# On Random Dynamic Spectrum Access for Cognitive Radio Networks

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*Abstract*—The *dynamic spectrum access* (DSA) capability of *cognitive radio networks* (CRN) promises to resolve both the *spectrum scarcity* and the low spectrum utilization problems caused by today's *static spectrum access* (SSA) policy. With DSA, CRN nodes search the dynamically accessible spectrum bands for communication. In this paper, we study a random DSA scheme, where each node randomly selects its operating band based on the locally detected accessible spectrum bands. This scheme does not need the coordination or exchange of control messages to select a communication band between a sender and a receiver, and is desirable in certain scenarios. We analyze the performance of this random DSA scheme. Numerical results show that the random DSA scheme can achieve 60% of the theoretical maximum performance.

## I. INTRODUCTION

Today's *static spectrum access* (SSA) policy grants a fixed spectrum band to each licensed user for exclusive access. With the rapidly proliferated wireless services, SSA is exhausting the radio spectrum and leaves almost no more spectrum for future demands, a problem known as *spectrum scarcity*. On the other hand, a large number of licensed spectrum bands are considerably under-utilized in both time and spatial domains [1, p.9-16]. These two issues have motivated the development of *dynamic spectrum access* (DSA) policy, allowing the *secondary user* (SU) to dynamically detect idle licensed bands (referred to as *channels* in this paper) and temporarily access them, using *cognitive radio* [2], which can dynamically reconfigure the transmission and reception parameters to carry out communication in different bands. To avoid interference to the *primary user* (PU), SU needs to detect the PU activity in the band, e.g., through a spectrum sensor, and has to give up the spectrum band when PU starts using the band.

Recently there have been many research efforts on DSA. These studies primarily fall into two categories. In the first category, an SU is assumed to be a communication session between a pair of transmitter and receiver, and demands a dedicated band/channel for communication (e.g., see [2]–[7] and references therein). Thus the problem is how to allocate each session a channel different from other sessions. In the second category, an SU is a single node in a cognitive radio network (CRN). Unlike the first category, an SU should not be allocated with a dedicated channel, but has to share a channel with at least one other SU to form communication session(s). Furthermore, it allows multiple SUs (multiple sessions) to multi-access the same channel. On the other hand, to reduce *co-channel interference*, we do not want too many SUs (nodes) staying in a common channel. Ideally, each occupied channel should have only two nodes to eliminate co-channel interference. For the second category, an important problem is that when an SU (transmitter) wants to send traffic to another SU (receiver), how the former finds the latter since every SU dynamically changes the operating channel (due to the dynamic availability of spectrum bands). This is known as the *channel selection* problem in multi-channel MAC protocols. There have been quite a few MAC protocols proposed for DSA in CRN [8], [8]–[14]. These efforts assumed a common control channel, used by neighboring nodes to negotiate a *data channel* for packet transmissions.

In this paper we study channel selection without relying on coordination or exchange of control messages between CRN nodes. Our motivation is two folds. First, using a (dedicated) common control channel for coordination may not be feasible in certain scenarios. For instance, the ISM band that is suggested by some studies as the control channel can get crowded in urban areas, since it is an unlicensed band and thus shared by many wireless services. Second, using data channels for coordination (i.e., without requiring a dedicated control channel) is difficult for DSA and likely results in high overhead, as the data channels are dynamically and temporarily accessible only.

We study a random channel selection scheme for DSA, where each node randomly picks an accessible channel to be its operating channel. This scheme does not need coordination or exchange of control messages to select a communication channel between a sender and a receiver, and thus there is no control overhead. Furthermore, this scheme can be used as a supplement for control-based channel selection algorithms when the control channel is congested or jammed, or nodes lose contact with each other in the case that data channels are used for coordination. At last, we show that this scheme can achieve good performance, approximately 60% of the theoretical maximum performance.

The remainder of the paper is organized as follows. In

next section, we describe the DSA network model under the random channel selection scheme. In Section III, we develop a model for performance analysis. Section IV presents numerical results and Section V concludes our paper.

