On Multi-channel Opportunistic Access in Heterogeneous Cognitive Radio Networks

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***Abstract*—In the paper, we study optimal transmission strategies in multi-channel opportunistic spectrum access (OSA) networks where one secondary user (SU) opportunistically accesses multiple orthogonal channels of primary users (PUs) under a continuous time Markov chain modeling of the channel occupancy by the PUs. Referred to as tunable threshold strategy, at a given time the SU chooses one channel of a given PU, decides if it should transmits or not and if so it protects the PU of this channel. To be operational, such a structure depends on the capability of the SU radio front-end to perform channel sensing. We consider one scenario where the SU node can simultaneously sense multiple channels and another scenario where the SU node can sense only one channel at a time. For each scenario, we develop the structure of the optimal transmission strategy and analyse the performance. We show that the optimal transmission strategy can be implemented using a simple tunable threshold algorithm.**

Index Terms*—Opportunistic spectrum access, MAC, multichannel, cognitive radio networks

I. INTRODUCTION

The concept of Dynamic Spectrum Access (DSA) has been envisaged in the context of secondary sharing of the spectrum, with the objective that sharing is transparent to the spectrum licensee, also called the primary user (PU). The spectrum is shared with secondary users (SU)s but absolute protection is demanded for PUs on all channels. As part of the DSA, the opportunistic spectrum access (OSA) approach encompasses operating regime in which the spectrum is shared on the interference tolerance basis: a SU has open access to the multiple channels of PUs when the PUs are not transmitting, provided that the level of interference caused by the SU is kept below a prescribed tolerance level [1]. We refer to such a regime the OSA medium access control (OSA MAC).

Following the OSA model, the OSA MAC protocol is the main element that determines the efficiency of secondary sharing of the spectrum with the PUs. The fraction of channel bandwidth used by successfully transmitted messages of a SU, also called *throughout*, gives a good indication of the efficiency of an operational OSA MAC, and the maximum value it can attain is known as the *capacity* of the protocol. However, the diverse behavior of different PUs on various channels creates spectrum opportunities having different characteristics that affects the design of the OSA MAC protocol and therefore inherently puts limitations on the capacity it can achieve [1],[2].

For an optimal design of OSA MAC, it is of interest to characterize the maximum throughput as an objective function, with optimal sensing and transmission strategies being the set of optimization variables. Here, the sensing strategy suggests which channel to sense and the transmission strategy determines whether to transmit or not.

In the paper, we study optimal transmission strategies in multi-channel OSA networks where one SU opportunistically accesses multiple orthogonal channels of PUs under a continuous time Markov chain modeling of the channel occupancy by the PUs. Referred to as tunable threshold strategy, at a given time the SU chooses one channel of a given PU, decides if it should transmit or not and if so it protects the PU of this channel. To be operational, such a structure depends on the capability of the SU radio front-end to perform channel sensing. We consider one scenario where the SU node can simultaneously sense multiple channels and another scenario where the SU node can sense only one channel at a time. For each scenario, we develop the structure of the optimal transmission strategy and analyse its performance. We show that the optimal transmission strategy can be implemented using a simple tunable threshold algorithm. The performance of this class of threshold strategies is analyzed and it characterizes the maximum throughput of a multi-channel OSA network as a function of the collision tolerance and the number of channels.

A first cognitive MAC protocol supporting secondary sharing over multiple primary channels was presented in [3]. The optimal sensing problem that governs the channel selection for opportunistic communications over multiple channels was addressed in [4]. Assuming that both PU and SU follow the same transmission structure, it was shown that the sensing policy has a simple structure that reduces the channel selection to a counting procedure and it avoids the need for knowing the channel transition probabilities. A separation principle that decouples the design of sensing and access policies was advanced in [5].

A more realistic model that characterizes the spectrum occupancy of PUs as on-off continuous time Markov processes was presented in [6]. The problem of designing cognitive MAC protocol was extended to multiple continuous time Markovian channel in [7], where the sensing policy is restricted to a periodic sensing scheme yielding to a simple and practical access strategy that satisfies interference constraints.

