CHANNEL AND SENSING AWARE CHANNEL ACCESS POLICY FOR MULTI-CHANNEL COGNITIVE RADIO NETWORKS

Shu-Hsien Wang, Chih-Yu Hsu, and Y.-W. Peter Hong

Institute of Communications Engineering, National Tsing Hua University, Taiwan

ABSTRACT

We propose a reservation-based channel access policy for multi-channel cognitive radio networks. To enhance the throughput of secondary users (SUs), SUs are allowed to select channels opportunistically according to both the local channel state information (CSI) and the spectrum sensing outcomes. SUs will then compete for the right of transmission on the chosen channel by emitting reservation packets to the access point sequentially according to their local CSI. We further devise a proper threshold on channel gains such that only the SUs whose channel gains are sufficiently high can reserve channels and the interference from SUs to the licensed network can be limited. A channel aware splitting algorithm is adopted to schedule the SU with the highest channel gain to transmit at each time instant. From simulations, the proposed channel access policy outperforms the policies that take into consideration only CSI or sensing outcomes.

Index Terms— cognitive radio, channel access policy, multi-user diversity.

1. INTRODUCTION

In most countries, radio spectrum has been licensed for different wireless applications, but have not been utilized efficiently [1]. This has motivated recent studies on cognitive radio technology, which enables unlicensed (or secondary) users to sense vacancies in the spectrum, to opportunistically access the spectrum when it is vacant, and to retreat whenever the licensed (or primary) user returns. Many opportunistic spectrum access policies have been proposed in the literature, e.g., in [2, 3]. In these works, secondary users (SUs) are allowed to access the channel based on strategies that take into consideration the spectrum occupancy states in different channels of the primary user (PU). However, we argue that when multiple SUs are present in the system, system throughput can be further improved by utilizing channel-aware policies to exploit multiuser diversity. Hence, our goal is to develop channel access policies that take into consideration both the channel quality and the sensing outcomes.

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In conventional networks, multiuser diversity has been exploited to maximize system throughput by scheduling the user with the highest channel gain to transmit in each time slot [4, 5]. This scheduling policy requires a central control and knowledge of the channel state information (CSI) of all transmission links. This can be extremely resource-consuming, especially in a network with large amount of users. Motivated by these issues, distributed channel-aware scheduling policies, such as those in [5, 6], have also been proposed and have been shown to yield little loss in throughput. Specifically, in these works, each user is allowed to determine its transmission probability according to only its local CSI.

The main contribution of this work is to propose a channel and sensing aware channel access policy for multi-channel cognitive radio networks, where each SU will choose a channel to transmit on based on its knowledge of the channel qualities and the spectrum sensing outcomes. This work extends upon our previous work in [7], where we proposed a reservation-based MAC protocol for SUs in a single-channel scenario. Specifically, in the beginning of each frame, SUs will send out a reservation packet to compete for the channel. The AP utilizes a channel-aware binary splitting algorithm to resolve collision and, through the process, select the user with the best channel to transmit. A lower threshold on the channel quality of transmitting SUs is set based on the sensing outcome in order to limit the probability of collision between SUs and PUs. In multi-channel cognitive radio networks, each SU must additionally decide on which channel to access before the reservation phase begins. On the one hand, SUs that choose channels with large probability of being idle may have little chance of winning the channel since it may be overly congested. On the other hand, SUs that choose channels with low probability of being idle may have a high risk of colliding with PU. In this work, we propose a channel selection algorithm for SUs that takes into consideration both the sensing outcome and the local CSI.

2. SYSTEM MODEL

Consider a cognitive radio network with L backlogged SUs communicating to an access point (AP), and the entire secondary network lies within the coverage area of PUs. Assume that the spectrum belonging to PUs is partitioned into M

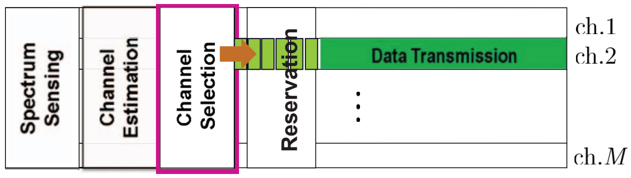

Fig. 1. System flow of secondary networks.

