HC-MAC: A Hardware-Constrained Cognitive MAC for Efficient Spectrum Management

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***Abstract*—Radio spectrum resource is of fundamental importance for wireless communication. Recent reports show that most available spectrum has been allocated. While some of the spectrum bands (e.g., unlicensed band, GSM band) have seen increasingly crowded usage, most of the other spectrum resources are underutilized. This drives the emergence of open spectrum and dynamic spectrum access concepts, which allow unlicensed users equipped with cognitive radios to opportunistically access the spectrum not used by primary users. Cognitive radio has many advanced features, such as agilely sensing the existence of primary users and utilizing multiple spectrum bands simultaneously. However, in practice such capabilities are constrained by hardware cost. In this paper, we discuss how to conduct efficient spectrum management in ad hoc cognitive radio networks while taking the hardware constraints (e.g., single radio, partial spectrum sensing and spectrum aggregation limit) into consideration. A hardware-constrained cognitive MAC, HC-MAC, is proposed to conduct efficient spectrum sensing and spectrum access decision. We identify the issue of optimal spectrum sensing decision for a single secondary transmission pair, and formulate it as an optimal stopping problem. A decentralized MAC protocol is then proposed for the ad hoc cognitive radio networks. Simulation results are presented to demonstrate the effectiveness of our proposed protocol.**

***Index Terms*—Cognitive MAC, open spectrum, optimal spectrum sensing, spectrum aggregation.**

I. INTRODUCTION

CURRENT usable radio spectrum has almost been allocated to various spectrum-based services, which hinders the further advance and innovation of wireless communication. However, recent reports indicate unbalanced use in different spectrum bands: with a small portion of spectrum (e.g., cellular band, unlicensed band) increasingly crowded, most of the rest allocated spectrum is underutilized [9][10].

With the underutilization of valuable spectrum resource and greatly increased demand of spectrum for wireless communication services, more efficient spectrum management schemes are needed. Open spectrum and dynamic spectrum access systems have drawn great interest recently [21][22]. In these systems, licensed users (primary users) have high priority to use their spectrum; meanwhile, when the spectrum is not used by primary users, unlicensed users (secondary users) are allowed to opportunistically access that spectrum to enable communication or improve service quality. There are several major projects within the scope of open spectrum and dynamic spectrum access, such as DARPA XG program [11][12], DIMSUMnet project [13], DRiVE/OverDRiVE project [14], etc. The fundamental hardware requirement for the open spectrum is cognitive radio, which is a type of radio that has the ability to intelligently recognize the status of radio spectrum environment and adaptively change its transmission parameters such as transmission frequency and bandwidth, power efficiency, modulation schemes, etc.

In this paper, we investigate the Media Access Control (MAC) protocol which is of significant importance in ad hoc cognitive network. The cognitive MAC should fully utilize the advanced capability provided by cognitive radio to optimize the network performance. Specifically, cognitive MAC should make efficient sensing decisions to explore spectrum opportunity which is different from the physical layer issue of how to detect the existence of primary signal, and to utilize such opportunity to conduct data transmission. Since there is no centralized manager in an ad hoc cognitive radio network, such sensing and accessing operations must be coordinated among multiple secondary users, which brings further challenges.

Several cognitive MAC protocols have been proposed in the literature to address various issues in cognitive network [4][2][5][18]. However, all these protocols pay little attention to the hardware limitation of cognitive radio. They either assume multiple radios for each secondary device or assume full spectrum sensing ability for wide spectrum band. To the best of our knowledge, Decentralized Cognitive MAC (DC-MAC) is the first work that assumes the partial sensing ability of cognitive radio in a spectrum management system and studies a joint sensing and transmission decision [3]. However, the influence of sensing overhead for the multi-channel opportunity has not been fully considered. Besides the open spectrum context, there are also many existing research works about multiple channel MAC design. The absence of primary users makes them fundamentally different from cognitive MAC design.

Different from the existing approaches, we consider hardware limitations of practical cognitive radios. We identify two types of hardware constraints of a cognitive radio: (1) *sensing constraint*: for a given geometrical area, spectrum opportunity of interest may span a wide range of bandwidth.

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However during any given period, fine sensing can only be conducted within a small portion of spectrum; (2) *transmission constraint*: spectrum used by a secondary user has maximum bandwidth limit and maximum fragmentation number limit, which stems from the limitation of Orthogonal Frequency Division Multiplexing (OFDM) [7]. These constraints bring new research challenges and also opportunities in cognitive MAC design. Here, we consider the typical scenario where secondary users are all equipped with a single cognitive radio which cannot sense and transmit simultaneously. Fine spectrum sensing is a costly operation in terms of the consumed time for a unit bandwidth of spectrum. Discontiguous OFDM technology [23] is used for spectrum aggregation but the maximum spread bandwidth and the maximum number of fragments are limited. For the protection of primary users, a maximum detection time interval is used similar to that in IEEE 802.22, which represents the maximum time of interference from secondary users that a primary user can tolerate.

These constraints and assumptions require the secondary users to sense spectrum before transmission and impose a time limit of continuous transmission for secondary users. Note that, only when a certain band of spectrum is sensed, the status of the band is known for secondary users. Thus, there is a tradeoff between the spectrum accessing opportunity and spectrum sensing overhead. For a single transmission pair, the more spectrum bands are sensed, the more spectrum opportunities can be explored, but the larger sensing overhead will be. A fundamental problem is for secondary users to determine how to sense the spectrum intelligently (e.g., whether or not to sense further based on the current situation) and optimize the expected throughput. To solve this problem, we incorporate the sensing overhead and the transmission parameter limitations into our protocol design. We model the sensing process as an optimal stopping problem which can be solved by the principle of backward induction. However, the computation overhead of such optimal solution is quite large which is not suitable for real-time MAC protocols. We then propose to use k-stage look-ahead method to approximate the optimal solution with reduced overhead. In the practical protocol design, sender and receiver synchronization is an issue because of the spectrum heterogeneity. Moreover, the multiple user contention for available spectrum should also be considered. In our proposed HC-MAC, we use a common channel to facilitate the exchange of various control messages and contentions among secondary users; the sensing and transmission of a single pair are reserved to prevent message collisions from neighboring nodes. We make use of the block of sensing decision as a basic component for our protocol. Moreover, the protocol does not require global time synchronization.

This paper makes the following contributions:

1) Explicitly consider the hardware-constraints of cognitive radio used by secondary users. Under the assumptions of cognitive radio hardware and system requirement, identify the problem of spectrum sensing and spectrum access tradeoff and formulate it as an optimal stopping problem.
2) Propose a MAC protocol taking advantage of the intelligent sensing decision process. It also makes coordination among multiple competing transmission pairs. Extensive simulations verify the effectiveness of our protocol.

The remainder of the paper is organized as follows. In Section II, we describe the background of open spectrum system and the motivation of this paper. The optimal sensing decision is discussed in Section III, with approximation algorithms and numerical results. Section IV gives the detailed protocol design for cognitive network. We use ns-2 simulator to evaluate the performance of the HC-MAC protocol in Section V. Section VI discusses some assumptions and extensions. Related work is given in Section VII. We conclude the paper in Section VIII.