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Interesting results were reported in [8], where it was shown that when the collision constraints are tight, a periodic sensing scheme with memoryless access is optimal compared to the case when all channels are simultaneously sensed. Different from that, we introduce an alternative way to represent the SU's limitations, which allows us the application of maximum entropy principle to construct the hopping sensing sequence, and thereby derive optimal dynamic access strategies.

The rest of the paper is organized as follow. Section II describes the system model that characterizes PU and SU activities. Section III describes operational properties of the multichannel cognitive access. Section IV presents the structural solutions of the multichannel cognitive access policies. Section V reports numerical results. Section VI concludes the paper.

II. System Model

In this section, we describe the basic elements of a typical OSA system for which we derive the system protocol types and their operating procedures. Two protocols are described and analyzed, which we call multi-channel sensing capability (MCSC) and single-channel sensing capability (SCSC). These in turn serve as a mean to evaluate the OSA network performance with respect to technical and regulatory aspects.

We consider the scenario where a single SU is trying to access N independent channels by using a time slotted transmission structure. Three elements compose such a scenario: the primary networks with spectrum, a secondary network with usage and the OSA MAC responsible to carry out the sharing of spectrum among PUs and SUs.

A. PU Model

We consider a heterogeneous network with N orthogonal channels indexed by i, $i = 1, 2, ..., N$. The index i designates a PU channel and the PU activities on different channels are independent. A channel is required to have the following attributes to be a candidate for secondary sharing.

1) Channel occupancy: we assume that the occupancy of each channel by PU transmissions follows a two state homogeneous continuous time Markov chain. The two states of channel i denotes the idle state(0) and the busy state(1). This is motivated by the packet-based traffic pattern for PUs activity [9]. The Markovian assumption means that the sojourn time attached to each state is exponentially distributed with parameter λ_i^{-1} for the idle state and μ_i^{-1} for the busy state, respectively. The transition rate matrix Q_i of the occupancy of PU channel i is given by

$$Q_i = \begin{pmatrix} -\lambda_i & \mu_i \\ \mu_i & -\lambda_i \end{pmatrix} \tag{1}$$

Let the probability vector $\{\eta_i(0), \eta_i(1)\}$ be the stationary distribution of the ith channel occupancy model associated with Q_i. This is given by

$$\eta_i(0) = \frac{\mu_i}{\lambda_i + \mu_i}, \quad \eta_i(1) = \frac{\lambda_i}{\lambda_i + \mu_i} \tag{2}$$

2) Interference tolerance: although the networks of the PUs were not designed to tolerate interference from secondary transmissions, we assume that the collision in these networks caused by a SU transmission is under control. This enables us to evaluate the effect of interference caused by the SU to a channel in terms of the capacity loss considered acceptable by the PU rather than as a reliability consideration [10]. We assume that for each candidate PU channel there is a packet collision probability denoted by ζ_i. This is defined as the maximum probability of collision for a packet on channel i that the PU can tolerate.

B. SU Model

We consider a single SU trying to opportunistically access the N channels so as to maximize its throughput, but it can transmit using only one channel at a time. The SU is cognitive radio equipped. Time is slotted into discrete time steps indexed by t, $t = 1, 2, ..., T$, but the PUs are not synchronized to it.

For an effective usage of the spectrum by the SU communications, a spectrum opportunity is associated with two characteristics. One includes the estimate of the probability of a channel being free from PU's activity whereas the other includes the estimate of the collision rate of the service being provided on the channel. Thus, we associate the following attributes to the notion of spectrum opportunity.

1) Opportunity identification: the notion of spectrum opportunity is local to a pair of SU nodes. Specifically, a SU is capable of channel sensing, then a channel in the spectrum is an opportunity for secondary sharing if no primary signal is heard, and thereafter the channel is deemed idle at both the sender and receiver of the SU pair. We assume that the SU accurately executes the channel sensing operation. In this way, the performance of channel sensing over a long run provides the actual estimate of the probability that a channel is free from PU's activity at any given time.

