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Distributed power control and random access for spectrum sharing with QoS constraint ☆

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ABSTRACT

Distributed spectrum sharing with minimum quality of service (QoS) requirement and interference temperature (IT) constraint is studied in this paper. This problem can be formulated as a non-convex optimization problem with conflicting constraints. To make solutions to this problem feasible, random access and power control are jointly considered. The challenges in solving this problem arise from the coupling in utility functions, the conflicting constraint sets, and coupled control variables. Moreover, there is no centralized controller or base station in networks to coordinate unlicensed users' transmission and protect active users' QoS under IT constraint. By introducing variable substitution and transformation, we derive a distributed random access and power control algorithm that can achieve global optimal solution to the original problem. Convergence of the algorithm is proven theoretically. Simulation results demonstrate that both QoS guarantee and interference avoidance can be achieved even with channel gain variations.

1. Introduction

The frequency spectrum for radio signal transmission is currently allocated in a static manner, where bands are licensed to users by government agencies and thus licensed users have the exclusive rights to access the allocated band. At the same time, studies show that the spectrum has been used inefficiently in licensed bands [1]. In contrast, the spectrum left by licensed users cannot meet the increasing demands for radio resources. To solve this demand and utilization dilemma, dynamic spectrum sharing approaches appear to be a good alternative. One of the approaches, called the underlay sharing approach exploits the spread spectrum techniques in cellular networks. Once a spectrum allocation map has been acquired, unlicensed devices can coexist with licensed users on the same frequency, provided that unlicensed users can limit the interference to licensed users. To quantify the interference, the Federal Communication Commission (FCC) proposed a new metric named the interference temperature (IT) [2]. The IT is defined to be the radio frequency power measured at a receiving antenna per unit bandwidth.

In this paper, we focus on the underlay spectrum sharing in ad hoc networks where all unlicensed users spread their transmission powers across the entire available band under the IT constraint. In this context, power control is used to limit interference among unlicensed users and to licensed receivers and, hence, maximize spectrum usage. The signal-to-interference-and-noise ratio (SINR) at the unlicensed receiver determines the successful transmission at physical layer. However, to satisfy the minimum SINR requirement that characterizes the quality of service (QoS) constraint on the bit-error rate at individual receivers, the transmitting power of an unlicensed user may exceed its maximum value or even violates the IT constraint. To balance the minimum SINR requirement and IT constraint, and further to efficiently and fairly utilize spectrum, transmission power and channel access must be determined by coordination among unlicensed users [3]. In ad hoc networks without infrastructure, this coordination should be implemented distributively.

Taking these factors into consideration, we formulate a joint random access and power control problem under IT and QoS constraints. To protect the primary transmission, some nodes called measurement points are deployed to monitor the real-time IT of the concerned band at their locations. Due to the interference relationship among wireless links and coupling between transmission

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power and channel access, the formulated problem is non-convex and non-separable in control variables. After variable transformation and introduction of an auxiliary variable, the optimization problem can be turned into a convex one. Then a distributed random access and power control algorithm is proposed within the framework of layering as optimization decomposition [4]. The transmission power of a link is updated not only to maintain its own QoS but also to limit interference to peer unlicensed users as well as licensed users. The random access of a transmission is aimed at satisfying its own channel access requirement and supporting other active links' QoS requirement. The only involvement of a measurement point in the implementation of this algorithm is that when the aggregate IT violates the given upper bound the measurement point will broadcast the current IT to all the unlicensed transmitters. Furthermore, we prove that the proposed algorithm can converge to the global optimum. Simulation demonstrates that convergence of this algorithm can be ensured even with channel gain variations.

The rest of this paper is organized as follows. In Section 2, we review some related work on spectrum sharing and non-convex optimization. The system model is presented in Section 3. The spectrum sharing problem is formulated in Section 4. In Section 5, we propose our joint random access and power control algorithm for spectrum sharing. Convergence results of the algorithm are also given in Section 5. Section 6 includes performance evaluation of the proposed algorithms. We conclude the paper and give future research direction in Section 7.