II. PRELIMINARIES AND MOTIVATION

In this section, we give a brief description of the open spectrum system, and then present system architecture for a single cognitive radio MAC protocol and its key issue of sensing and transmission decision.

A. Preliminary of Open Spectrum System

Current fixed allocation of radio spectrum results in significant underutilization of spectrum resources. The concept of open spectrum system aims to make flexible use of these radio spectrum resources. With a given open spectrum system, some spectrum bands are of interest for *primary users* and *secondary users*. Primary users possess the licenses of these spectrum bands which are granted by Government. Normally, these primary users are legacy systems previously deployed in an area; however, the actual utilization of their spectrum may be quite low. Since little spectrum is available in this area, new spectrum-based communication systems cannot be deployed. However, with the help of open spectrum, these new systems named secondary users are able to request the opportunistic usage of these spectrum bands from the primary users. Secondary users can only use the spectrum on a lease or non-interference basis. Both primary users and secondary users can benefit from open spectrum system: primary users may generate extra revenue from the leasing contract, while secondary users can enable the communication which is not possible previously.

The operations of secondary devices usually have two stages: sensing and transmission. In this paper, we assume the sequential execution of these operations. During sensing stage, PHY-layer sensing and MAC-layer sensing are used to detect the primary users and protect their service quality. PHY-layer sensing adapts modulation schemes and parameters to measure and detect the primary users' signals on different channels while MAC-layer sensing is to determine when and which channel the secondary user should sense. MAC-layer sensing decision is the main focus in this paper. After the information of spectrum has been collected in the sensing stage, actual data transmission can be conducted on the channels not used by primary users during the transmission stage.

B. Motivation

Current hardware development of cognitive radio is still at its infancy. Even in the future when cognitive radio is powerful

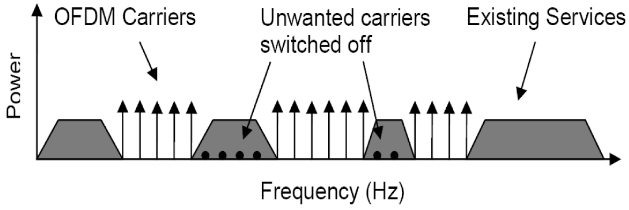


Fig. 1. Discontiguous OFDM for using fragmented spectrum.

enough to change its sensing and transmission parameter at its will, the cost to achieve this may still be quite high. In other words, cognitive radio will have certain hardware constraints. For wide-band spectrum sensing, there exists a certain limitation such as time consumption. Therefore, a common assumption is that a cognitive radio is capable to sense limited bandwidth of spectrum during a certain amount of time (call it *sensing constraint*). For different spectrum sensing approaches and different types of primary users, the time overhead varies.

After sensing for a period of time, each secondary user has some information about spectrum status, i.e., whether primary users are active in these spectrum bands. Based on such information, secondary users can opportunistically use the unused spectrum bands. However, they must make sure their transmission will not generate harmful interference when primary users want to use the spectrum. In many cases, the idle spectrum is discontinuous. OFDM is very suitable to *aggregating* discontinuous spectrum due to the ability to *switch off* unwanted subcarriers, and hence produces a signal with a non-contiguous frequency spectrum which may be tailored to transmitting in available spectrum fragments, as shown in Figure 1. However, the spectrum which can be utilized by a single secondary node for its transmission is limited by hardware constraints (call it *transmission constraint*). According to the recent report of Ofcom [7], using today's hardware technology, both the width of spectrum aggregated and the number of fragments within this width are limited for a single secondary device.

The two limitations, sensing constraint and transmission constraint, raise the problem of how to optimize the sensing decision for each sensing slot. A simple example shown in Figure 2 is used to illustrate the need for intelligent sensing decision. Assume each channel can provide the same data rate, B; the sensing time for a single channel is t and the maximum transmission time is T. Suppose that starting at the time t_0, a secondary user is about to take the next round of sensing and transmission. With the channel conditions unknown at that moment, it has to sense the spectrum. After two slots of sensing, the secondary user can just stop at time t_2 and use the available channels (1 available channel) for transmission during the maximum transmission time of T with the achievable data rate $BT/(T + 2t)$, which is depicted by *Decision A* in Figure 2(a). Instead, it can aggressively continue to sense the next unknown channel as shown by *Decision B*, which results in the data rate $2BT/(T + 3t)$ if this channel is available as Figure 2(b) and $BT/(T + 3t)$ if unavailable as Figure 2(c).

If more channels are sensed, more channels may be available for transmission; however, the sensing time overhead is also increased because of the sensing constraint. Moreover, the degree of availability of spectrum channels also influences the decision making. In addition, the sensing decision should take the transmission constraint into consideration. If the explored spectrum opportunity is more than a secondary user can utilize, it is a waste of time. Such sensing decision problem has not been fully investigated by the existing work in open spectrum systems. In many existing works, a fixed number of channels are sensed and available channels among them are used, such as 3 continuous channels in IEEE 802.22 [4].

In the next section, we show how a secondary transmission pair can make efficient sensing and access decisions.

III. SENSING AND ACCESSING DECISION

A. Channel Diversity and Sensing Overhead

There are multiple channels under consideration, and each channel is occupied by random primary traffic, which exposes itself as a spectrum opportunity with certain probability. According to the Shannon theory [6], for a single secondary user, the theoretical throughput upper bound is proportional to the bandwidth used: $R = W \log(1 + SNR)$, where R is the data rate, W is the transmission bandwidth and SNR is the received signal strength and noise rate. Therefore if a secondary user can exploit more channels and fully utilize them, significant throughput increase can be achieved.

For the protection of primary users and for the exploitation of the spectrum opportunities, secondary users must sense channels before they can actually use them. Further negotiation between a sender and its receiver is also needed for exchanging their channel availability information. These operations consume the effective transmission time of secondary users. Therefore, there is a tradeoff between exploring more idle channels and encountering more sensing overhead, which is of great importance in the design of a multiple channel cognitive MAC protocol.

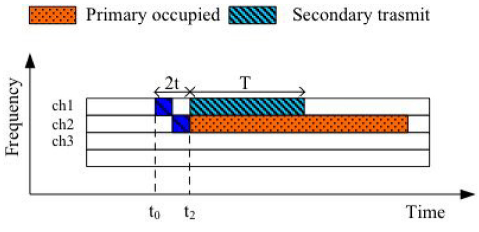
B. Optimal Stopping of Spectrum Sensing

The spectrum sensing decision problem can be formulated as an *optimal stopping* problem. Here we briefly introduce the theory of stopping rule and optimal stopping [1][19].

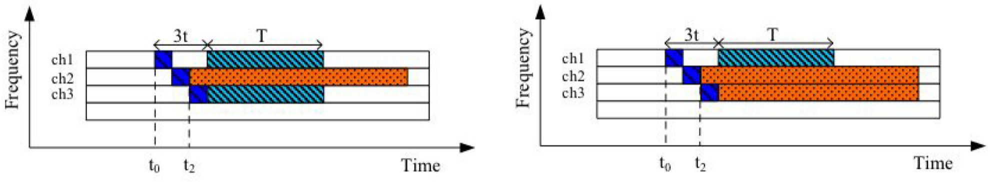
Stopping rule is defined by two objects:

1) a sequence of random variables, $X_1, X_2, \ldots$, whose joint distribution is assumed to be known,
2) a sequence of real-valued reward functions, $y_0, y_1(x_1), y_2(x_1, x_2), \ldots, y_\infty(x_1, x_2, \ldots)$.