2) Interference constraint: a spectrum opportunity depends on the type of collision constraint imposed by PUs, which in turn is determined by the communication activities of the PUs. Let the collision probability for PU on channel i denoted by ξ_i be the fraction of collided packets in packets fully transmitted by the particular PU. Therefore the collision constraint imposed on channel i is given by

$$0 \leq \xi_i \leq \zeta_i, \quad i = 1, 2, ..., N \tag{3}$$

We talk of equal collision constraints if $\zeta_i = \zeta$ for all i. Also, this can be considered as the PU protection requirement in the sense that PU communications experiencing collision below ζ_i do not affect the reliability of the overall PU service being provided on channel i.

Throughout the paper, for a particular PU channel i, we refer to ξ_i as *capacity cost*, and ζ_i as *capacity limit*. We assume that the SU has the estimate of the PUs traffic parameters $(\lambda_i,\ \mu_i)$ whose values are integer multiples of the SU slot length. Also the stationary probabilities $\{\eta_i(0), \eta_i(1)\}$ and the capacity constrains are known a priori.

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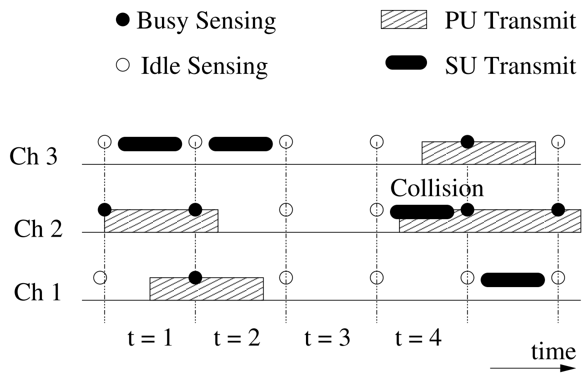

Figure 1. Illustration of the SCSC protocol. All channels are simultaneously sensed. Each SU slot consists of a sensing period and a transmission period. Open circles denote idle sensing result. Filled circles denote busy sensing result. An idle slot happens when the protocol decides so ($t = 3$). A collision happens when the SU starts transmission and PU returns before the end of the SU transmission period ($t = 4$).

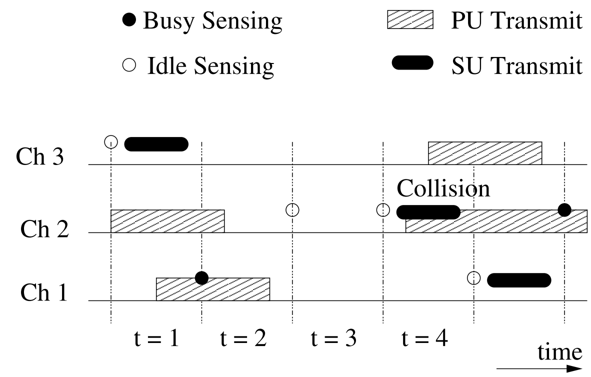

Figure 2. Illustration of the SCSC protocol. One channel is sensed at a time. Each SU slot consists of a sensing period and a transmission period. Open circles denote the idle sensing result. Filled circles denote the busy sensing result. An idle slot happens when the protocol decides so ($t = 3$). A collision happens, when the SU starts transmission and PU returns before the end of the SU transmission period ($t = 4$).

C. Modeling of OSA MAC

Here we describe the system protocols, their underlying algorithms and basic assumptions.

A typical OSA MAC protocol operates by sensing the spectrum at the beginning of each slot, then it uses the sensing results to decide if and in which channel to transmit during the remainder of this paricular slot. Since a collision with PUs can occur, it uses an acknowledgment scheme to be informed of its success or failure.

The various protocols considered defer by the spectrum sensor ability to carry out spectrum sensing. However, in all cases the SU senses the N channels and operates as follows.

We first describe the multi-channel sensing capability (MCSC) as is illustrated in Figure 1. The assumption here is that the SU node is equipped with an additional radio dedicated for sensing. In this case if the spectrum sensor has a broadband sensing capability the N channels can be sensed simultaneously in each time slot. This gives rise to the MCSC.

i) if the selected channel i is observed idle, with probability ω_i the SU transmits and with probability (1 - ω_i) the SU delays this transmission until the next slot;
ii) if the selected channel i is observed busy, with probability 1 the SU does not transmit.

