Hardware-constrained Multi-Channel Cognitive MAC

Juncheng Jia and Qian Zhang
Department of Computer Science and Engineering,
Hong Kong University of Science and Technology, Hong Kong,
Email: {jiajc, qianzh}@cse.ust.hk

Abstract—Open spectrum systems allow unlicensed secondary users equipped with cognitive radio to opportunistically access the spectrum underutilized by primary users. Cognitive radio has many advanced features, such as agilely sensing the signal of primary users and utilizing multiple spectrum bands simultaneously, etc. However, the capability of practical cognitive radios is constrained by hardware cost, resulting in partial spectrum sensing and spectrum aggregation limit. In this paper, we take such constraints into consideration and investigate efficient spectrum management in ad hoc cognitive networks with single cognitive radio. A hardware-constrained cognitive MAC, HC-MAC, is proposed to conduct accurate spectrum sensing and spectrum access decision. We identify the 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 network. Simulation results are given to demonstrate the effectiveness of our proposed protocol.

I. INTRODUCTION

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

Observing such underutilization of valuable spectrum resource and greatly increased demand of spectrum for wireless communication services, more efficient spectrum management schemes are needed. Open spectrum system has drawn great interest recently. In these systems, the licensed users (i.e., primary users) have priority to use their spectrum; however, when the spectrum is not used by primary users, unlicensed users (i.e., secondary users) are allowed to opportunistically access the spectrum to enable communication or improve service quality. The fundamental hardware requirement for the open spectrum is cognitive radio. Cognitive radio is a type of radio which has the ability to recognize the status of radio spectrum environment and can easily change its transmission parameters online, i.e., the spectrum sensing ability and frequency agility. The ultimate goal is for the secondary network equipped cognitive radio (call it as cognitive network) to take better usage of spectrum.

In this paper, we investigate the Media Access Control (MAC) protocol which is of significant importance in ad hoc cognitive network. Cognitive MAC should make good 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. Several cognitive radio MAC protocols have appeared in the literature. In the standard of IEEE 802.22 [4], distributed sensing and synchronization are coordinated by infrastructures with two-stage sensing, i.e., fast sensing using energy detection and fine sensing using feature detection. Dynamic Open Spectrum Sharing (DOSS) MAC is allowing nodes to adaptively select an arbitrary spectrum for the incumbent communication subject to spectrum availability which makes efficient use of idle spectrum [2]; Ad hoc Secondary MAC (AS-MAC) is proposed for secondary users to coexist with Global System for Mobile (GSM) network where the issues of transmission status management of secondary users are addressed [5]. However, all these mentioned protocols, with or without the aid of infrastructure, pay little attention to the hardware limitations of cognitive radio. They either use just a small constant number of spectrum channels 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 the cognitive radio in a spectrum management system and studies a joint sensing and transmission decision [3]. However, the influence of sensing overhead for the multiple channel opportunity is not fully considered. In general MAC designs, Multi-band Opportunistic Auto Rate (MOAR) [8] considers channel scanning overhead when searching for better quality channels. However, the presence of primary users and usage of cognitive radios make our problem unique.

Different from the existing approaches, we observe the current limitations for practical cognitive radios. We identify the hardware constraints in two aspects: sensing constraint: for a given geometrical area, spectrum opportunity of interest may span a wide range of bandwidth, while at any given period accurate and fine sensing can only be conducted within a small portion of spectrum; transmission constraint: spectrum used by secondary users has maximum bandwidth limits and spectrum fragmentation number limits which stems from the number of radios and Orthogonal Frequency-Division Multiplexing (OFDM) technology limitations [7]. In this paper, we consider cognitive networks consisting of single cognitive radio secondary users. The cognitive radio can not sense and transmit simultaneously, and discontinuous OFDM is used for spectrum aggregation but the maximum spread bandwidth and the number of fragments are limited. For the protection of primary users, a maximum detection time interval is used, which represents the maximum time of interference
from secondary signal a primary user can tolerate before it wants to use the spectrum.