equal-bandwidth channels. The spectrum of channel m will be either idle or occupied by PUs, say, $\mathcal{H}_0^{(m)}$ or $\mathcal{H}_1^{(m)}$. Suppose PUs transmit in a slotted fashion. The presence or absence of PU signals on channel m can be characterized by the prior probabilities $v_i^{(m)} = \Pr\{\mathcal{H}_i^{(m)} \text{ is true on channel } m\}$ for $i = 0, 1$. The AP of the secondary network will perform spectrum sensing periodically by itself at the beginning of each slot. Suppose that the AP has M sets of transceivers and is capable of sensing all channels simultaneously and then broadcast the sensing outcomes to all SUs. Denote by $\{\mathcal{D}^{(m)}\}_{m=1}^M \in \{0,1\}$ the sensing outcomes of all channels, refering to the cases that the spectrum of channel m is sensed to be $\{$idle,busy$\}$. The performance of spectrum sensing can be characterized with the false alarm probabilities $\{P_{FA}^{(m)}\}_{m=1}^M$ and the miss detection probabilities $\{P_M^{(m)}\}_{m=1}^M$. Given the sensing outcomes, the probability of channel m being idle is

$$\omega^{(m)}(\mathcal{D}^{(m)}) = \Pr\left\{\mathcal{H}_0^{(m)} \text{ is true}\middle|\mathcal{D}^{(m)}\right\} \tag{1}$$
$$= \begin{cases} \frac{v_0^{(m)}(1-P_{FA}^{(m)})}{v_0^{(m)}(1-P_{FA}^{(m)})+v_1^{(m)}P_M^{(m)}}, & \text{if } \mathcal{D}^{(m)} = 0, \\ \frac{v_0^{(m)}P_{FA}^{(m)}}{v_0^{(m)}P_{FA}^{(m)}+v_1^{(m)}(1-P_M^{(m)})}, & \text{if } \mathcal{D}^{(m)} = 1. \end{cases}$$

We refer to $\underline{\omega}(\underline{\mathcal{D}}) = \left(\omega^{(1)}(\mathcal{D}^{(1)}), ..., \omega^{(M)}(\mathcal{D}^{(M)})\right)$ as the belief vector under the sensing outcomes $\underline{\mathcal{D}} = (\mathcal{D}^{(1)}, ..., \mathcal{D}^{(M)})$. To improve spectrum utilization and avoid interference with PU's transmissions, SUs should carefully determine their channel access policy with knowledge of the belief vector.

After sensing spectrum states, the AP will broadcast pilot symbols to help each SU estimate the channel between the AP to itself. Let $\gamma_i^{(m)}$ be the channel gain on the m-th channel between SU i and the AP. Assume that $\gamma_i^{(m)}$ is reciprocal in uplink/downlink channels, and is identical and independently distributed (i.i.d.) among users and across time with density $f(\gamma_i^{(m)})$ and cumulative distribution function (CDF) $F(\gamma_i^{(m)})$. Let define $\underline{\gamma}_i = (\gamma_i^{(1)}, \gamma_i^{(2)}, ..., \gamma_i^{(M)})$ as the local CSI of SU i. Suppose that each SU is equipped with only one set of transceiver such that it can access only one channel at each time instant. Based on the local CSI and the sensing outcomes (thus, the belief vector), each SU will select one channel to access and then perform the channel reservation on the chosen channel. Let denote by

$$\phi_i^{(m)}(\underline{\gamma}_i, \underline{\omega}) : ([0,\infty)^M \times [0,1]^M) \to [0,1]$$

the probability that SU i decides to reserve and transmit on the m-th channel, where $\phi_i^{(m)}$ is referred to as the channel selection policy of SU i on channel m with $\sum_{m=1}^M \phi_i^{(m)}(\underline{\gamma}_i, \underline{\omega}) = 1$. Thereafter, we adopt the reservation-based MAC protocol proposed in [7] where each SU will emit reservation packet to the AP opportunistically on the chosen channel according to its local CSI, and a channel-aware splitting algorithm is used to resolve the collision among reservation packets from different SUs. The system flow is shown in Fig.1.

When an SU transmits on the m-th channel, a collision occurs if a PU is transmitting on the same channel. In order to prevent collision with PU signals, SUs should carefully determine their transmission probability according to their belief vector. To take into consideration the quality of the channels, each SU's transmission probability can be controlled by a channel-aware thresholding policy as proposed in [7], where only SUs with channel gains greater than $\Gamma_{\text{lower}}^{(m)}(\underline{\omega})$ are allowed to reserve the channel. Let $P_t^{(m)}(\underline{\omega})$ be the probability that at least one SU transmits on channel m given the belief vector $\underline{\omega}$. As shown in [7], collision can be effectively resolved and the SU with the largest channel gain will always prevail when the time slots in the reservation period is sufficiently large. Hence, the transmission probability can be approximated by