Next we describe the single-channel sensing capability (SCSC) as is illustrated in Figure 2. Here the assumption is that a single radio is shared by both the sensing operation and the transmission operation. In this case the spectrum sensor is limited to sensing one of the N channels at a time, while the remaining channels are hidden. This gives rise to the SCSC.

III. MULTICHANNEL COGNITIVE ACCESS PROPERTIES

In this section, we analyze the performance of the MSSC protocol and SCSC protocol, respectively. This provides the foundation for analytical characterizations of the capacity of the system for these access protocols.

A. Preliminaries

Prior to developing on the performance of the access protocols, we characterize the throughput of the system and the capacity costs as follows. We have assumed that each packet of SU is of constant length requiring t time for transmission. Let π be a method used to select a channel in each time slot t, and with probability ω_i the SU has access to the selected channel. By using π, if the transmission of SU packet has no overlap with the transmission of a PU packet, we consider the SU to have a successful access to the channel i for t time. Further, let $P_{succ,i}$ be the probability that channel i contains a success transmission of a SU for t time. This happens if the channel i is observed idle and also remains idle for the duration t. The throughput of this policy is given by

$$J(\pi) = \sum_{i}^{N} \omega_i P_{succ,i} \quad (4)$$

$$P_{succ,i} = \eta_i(0)\text{exp}(-\lambda_i t) \quad (5)$$

Besides, the SU is considered to be penalized of the interference mitigation attempt failures. Now, let us difine π such that the SU keeps transmitting on a particular channel until a collision happens. Under the assumption that a SU slot is no greater than the maximum of PU packet lengths, and also that the sensing outcome of the SU is perfect, we observe that there may be at most one PU packet collision that may occur whenever the PU returns and after a SU has already sensed the channel to be idle and started a transmission. Therefore the collision probability of PU for a packet experiencing collision on channel i, also referred to as the capacity cost ξ_i under this policy, is given by

$$\xi_i = \frac{E[N_i^c]}{E[N_i]}, \quad \forall i \quad (6)$$

$$E[N_i^c] = 1 - \text{exp}(-\lambda_i t) \quad (7)$$

$$E[N_i] = 1 - \eta_i(0)\text{exp}(-\lambda_i t) \quad (8)$$

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where N_i^c and N_i are random variables representing the number of collided and transmitted PU packets, respectively. Also $E[\cdot]$ denotes the expectation of a random variable.

B. Multi-Channel Sensing Capability (MCSC)

We assume that the SU has the capability to simultaneously sense all channels, but it can use at most one channel at a time to execute its transmission. However, over time its transceiver device can switch among different channels.

Let $s_i(t) \in \{0, 1\}$ be the state of channel i such that a SU executes sensing at time t and then it observes the channel being idle(0) or busy(1). For clarity purposes, we denote the outcome of channel sensing as the true state because we assume the channel sensing to be error free.

The process $\{s_i(t), t \in T\}$ characterizes the occupancy of channel i and it is assumed to have a discrete-time Markovian structure. Let $\mathbf{S}(t) = [s_1(t), s_2(t), ..., s_N(t)]$ be the actual system state under MCSC such that the process $\{\mathbf{S}(t), t \in T\}$ characterizes the actual occupancy of the N channels. We assume that all $\{s_i(t)\}$ are independent Markov chains, so that $\{\mathbf{S}(t)\}$ has also a Markovian structure. This is completely specified by the state space $\mathcal{S} = \{\mathbf{s}\}$, $\mathbf{s} \in \{0, 1\}^N$. Let $F(\mathbf{s})$ be the probability of state $\mathbf{s}$. It can be evaluated by using $\{\eta_i(0), \eta_i(1)\}$, $\forall i$. As such, the SU maintains the actual state of the system at the beginning of each time slot t, $\mathbf{S}(t) = \mathbf{s}$.

