a Ph.D. candidate in the Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, Canada. Her research interests include cognitive radio systems, spectrum sensing, and protocol design for mobile ad hoc networks.



Alexander Wong received the B.A.Sc. degree in Computer Engineering from the University of Waterloo, Waterloo, ON, Canada, in 2005 and the M.A.Sc. degree in Electrical and Computer Engineering from the University of Waterloo, Waterloo, ON, Canada, in 2007, and a Ph.D. degree in the Department of Systems Design Engineering from the University of Waterloo, in 2010. He has published refereed journal and conference papers, as well as patents, in various fields such as computer vision, graphics, image processing, multimedia systems, and wireless communications. His research interests revolve around cognitive radio networks, image processing, computer vision, and pattern recognition. He has worked on projects in image registration, image denoising, image super-resolution, image segmentation, biomedical tracking, and image and video coding and transmission.



Pin-Han Ho received his B.Sc. and M.Sc. degree from the Electrical Engineering department in National Taiwan University in 1993 and 1995, respectively, and Ph.D. degree from Queens University at Kingston at 2002. He is now an associate professor in the Department of Electrical and Computer Engineering, University of Waterloo, Canada. Professor Pin-Han Ho is the author/co-author of more than 150 refereed technical papers, several book chapters, and the coauthor of a book on optical networking and survivability. His current research interests cover a wide range of topics in broadband wired and wireless communication networks, including survivable network design, wireless Metropolitan Area Networks such as IEEE 802.16 networks, Fiber-Wireless (FIWI) network integration, and network security. He is the recipient of Distinguished Research Excellent Award in the ECE department of U of Waterloo, Early Researcher Award (Premier Research Excellence Award) in 2005, the Best Paper Award in SPECTS02, ICC05 Optical Networking Symposium, and ICC07 Security and Wireless Communications symposium, and the Outstanding Paper Award in HPSR02.