$$\begin{aligned} P_t^{(m)}(\underline{\omega}) &\approx \Pr\{\text{at least one SU whose gain } \geq \Gamma_{\text{lower}}^{(m)}(\underline{\omega})\} \\ &= 1 - F_{max}^{(m)}(\Gamma_{\text{lower}}^{(m)}(\underline{\omega})), \end{aligned} \tag{2}$$

where $F_{max}^{(m)}(\gamma)$ is the CDF of the highest channel gain among the SUs competing on channel m. For example, if there are exact ℓ SUs competing on channel m, $F_{max}^{(m)}(\gamma) = [F(\gamma)]^\ell$. To constrain that the probability of colliding with PUs should not be greater than p_{col}, that is,

$$P_t^{(m)}(\underline{\omega}) \cdot \left(1 - \omega^{(m)}\right) \leq p_{col}, \tag{3}$$

$$\Rightarrow P_t^{(m)}(\underline{\omega}) \leq \min\left\{1, \frac{p_{col}}{\left(1-\omega^{(m)}\right)}\right\}, m=1, ..., M, \tag{4}$$

we should carefully choose appropriate $\{\Gamma_{\text{lower}}^{(m)}(\underline{\omega})\}_{m=1}^M$ to satisfy the above equation. However, the difficulty in designing $\{\Gamma_{\text{lower}}^{(m)}(\underline{\omega})\}_{m=1}^M$ is that the exact number of SUs competing on the same channel will depend on the channel selection policy and can vary across time.

In the following, we devise a channel and sensing aware channel access policy (including channel selection and reservation threshold design) that maximizes SUs' throughput under a constraint on the probability of collision with PUs.

3. CHANNEL ACCESS POLICY

Since the CSI is i.i.d. among users and the belief vector will be known at all SUs, maximizing the sum throughput of all

SUs will be the same as maximizing the individual throughput of each SU. Thus, for SU i, we shall optimize:

$$\max_{\{\phi_i^{(m)},\Gamma_{\text{lower}}^{(m)}\}} \mathbf{E}_{\underline{\gamma}_i}\left[\sum_{m=1}^{M}\phi_i^{(m)}(\underline{\gamma}_i,\underline{\omega})\omega^{(m)}\mathcal{P}_i^{(m)}(\gamma_i^{(m)},\underline{\omega}) \times \mathbf{1}_{[\gamma_i^{(m)}\geq\Gamma_{\text{lower}}^{(m)}(\underline{\omega})]}\frac{2W}{M}\log\left(1+\frac{\gamma_i^{(m)}}{2N_0W/M}\right)\right]$$

$$\text{subject to } \sum_{m=1}^{M}\phi_i^{(m)}(\underline{\gamma}_i,\underline{\omega})=1, \tag{5}$$

$$\phi_i^{(m)}(\underline{\gamma}_i,\underline{\omega})\in[0,1],\ (1-\omega^{(m)})P_t^{(m)}\leq p_{col},\forall m,$$

where N_0 is the power spectral density of Gaussian noise, $\frac{2W}{M}$ is the bandwidth of one channel, and

$$\mathcal{P}_i^{(m)}(\gamma_i^{(m)},\underline{\omega}) \triangleq \Pr\left\{\begin{array}{c}\text{SU } i\text{'s channel gain higher than those of}\\ \text{other SUs competing on same channel}\end{array}\middle|\begin{array}{c}\underline{\omega},\gamma_i^{(m)},\\ \Phi_i^{(m)}=1\end{array}\right\},$$

with $\Phi_i^{(m)}$ being a Bernoulli random variable parameterized by $\Pr\{\Phi_i^{(m)}=1\}=\phi_i^{(m)}(\underline{\gamma}_i,\underline{\omega})$. The probability that SU i will successfully reserve the channel m can be expressed as

$$\begin{aligned}\mathcal{P}_i^{(m)}(\gamma_i^{(m)},\underline{\omega}) &= \mathbf{E}\left[\mathbf{1}_{[\gamma_i^{(m)}\geq\gamma_j^{(m)}\cdot\Phi_j^{(m)},\forall j\in\{1,\dots,L\}]}\middle|\underline{\omega},\gamma_i^{(m)},\Phi_i^{(m)}=1\right]\\ &= \prod_{\substack{j=1\\ j\neq i}}^{L}\left\{1-\mathbf{E}\left[\mathbf{1}_{[\gamma_i^{(m)}<\gamma_j^{(m)}\cdot\Phi_j^{(m)}]}\middle|\underline{\omega},\gamma_i^{(m)},\Phi_i^{(m)}=1\right]\right\}.\end{aligned}$$

Please note that, the probability $\mathcal{P}_i^{(m)}(\gamma_i^{(m)},\underline{\omega})$ is averaged over all other SUs j's channel gain, $j\neq i$. Moreover, since the channel gain is assumed to be i.i.d., the selection policy $\phi_i^{(m)}$ is identical for all SUs and so is the probability $\mathcal{P}_i^{(m)}$. However, finding the optimal channel selection policy and thresholds $\{\Gamma_{\text{lower}}^{(m)}\}$ jointly by solving (5) is intractable. Therefore, we propose a sub-optimal scheme that optimizes the channel selection policy by maximizing the throughput without considering the collision probability constraint (i.e., without considering the threshold $\{\Gamma_{\text{lower}}^{(m)}\}$). Thereafter, based on the sub-optimal selection policy, we tackle the collision constraint by choosing appropriate thresholds.