Given these two objects, the associated stopping rule problem is described as follows. The sequence of $X_1, X_2, \ldots$ can be observed for as long as possible. For each $n = 1, 2, \ldots$, after observing $X_1 = x_1, X_2 = x_2, \ldots, X_n = x_n$, the decision is either to stop and receive the known reward $y_n(x_1, \ldots, x_n)$, or to continue and observe X_{n+1} for further decision. If the decision is not to take any observations, the received reward is a constant amount, y_0. If never stopping, the received reward is $y_\infty(x_1, x_2, \ldots)$. The goal is to choose a time to stop such that the expected reward is maximized.



(a) Decision A: Stop Sensing at t_2



(b) Decision B: Continue Sensing at t_2 with *ch3* available

(c) Decision B: Continue Sensing at t_2 with *ch3* unavailable

Fig. 2. Different sensing decisions.

A stopping rule problem has a finite horizon if there is a known upper bound on the number of stages at which one may stop. If stopping is required after observing $X_1, X_2, \ldots, X_N$, we say the problem has a horizon N. A finite horizon problem is a special case of the general stopping rule problem with $y_{N+1} = \ldots = y_\infty = -\infty$. Finite horizon stopping rule problems can be solved by the method of backward induction [1]. Since we must stop at stage N, we first find the optimal rule at stage $N-1$. Knowing the optimal rule at stage $N-1$ we find the optimal stopping rule at stage $N-2$ and so on, until back to the initial stage. In particular, we define

$$V_N^{(N)} = y_N(x_1, x_2, \ldots, x_N), \tag{1}$$

and then inductively for

$$\begin{aligned} V_n^{(N)} &= \max\{y_n(x_1,\ldots,x_n), \\ &\quad E[V_{n+1}^{(N)}(x_1,\ldots,x_n,X_{n+1})|X_1 = x_1,\ldots,X_n = x_n]\}. \end{aligned} \tag{2}$$

Let X_n denote the 0-1 (occupied-idle) state of the n^{th} channel probed and the probability $Pr(X_n = 1) = p$ is assumed to be equal for every channel. Let y_n denote the payoff of stopping probing and transmission after probing n channels. y_n is a function of the aggregated channel availability and depends on the radio technology. Here we generalize the constraints for the cognitive radio: the maximum number of adjacent channels a single secondary user can simultaneously use is W, the maximum number of spectrum fragments it can aggregate is F. For a band of spectrum with adjacent channels $\{i, i+1, \ldots, j\}$, we denote the number of fragments as $Frag(i,j)$. Let b_n be the maximum number of usable channels within n adjacent channels (starting from 1), subject to the above constraints (W,F), namely

$$b_n(x_1,\ldots,x_n) = \max_{\substack{1\le i\le j\le n\\ j-i+1\le W\\ Frag(i,j)\le F}} \sum_{k=i}^{j} x_k. \tag{3}$$

The function y_n can be written as

$$\begin{aligned} y_n(x_1,\ldots,x_n) &= \frac{T}{T+nt} b_n(x_1,\ldots,x_n) \\ &= \frac{c}{c+n} b_n(x_1,\ldots,x_n), \end{aligned} \tag{4}$$

where $c = T/t$. We assume each available channel presents a unit of data rate, then y_n is actually the total effective data rate during the time interval $T + nt$ after making the stopping and transmission decision.

Assume the maximum number of channels a user can probe before make a stopping decision is at most K, which means this is a finite horizon problem, solvable by using the backward induction principle. Denote

$$\begin{aligned} V_K^{(K)}(x_1,\ldots,x_K) &= y_K(x_1,\ldots,x_K) \\ &= \frac{c}{c+K} b_K(x_1,\ldots,x_K), \end{aligned} \tag{5}$$

then

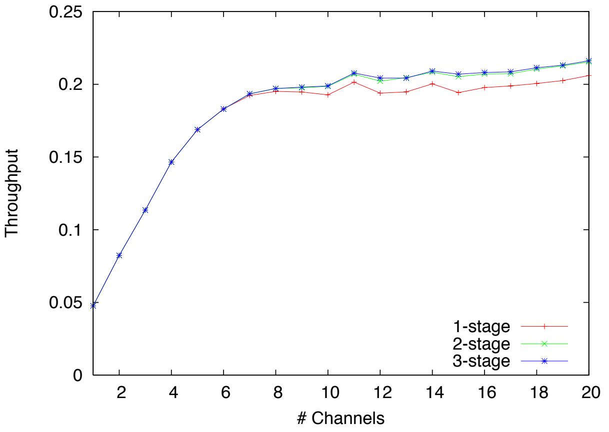
$$\begin{aligned} &E[V_K^{(K)}(x_1,\ldots,x_{K-1},X_K)|X_1 = x_1,\ldots,X_{K-1} = x_{K-1}] \\ &= \frac{c}{c+K}[pb_k(x_1,\ldots,x_{K-1},1) + qb_K(x_1,\ldots,x_{K-1},0)], \end{aligned} \tag{6}$$

where p, q are the probabilities of $X_k = 1$ and $X_k = 0$ respectively; and inductively for $n = K-1$ backward to $n = 2$,

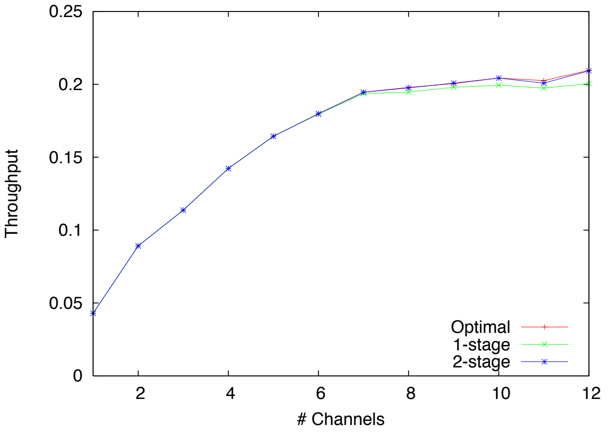
$$\begin{aligned} V_n^{(K)}(x_1,\ldots,x_n) &= \max\{y_n(x_1,\ldots,x_n), \\ &\quad E[V_{n+1}^{(K)}(x_1,\ldots,X_{n+1})|X_1 = x_1,\ldots,X_n = x_n]\}, \end{aligned} \tag{7}$$

$$\begin{aligned} &E[V_n^{(K)}(x_1,\ldots,x_{n-1},X_n)|X_1 = x_1,\ldots,X_{n-1} = x_{n-1}] \\ &= pV_n^{(K)}(x_1,\ldots,x_{n-1},1) + qV_n^{(K)}(x_1,\ldots,x_{n-1},0). \end{aligned} \tag{8}$$

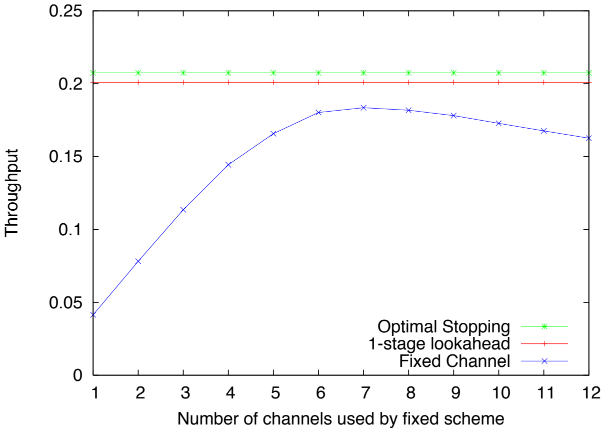
Obviously, we should have a sensing at the beginning, with an observed result x_1. Then we compare y_1 with $E[V_2]$, make the decision, and so on. At each stage, $\{E[V_n]\}$ defines the optimal stopping rule.