## II. NETWORK MODEL UNDER RANDOM DSA

### A. Dynamically Accessible Channels

From the perspective of SU, a channel simply alternates between the accessible (no PU activity) and the inaccessible (with PU activity) states. We assume that the channel accessible/inaccessible durations are random variables, which may follow arbitrary distribution, and model the channel activity as a semi-Markov process. Let $\mathbb{M}$ denote the total number of channels in the spectrum sensing range of CRN nodes. Let $\lambda_i$ and $\mu_i$ ($1 \leq i \leq \mathbb{M}$) denote the average inaccessible and accessible durations of channel $i$, respectively. Let state '0' and '1' indicate that the channel is inaccessible and accessible, respectively. The fraction of time that the channel is inaccessible or accessible is given as

$$\xi_i(0) = \frac{\lambda_i}{\lambda_i+\mu_i}, \qquad \xi_i(1) = \frac{\mu_i}{\lambda_i+\mu_i}.$$

Let $\boldsymbol{\xi}_i = [\xi_i(0), \xi_i(1)]$. Let $M$ denote the number of accessible channels at a given time. We assume that the PU activities of different channels are independent. Then we have the *probability mass function* (pmf) of $M$ as $f_M = \boldsymbol{\xi}_1 * \cdots * \boldsymbol{\xi}_{\mathbb{M}}$, where $*$ indicates convolution. If $\lambda_i = \lambda$ and $\mu_i = \mu$ for all $1 \leq i \leq \mathbb{M}$, then $f_M$ becomes the binomial distribution with parameters $\mathbb{M}$ and $\frac{\lambda}{\lambda+\mu}$.

### B. CRN Node Operations

We assume that each node has a single cognitive radio for communication, and a fast wideband spectrum sensor for spectrum analysis (e.g., the spectrum sensor in [15] can sense/analyze a spectrum band of 528 MHz in the order of 20 $\mu$s). To give a node opportunities to communicate with every neighbor, we let CRN nodes periodically change their operating channels, so that a node meets different neighbors over time[1]. In other words, CRN nodes operate in a time slotted mode[2]. A node uses its spectrum sensor to detect accessible channels in each time slot, and randomly selects one of them as its operation channel. Then this node switches its cognitive radio to the selected channel. If there are two or more CRN nodes switching to the same accessible channel, then these nodes use some existing multiple access MAC protocol (e.g., CSMA/CA) to access this channel and communicate with each other. The time synchronization between nodes is performed when they meet in the same channel (e.g., using the approach in [16]).

In this paper, our objective is to examine the maximum achievable capacity/throughput, which can be obtained by

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[1]A node meets a neighbor when it selects and switches to the same operating channel of the neighbor

[2]The PU may or may not operate in slotted mode. In the case that the operation channel of a CRN node becomes inaccessible within a time slot, due to appearance of PU activity, the CRN node simply switches to another channel, which is similar to a continuous channel switching within a time slot, to be discussed in Section III-C.

assuming that a node always has traffic to each neighbor, as in several studies (e.g., [4]). With this assumption, the throughput is approximately determined by the number of channels that are utilized for SU communications, which are called *utilized channels* (see next section). In fact, with our simulations, the packet-level throughput is predominantly impacted by the number of utilized channels, rather than the distributions of communication nodes among channels with a given number of utilized channels. Hence, in this paper, the number of utilized channels will be used as the performance metric. If needed, one may obtain the packet-level throughput through the analytical models of MAC protocols (e.g., [17], [18]), by conditioning on the number of utilized channels obtained by our model.

## III. ANALYSIS OF RANDOM DSA

As discussed previously, in each time slot, every node randomly selects an operating channel among the accessible channels detected by its spectrum sensor, and switches its cognitive radio to this channel. After all nodes have switched to their selected channels, the accessible channels fall into three types: 1) channels containing two or more nodes, termed *utilized channels*; 2) channels containing only one node, termed *single-node channels*; and 3) *empty channels*, without any node. We call the first type of channels as 'utilized channels' because the nodes on such a channel can send packets to each other (as described in the preceding section, we assume that a node always has traffic to each neighbor), while the second and third types of channels do not contribute to traffic transportation (which involves at least one transmitter and one receiver). After detecting that it is in a single-node channel, e.g., after sending several *hello* packets but never receiving any reply, a node may want to continue to switch to another channel, expecting to meet other nodes in the new channel. We will model such *continuous channel switching* (CCS) within a time slot through a *discrete time Markov chain* (DTMC).

The following analysis is conditioned on the number of accessible channels, i.e., treat $M$ as a known number. If needed, one can easily obtain the unconditioned result based on the pmf of $M$ given in Section II-A. In the ensuing discussion, we first examine the number of utilized channels. Next we derive the joint pmf of the utilized and single-node channels after the first channel switching in a time slot. This joint pmf is then used as the initial state probability for the DTMC, to obtain the state probability (or the joint pmf of utilized and single-node channels) after each additional channel switching. Based on the state probability, the mean number of utilized channels after each CCS can be obtained.