3.1. Channel Selection Policy

We first simplify our optimization problem as

$$\max_{\{\phi_i^{(m)}\}} \mathbf{E}_{\underline{\gamma}_i}\left[\sum_{m=1}^{M}\phi_i^{(m)}(\underline{\gamma}_i,\underline{\omega})\omega^{(m)}\mathcal{P}_i^{(m)}(\gamma_i^{(m)},\underline{\omega}) \times\frac{2W}{M}\log\left(1+\frac{\gamma_i^{(m)}}{2N_0W/M}\right)\right] \tag{6}$$

subject to $\Sigma_{m=1}^{M}\phi_i^{(m)}(\underline{\gamma}_i,\underline{\omega})=1,\phi_i^{(m)}(\underline{\gamma}_i,\underline{\omega})\in[0,1],\forall m.$

Although we have removed the collision constraint, the problem is still hard to deal with since the selection policy is still embedded in the derivation of probability $\mathcal{P}_i^{(m)}(\cdot)$. By observing the above problem, if the probability functions $\mathcal{P}_i^{(m)}(\gamma_i^{(m)},\underline{\omega})$ are known, the maximization problem becomes a linear programming (LP) program, where the optimal channel selection policy is given by

$$\phi_i^{(m)}(\underline{\gamma}_i,\underline{\omega})=\mathbf{1}_{[G_i^{(m)}(\gamma_i^{(m)},\underline{\omega})\geq G_i^{(m')}(\gamma_i^{(m)},\underline{\omega}),\forall m'\neq m]}, \tag{7}$$

and $G_i^{(m)}(\gamma_i^{(m)},\underline{\omega})\triangleq\omega^{(m)}\mathcal{P}_i^{(m)}(\gamma_i^{(m)},\underline{\omega})\log\left(1+\frac{\gamma_i^{(m)}}{2WN_0/M}\right)$. Moreover, given the selection policy in (7), the probability that SU i successfully reserves channel m is given by

$$\begin{aligned}&\mathcal{P}_i^{(m)}(\gamma_i^{(m)},\underline{\omega}) \\ &=\prod_{\substack{j=1\\ j\neq i}}^{L}\left\{1-\int_{\gamma_i^{(m)}}^{\infty}\mathbf{E}_{\underline{\gamma}_j\setminus\gamma_j^{(m)}}\left[\mathbf{1}_{[G_j^{(m)}\geq G_j^{(m')}]}\right]f(\gamma_j^{(m)})d\gamma_j^{(m)}\right\}.\end{aligned} \tag{8}$$

The channel selection policy can be solved by the proposed iterative algorithm.

Initialization: All SUs are equally distributed among all channels, thus, $\mathcal{P}_i^{(m)}(\gamma_i^{(m)},\underline{\omega})=[F(\gamma_i^{(m)})]^{(L-1)/M}$, $m=1,...,M$, where $(L-1)/M$ is the number of competitors on channel m against SU i.

Step 1: For any $\underline{\gamma}_i$, given $\underline{\omega}$ and $\mathcal{P}_i^{(m)}(\gamma_i^{(m)},\underline{\omega})$, update the channel selection policy as given in (7).

Step 2: Update the successful reservation probability as (8). Repeat Step 1-2 until $\phi_j^{(m)}$ and $\mathcal{P}_i^{(m)}$ converge.