(a) Approximation results for 1-stage, 2-stage and 3-stage look-ahead.



(b) Difference between 1-stage (2-stage) and optimal.



(c) Results for optimal stopping, 1-stage look-ahead and fixed channel scheme.

Fig. 3. Numerical results for approximation rules ($c = 10, p = 0.5, W = 6, F = 2$).

C. Complexity Reduction

Such a backward induction solution is a type of dynamic programming, which has the exponential complexity. For a small number of channels, direct computation is possible. However, with the increase of the number of channels, computation time grows exponentially. For a practical MAC protocol, we have to reduce the computational complexity to a reasonable level. In the following, we introduce the k-stage look-ahead rules to approximate the optimal stopping rule.

The k-stage look-ahead rules decide at each stage whether to stop or continue, according to whether the optimal rule among those truncated k stages ahead stops or continues. Thus at stage n, if the optimal rule among those truncated at $n+k$ continues, the k-stage look-ahead rules continue; otherwise, the k-stage look-ahead rules stop. The stopping time N_k is defined as

$$N_k = \min\{n \ge 0 : y_n(x_1, \dots, x_n) \ge E[V_{n+1}^{(n+k)}(x_1, \dots, X_{n+1}, \dots, X_{n+k}) | X_1 = x_1, \dots, X_n = x_n]\}. \tag{9}$$

When $k = K - n$, it is optimal. This is the tradeoff between the performance of optimality and computational cost.

We use numerical results to show the degree of approximation. Figure 3 shows the approximation results, with the parameters $c = 10, p = 0.5, W = 6, F = 2$. For each run, we randomly generate the availability (0, 1) according to the parameter p. We apply different sensing strategies and get the results of y_n. The throughput is averaged over 200 random runs. Figure 3(a) shows the results when we vary the number of stages look-ahead ($k = 1, 2, 3$) and the number of channels. We can see the difference between 1-stage look-ahead and k-stage look-ahead ($k > 1$) is small. They tend to converge for large channel numbers. According to the numerical results in Figure 3(b), 1-stage or 2-stage look-ahead is almost optimal. Since the optimal solution is the up-bound limit for k-stage look-ahead rules when k is approaching the total channel number, we can approximate the optimal result using 1-stage or 2-stage look-ahead approach. As a comparison, if a fixed number of channels are sensed, the results will be much worse than the optimal or the approximation ones, as shown in Figure 3(c). Optimal stopping and its approximation results are always better because their decisions in each sensing slot are based on the observations so far.

IV. HC-MAC: Hardware-Constrained Multi-Channel Cognitive MAC

In this section, we present the design for our proposed hardware-constrained multi-channel cognitive MAC protocol, HC-MAC. Some necessary assumptions are summarized as follows.

1) There are totally N adjacent channels of interest, $\{ch_i\}_N$. Here the term channel refers to the physical channel which is a spectrum band with a certain amount of bandwidth. We do not consider the logical channels such as different coding schemes in Code Division Multiple Access (CDMA). For simplicity, we assume each channel has the same bandwidth B.
2) A common channel ch_0 is available for secondary users at any time. This can be the unlicensed band in practice. This common channel is used as the control channel where secondary users make competition and collaboration as described later.
3) Primary users use N channels for their data transmissions. The states of N channels at time t in any location of the area are given by $\{X_1(t), X_2(t), \dots, X_N(t)\}$

where $X_i(t)$ is in $\{0 \text{ (occupied)}, 1 \text{ (idle)}\}$. If the traffic of primary users follows Poisson traffic model, the probability of the states $\{X_i(t)\}$ can be determined.

4) Each secondary node is equipped with a single cognitive radio. The radio can either transmit or listen (sense), but cannot do both simultaneously. Based on the hardware costs, there will be limitations on the maximum number of idle channels and the maximum number of spectrum fragments that a cognitive radio can use for transmission. The time for primary signal detection depends on different spectrum sensing mechanisms and also the primary signal type. We use t_s to denote the time to detect primary signal in a single channel and it cannot be neglected. The sensing results are assumed to be accurate.
5) There exists a certain degree of interference from secondary users' activity which is tolerable for primary users. Since our focus is on the overlay perspective of spectrum sharing, we use maximum tolerable interference time T as a hard protection criteria for primary users [4]. We assume each primary activity in a channel lasts a relatively long period of time compared with T. Therefore, as long as a secondary user's data transmission ruled by the designed cognitive MAC protocol does not exceed the time limit T, it is considered safe for the primary users. In this paper, the same T applies to all primary users.

With these assumptions, we will encounter the following challenges when designing a cognitive MAC which explores the opportunity of transmission within multiple available channels.

1) *Spectrum sensing for existence of primary users before data transmission.* Since the channel conditions are not known in advance, to protect primary users, the shared spectrum band must be sensed first. The optimal sensing decision should be made according to the optimal stopping rule previously described.
2) *Synchronization between sender and receiver.* The sensing results at the sender and the receiver need to be exchanged because of the spectrum heterogeneity seen by them. The overhead for these information exchanges should also be included in the calculation of the optimal stopping rule. Final sensing stopping and transmission decisions are after the last message exchange.
3) *Multi-channel hidden terminal problem.* In multi-channel systems, especially those consisting of single radio equipped devices, new hidden terminal problems arise. This is because a single radio device may listen to different channels, which makes it difficult to use virtual carrier sensing to avoid the hidden terminal problem.

A. Protocol Overview

We first give an overview of the protocol design. The time frame in HC-MAC consists of a series of secondary operations depicted in Figure 4. The whole time frame can be separated to 3 parts: contention, sensing, transmission. Three types of packets are introduced to facilitate these operations. Note that all these packets are sent on the common channel:

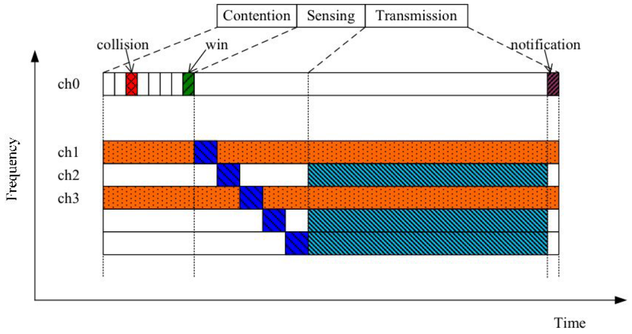


Fig. 4. MAC operation phases.

