Ad Hoc Networks 37 (2016) 183–194

Contents lists available at ScienceDirect

Ad Hoc Networks

journal homepage: www.elsevier.com/locate/adhoc

On power control in full duplex underlay cognitive radio networks☆

Ningkai Tang[a], Shiwen Mao[a,*], Sastry Kompella[b]

[a] Department of Electrical and Computer Engineering, Auburn University, Auburn, AL, USA
[b] Information Technology Division, Naval Research Laboratory, Washington, DC, USA

ARTICLE INFO

Article history:
Received 29 November 2014
Revised 24 May 2015
Accepted 27 August 2015
Available online 7 September 2015

Keywords:
Cognitive radio
Control theory
Full duplex transmission
Interference mitigation
Power control
Stability

ABSTRACT

Both cognitive radio (CR) and full duplex transmissions are effective means to enhance spectrum efficiency and network capacity. In this paper, we investigate the problem of power control in an underlay CR network where the CR nodes are capable of full-duplex (FD) transmissions. The objective is to guarantee the required quality of service (QoS) in the form of a minimum signal-to-interference-plus-noise (SINR) ratio at each CR user and keep the interference to primary users below a prescribed threshold. We design an effective distributed power control scheme that integrates a proportional-integral-derivative (PID) controller and a power constraint mechanism to achieve the above goals. We analyze the stability performance of the proposed scheme and develop a hybrid scheme that can switch between FD and half duplex (HD) modes. The proposed scheme is validated with extensive simulations.

1. Introduction

In recent years, an unprecedented increase in wireless data has been observed. This is largely due to the proliferation of smartphones, tablets and other wireless devices, each generating tens or hundreds times of wireless data than a traditional mobile phone [2]. The exploding wireless data calls for effective technologies for enhancing spectrum utilization and wireless network capacity. To this end, cognitive radios (CR) have been recognized as one of the key technologies to meet this grand challenge on wireless network capacity. As an effective means of sharing spectrum among licensed (i.e., primary) users (PU) and unlicensed (i.e., secondary) users (SU), CR has been demonstrated to achieve high utilization of the scarce spectrum resource [3,4].

In CR networks, the most important design factor is to balance the tension between PU protection and SU spectrum access gains [3]. On one hand, the capacity of SUs should be maximized to "squeeze" the most out of the spectrum. On the other hand, the adverse impact to PUs, resulting from sharing spectrum with SUs, should be kept below a tolerable level. Obviously, these are two conflicting goals that should be balanced in the design of CR networks. In the so-called overlay CR networks, PU protection is achieved by spectrum sensing and spectrum access only when the PUs are sensed absent [3]. In the so-called underlay CR networks, both PU and SU transmissions coexist in the same spectrum band, and PU protection is achieved by carefully controlling the power of the SU transmitters [5].

Recently, a breakthrough in wireless communications is full duplex (FD) transmissions [6–9]. Traditionally, wireless communications are all half duplex (HD) due to the large path loss typical in wireless transmissions. If FD transmission is allowed, the self-interference will be so strong (like the sun) and the weak received signal from a remote transmitter (like stars) will be completely overwhelmed and cannot be

☆ This paper was presented in part at IEEE MILCOM 2014, Baltimore, MD, USA, Oct. 2014 [1].

* Corresponding author. Tel.: +1 334 844 1845; fax: +1 334 844 1809.
E-mail addresses: nzt0007@tigermail.auburn.edu (N. Tang), smao@ieee.org (S. Mao), sk@ieee.org (S. Kompella).

http://dx.doi.org/10.1016/j.adhoc.2015.08.018
1570-8705/

decoded. Recently, encouraging results have been reported on enabling FD wireless transmissions in both single link and a network setting [6–9]. The enabler of FD is the recent advances in self-interference suppression (SIS). Various effective SIS techniques have been proposed and tested, such as antenna separation [6], antenna cancellation [7], signal inversion and adaptive cancellation [8], and combined optimal antenna placement and analog cancellation [10]. In [10], the authors presented a practical implementation that can suppress self-interference (SI) for up to 80 dB, which should be sufficient for many application environments [11]. The achievable capacity gain of FD in a network setting is investigated in a few recently works [12–14], where inter-link interference and spatial reuse are the major limiting factors for the FD gain [13].

