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FULL-DUPLEX COGNITIVE RADIO: ENHANCING SPECTRUM USAGE MODEL

Abhinav Lall[1] , O. P. Singh[2] , Ashish Dixit[3]

[1,2,3]*Department of Electronics and Communication Engineering, ASET.*
Amity University Lucknow Campus.(India)

ABSTRACT

With the rapid growth of demand for ever-increasing data rate, spectrum resources have become more and more scarce. As a fore-seen promising technique to increase the efficiency of the spectrum utilization, cognitive radio (CR) technique has the great potential to meet such a requirements by allowing the un-licensed users to co-exist with the licensed bands. In the conventional CR systems, the spectrum sensing is performed at the beginning of each time-slot before the data is transmitted. This unfortunately results with two major problems: 1) Transmission time reduction due to the sensing, and 2) Sensing accuracy impairment due to the data transmission.

To tackle these problems, in this paper we present a new design idea for future CR by exploring the full-duplex (FD) techniques to achieve the simultaneous spectrum sensing and data transmission. With FD radios equipped at the secondary users (SUs), the SUs can simultaneously sense and access the vacant spectrum, and hence, significantly improve sensing performance and meanwhile increase data transmission efficiency.

I. INTRODUCTION

The existing new wireless technologies, as smart phones, wireless computers, business networks and WiFi home are rapidly consuming radio spectrum. Unlike wired Internet, the wireless world has a limited amount of links formultiple use. Consequently, traditional regulation of the spectrum requires a fundamental reform in order to allow for the more efficient use of precious resource of airwaves. Cognitive radio (CR) has widely been recognized as promising technique to increase the efficiency of the spectrum utilization. It allows the un-licensed secondary users (SUs) to coexist with the primary users (PUs) in the licensed bands. There are basically two kinds of CR network (CRN): the underlay and the overlay. In underlay CRNs, SUs transmitts at a limited power such that they do not cause a harmful interference to primary networks. The restricted power limits transmit range of SU. In the overlay mode, SUs need to accurately sense transmissions of PU spectrum, identifying unused spectral holes for transmission and leave it when the incumbent radio system is ready to transmit.

Most of the existing CRN deploy a half-duplex (HD) radio to transmit and receive signal in two orthogonal channels and the SU employ a well-known “Listen-before-Talk” (LBT) protocol, in the which SU sense target channel before transmission. Though proved to be effective, LBT protocol actually dissipates the precious resources by employing the time-division duplexing, and hence, unavoidably suffer from two major problems:

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- The SU have to sacrifice the transmission time for the spectrum sensing, and even if spectrum hole is long and continuous, data transmission needs to be split into a small discontinuous slot;
- During SU transmission, SU cannot detect changes of PU state, which leads to collision when PU arrive and the spectrum waste when PU leave.

Thus, it would be desirable for SU to continuously monitor spectrum and mean-while transmit whenever spectrum holes are detected. This, seems impossible with a conventional HD system. A full-duplex (FD) system, where the node can send and receive signal at the same time and the frequency resources, offers the potential to achieve a simultaneous sensing and transmission in CRN.

In summary, FD technology enable to explore another dimension of a network resource for increasing capacities of CRN. This requires a new design of signal processing techniques, and resource allocation algorithms, and network protocol. For example, one of the major challenges that are faced by FD-CR is how to optimize a transmitted power for the FD source node to maximize a system throughput. This article comprehensively discusses a novel approach design issues, practical algorithms for FD-CR systems, andkey system parameter derivation. In addition, here extend the proposed FD-CR to *distributed* and *centralized* network scenarios,

II. BASICS OF FULL-DUPLEX COMMUNICATIONS AND COGNITIVE RADIO

This section briefly introduces a basic FD communication system and the conventional LBT protocol.

2.1 The Full-Duplex Communication System:

Fig. 1 presents the simple two-node FD communication system with transmitter and a receiver antenna at each node. FD technique allows the two nodes to transmit and receive signals at the same frequency and time intervals, i.e., node '*I*'can transmit its signal 'x_i (i = 1,2)'with a transmitter antenna and receive

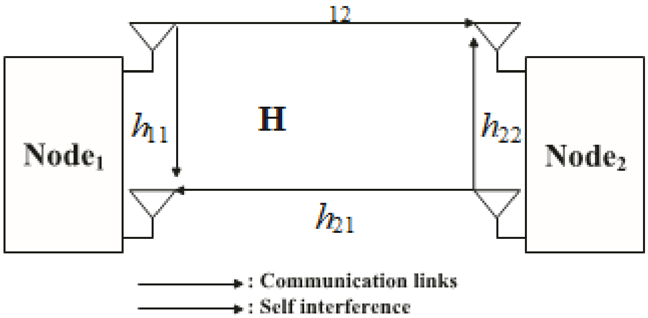


Fig. 1.Full-Duplex Wireless Communications

'x_{3-I}' from other node via a receiver antenna of the same channel simultaneously. However, this does leads to severe self-interference caused by signal leakage from the transmitter RF unit to the receiver RF unit, as shown in Fig. 1. In practical FD system, the self-interference cannot be completely cancelled, such that signals received at each node is a combination of the signal transmitted by other sources, the RSI, and the noise. The RSI can be typically modelled as AWGN, Rayleigh or Rician distributed variables of which the variance is proportional to transmitted power.