1) C-RTS/C-CTS: contention and spectrum reservation in contention part.
2) S-RTS/S-CTS: exchange channel availability information between sender and receiver in each sensing slot.
3) T-RTS/T-CTS: notify the neighboring nodes the completion of the transmission.

Figure 5 shows the state diagram for our HC-MAC. If one node wants to transmit, it first sends a C-RTS on ch_0 after random backoff. The intended receiver replies a C-CTS on ch_0. Any secondary node hearing either the C-RTS or C-CTS message will defer their operation and wait for the notification message on ch_0. After reserving the sensing period, the transmission pair conducts sensing in each channel and exchange S-RTS and S-CTS on ch_0 if that channel is available for both sides. A failure of such S-RTS/S-CTS in a channel indicates that the channel is not available. The optimal stopping rule in previous section is used to decide the time to stop sensing. When an agreement is made between a sender and a receiver, data transmission is conducted in the selected channels. When the transmission finishes, they will switch back to the control channel again and exchange T-RTS/T-CTS. This T-RTS/T-CTS exchange ends other neighbors' deferment and the neighboring node participates in another round of contention.

B. Protocol Design

1) Contention: HC-MAC does not require global synchronization. Any node entering the network first listens to control channel ch_0 for a time interval $t_d = t_p K + T$. This allows the new node to observe the current spectrum activities. Since any neighbor nodes cannot sense more than time $t_p K$ and transmit more than time T, a new node will not miss any control packet in its neighborhood. During the period, if a C-RTS (C-CTS) is received, it will defer and wait for the T-RTS (T-CTS). If T-RTS (T-CTS) is received or time t_d is expired before receiving a T-RTS (T-CTS), the new node participates in the contention process if it wants to transmit.

During the contention period, a media access scheme similar to IEEE 802.11 DCF model is used. A node reserves time for the following sensing and transmission operations within the neighborhood by exchanging C-RTS/C-CTS messages with the target node on the control channel. When a node wants to send packets to another node, it first sends a C-RTS packet to the destination on the control channel. The receiver, upon receiving the C-RTS, will reply a C-CTS packet. Other nodes

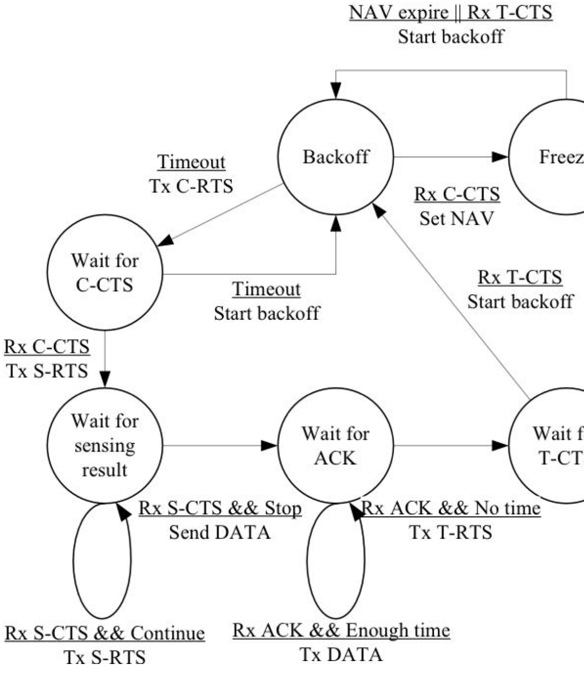


Fig. 5. State transition diagram of HC-MAC.

overhearing these packets defer their sensing and transmission, and wait for the notification from this transmission pair or a timeout.

When a transmission is finished, other neighboring nodes contend the control channel with random backoff. Each of them chooses a backoff counter within a contention window. Each node maintains a variable cw, the contention windows size, which is reset to a minimal value initially. The counter is deducted by one after each contention slot. When the backoff counter reaches zero, the node will try to reserve the control channel by sending a C-RTS to the destination. If the C-RTS packets from neighboring nodes collide, they will double their contention windows. The node with the smallest contention window wins, and starts the next stage while other nodes freeze the counter until next contention period.

2) Sensing: A transmission pair which wins the contention will reserve the channels and start to sense the spectrum. The sensing phase has one or several sensing slots, each of which includes the actual spectrum sensing and negotiation between sender and receiver. Since the sender and receiver are now synchronized, they sense each channel with the same amount of time interval t_s. After getting the results, the sender will send an S-RTS to the receiver including the availability indicator. Upon receiving S-RTS, the receiver will reply with an S-CTS packet. Upon a successful exchange is made between them, the spectrum availability for this channel is observed. Thus, another overhead comes from such exchange of S-RTS and S-CTS, which is denoted by t_e. The total cost to obtain the status information of a channel is $t = t_s + t_e$.

A sensing stopping or continuing decision is made at the end of each spectrum sensing slot. The decision follows the optimal stopping rule described previously. The unit spectrum sensing time t, the maximum transmission time T and the hardware constraints (we assume they are identical for all secondary nodes) are used to achieve the stopping decision. The decision is made by the sender and receiver simultaneously and does not need any further negotiation.

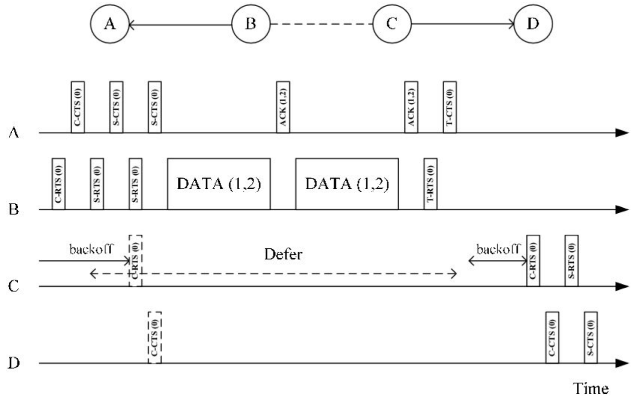


Fig. 6. An example of 2 competing flows.

For the probability of channel availability, they are assumed to be known for the secondary nodes. If the probability is not known in advance, the probability can be estimated with the information collected at each sensing of the channels. If channel conditions are similar for all the channels, the aggregated information for all channels is used to estimate the common availability probability; otherwise, separated probability is estimated for each of the channels. An estimation window with the size EW can be used to approximate the probability with the information collected within the past EW sensing slots. The previous estimation between the sender and receiver must be synchronized, otherwise different decisions will occur. This is achieved by piggybacking RTS/CTS exchanges in contention and sensing stages. Each RTS/CTS exchanges the estimation, while the final decision uses the average of these two.

3) Transmission: After the transmission pair makes the stopping decision, they begin to use a set of available channels to transmit packets. The transmission can include multiple data packets and corresponding ACK packets. The maximum transmission time is equal to T. After finishing the transmission, the sender will send a T-RTS to announce the completion of transmission; upon receiving the T-RTS, the receiver replies T-CTS. This information exchange ends the deferring of the neighboring nodes and starts the next round of contention.