2. Related work

Spectrum sharing between licensed users and unlicensed users can be classified as overlay and underlay schemes. In the overlay spectrum sharing unlicensed users access the network dynamically by using a portion of spectrum that has not been used by licensed users. For more discussions on the overlay spectrum sharing, see [5,2]. We focus on the underlay spectrum sharing, especially the scheme based on IT model. In [6], Huang et al. proposed the uplink spectrum sharing algorithm based on auction theory. They characterized the selfishness of unlicensed users without considering the maximum transmission power and QoS constraints of individual users. The base station, which is co-located with IT measurement point, allocates the uplink transmission powers proportionally to unlicensed users' bids. Wang et al. [7] investigated the individual users' throughput maximization under IT constraint. To penalize the individual users' selfishness, they relied on the pricing scheme in [8] to limit strong interference in power control. However, the pricing scheme with the participation of a centralized base station (BS) cannot be implemented in ad hoc networks. It is noted that all these literatures consider how to utilize spectrum without QoS constraint. Xing et al. [3] formulated the spectrum sharing under IT and QoS constraint as a geometric programming problem in cellular networks. To make it possible for each active user to maintain minimum QoS requirement under IT constraint, some active unlicensed links will be switched off temporarily by solving a centralized operator problem at BS. To mitigate the implementation overhead, a learning automata algorithm is proposed in [3] and BS needs to collect each unlicensed links' SINR and aggregate IT for updating uplink access probability. A non-cooperative power control game with IT constraint was formulated by Jia and Zhang in [9] for ad hoc networks, where the IT measurement point informs the unlicensed link that generates the maximum received power to back off when current measured IT exceeds the given upper bound. However, the back-off scheme in [9] did not take into account QoS requirement of unlicensed users.

The key difference between those works mentioned and ours is that this paper studies a distributed spectrum sharing scheme to satisfy the minimum QoS and IT constraints simultaneously in ad hoc networks. Similar log transformation approach was proposed in [10] to derive power control in cellular networks by solving a non-convex optimization problem satisfying QoS constraints. In our formulation, there is also the coupling between different kinds of control variables, i.e., transmission power and channel access probability. This coupling together with coupled utility and constraint sets have to be tackled when searching for an efficient algorithm which can be easily implemented.

3. System model

The wireless network considered here is formulated as a set $\mathcal{L}$ of radio links with each link corresponding to an unlicensed transmitter and a receiver. Each transmitter is assumed to have a fixed channel gain to its intended receiver as well as fixed gains to all other receivers in the network. The quality of each link is determined by the SINR at the intended receiver. In a network with $|\mathcal{L}|$ interfering links we denote the SINR for the ith user as

$$\gamma_i = \frac{G_{ii}p_i}{\eta^2 + (\sum_{j\neq i, j\in\mathcal{L}} G_{ij}p_j)/S},$$

where $G_{ij} > 0$ is the channel gain from the transmitter of the jth link to the receiver of the ith link, p_i is the power of the ith transmitter, η^2 is the background noise power that is assumed to be the same for all users, and S is the normalized spreading sequence.

The IT is a measurement of the power and bandwidth occupied by interference. Interference temperature T_{I} is specified in Kelvin and is defined as [11]

$$T_{\mathrm{I}}(f_c, B) = \frac{P_{\mathrm{I}}(f_c, B)}{kB},$$

where $P_{\mathrm{I}}(f_c, B)$ is the average interference power in Watts centered at f_c, covering bandwidth B measured in Hertz. Boltzmann's constant k is 1.38×10^{-23} J/K [11]. For a given bandwidth, FCC imposes an IT limit to restrict the interference to licensed receiver at a given frequency in a particular location. In this paper, we assume that there are measuring points monitoring the real-time IT at particular band in their locations. Thus, if the aggregate IT at measurement points is lower than a given threshold, the protection to the licensed receiver can be achieved. Then the constraint that the total received power does not exceed that threshold at a measurement point is given by

$$\sum_{i=1}^{|\mathcal{L}|} p_i G_{0i} \leqslant T, \tag{1}$$

where G_{0i} is the channel gain from user i's transmitter to the measurement point, and $T > 0$ is a pre-defined threshold. The model (1) considers that only a single measurement point is deployed. Under the scenario that multiple measurement points are deployed, all IT constraints should be satisfied simultaneously. Our method proposed later can be extended to the multiple measurement points case.

4. Problem formulation

The demand for QoS from unlicensed transmission is denoted by a utility of SINR, $u_l(\gamma_l)$, $\forall l$, where $u_l(\cdot)$ is a twice differentiable, increasing function of γ_l. The minimum QoS requirement of link l is γ_{l0}. The social utility maximization problem with QoS and IT constraints can be formulated as follows:

$$\text{(P1)} \quad \begin{array}{ll} \max_{\mathbf{p}\in\mathcal{P}} & \sum_{l\in\mathcal{L}} u_l(\gamma_l) \\ \text{subject to} & \gamma_l \geqslant \gamma_{l0} \quad \forall l, \\ & \sum_{i=1}^{|\mathcal{L}|} p_i G_{0i} \leqslant T, \end{array}$$