In a recent work [11], the authors propose to integrate FD in overlay CR networks. It is demonstrated that an FD-enabled SU can operate in either simultaneous transmit-and-sense mode or simultaneous transmit-and-receive mode. The authors analytically study the performance of the two modes and evaluate the sensing-throughput tradeoff for both modes. Motivated by this work, in this paper, we investigate the problem of integrating FD in underlay CR networks. We consider a primary network co-located with multiple SU links. The SUs are capable of FD transmissions. As discussed, the key design issue for underlay CR networks is how to design an effective power control scheme to achieve the dual goal of PU protection and SU spectrum access gain maximization.

For PU protection, we consider multiple detection points (DP) in the network for measuring interference from SU transmissions. Such DPs can be special devices deployed at strategic locations, such as base stations in primary networks [18]. The PUs incorporate a short Quiet Period in each time frame as in IEEE 802.22 Wireless Regional Area Networks (WRAN) [15], during which the PUs stop their transmissions and the DPs can measure the interference from SU transmissions together with other noise to set the noise floor for SUs. Based on the noise floor set by DPs, each SU transmitter adjusts its transmit power to achieve the primary goal of keeping the measured interference to PUs below a prescribed threshold, and the secondary goal of guaranteeing the quality of service (QoS) of SUs in the form of a minimum signal-to-interference-plus-noise ratio (SINR).

We develop a distributed power control scheme that consists of a proportional-integral-derivative (PID) controller, for satisfying the SU QoS requirements, and an additional power constraint mechanism, for PU protection. We analyze the stability of the proposed power control scheme and develop a hybrid HD–FD scheme for harvesting the benefits of both modes under various network and system settings. The proposed schemes are evaluated with extensive simulation studies.

In the remainder of this paper, we first present the system model and problem statement in Section 2. In Section 3 we develop the power control scheme and in Section 4 we analyze its stability performance and develop a hybrid HD/FD scheme. Simulation results are presented in Section 5 and related work discussed in Section 6. Section 7 concludes the paper.

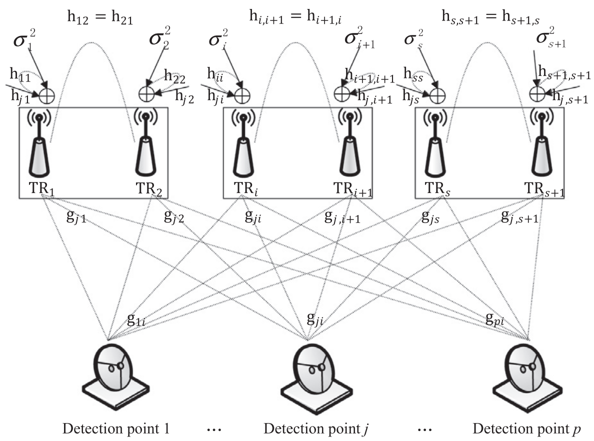

Fig. 1. An FD underlay CR network considered in this paper.

2. System model and problem statement

2.1. System model

Consider an underlay CR network as illustrated in Fig. 1. There is a primary network with active transmissions using a licensed spectrum band. A co-located secondary network consists of $(s+1)$ SUs, termed TR_i, $i = 1, 2, \ldots, s+1$, where s is an odd number. The SUs are paired to form $(s+1)/2$ FD transmission links, i.e., TR_i is transmitting to, and simultaneously receiving from TR_{i+1}, while i is an odd index. Due to the underlay spectrum sharing policy, the SUs are allowed to use the same spectrum band as the primary network. For protection of the primary network, there are p detection points (DP) in the primary work that measure the interference from the secondary transmissions during the Quiet Periods [15]. As discussed, such DPs can be standalone devices deployed in strategic locations in the network area, or simply a piece of program running in the primary receivers or SUs. The measured SU interference should be kept below a threshold at the DP locations by effectively controlling the power of the secondary transmitters.

Note that the DPs are an important part of the network architecture considered in this paper. In fact, although in the earlier stage, especially in dynamic spectrum access (DSA), it was desirable to make spectrum sharing unobtrusive to PUs [4], the great benefits and need of participation/cooperation of PUs in spectrum sharing has been recognized in recent works [16,17]. This is particularly true in underlay CR networks, where CR users can access the spectrum freely as long as the interference PUs receive is below a threshold. In such networks, CR users need to know the interference level at primary users, which is extremely challenging (or impossible) without deploying some measurement mechanisms or involvement of PUs.

To address this problem, there has been proposals on deploying spectrum sensors in the CR network [18,19], i.e., “use a large number of sensors to properly ‘sniff’ the RF environment, wherever it is feasible. The large number of sensors is needed to account for the spatial variation of the RF stimuli from one location to another” [18]. This is actually