Analysis and Optimization of Random Sensing Order in Cognitive Radio Systems
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Abstract—Developing an efficient spectrum access policy enables cognitive radios to dramatically increase spectrum utilization while assuring predetermined quality of service levels for the primary users. In this letter, modeling, performance analysis, and optimization of a distributed secondary network with random sensing order policy are studied. Specifically, the secondary users create a random order of the available channels to sense and find a transmission opportunity in a distributed manner. For this network, the average throughputs of the secondary users and average interference level between the secondary and primary users are evaluated by a new Markov model. Then, a maximization of the secondary network performance in terms of throughput is proposed. The primary interference is proposed. Then, a simple and practical adaptive algorithm is developed to optimize the network in a distributed manner. Interestingly, the proposed algorithm follows the variations of the wireless channels in non-stationary conditions and besides having substantially lower computational cost, it outperforms static brute force optimization. Finally, numerical results are provided to demonstrate the efficiencies of the proposed schemes. It is shown that fully distributed algorithms can achieve substantial performance improvements in cognitive radio networks without the need of centralized management or message passing among the users.

Keywords—Cognitive radio, sequential channel sensing, Markov model, average throughput, average interference.

I. INTRODUCTION

TH limited spectrum resources and intense growth of high data rate communications have motivated opportunistic spectrum access using the promising concept of cognitive radio networks. Cognitive radio networks can promote spectrum utilization by allowing low-priority secondary users (SUs) to opportunistically exploit the unused licensed channels of high-priority primary users (PUs). Meanwhile, due to preemptive priority of the PUs to access the channels, the SUs must vacate the channel whenever the corresponding PUs appear. In this case, a set of procedures called spectrum handoff (SHO) is initiated to help the SU to effectively find a new transmission opportunity and resume its unfinished transmission [1]. To this end, temporarily-available transmission opportunities must be explored first.

Generally speaking, there exists more than one channel to be sensed by an SU. Here, we assume that the SUs can sense and possibly transmit on one channel at a time due to processing and hardware constraints. Therefore, an SU sorts the channels in an order, senses the first channel of the order, and transmits on the channel provided that it is sensed free. If the channel is sensed busy, the SU initiates the SHO procedure and then senses the second channel of the sensing order. This kind of sensing-access is called sequential channel sensing [1].

The SUs sense the channels at the beginning of each time slot and initiate the SHO procedure whenever the current channel is sensed busy. Optimal and suboptimal sensing orders of a CRN containing only one SU are developed in [2], [3], which maximize the average achievable throughput of the SU in a time slot. These results have been further extended for a CRN with two [4] and multiple SUs [5], [6]. Most of the literatures, however, focus on single SU or centralized CRNs [2]–[6]. In [7], an autonomous sensing order setting strategy is proposed for distributed CRNs with the aim of minimizing the likelihood of collisions with other SUs. But, the miss detection probability is assumed zero, meaning that the SUs do not make interference for the PUs as well as other SUs. Therefore, quality of service (QoS) provisioning for the PUs is not addressed in that study. In [8], the authors exploit a modified p-persistent MAC protocol to set the sensing orders of the SUs in a distributed manner.

In this letter, we investigate the performance of random sensing orders policy (RSOP) for the SUs. That is, once an SHO is triggered, all the SU create a set of random channels to be sensed. Then, the sequential channel sensing process is initiated. We provide required guidelines for modeling the behaviors of the SUs using a finite state Markov chain. By this model, the performance of the random sensing order policy is derived, and an effective algorithm is developed to optimize the performance of the CRN in a distributed fashion. Compared to the literature mentioned above, this is the first paper to 1) consider the problem of SHO for sequential channel sensing in a distributed set-up with multiple SUs with more realistic assumptions including miss detection and false alarm probabilities, 2) investigate the impact of the SUs’ transmissions on the channel occupation probabilities, 3) derive the accumulated interference caused by other SUs’ transmissions, 4) pose an optimization problem and develop a practical adaptive algorithm to maximize the average throughput while provisioning QoS for the PUs.

II. RANDOM SENSING ORDER

In the sequential channel sensing methodology, once a hand-off is requested, each SU’s time slot divides into sensing and transmission modes. In the sensing mode, the SUs sequentially sense the channels based on their sensing orders [2]–[6]. The procedure continues until one of the following events happens [8]: (a) transmission opportunities are found for all the SUs, (b) no time remains for sensing new channels in the time slot, or (c) non-sensed channels are remained.