### A. Mean Number of Utilized Channels

Let $N$ denote the number of nodes in the network. Let $M$ denote the number of accessible channels in the current time slot, and we denote these channels as $\{1, \ldots, M\}$ without loss of generality. Due to sensing errors (e.g., miss-detection and false alarm) or partial coverage of some channels, a node may

not have detected all $M$ accessible channels, and different nodes may have detected different sets of accessible channels. Let $\mathcal{C}_i$ ($1 \leq i \leq N$) denote the set of accessible channels detected by node $i$. We assume that each channel in $\mathcal{C}_i$ is randomly detected by node $i$ with a probability $p$, called *channel detection probability* in this paper.

Let $X_{i,j}$ denote the event that node $i$ switches to channel $j$. We have

$$\Pr(X_{i,j} \mid j \in \mathcal{C}_i, |\mathcal{C}_i| = v) = \frac{1}{v}, \tag{1}$$

for random channel selection, where $|\bullet|$ indicates the cardinality.

Next we calculate the probability that node $i$ has detected $v$ accessible channels, and channel $j$ is one of them, i.e., $|\mathcal{C}_i| = v$ and $j \in \mathcal{C}_i$. We have

$$\Pr(j \in \mathcal{C}_i, |\mathcal{C}_i| = v) = \begin{cases} 0, & \text{if } v = 0 \\ p \times B(v-1; M-1, p), & \text{if } v \geq 1 \end{cases} \tag{2}$$

where $B(v - 1; M - 1, p)$ is the binomial distribution with parameters $M - 1$ and $p$. Based on Eqs. (1) and (2), we have

$$\begin{aligned} \Pr(X_{i,j}) &= \sum_{v=0}^{M} \Pr(X_{i,j} \mid j \in \mathcal{C}_i, |\mathcal{C}_i| = v) \\ &\quad \times \Pr(j \in \mathcal{C}_i, |\mathcal{C}_i| = v) \\ &= \sum_{v=1}^{M} \frac{1}{v} \times p \times \binom{M-1}{v-1} p^{v-1} (1-p)^{M-v} \\ &= \frac{1}{M} \left( 1 - (1-p)^M \right). \end{aligned} \tag{3}$$

Eq. (3) shows that $\Pr(X_{i,j})$ does not depend on $i$ and $j$.

Let the random variable $U_j = 1$ or $0$ denote that channel $j$ is utilized or not, after all nodes have switched to their selected channels. Channel $j$ is not utilized iff it contains zero or one node, which means that the events $X_{1,j}, \dots, X_{N,j}$ are all false, or only one of them is true. Moreover, for a fixed $j$, the events $X_{1,j}, \dots, X_{N,j}$ are independent. Thus we have

$$\Pr(U_j = 0) = \prod_{i=1}^{N} \Pr(\bar{X}_{i,j}) + \sum_{i=1}^{N} \Pr(X_{i,j}) \prod_{k=1, k \neq i}^{N} \Pr(\bar{X}_{k,j}), \tag{4}$$

where $\bar{X}$ denote the complement event of $X$.

Let $U = \sum_{j=1}^{M} U_j$ denote the total number of utilized channels. Then the mean number of utilized channels is

$$\mathrm{E}(U) = \sum_{j=1}^{M} \mathrm{E}(U_j) = \sum_{j=1}^{M} (1 - \Pr(U_j = 0)). \tag{5}$$

Denote $\beta = \Pr(X_{i,j}) = \frac{1}{M} \left( 1 - (1-p)^M \right)$. Substituting Eq. (3) into Eq. (4) and (5), we obtain the mean number of utilized channels, $\mathrm{E}(U)$, as follows

$$\mathrm{E}(U) = M \left( 1 - (1 + (N-1)\beta)(1 - \beta)^{N-1} \right). \tag{6}$$

### B. Joint pmf of Utilized and Single-Node Channels

To make the problem tractable, we assume that the detected accessible channels are the same for all nodes in this subsection, and without loss of generality, let $M$ denote the number of accessible channels as earlier. In fact, we expect that most accessible channels of a node are common to other nodes as

well, and therefore our analysis is a good approximation of the real behavior. Let $U$ and $Y$ denote the number of utilized channels and single-node channels, respectively. The joint pmf of $Y$ and $U$ depends on $N$ and $M$, and we denote it as $f_{Y,U}(y, u \mid N, M)$. This joint pmf also determines the pmf of the number of empty channels since the latter is equal to $M - U - Y$.