Consider an arbitrary time slot t, then a status vector $\mathbf{s} = [s_1, s_2, ..., s_N]$ indicates which channels have been already sensed and also the state of each channel. In this time slot, when channel i is idle, we use $X_i(t)$ to denote a state that indicates the number of channels currently idle including the channel i. $X_i(t)$ takes its values in the set $\{1, 2, ..., N\}$. Let $[X_i = x] = \{\mathbf{s}|X(s) = x, s_i = 0\}$ be the set of idle channels at state x, $x \in \{1, 2, ..., N\}$. The probability of X_i gives, respectively, the PMF$(p_{X_i}(x))$ and CDF$(F_{X_i}(x))$ denoted by

$$\begin{aligned} p_{X_i}(x) &= \sum_{[X_i=x]} \frac{F(\mathbf{s})}{x} \\ F_{X_i}(x) &= \sum_{j=1}^{x} p_{X_i}(j), \quad 1 \leq x \leq N \end{aligned} \tag{9}$$

where $F_{X_i}(x)$ denotes the probability of state x given that channel i is idle.

Let Π denote the set of all MCSC policies. We characterize an access mode $\pi_{\mathtt{MC}} \in \Pi$ as follows. In each time slot, a SU maintains its transmission probability $\omega_i(x, \mathbf{s})$ with which it decides to transmit on channel i at state x given $\mathbf{s}$ or not.

The maximazation of the system throughput for the MCSC protocol can be done by specifying:

- The normalization, which is given by

$$\sum_{i=1}^{N} \omega_i(x, \mathbf{s}) \leq 1, \quad \omega_i(x, \mathbf{s}) \geq 0 \tag{10}$$

- The capacity cost $\xi_{i,N}(\pi_{\mathtt{MC}X})$ of using channel i, which is given by:

$$\xi_{i,N}(\pi_{\mathtt{MC}}) = \sum_{x=1}^{N} F_{X_i}(x) \omega_i(x, \mathbf{s}) \frac{1 - \exp(-\lambda_i t)}{1 - \eta_i(0)\exp(-\lambda_i t)} \quad \forall i \tag{11}$$

- The capacity constraints, which is given by

$$\xi_{i,N}(\pi_{\mathtt{MC}}) \leq \zeta_i, \quad i = 1, ..., N \tag{12}$$

C. Single Channel Sensing Capability (SCSC)

We assume that the SU can sense at most one channel at a time. Let $\{D_i\}$, $i = 1, ..., N$, be the set of system states under SCSC such that the system is at state $D_i(t)$ when the SU senses the i-th channel in slot t and it observes the channel i being idle. The state probabilities $\{p_i\}$, $i = 1, ..., N$, with the entropy function H given by

$$H(p_1, ..., p_N) = -\sum_i p_i \ln(p_i) \tag{13}$$

denotes how likely it is that the channel i is idle(0) before sensing starts at any time slot t. We assume p_i are independent and without loss of generality we also assume that $p_1 \geq p_2 \geq ... \geq p_N$.

Let $\hat{\Pi}$ denote the set of all SCSC. We characterize an access mode $\pi_{\mathtt{SC}} \in \hat{\Pi}$ as follows. In each time slot, a SU maintains its transmission probability $\omega_i(s_i)$ with which it decides to transmit on channel i at state D_i given s_i or not.

The maximazation of the system throughput for the SCSC protocol is done as follows.

1) Prior Information: we assume that we know about the state probabilities $\{p_i\}$, $i = 1, 2, ..., N$:

- The normalization

$$\sum_{i=1}^{N} p_i = 1 \tag{14}$$

- The capacity cost $\xi_i^{\mathtt{SC}}$ on each channel i, and the average capacity limit $\bar{\zeta}$ over all channels

$$\xi_i^{\mathtt{SC}} = \omega_i \eta_i(0) \frac{1 - \exp(-\lambda_i t)}{1 - \eta_i(0)\exp(-\lambda_i t)} \tag{15}$$

$$\bar{\zeta} \geq \sum_{i=1}^{N} p_i \xi_i^{\mathtt{SC}} \tag{16}$$

2) Maximum Entropy: The maximization of the system's entropy function subject to the prior information expressed by (14)-(15) can be done by Lagrangian's method after specifying the "Lagrangian multipliers" α and β. Thus, this leads to the solutions:

$$p_i = \exp\left[-(\xi_i^{\mathtt{SC}}\beta + \alpha + 1)\right], \quad \forall i \tag{17}$$

where

$$\alpha = \ln\left[\sum_{i=1}^{N} \exp(-\xi_i^{\mathtt{SC}}\beta)\right] - 1 \tag{18}$$

$$g(\beta) = \sum_{i=1}^{N} (\bar{\zeta} - \xi_i^{\mathtt{SC}} \exp\left[(\bar{\zeta} - \xi_i^{\mathtt{SC}})\beta\right], \quad \beta \geq 0 \tag{19}$$

The structure of the hopping sequence is provided by the parameter β.