These constraints and assumptions impose a limit of continuous transmission for secondary users and require the secondary users to sense spectrum before transmission. However, only when a certain band of spectrum is sensed, the status of the band is known for secondary users. There is a tradeoff between the spectrum opportunity and sensing overhead. For a single transmission pair, the more spectrums are sensed, the more spectrum opportunity can be explored. However the larger sensing overhead will be. A fundamental problem is for secondary users 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 and 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 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 be considered, such as the hidden terminal problem. In the proposed HC-MAC, we use a common channel for various control messages and contention of secondary users; the sensing and transmission of single pair is reserved to prevent message collisions from neighboring nodes, and makes use of the block of sensing decision as a basic component. Further, the protocol does not require global time synchronization.

The remainder of the paper is organized as follows. In Section II, we describe the key observation that motivates our work. The optimal sensing decision is discussed in Section III, with the approximation algorithm. Section IV gives the detailed protocol design for cognitive network. We use simulations to evaluate the performance of the HC-MAC protocol in Section V. We conclude the paper in Section VI.

II. MOTIVATION

Current hardware development of cognitive radio is still at its infancy. For wide-band spectrum sensing, there exist certain limitations such as time consumption and energy constraint. A general assumption is for a single cognitive radio to be able to sense a limited bandwidth of spectrum during a certain amount of time (call it sensing constraint). For different spectrum sensing approach and different types of primary users, the time overhead varies.

After sensing for a period of time, each secondary user has the information of the spectrum condition in these spectrum bands, i.e., whether primary users are active in these spectrums. Based on such information, secondary users can opportunisticly use the unused spectrums. However, they must make sure their transmission will not generate harmful interference in the spectrum currently used by primary users. In many cases, the idle spectrum is discontinuous. Orthogonal Frequency Division Multiplexing (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. 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 is limited for a single secondary device.

The two limitations, i.e., sensing constraint and transmission constraint, raise the problem of how to optimize the sensing decision for each sensing slot. A simple example shown in Fig. 1 is used to illustrate the need for good sensing decision making. Each channel has the same bandwidth, $B$; 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 channel $Chn_1$ for transmission during the maximum transmission time of $T$ with the effective data rate $BT/(T+2t)$, which is depicted in Decision A. Instead, it can aggressively continue to sense the next unknown channel as shown in Decision B, which results in the data rate $2BT/(T+3t)$ if this channel is available as shown in Fig. 1(b) or $BT/(T+3t)$ if unavailable as shown in Fig. 1(c).
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].

As presented in the next section, we formulate the above decision problem with sensing and transmission constraints as an optimal stopping problem. In our MAC design, we use the simple design principle: sensing mechanism is used as a basic component in the protocol, where high throughput is achieved for a single transmission pair by using the efficient approximation algorithm; under the assumption that there exists a common available channel, contention based random access in control channel is used by multiple secondary users to reserve the time interval for the following sensing and transmission.

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. Therefore if a secondary user can exploit more channels and utilize available channels, significant throughput increase can be achieved.

However, the idle channels at each node may be different because of the primary traffic variation and mobility. For the protection of primary users and for the exploitation of the spectrum opportunities, secondary users must sense channels with unknown condition before they can actually use them. Further negotiation between a sender and a receiver is also needed for exchanging their channel availability conditions. Only if a channel is available at both sides, it can be utilized for secondary use of that link. These operations consume the effective transmission time of the 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. To express this issue more explicitly, suppose the maximum continuous transmission period for a secondary link is $T$, the sensing and negotiation overhead is $t$. Then the problem becomes how many channels a secondary user should explore so that the expected throughput is maximized.

B. Optimal Stopping of Spectrum Sensing

The spectrum sensing decision problem can be formulated as an optimal stopping problem [1][8]. 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 each channel. The expected value of $X_n$ is $\mu = E[X_n]$. Let $y_n$ denote the expected 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 spectrum span (can be discontinuous), in terms of the number of channels, a single secondary user can simultaneously use is $W$; the maximum number of spectrum fragments it can aggregate is $F$ [7]. For a band of spectrum with adjacent channels $\{i, i+1, ..., j\}$, we denote the number of fragments as $\text{Frag}(i, j)$. Let $b_n$ be the maximum number of idle channels within $n$ adjacent channels (starting from 1), subject to the above constraints ($W, F$), namely

$$b_n(x_1, ..., x_s) = \max_{\sum_{k=1}^{j} v_k} \left( \sum_{k=1}^{j} x_k \right)$$

(1)

The reward function $y_n$ can be written as

$$y_n(x_1, ..., x_s) = \frac{T}{T + nb_n(x_1, ..., x_s)} = \frac{c}{c + K} b_n(x_1, ..., x_s).$$

(2)

where $c = T/t$, $y_n$ is actually the effective data rate during the time interval $T$ after make the stopping and transmission decision.