The random channel selection by $N$ nodes for $M$ channels is similar to distributing $N$ balls into $M$ boxes. The total number of possible arrangements is $M^N$. We introduce two functions:

- $G(k, h)$, denoting the number of arrangements that each box contains two or more balls, when distributing $k$ balls into $h$ boxes,
- $F(i, j \mid N, M)$, denoting the number of arrangements that when distributing $N$ balls into $M$ boxes, exactly $i$ boxes are occupied, and among the $i$ boxes, there are $j$ boxes that each contains exactly one ball. Note that among the remaining $(i - j)$ boxes, each contains two or more balls.

The $F(i, j \mid N, M)$ can be computed as follows:
1) Select $i$ boxes from $M$ boxes,
2) Select $j$ boxes from $i$ boxes,
3) Select $j$ balls from the $N$ balls,
4) Place the $j$ balls in Step 3 into the $j$ boxes in Step 2 such that each of the $j$ boxes contains exactly one ball,
5) Among the $N$ balls, there remain $(N - j)$ balls that have not been placed into boxes, and among the $i$ boxes, there remain $(i - j)$ boxes that have not been placed with balls. Distribute these $(N - j)$ balls into the $(i - j)$ boxes so that each box contains two or more balls. The number of possible arrangements in this step is $G(N - j, i - j)$.

Multiplying the possibilities in the above 5 steps, we have

$$F(i, j \mid N, M) = \begin{cases} 0, & \text{if } i < j \\ \binom{M}{i} \binom{i}{j} \binom{N}{j} j! G(N-j, i-j), & \text{if } i \geq j \end{cases} \tag{7}$$

Now we discuss how to compute $G(k, h)$, which can be represented as

$$G(k, h) = \sum_{m_1, \dots, m_k} \frac{k!}{\prod_{v=1}^{k} m_v!}, \tag{8}$$

for $m_1, \dots, m_k$ such that $k = \sum_{v=1}^{k} m_v$ and $m_v \geq 2$ for $v$. However, the brute-force computation of Eq. (8) is time-consuming. We present a recursive algorithm which utilizes dynamic programming to efficiently compute $G(k, h)$. We define $H(k, h)$ as the number of arrangements that all $h$ boxes are occupied, when distributing $k$ balls into $h$ boxes. By Eq. (11.7) in [19, p.60], we have

$$H(k, h) = \sum_{v=0}^{h} (-1)^v \binom{h}{v} (h - v)^k.$$

On the other hand, we must have

$$H(k, h) = \sum_{j=0}^{h} F(h, j \mid k, h), \tag{9}$$

since if all $h$ boxes are occupied, then the number of boxes that contain exactly one ball must be either $0, 1, \dots,$ or $h$.

$G(k, h)$ can be computed as follows.

$$G(k, h) = F(h, 0 \mid k, h) = H(k, h) - \sum_{j=1}^{h} F(h, j \mid k, h) \quad (10)$$

For $F(h, j \mid k, h)$ in Eq. (10), we observe that if among the $h$ occupied boxes, there are exactly $j$ boxes that each contains one ball, then the remaining $(h - j)$ boxes each must contain two or more balls, and thus the total number of balls in the $h$ boxes is at least $j + 2(h - j)$. On the other hand, since we are distributing $k$ balls into $h$ boxes, then we must have $k \geq j + 2(h - j)$, from which, we obtain $j \geq 2h - k$. Furthermore, for trivial values of $k$ and $h$, we can obtain $G(k, h)$ directly. At last we obtain $G(k, h)$ as follows.

$$G(k, h) = \begin{cases} 1, & \text{if } k = h = 0 \\ 0, & \text{if } k < 0 \text{ or } h < 0 \\ 0, & \text{if } k \neq 0 \text{ and } h = 0 \\ 0, & \text{if } k = 0 \text{ and } h \neq 0 \\ 0, & \text{if } h > 0 \text{ and } k < 2h \\ H(k, h) - \sum_{j=\max(1, 2h-k)}^{h} F(h, j \mid k, h) \\ \quad , \text{ otherwise} \end{cases} \quad (11)$$

Note that we define $G(0, 0) = 1$, which is sometimes needed in the computation of Eq. (7).