IV. Multichannel Cognitive Access Policies

Simple structural solutions are presented as optimal algorithms for the MCSC protocol and the SCSC protocol, respectively.

A. MCSC Structure

The setting of the optimal MCSC algorithm is as follows. Let K, $1 \leq K \leq N$, be the threshold of the MCSC algorithm such that for each channel i the following conditions are met.

- Given $\{\xi_{i,K}\}$, $1 \leq K \leq N$, for each channel i, we find the threshold K by using $\zeta_i \in [\xi_{i,K-1}, \xi_{i,K}]$
- For the channel i currently observed busy,
$$\omega_i(x, \mathbf{s}) = 0$$
- For the channel i currently idle at state x, threre are tree subcases.
  - For the states x such that $x = K$ and $K \geq 1$
  $$\omega_i(x, \mathbf{s}) = \frac{\zeta_i - \xi_{i,K-1}}{x\,[\xi_{i,K} - \xi_{i,K-1}]}, \quad \xi_{i,0} = 0$$
  - For the states x such that $x < K$ and $K > 1$
  $$\omega_i(x, \mathbf{s}) = \frac{1}{x}$$
  - For the states x such that $x > K$
  $$\omega_i(x, \mathbf{s}) = 0$$

Therefore, the throughput of the MCSC is given by

$$J(\pi_{\texttt{MC}}) = \sum_{i=1}^{N}\sum_{x=1}^{N}\omega_i(x, \mathbf{s})\eta_i(0)\text{exp}(-\lambda_i t) \qquad (20)$$

B. SCSC Structure

The setting of the optimal MCSC algorithm is as follows. Let G, $1 \leq G \leq N$, be the threshold of the SCSC algorithm such that for all channels N the following conditions are met.

- Given $\{\xi_G\}$, $1 \leq G \leq N$, for the N channels, we find G by using $\bar{\zeta} \in [\xi_{G-1}, \xi_G]$, $\xi_0 = 0$.
- For the case that either $G = 1$ or $G > N$, then β, $\{p_i\}$ and $\{\omega_i\}$ are given respectively by
$$\beta = 0, \quad p_i = \frac{1}{N}, \qquad \omega_i = \min\left(1, \frac{\bar{\zeta}}{\xi_i}\right), \quad \forall i$$
- For the case that $G > 1$, then β, $\{p_i\}$ and $\{\omega_i\}$ are given respectively by
$$\beta > 0, \quad p_i = \exp\left[-(\xi_i\beta + \alpha + 1)\right], \quad \omega_i = 1, \quad \forall i$$

Therefore, the throughput of the SCSC is given by

$$J(\pi_{\texttt{SC}}) = \sum_{i=1}^{N} p_i\omega_i\eta_i(0)\text{exp}(-\lambda_i t) \qquad (21)$$

V. Numerical Results

In this section we report two numerical results: one on the performance of the MCSC approach and the other on the performance of the SCSC approach. In particular, the throughout performance for both MCSC and SCSC defines, for a given set of PUs channels characteristics, the capacity of a multi-channel opportunistic system with multi-channel sensing and single-channel sensing, respectively.

For the purpose of performance comparison, we use the periodic sensing with memoryless access (PSMA) approach optimized for strict collision constraints regime [7],[8]. This means that the collision probability on individual channels must be small.