One simple example is shown in Figure 6, where pairs A-B and C-D contend for transmission. After pair A-B obtains the control channel ch_0 (indicated by the number in the parenthesis) via C-RTS/C-CTS control message exchange, pair A-B starts to sense while pair C-D freezes its state and backs off. When it finishes sensing two channels (ch_1, ch_2) and exchanging S-RTS/S-CTS messages, pair A-B makes a decision to stop sensing and enters into transmission stage. It uses the two available channels simultaneously to transmit DATA packets and the associated ACK packets. When the maximum transmission time T is almost expired, it stops transmission and switches back to the control channel. To notify the completing of spectrum usage, T-RTS/T-CTS messages are sent. Upon receiving this last message exchange, pair C-D resumes its counting down of the back off timer and competes with pair A-B for the next round of spectrum usage.

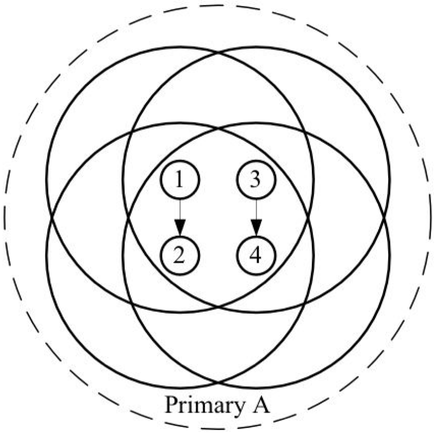


Fig. 7. 1 primary user and 2 secondary pairs.

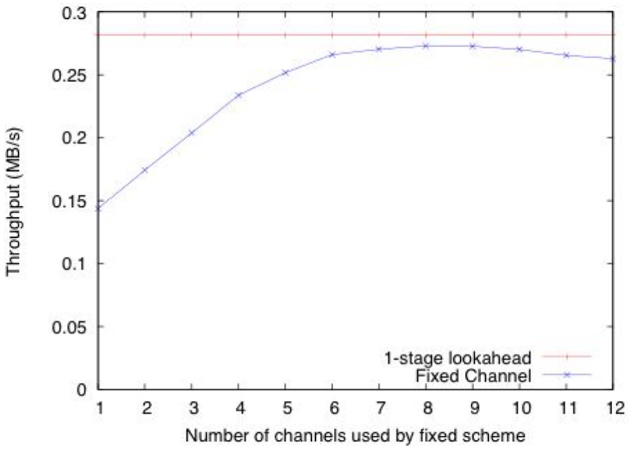


Fig. 8. The throughput with different fixed numbers of sensing channels.

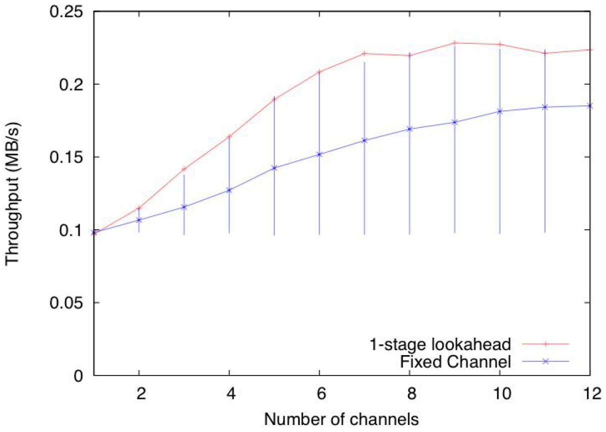


Fig. 9. The throughput with different total numbers of channels.

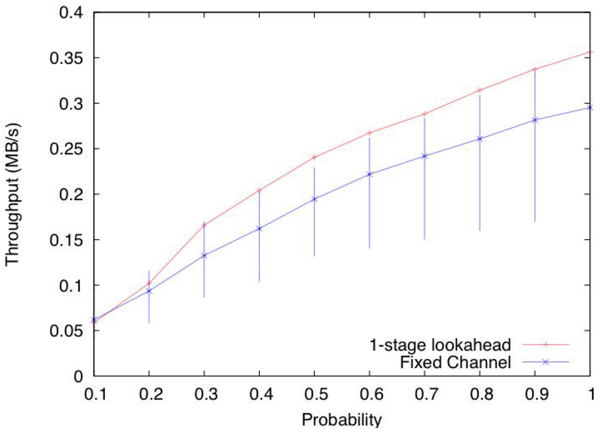


Fig. 10. The throughput with different probability of channels availability.

V. PERFORMANCE EVALUATION

In this section, we present the simulation results for the performance evaluation of the protocol. The simulations are conducted by ns-2 [20]. We first consider a fully connected topology consisting of 2 transmission pairs covered by a single primary user. The results of HC-MAC and a scheme using a fixed number of sensed channels are compared. The performance of secondary users under different primary traffic usages and different transmission parameter setups is evaluated. The adaptation feature of HC-MAC is also demonstrated. After that, spectrum heterogeneity with fully connected topology is investigated with 2 primary users covering different sets of secondary users. Random topology is simulated to manifest the influence of primary user and secondary user density.

In all of the following simulation setups, the bandwidth of each channel is 1MHz, and the secondary users have the same hardware constraints, maximum spread bandwidth $W = 6$ channels, and maximum fragments $F = 2$ fragments. Saturated CBR traffic flows are used by secondary users.

In many of the simulations below, we compare our HC-MAC which makes intelligent sensing decision with the intuitive scheme which fixes the number of channels sensed.

A. Fully-Connected, Spectrum-Homogeneous Topology

Figure 7 shows the first considered topology, where one primary user covers two secondary transmission pairs. These two pairs are fully connected, thus the performance difference due to the topology is avoided. In addition, the spectrum opportunities exposed to two pairs are identical. The performance comparison for our MAC protocol with optimal stopping approximation (1-stage look-ahead) and with fixed number of sensed channels is given in Figure 8. The approximation scheme is better than the fixed scheme which is consistent with our previous numerical results. We also examine the performance under different parameter settings. As shown in Figure 9, with increasing number of total channels, the throughput of secondary users increases. This is because more bandwidth can be used simultaneously. In Figure 10, when the probability of channel availability increases, the secondary throughput is also increased. Similar observation is shown in Figure 11 for maximum transmission time interval.

We further present the performance of HC-MAC under the situation when primary user's spectrum usage varies. The result is compared with the fixed scheme with a certain value for the number of sensed channels in Figure 12. Since our scheme is adaptive in that the exploration of spectrum opportunity is according to the actual primary spectrum usage,

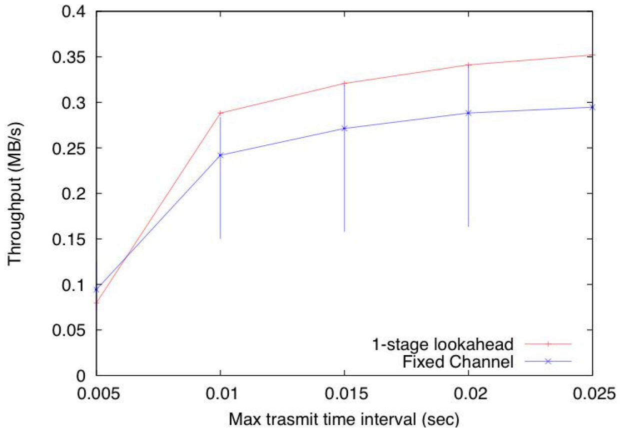


Fig. 11. The throughput with different max transmission time interval.