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

$$V^{(K)}(x_1, ..., x_K) = V(x_1, ..., x_K) = \frac{c}{c + K} b_k(x_1, ..., x_K),$$

(3)

then its expected value is

$$E[V^{(K)}(x_1, ..., x_K-1, X_{K})|X_1 = x_1, ..., X_{K-1} = x_{K-1}]$$

$$= \frac{c}{c + K} [p \times b_k(x_1, ..., x_{K-1}) + q \times b_k(x_1, ..., x_{K-1})],$$

(4)

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

$$V^{(K)}(x_1, ..., x_n) = \max_{\sum_{k=1}^{j} v_k} \{y_n(x_1, ..., x_n),$$

$$E[V^{(K)}(x_1, ..., X_{n-1}+x_n)|X_1 = x_1, ..., X_{n-1} = x_{n-1}]\}. \}$$

(5)

$$E[V^{(K)}(x_1, ..., x_{n-1}, X_n)|X_1 = x_1, ..., X_{n-1} = x_{n-1}]$$

$$= p \times V^{(K)}(x_1, ..., x_{n-1}) + q \times V^{(K)}(x_1, ..., x_{n-1})].$$

(6)

Obviously, we should have a sensing at the beginning, with result $x_1$, since $E[V_2] \geq 0$. 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.

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 continues; otherwise, the k-stage look-ahead rules stops. The stopping time \( N_k \) is defined as
\[
N_k = \min \{ n \geq 0 : y_n(x_1, \ldots, x_n) \geq E(V_{n+1}^{(n+k)}(x_1, \ldots, X_{n+1}, \ldots, X_{n+k}) | X_1 = x_1, \ldots, X_n = x_n) \},
\]
when \( k = K - n \), it is optimal. This is the tradeoff between the degree of optimality and computational cost. In this paper, we approximate the optimal result using 1-stage look-ahead approach. If a fixed number of channels to be sensed, the results are much worse than the optimal and approximation ones.

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 \( N \) frequency 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 scheme in 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. We consider a general case in which primary users are randomly distributed in an area, using \( \{ch_i\}_N \) for their data transmissions. The state of \( N \) channels at time \( t \) is given by \( \{X_1(t), X_2(t), \ldots, X_N(t)\} \) where \( X_i(t) \) is in \{0 (occupied), 1 (idle)\}. If 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 are limitations on the maximum number of idle channels and the maximum number of spectrum fragments a cognitive radio can use for transmission; a simple case is for a cognitive radio to utilize any idle channel 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 [4]. Let each primary activity in a channel last a relative long 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.

The time frame in HC-MAC is a unit of secondary operations as shown in Fig. 2. The whole time frame can be separated to 3 parts: contention, sensing, transmission. Three types of packets are introduced to facilitate these operations:

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.

A. Contention

HC-MAC does not require global synchronization. Any node entering the network first listens to control channel \( ch_0 \) for a time interval \( t_p = t_s K + T \). This is to allow the new node observe the current spectrum activities. Since any neighbor nodes can not sense more than time \( t_s K \) 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), new node participates in the contention process if it wants transmit.

During the contention period, a multiple 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 through the control channel by exchanging RTS/CTS messages with the target node. When a node wants to send packets to another node, it first sends a C-RTS packet to the destination through the control channel. The receiver, upon receiving the C-RTS, will reply a C-CTS packet. Other nodes overhear these packets defer their sensing and transmission, and wait for the notification from the transmitter/receiver pair or a timeout.

When a transmission is finished by a pair of nodes, 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 \( cw_0 \), the
contention windows size, which is reset to a value $CW_{min}$ initially. The counter is deducted by one after each time 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 window which lowers the probability of another collision. The node with the smallest contention window wins, and starts the next stage while other nodes freeze the counter until next contention period.