In calculations, the slot duration t is chosen to be $t = 0.25ms$. The selection of the channel parameters are motivated from the experiments conducted in [6]. For the operating environments, we use examples of network configurations with $N = 2, 3$ parallel primary channels, and the channels parameters being:

- For $N = 2$, $\lambda = [1/4.20, 1/3.23]$ ms^{-1} and $\mu = [1/2.32, 1/1.11]$ ms^{-1}.
- For $N = 3$, $\lambda = [1/6.23, 1/4.20, 1/3.23]$ ms^{-1} and $\mu = [1/3.12, 1/2.32, 1/1.11]$ ms$^{-}1$.

A. Performance of the MCSC Structure

We study the throughput of the MCSC approach in comparison to the throughput of PSMA approach. In Figure 3 we plot the throughputs of MCSC approach and the PSMA approach for the two network configurations and the capacity limit on each channel ζ_i ranging in $[0.01, 0.15]$.

It is observed that, for each network configuration, MCSC gives poor performance similar to PSMA when the constraints are strict. This happens when $\zeta \in [0, 0.0475]$ in the figure marked MCSC($N = 2$) with $K_1 = 2$, $K_2 = 1$ obtained through computation, and also when $\zeta \in [0, 0.025]$ in the figure marked MCSC($N = 3$) with $K_1 = 3$, $K_2 = K_3 = 2$ obtained through computation. However, the throughout of MCSC substantially improves compared to the throughout of PSMA until the constrains relax on each channel. This happens when $\zeta \in [0.1225, 0.15]$ in the figure marked MCSC($N = 2$) with $K_1 = K_2 = 2$ obtained through computation, and also when $\zeta \in [0.0875, 0.15]$ in the figure marked MCSC($N = 3$) with $K_1 = K_2 = K_3 = 3$ obtained through computation. This reflects the threshold nature of MCSC. In particular, when N is fixed, a strict capacity constraint is achieved with the reduction in the number of channels, requiring the SU to use a small set of channels. In case the capacity constraints relax, only the SU with advanced cognitive radio capabilities can use all spectrum, resulting in substantial throughput improvement.

B. Performance of the SCSC Structure

Similarly, we study the throughput of the SCSC approach in comparison to the throughput of the PSMA approach. In Figure 4 we plot the throughputs of the SCSC approach and

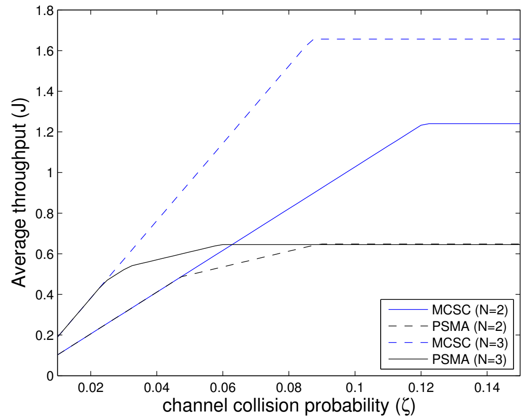

Figure 3. Comparison of the throughputs of the MCSC and PSMA approaches

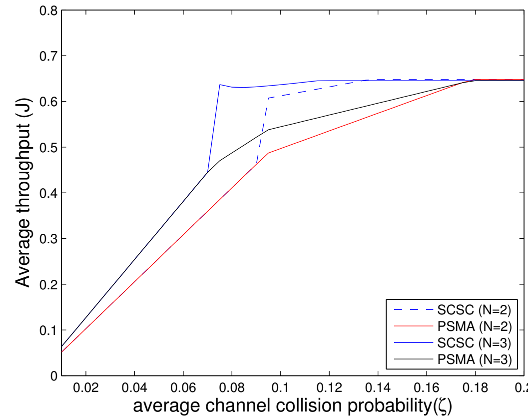

Figure 4. Comparison of the throughputs of the SCSC and PSMA approaches

the PSMA approach for the two network configurations and the average capacity limit $\bar{\zeta}$ over all channels ranging in $[0.01, 0.2]$.

It is observed that, for each network configuration, SCSC gives poor performance similar to PSMA approach when the constrains are strict. This happens when $\bar{\zeta} \in [0, 0.09]$ in the figure marked SCSC($N = 2$) with $\beta = 0$ obtained through computation. The throughput of SCSC saturates when the constraint on each channel relaxes. This happens when $\bar{\zeta} \in [0, 0.14]$ in the figure marked SCSC($N = 2$) with $\beta = 0$ obtained through computation. Similarly, this reflects the threshold nature of SCSC. In particular, $\beta = 0$ features the case where the channels exhibit equal opportunities, therefore it is likely that the SU can use the spectrum without sophisticated learning techniques.