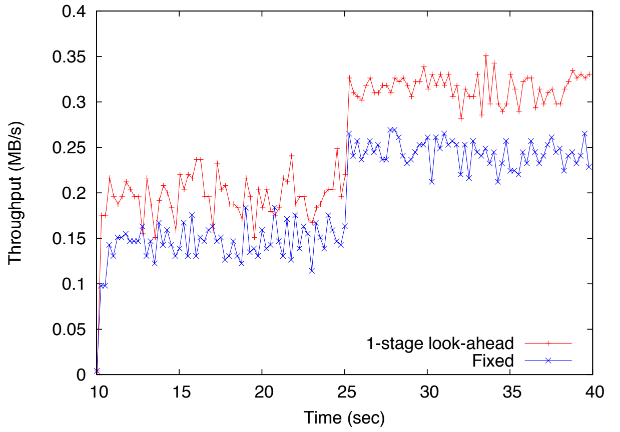


Fig. 12. Throughput comparison with time-varying primary spectrum usage ($p = 0.4$ during 10s-25s and $p = 0.8$ during 25s-40s).

the throughput is changing with the spectrum availability and is better than the fixed scheme.

B. Fully-Connected, Spectrum-Heterogonous Topology

For the second considered topology shown in Figure 13, two primary users are covering two secondary transmission pairs. The spectrum heterogeneity is examined with different spectrum availabilities for the two flows ($p = 0.4$ for flow 1-2, $p = 0.8$ for flow 3-4) while other parameters are the same. In Figure 14, the performance is compared with fixed scheme with 5 sensed channels. The adaptive decision makes our scheme outperform the fixed one. The overall throughput of flow 3-4 is higher than flow 1-2, since there exists more spectrum opportunity for flow 3-4. The fluctuation of the curves is due to the contention between these two flows and changing of primary traffic.

C. Random Topology

We consider the random topology with the size of 1500×1500. 4 non-overlaying primary users are located in the topology with same parameters for simplicity (spectrum availability probability p is 0.5). Secondary users are uniformly distributed within the area. We give the results of network throughput for secondary users with different numbers of secondary single hop flows in Figure 15. Our scheme performs better than the fixed scheme with 4 sensed channels. The performance in a single random topology with 15 secondary flows and time varying primary traffic is shown in Figure 16. Spectrum availability probability p is 0.4 during the first half time, 0.8 for the secondary half. Again our scheme is more efficient in capturing the spectrum opportunity than the fixed scheme.

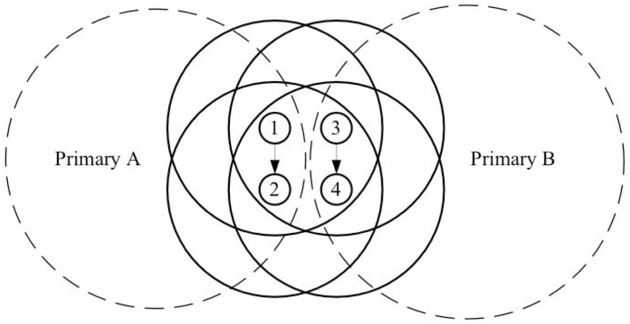
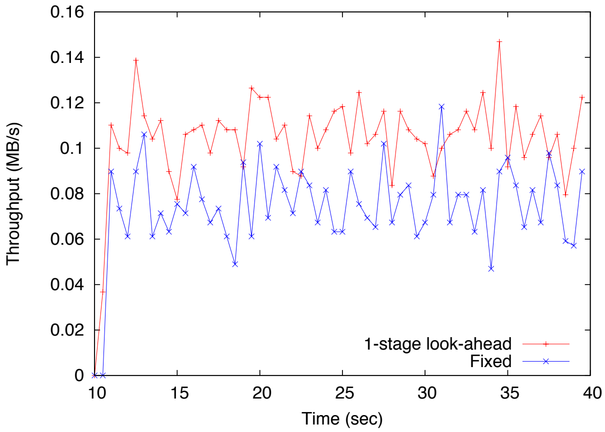
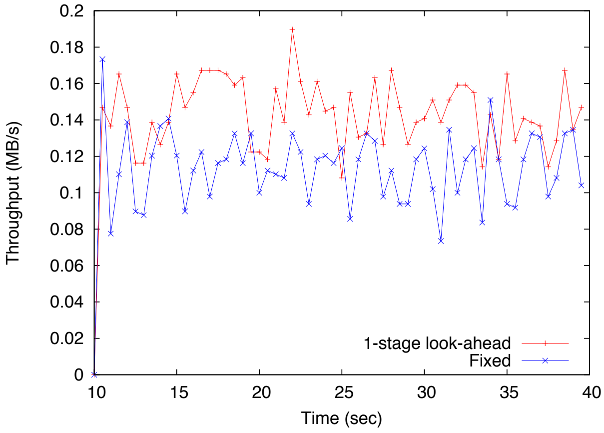


Fig. 13. 2 primary users and 2 secondary pairs.



(a) Throughput of flow 1-2.



(b) Throughput of flow 3-4.

Fig. 14. Individual throughput for 2 secondary pairs in Figure 13.

VI. DISCUSSION

One issue in HC-MAC is the influence of secondary spectrum usage to the primary signal detection. Our protocol ensures that a secondary pair A-B who wins in the con-

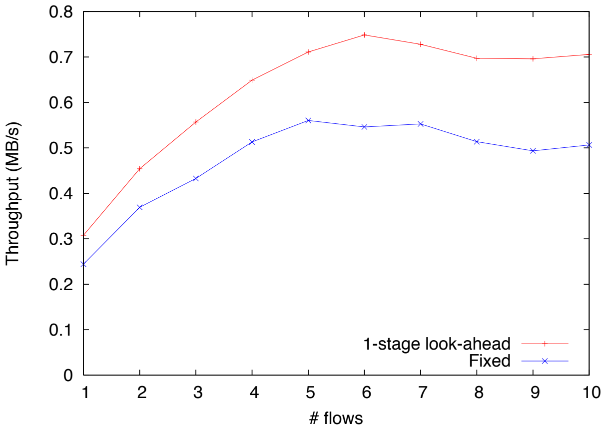


Fig. 15. 4 primary users and random secondary single hop flows.