In Eq. (11), $F(h, j \mid N, M)$ can be recursively obtained from Eq. (7). The joint pmf of $U$ and $Y$, $f_{Y,U}(y, u \mid N, M)$ for $0 \leq y \leq M, 0 \leq u \leq M - y$, can then be obtained as,

$$f_{Y,U}(y, u \mid N, M) = \frac{F(y + u, y \mid N, M)}{M^N} .$$

### C. Continuous Channel Switching (CCS)

We call the nodes switched to single-node channels as *isolated nodes*. In this section, we consider that isolated nodes continue to switch channels in the current time slot until they meet other nodes. Specifically, after a channel switching, each node may wait for a period of time to detect if there are other nodes in this channel, and after the duration of this *channel checking*, if the node realizes that it is in a single-node channel, then it starts another round of channel selecting, switching, and checking.

The CCS of isolated nodes can be modeled as a DTMC. Each round of channel switching can be modeled as one transition for the DTMC. The state space of the DTMC is defined as

$$\mathcal{S} = \{\langle y, u \rangle \mid 0 \leq y \leq M, 0 \leq u \leq M - y\},$$

where state $\langle y, u \rangle$ indicates that there are $y$ single-node channels and $u$ utilized channels.

When the DTMC is in state $\langle y, u \rangle$, since there are $y$ single-node channels and each contains an isolated node, then there are $y$ isolated nodes that will continue to the next round of channel switching. The remaining $N - y$ nodes are already in utilized channels, where $N$ is the total number of nodes. Among the $y$ isolated nodes, each node randomly selects one among the $M$ channels for channel switching. If it selects the current operating channel, then this node stays on the current

operating channel to expect other isolated nodes to switch to this channel. Clearly an isolated node has probability of $\frac{u}{M}$ to switch to some utilized channels since there are $u$ utilized channels at state $\langle y, u \rangle$. Define $A_r$ $(0 \leq r \leq y)$ as the event that when the DTMC is at state $\langle y, u \rangle$, there are $r$ $(0 \leq r \leq y)$ isolated nodes that switch to the $(M - u)$ non-utilized channels (single-node or empty channels). Then we have

$$\Pr(A_r) = \binom{y}{r} \cdot (1 - \frac{u}{M})^r \cdot (\frac{u}{M})^{y-r}.$$

The transition probability of the DTMC from state $\langle y, u \rangle$ to $\langle w, u + v \rangle$ is given as follows, with $0 \leq w \leq y, 0 \leq v \leq \lfloor \frac{y}{2} \rfloor$ such that $f_{Y,U}(w, v \mid r, M - u) > 0$ for some $r$ $(0 \leq r \leq y)$.

$$P(\langle y, u \rangle, \langle w, u + v \rangle) = \begin{cases} \sum_{r=0}^{y} \Pr(A_r) \times f_{Y,U}(w, v \mid r, M - u), & \text{for } w, v \\ \quad \text{such that } f_{Y,U}(w, v \mid r, M - u) > 0 \text{ for some } r. \\ 0, & \text{otherwise.} \end{cases}$$

Denote the pmf $f_{Y,U}(y, u \mid N, M)$ obtained in Section III-B as a vector $\boldsymbol{\sigma}^{(0)} = [\sigma_{\langle y,u \rangle}]_{\langle y,u \rangle \in \mathcal{S}}$, where $\sigma_{\langle y,u \rangle} = f_{Y,U}(y, u \mid N, M)$. This is the initial state probability vector of the DTMC. Denote

$$\boldsymbol{P} = [P(\langle y, u \rangle, \langle w, v \rangle)]_{\langle y,u \rangle, \langle w,v \rangle \in \mathcal{S}}$$

as the transition probability matrix of the DTMC. Then the state probability of the DTMC after $k$ CCS is given as

$$\boldsymbol{\sigma}^{(k)} = \boldsymbol{\sigma}^{(0)} \times \boldsymbol{P}^{k-1}.$$

Based on the state probability $\boldsymbol{\sigma}^{(k)}$, we can easily calculate the mean number of utilized channels with $k$ CCS as

$$\mathrm{E}(U) = \sum_{u} u \times \left( \sum_{y} \boldsymbol{\sigma}^{(k)}_{\langle y,u \rangle} \right).$$

### IV. NUMERICAL RESULTS

To verify the analytical model developed in the preceding section, we have simulated a single-hop CRN. The time slot is assumed 10 milliseconds. The simulation time is 5000 seconds. We collect the number of utilized channels in each slot and then compare the average value to the analysis results. As can be seen in the following, the simulation results match the analysis results well.