The order of the channel heavily affects QoS parameters of the SUs and PUs and can be optimally determined in a centralized CRN [2], [5], wherein the SUs are placed in a list so that the average achievable throughput is maximized. However, those proposals cannot be directly applied to a distributed CRNs. For the networks, a simple sensing order is proposed in [8], wherein the channels are arranged by their indices.
While this sensing order facilitates the network modeling and performance evaluation, a high level of contention to access the spectrum resources is imposed to the SUs, which significantly degrades the average throughput of the CRN.

In order to mitigate the aforementioned problem, the RSOP can be used. In this scheme, an SU randomly (with uniform distribution) chooses a target channel in each sensing interval. Therefore, the requests of the SUs are distributed among all available channels, and thereby the reduction of the contention level among the SUs increases the CRN throughput. In order to further decrease the contention and provide multiple access among the SUs, a modified version of the conventional persistent multiple access protocol is proposed in the letter. That is, each SU senses each channel with the probability $p$ and skips the sensing process with the probability $(1 - p)$.

From the above discussions, the channel sensing-access policy of the RSOP follows a Markov process, and the following statements enable us to find the transition probabilities:

- An SU can successfully transmit on each channel, if it is free, and the false alarm does not occur. Once this event happens, the SU’s state changes to the transmitter nodes, and it transmits on the channel for the rest of the time slot.
- The interference happens whenever the channel is busy, and the SU mistakenly senses it free.
- If either the SU skips sensing process in a step, with probability $p$, or sense a channel busy, it tries to randomly choose a new channel and then sense it, in the next step.

By a Markov chain analysis, we can show that the average throughput of each SU and the average interference time due to the SUs’ transmissions depend on sensing time $\tau$ and channel access probability $p$. We denote by $r(\tau, p)$ and $I(\tau, p)$ the average throughput and the average interference time, respectively. Hence, the performance of the CRN can be optimized by choosing the values of $p$ and $\tau$ that maximize the average throughput $r(\tau, p)$, as a QoS metric for the SU, and bounding the interference time $I(\tau, p)$, as a QoS metric for the PUs as well as the SUs. That is,

$$[\tau^*, p^*] = \arg\max_{\tau, p} r(\tau, p)$$

s.t. $t_f(\tau, p) \leq t_f^{\text{max}}$

$$0 \leq \tau \leq T$$

$$0 \leq p \leq 1,$$

where $T$ is a time slot duration, and $t_f^{\text{max}}$ represents the maximum tolerable value of the interference time.

By estimating the average throughput and interference level [9], and comparing with previous estimations, we implement a fully distributed algorithm to adjust the channel sensing time and probability of each SU in each sensing step. In this algorithm, an SU decreases $p$, and tries to contribute in reduction of contention level in the CRN, if several SUs contend to access the same channels. Also, the algorithm let the SUs to increase their transmission time and consequently average throughput if the interference level constraint is not violated. Let $N_s$ and $N_p$ be the number of SUs and PUs, respectively. Table I demonstrates the performance enhancement due to optimal $p$ and $\tau$ derived in (1), and compares the average throughput and interference for two scenarios: (i) optimal values, which are obtained by a brute force numerical optimization search and (ii) adaptive values as achieved by the proposed algorithm. As expected, adopting the optimal and adaptive values for $p$ and $\tau$ increases the average throughput while the interference meets the constraint. Specifically, for the case $N_s = 3, N_p = 7$, the average throughput of the SUs achieved by the optimal design respectively is about 24% more than the one achieved in $p = 0.8, \tau = 0.17$. Also, from the table, the proposed algorithm outperforms even static optimal design; because in the optimal design all the SUs adopt the same sensing time and access probability, whereas the proposed algorithm let the SUs to follow the variation of the wireless environment, and adaptively adjust the above values.

### III. Conclusion

Modeling and performance evaluation of random sensing order policy (RSOP) in a distributed cognitive radio network (CRN) were investigated in this letter. The required guidelines for modeling the behaviors of the secondary users were discussed, and the performance of the RSOP in terms of the average throughput of the CRN and average interference levels between the SUs and the primary users was evaluated. Then, two approaches for optimizing the performance of the CRN were studied and compared. The proposed algorithm enhances the performance of the CRN without high computational burden, as demonstrated through numerical performance evaluation.

### References