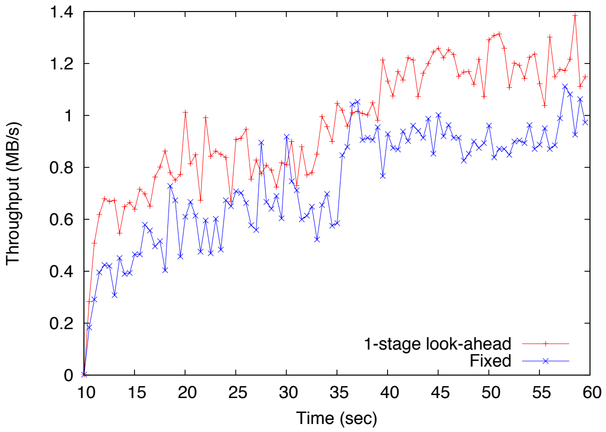


Fig. 16. A random topology with 15 secondary flows ($p = 0.4$ in 10s-35s, $p = 0.8$ in 35s-60s).

tention period senses the spectrum with neighboring nodes silenced. However, the two hop away nodes which do not receive the C-RTS/C-CTS packets can still perform their operations freely. The transmission of these faraway nodes on the channels sensed by pair A-B will make the sensing results of the existence of primary activity inaccurate. Pair A-B may conclude with an occupation of primary user while the signal is actually generated by another secondary user. Therefore, the spectrum utility is degraded. We call this problem as *sensing exposed terminal problem*. An effective method in terms of spectrum sensing accuracy is to force all the secondary users quiet during a certain time interval, which is used in IEEE 802.22 (fast sensing stage and fine sensing stage). However, such global synchronized sensing requires global time synchronization, which is feasible for the infrastructure mode IEEE 802.22, but not available in ad hoc cognitive radio network. More efficient solutions for the sensing exposed terminal problem are needed.

For the HC-MAC protocol, we let a transmission pair to reserve multiple channels for a certain period of time for its sensing and transmission. Multi-channel opportunity is explored for this single pair. However, the spectrum utilization is not optimized, since the available channels not used by this pair are not utilized by neighboring pairs either. If after the sensing process the transmission decision is sent to the neighbors, the neighboring pairs can skip these channels to sense and access other channels. However, the potential problem is that with a single radio and variable sensing and access time, multi-channel hidden problem will screw up the control message reception. One possible method is to equip each secondary device with another regular radio. This radio is dedicated for the control message exchanges. The sensing results and access decisions can then be exposed to neighbors in real time on the control channel. The increased cost of hardware of this additional radio is the main concern.

VII. RELATED WORK

Several MAC protocols have been developed for more flexible and efficient use of spectrum resource built on top of the cognitive radio. Meanwhile, some issues in the design of cognitive MAC also arise in general MAC protocols. In this section, we will briefly summarize these relate works.

A. Cognitive MAC

There are several research efforts on cognitive MAC protocol design in both industry standardization and academic research projects. From the standardization point of view, the current IEEE 802.22 draft is the first world-wide standard related to cognitive radio. Its MAC employs the superframe structure [4]. Synchronized distributed sensing is used, which further consists of fast sensing with energy detection and fine sensing with feature detection. At the beginning of every superframe, base station (BS) sends special preamble and SCH (superframe control header) through each TV channel (up to 3 contiguous channels) that can be used for communication and is guaranteed to meet the incumbent protection requirements. Because of the limited number of channels IEEE 802.22 adopts, the sensing overhead is not a major issue. In addition, IEEE 802.22 is operated in a point-to-multipoint model, which is comparably easier than the cases without the control of the BS.

There are several ad-hoc model MAC protocols for cognitive radio in academic research projects. Most of them do not consider the hardware constraints on spectrum sensing ability and assume full spectrum sensing in a particular portion of spectrum. Dynamic Open Spectrum Sharing (DOSS) MAC [2] protocol allows nodes to adaptively select an arbitrary spectrum for the incipient communication subject to spectrum availability. In this protocol, after the operation of detection of primary users' presence, 3 operational channels (a busy tone band, a control band, and a data band) are set up. The biggest concern with this protocol is the need for multiple transceivers: one transceiver for each channel. Thus this protocol is not suitable for nodes with only one half-duplex radio. In [5] [18], AS-MAC protocol is proposed to coexist with a GSM cellular system; one of the control channels in GSM band is used as the secondary common control channel. A common control channel facilitates many spectrum sharing functionalities such as sender and receiver handshake, communication with a central entity, or sensing information exchange.

The sensing decision under hardware constraints of cognitive radio is considered in [3]. It is not assumed that each secondary user has full knowledge of the availability of all channels, which implies continuous full-spectrum sensing synchronous among secondary users. With the occupancy of interested channels by primary network assumed to follow a discrete-time Markov process, at the beginning of each slot, a secondary user with data to transmit needs to choose a set of channels to sense and a set of channels to access based on the sensing outcome. Such spectrum sensing and access decisions are made to maximize the throughput of the secondary user while limiting the interference to the primary network by fully exploiting the sensing history and the spectrum occupancy statistics. Joint sensing and access decision is formulated under the Partially Observable Markov Decision Process (POMDP). However, the tradeoff between sensing overhead and transmission throughput gain is not considered.

B. General Multi-Channel MAC

Many MAC protocols have been proposed to exploit multiple channels to increase the network capacity by using either multiple radios or just single radio. The multi-radio multi-channel MAC assigns the radios of each node to different channel and enables more simultaneous transmissions so that multiple channels can be used simultaneously for each user. For single-radio multi-channel MAC, the focus is to let different users transmit in parallel on distinct channels, which also increases the throughput and reduces the delay.

For Dynamic Channel Assignment (DCA) algorithm [16], control messages (RTS/CTS) are exchanged over a control channel and data transfer takes place over a number of data channels. The dedicated radio at the control channel and the problem of control channel saturation are the main concern. Slotted Seeded Channel Hopping (SSCH) algorithm is proposed in [15], where a number of channels are available for use and nodes exchange pseudo-random schedules for accessing the medium in a time-slotted manner. No dedicated control channel is needed so that the problem of control channel saturation is avoided. Multi-channel MAC (MMAC) [17] is proposed for single radio ad hoc networks. Multi-channel hidden terminal problem is addressed within synchronized slotted frames. The assumption of global synchronization may incur great overhead for large systems. These works give solutions for the problems also appeared in cognitive network, but the presence of primary users makes the fundamental difference for cognitive MAC protocol design.

Optimal stopping rules have been used by existing work in MAC layer protocols. MOAR [8] explores opportunity to skip frequency channels in search for better quality channels. To balance the tradeoff between the time and resource cost of channel measurement/channel skipping and the throughput gain available via transmitting over a better channel, optimal stopping rule is devised to maximize the expected throughput. In our paper, we focus on the gain from the simultaneous use of several channels with cognitive radio.

VIII. CONCLUSION

In this paper, we have proposed a MAC protocol HC-MAC that utilizes multiple channels to improve the cognitive radio network throughput and overall spectrum utilization. We take practical hardware constraints of cognitive radio used by secondary users into consideration: sensing constraints and transmission constraints. Besides, the primary users have certain specifications of their maximum tolerable interference from the secondary users. We then identify the problem for each secondary user on how to maximize their throughput by optimizing the sensing decision in a sequence of sensing processes. This problem can be formulated as a well-defined optimal stopping problem. Both optimal solution and approximation rule are obtained. We incorporate single secondary transmission pair's sensing decision into the design of HC-MAC for such hardware-constrained cognitive radio networks. Our MAC protocol also coordinates the contention and spectrum usage among multiple secondary pairs. Simulation results show the good performance of secondary users for various system configurations.

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