Fig. 1 illustrates the mean number of utilized channels $\mathrm{E}(U)$ as a function of $M$ (the number of accessible channels) in a 20-node CRN, with $p = 1$. One can see that the mean number of utilized channels first increases and then decreases when $M$ increases. In fact, when $M$ increases to be very large, $\mathrm{E}(U)$ approaches 0. This can be seen by letting $p = 1$ and expanding Eq. (6) to $\mathrm{E}(U) = \sum_{k=1}^{N} a_k \frac{1}{M^k}$, where $a_k$ is a quantity depending on $N$ only. When $M$ is large, this summation $\sum_{k=1}^{N} a_k \frac{1}{M^k}$ approaches 0. An interesting question raised by this observation is: given $N$, what is the value of $M$ that results in the maximum $\mathrm{E}(U)$, denoted as $U^*$ in the ensuing discussion. Fig. 2 plots $U^*$ as a function of $N$, and the corresponding $M$ that results in $U^*$, denoted as $M^*$, with
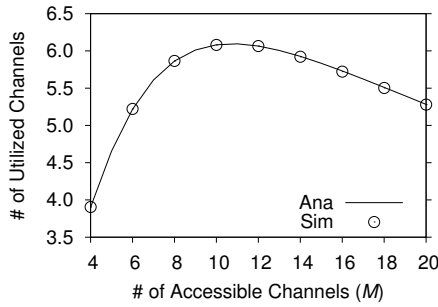
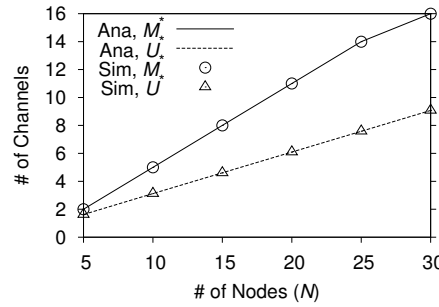Fig. 1. Mean # of utilized channels, $N = 20$, $p = 1$
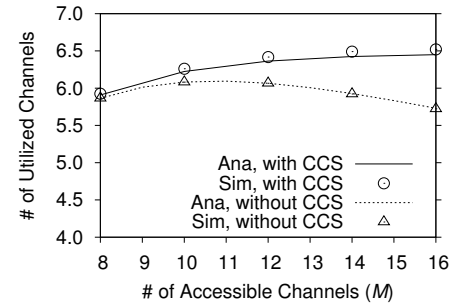


Fig. 2. $U^*$ and $M^*$, with $p = 1$



Fig. 3. Mean # of utilized channels with CCS

the channel detection probability $p = 1$. We have carried out many experiments using different $p$,[3] and have found similar $M^*$ and $U^*$ in all experiments, as long as $p$ is reasonably large, e.g., $p > 0.7$. Specifically we found $M^* \approx 0.5N$ and $U^* \approx 0.3N$ in all experiments. Considering that the theoretical maximum number of utilized channels is $\lfloor \frac{N}{2} \rfloor$ (two nodes in each channel), the random DSA scheme achieves approximately 60% of the maximum performance.

Next we examine how CCS affects the number of utilized channels. Fig. 3 plots the mean number of utilized channels for the 20-node CRN, with up to 3 CCS in each time slot. (The results without CCS are from the ones in Fig. 1.) One interesting observation is that with CCS, the number of utilized channels does not decrease any more when $M$ grows. In fact, it converges to a value slightly larger than $U^*$ without CCS. In other words, CCS offers a benefit that the CRN node does not need to worry about the range for random channel selection, i.e., no matter how large (or small) the $M$ is, a node can freely selects one operating channel from all detected accessible channels. On the other hand, in the case of no CCS, if $M$ is very large, the CRN nodes may need to negotiate and agree on a smaller range for channel selection to maintain an acceptable performance, since as shown in Fig. 1, if $M$ is large and each node freely selects operating channel from all accessible channels, the number of utilized channels would approaches 0.

## V. CONCLUSION

We have studied a random *dynamic spectrum access* (DSA) scheme, where each SU node randomly selects its operating channel from locally detected accessible channels. without relying on coordination or exchange of control messages. We have developed an analytical model for performance analysis. Based on the simulation results, the model is reasonably accurate. The numerical results also show that this DSA scheme can achieve approximately 60% of the maximum performance.

[3]The channel detection probability $p$ affects how many common channels detected by two nodes. The larger the $p$, the more common channels there are. On the other hand, the number of common channels affects the number of utilized channels. Therefore $p$ indirectly affects the number of utilized channels.

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