Random Sensing Order in Cognitive Radio Systems: Performance Evaluation and Optimization

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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 abstract, modeling, performance evaluation, 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 upon primary users return, and then find an optimal transmission opportunity in a distributed manner. After modeling the behavior of the SUs by a Markov chain, the average throughputs of the secondary users and interference level among the secondary and primary users are evaluated. Then, a maximization of the secondary network performance in terms of throughput while keeping under control the average interference is proposed. A simple and practical adaptive algorithm is developed to optimize the network. Interestingly, the proposed algorithm follows the variations of the wireless channels in non-stationary conditions and outperforms even static brute force optimization, while demanding few computations. 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 chain analysis, performance evaluation, distributed optimization.

I. Introduction

Tth 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 upon return of the corresponding PUs. In this case, a set of procedures called spectrum handoff (SHO) is initiated to help the SUs to find new transmission opportunities and resume their unfinished transmissions [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. In this case, an SU sorts the channels in an order, called sensing order, and transmits on first channel that is sensed free in the established order. If the channel is sensed busy, the SU initiates the SHO procedure and then senses second channel of the sensing order, and so on. Such a sensing-access is called sequential channel sensing [1].

Optimal and suboptimal sensing orders of a CRN containing only one SU are developed in [1], [2], which maximize the average achievable throughput of the SU in a time slot. The results have been further extended for a CRN with multiple SUs [3], [4]. Most of the literatures, however, focus on single SU or centralized CRNs [1]–[4]. An SHO framework for a distributed CRN without a common control channel is proposed in [5]. However, a wideband and perfect spectrum sensing is considered in the paper, meaning that the SUs would not make interference for the PUs and other SUs. Therefore, quality of service (QoS) provisioning for the PUs is not addressed. In [6], the authors exploit a modified p-persistent MAC protocol to set the sensing orders of the SUs in a distributed manner. However, it is assumed that the SUs can successfully transmit on the channel even if the PU presets on the channel. In fact, they focused on maximum achievable throughput and did not study the interference in the network. Consequently, there is no QoS guaranteeing mechanism for the PUs.

In this abstract, we investigate the performance of a CRN adopting random sensing order policy. That is, once an SHO is triggered, all the SU create a set of random channels to be sensed, and sequential channel sensing process is initiated. We discuss required guidelines for modeling the behaviors of the SUs using a finite state Markov chain. By this model, the performance of the RSOP is derived, and an effective algorithm is developed to optimize the performance of a 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 more realistic assumptions including miss detection and false alarm probabilities, 2) investigate the interferences among SUs-SUs and SUs-PUs, and keep both of them under control, 3) investigate the impact of the SUs' transmissions on the channel occupation probabilities, 4) propose simple and practical algorithms to keep the overall system performance at the optimum level while maintaining the QoS guarantees in non-stationary conditions.

II. Random Sensing Order

In the sequential channel sensing methodology, once a handoff 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 [1]–[4]. The procedure continues until [6]: (a) all SUs find transmission opportunities, (b) no time remains for sensing new channels in the time slot, or (c) no non-sensed channels remain.

The order of the channels can be optimally determined in a single user [1] or centralized multiple user [4] CRNs. However, we cannot directly apply those proposals to distributed CRNs. For such networks, simple sensing orders are proposed in [6], wherein the channels are arranged by their indices. While this order facilitates the network modeling and performance evaluation, it causes a high level of contention to access the same channels, which significantly degrades the average throughput of the CRN.

In order to mitigate the aforementioned problem, we propose to use optimal RSOP. In this scheme, an SU randomly (by uniform distribution) chooses a target channel in each sensing interval. Therefore, the requests of the SUs are uniformly distributed among all available channels, and thereby the CRN throughput increases by the reduction of the contention for accessing the same channels. In order to further decrease the contention and provide multiple access among the SUs, we propose that 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.
- An interference happens whenever a channel is busy, and an SU mistakenly senses it free.
- If either the SU skips sensing process in a step, with probability of 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 τ and channel access probability p. We denote by $r(\tau,p)$ and $t_I(\tau,p)$ 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 τ that maximize the average throughput $r(\tau,p)$, as a QoS metric for the SU, and bounding the interference time $t_I(\tau,p)$, as a QoS metric for the PUs as well as the SUs. That is,

$$\begin{aligned}[\tau^*,p^*] = \ & \underset{\tau,p}{\operatorname{argmax}} \quad r(\tau,p) \ , \\ \text{s.t.} \ \ & t_I(\tau,p) \le t_I^{\max} \ , \\ & 0 \le \tau \le T \ , \\ & 0 \le p \le 1 \ , \end{aligned} \tag{1}$$

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

By estimating the average throughput and interference level [4], and comparing with previous estimations, we develop 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

TABLE I. AVERAGE THROUGHPUT AND THE CORRESPONDING NORMALIZED INTERFERENCE ($t_I^{\max} = 0.05T$).

	Static Optimal Value		Adaptive Algorithm	
	Throughput	Interference	Throughput	Interference
$N_s = 3, N_p = 7$	1.4410	0.0478	1.4472	0.0399
$N_s = 5, N_p = 7$	1.9205	0.0500	1.9791	0.0497

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 τ derived in (1), and compares the average throughput and interference for two scenarios: (i) static 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 τ 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 $p = 0.8, \tau = 0.1T$. Also, from the table, the proposed algorithm outperforms even static brute force optimization, while demanding few computations. Because, all the SUs adopt similar values sensing time and sensing probabilities, whereas adaptive algorithm enables the SUs to dynamically adjust their sensing-access parameters in each sensing interval and follow the variations of a channel.

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 interference levels in the network 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 by numerical performance evaluation.

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