However, the spectrum opportunities depart from being uniform when $\bar{\zeta} = 0.0.095$ in the figure marked SCSC$(N = 2)$ with $\beta = 64.229$ obtained through computation, and also when $\bar{\zeta} = 0.075$ in the figure marked SCSC($N = 3$) with $\beta = 99.05$ obtained through computation. In this case, the SCSC makes it possible to resort to more structured sensing patterns, consequently it improves its throughout substantially compared to the PSMA approach.

We also note that the protocol threshold decreases with the increase in the number of channels, thus adding more channels provides for additional opportunities for secondary exploitation.

VI. Conclusion

Optimal transmission strategies in multi-channel opportunistic spectrum access (OSA) networks have been studied where one secondary (SU) opportunistically accesses multiple orthogonal channels of primary users (PUs) under a continuous time Markov chain modeling of the channel occupancy by the PUs. Optimal access strategies for a single user under the assumption that the SU has perfect knowledge on all channels have been analysed. A special case has been considered with limited sensing capability in which we first constructed a hopping sequence using the principle of maximum entropy. This hopping sequence is then used to devise the access strategy for the SU. We have shown that the channel selection strategy that maximizes the system entropy function subject to capacity constrains induces a hopping sequence with optimal access. Future work is about access policies with mutliple users.

References

[1] D. F. Marshall, "Dynamic spectrum access as a mechanism for transition to interference tolerant systems," in *IEEE New Frontiers in Dynamic Spectrum (DySPAN'10)*, Singapore, Apr. 2010, pp. 1–12.

[2] Q. Zhao, "Spectrum opportunity and interference constraint in opportunistic spectrum access," in *2007 IEEE International Conference on Acoustics, Speech and Signal Processing, ICASSP '07*, Honolulu, HI, Apr. 2007, pp. III605–III608.

[3] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized cognitive mac for opportunistic spectrum access in ad hoc networks: A pomdp framework," *IEEE Trans. Inf. Theory*, vol. 25, no. 3, pp. 589–600, May 2007.

[4] Q. Zhao, B. Krishnamachari, and K. Liu, "On myopic sensing for multi-channel opportunistic access: structure, optimality, and performance," *IEEE Trans. Wireless Commun.*, vol. 7, no. 12, pp. 5431 – 5440, Dec. 2008.

[5] Y. Chen, Q. Zhao, and A. Swami, "Joint design and separation principle for opportunistic spectrum access in the presence of sensing errors," *IEEE Trans. Inf. Theory*, vol. 54, no. 5, pp. 2053–2071, May 2008.

[6] S. Geirhofer, L. Tong, and B. Sadle, "Cognitive medium access: Constraining interference based on experimental models," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 95–101, Jan. 2008.

[7] Q. Zhao, S. Geirhofer, L. Tong, and B. Sadler, "Opportunistic spectrum access via periodic channel sensing," *IEEE Trans. Signal Process.*, vol. 56, no. 2, pp. 785–796, Jan. 2008.

[8] X. Li, Q. Zhao, X. Guan, and L. Tong, "Optimal cognitive access of markovian channels under tight collision constraints," vol. 29, no. 4, pp. 746–756, Apr. 2011.

[9] D. Willkomm, S. Machiraju, J. Bolot, and A. Wolisz, "Primary users in cellular networks: A large-scale measurement study," in *IEEE New Frontiers in Dynamic Spectrum (DySPAN'08)*, Singapore, Oct. 2008, pp. 1–11.

[10] A. P. Jardosh, K. N. Ramachandran, K. C. Almeroth, and E. M. Belding-Royer, "Understanding congestion in ieee 802.11b wireless networks," in *Proc. ACM SIGCOMM Workshops Conf. Comput. Commun.*, Philadelphia, PA, Aug. 2005, pp. 11–16.

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