3.2. Reservation Threshold

Given the channel selection policy derived from the proposed iterative method, the CDF of the highest channel gain on channel m among SUs selecting channel m can be given by

$$\begin{aligned}F_{max}^{(m)}(\gamma)&=\mathbf{E}\left[\mathbf{1}_{[\gamma\geq\gamma_j^{(m)}\cdot\Phi_j^{(m)},\forall j\in\{1,\dots,L\}]}\middle|\underline{\omega}\right]\\ &=\prod_{j=1}^{L}\left\{1-\int_{\gamma}^{\infty}\mathbf{E}_{\underline{\gamma}_j\setminus\gamma_j^{(m)}}\left[\mathbf{1}_{[G_j^{(m)}\geq G_j^{(m')}]}\right]f(\gamma_j^{(m)})d\gamma_j^{(m)}\right\}.\end{aligned}$$

By (2)-(4), the optimal thresholds that maximize the throughput of SUs and satisfy the interference constraint can be numerically solved by

$$\Gamma_{\text{lower}}^{(m)}(\underline{\omega})=(F_{max}^{(m)})^{-1}\left(1-\min\left\{1,\frac{p_{col}}{1-\omega^{(m)}}\right\}\right),\forall m. \tag{9}$$

4. SIMULATION

Consider a cognitive radio network operated in a licensed spectrum with bandwidth $W=3$ MHz and noise variance

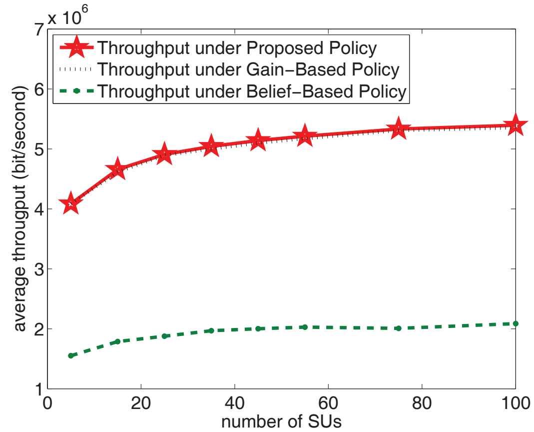

Fig. 2. Throughput with identical channels.

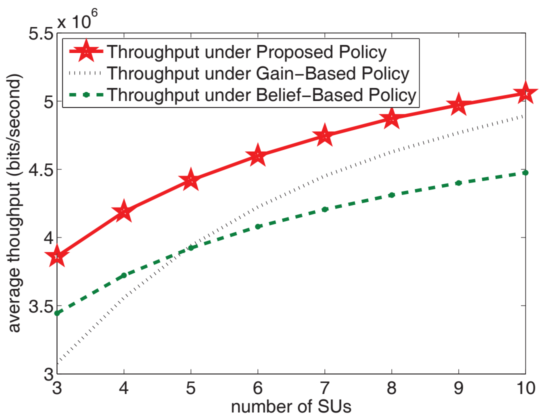

Fig. 3. Throughput with non-identical channels.

$N_0 = 10^{-6}$ watts/Hz, where the whole spectrum is partitioned into 3 equal-bandwidth channels. Suppose that the idle probabilities of the 3 channels are $v_0^{(m)} = 0.5$ for all m and the interference probability constraint on each channel is $p_{col} = 0.05$. The AP of secondary networks senses the spectrum states periodically with errors $P_{FA} = 0.1$ and $P_M = 0.05$. The channel gain between each SU to the AP is exponentially distributed with mean equal to 4. Fig. 2 shows the network throughput under the proposed channel and sensing aware channel access policy and the other two strategies. Under the gain-based policy, each SU selects the channel with the best channel quality regardless of the sensing outcomes. Under the belief-based policy, each SU always selects the channel whose idle probability is the highest among the three, leaving the other two channels unused even if they are idle. Hence, the throughput under the belief-based policy may be much worse than the other two policies. The reason that the throughput drawn from gain-based strategy almost reaches that under the proposed strategy is because that the idle probabilities among channels are identical.

Suppose that the idle probabilities among channels are asymmetric, let say, $v_0^{(1)} = v_0^{(2)} = 0.1$, $v_0^{(3)} = 0.9$, the throughput is depicted in Fig. 3. The intuition behind this figure is that, when the difference of idle probabilities is large, the belief-based channel access policy may outperform the gain-based strategy, especially when the number of SUs are small. Choosing the channel with the highest gain is not always a good policy when the idle probabilities diverse. However, if the number of SUs increases, that is, the multi-user diversity gain increases, the gain-based policy will be better than the belief-based policy again. By the way, our proposed channel and sensing aware channel access policy actually captures the feature of both gain-based and belief-based policies, and, thus, strikes a good balance between them.

5. CONCLUSION

We proposed a channel and sensing aware channel access policy for multi-channel cognitive radio networks. Each SU will choose one channel to access according to both the sensing outcomes and the local CSI to improve its throughput, and then reserve for transmission on the chosen channel if its channel gain is sufficiently large. An iterative algorithm was proposed to devise the channel selection policy. Our proposed reservation-based channel access policy outperforms the cases when SUs access the channel based on only the knowledge of local CSI or idle probabilities of all channels.

6. REFERENCES

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