B. Sensing

A transmission pair wins the contention will reverse 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 transmitter and receiver are now synchronized, they sense each channel with the same amount of time interval $t_e$. After getting the results, if the spectrum at the transmitter is available, it will send an S-RTS to the receiver. If the spectrum is also available at the receiver side, 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. When there is occupation at any side of the transmission pair, either explicit message exchange with S-RTS (S-CTS) in the common channel or timeout mechanism can be used. The negotiation message is quite short, so the interference for the primary user can be neglected. Since we use the timeout mechanism, i.e., no successful exchange before a timeout implies the occupation, another overhead comes from the exchange of another S-RTS and S-CTS if that channel is available for both sides, which is denoted by $t_e$. The total cost to obtain the status information of a channel is $t = t_e + t_e$.

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 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.

For the probabilities of channel availability, they are assumed to be known for the secondary nodes. In case the probability for channel availability is not known in advance, the probability can be estimated with the information collected at each sensing of the channels.

C. Transmission

After the transmission pair made 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, when there is much data to transmit. The maximum transmission time is equal to $T$. After finishing the transmission, the transmitter 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 node and starts the next round of contention.

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 with version 2.29 [11]. We first consider a fully connected topology consisting of 2 transmission pairs covered by a single primary user. The influence of different primary traffic usage, different transmission parameter setup for secondary user’s performance is evaluated. The adaptation feature of HC-MAC is also demonstrated. After that, spectrum heterogeneity with fully connected topology is investigated with 2 primary user covering different sets of secondary users. Random topology is simulated to manifest the influence of secondary user density.

In all the following simulation setups, the bandwidth of each channel $B = 1$MHz, 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. 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

In this topology, 1 primary user is covering 2 secondary transmission pairs. These 2 pairs are fully connected, thus the performance difference due to the topology is avoided. In addition, the spectrum opportunities exposed to 2 pairs are identical. The performance comparison for our MAC protocol with optimal stopping approximation (1-stage look-ahead) and with a fixed number of sensed channels (5 channels) is given in Fig. 3. The approximation scheme is better than the fixed scheme.

We also present the performance of HC-MAC when primary user’s spectrum usage is alternating. The result is compared with the fixed scheme (5 channels) in Fig. 4. Since our scheme is adaptive in that the exploration of spectrum opportunity is according to the actual primary spectrum utilization, the throughput is changing with the spectrum availability and is better than the fixed scheme.

B. Fully-Connected, Spectrum-Heterogenous Topology

For the second topology, 2 fully-connected secondary transmission pairs are covered by two different primary users. The spectrum heterogeneity is examined with different spectrum availability for the two flows ($p = 0.4$ and $0.8$ respectively) while other parameters are the same as before. The performance is compared with fixed scheme (5 channels) as shown in Fig. 5 and Fig. 6. The adaptive decision makes our scheme outperform the fixed one. The fluctuation of the curves is due to the contention between these two flows.
transmission pairs are regulated so that interference among such hardware-constrained cognitive networks. Nearby sensing processes. This problem can be mapped to as a well-defined optimal stopping problem. Both optimal solution and approximation rule is obtained. We design a HC-MAC for throughput by optimizing the sensing decision in a sequence of sensing channels.

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 = 0.5). Secondary users are uniformly distributed within the area. We give the results of network throughput for secondary users with different numbers of primary spectrum usage.

Fig. 3. The throughput with different fixed numbers of sensing channels.

Fig. 4. Throughput comparison with time-varying primary spectrum usage.

Fig. 5. Throughput of Flow 1 (p = 0.4).

Fig. 6. Throughput of Flow 2 (p = 0.8).

Fig. 7. 4 primary users and random secondary single hop flows.

Fig. 8. A random topology with 15 secondary flows.

secondary users is mitigated. Simulation results show the achievable throughput of secondary users for various system configurations.

VI. CONCLUSION

In this paper, we proposed a hardware-constrained cognitive MAC protocol for ad hoc cognitive network to utilize multiple channels so that the throughput of cognitive network and spectrum utilization are improved. The hardware constraints of cognitive radio used by secondary users include sensing constraints and transmission constraints. To protect primary users, certain specifications of their maximum tolerable interference from the secondary users are assumed. We 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 mapped to as a well-defined optimal stopping problem. Both optimal solution and approximation rule is obtained. We design a HC-MAC for such hardware-constrained cognitive networks. Nearby transmission pairs are regulated so that interference among secondary users is mitigated. Simulation results show the achievable throughput of secondary users for various system configurations.

REFERENCES