2.2 Conventional Cognitive Radio Communication System:

In a conventional CRN, SU are allowed to access spectrum allocated to PU without causing any severe interference at a primary network. The typical assumptionsthat are, PU do not notify SU when they begin or stop thr transmission, and do not wait when the SUis using the channel. Thus, SU needs to reliably identify spectrum holes to access and back-off when PUappears. Typically, SU trafficis slotted, and every SU time slot is divided into the two sub-slots for sensing and data transmissions. At the very beginning of each slot, all SUs sense the spectrum with a certain sensing strategy such as energy detection, matched filter detection, cyclostationary feature detection, or cooperative detection, and test the following two hypothesizes: (1) the spectrum is idle; and (2) the spectrum is occupied by a PU. Once the spectrum is judged idle, some SUs transmit in the rest time of the slot according to a certain scheduling scheme to minimize the probability of potential collision among SUs.

III. LISTEN-AND-TALK (LAT) PROTOCOL

The system model of the LAT protocol. Consider a CR system consisting of one PU and one SU pair in which SU1is the secondary transmitter and SU2is the receiver. Each SU is equipped with two FD antennas Ant_1 and Ant_2. SU_1 performs sensing and transmission simultaneously: the Ant_1 senses the spectrum continuously while the Ant_2 transmits data when a spectrum hole is detected. Specifically, at the end of each slot, SU_1 makes the decision in the PU's presence, and determines whether to transmit or not in the next time slot. Assuming that PU can utilize the spectrum freely, and thus, there existsa following four cases of spectrum utilization,

- $Case_1$: the spectrum is occupied only by the PU, and SU_1 is silent.
- $Case_2$: the PU is absent, and SU_1 utilizes the spectrum.
- $Case_3$: neither PU nor SU_1 is active, and there remains a spectrum hole.
- $Case_4$: the PU and SU_1 both transmit, and a collision happens.

Among these four cases, $Case_1$ and $Case_2$ are the normal cases, and $Case_3$ and $Case_4$ are referred to as spectrum waste and collision, respectively.

Comparison between the LAT and Conventional LBT Protocol:

LBT and LAT protocols, the comparison under the same model. For fairness, inthe LBT, SU_1 uses both antennas for sense and transmission, and correlation between the two antennas need to be considered. In the LBT, the data transmission time is reduced because of spectrum sensing, while in LAT, the RSI is the main problem that decreases the performance. The LAT performs better due to its higher utilization efficiency of the spectrum holes and prompt detection and reaction to the PU's state change.

IV. FULL-DUPLEX COGNITIVE RADIO APPLICATIONS

5.1 Distributed Scenarios

The distributed scheme does not have any central infrastructure for coordinating the common channel access procedure. Hence, each FD-CR user that is going to transmit has to take the contention procedures and resolve possible collisions.

Distributed Spectrum Access Scheme*:* We first introduce a simple distributed FD-CR system. Consider *M* non-cooperative FD-SUs contending for one channel of PUs [10]. Each SU senses the channel by the LAT protocol independently, and accesses the spectrum without communicating with each other. To avoid collision among SUs, a distributed dynamic spectrum access (DSA) scheme is needed. The difference of using the FD technique in the design of DSA scheme is that PUs are no longer "blind" to SUs when SUs are transmitting data, instead, SUs can detect in real time the state changes of PUs and other SUs continuously, and when collision happens, SUs can backoff immediately before finishing the current packet. This brings about the possibility of a new DSA scheme with the less spectrum waste and shorter collision length.

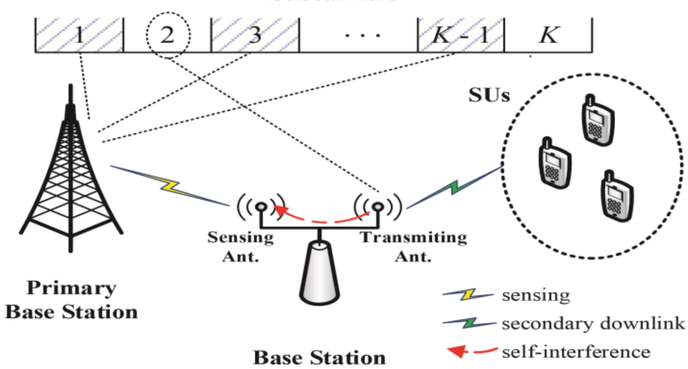
Full-Duplex MIMO System*:* As shown in Fig. 4, it consists of a pair of FD MIMO transceivers, nodes *A* and *B* , where each node is equipped with multiple antennas (N), respectively. In each node, some antennas (N_s) are used for sensing, some (N_t) for data transmission, and some (N_r) can be used for receiving data from the other CR node. Both nodes operate in the same frequency band at the same time. Hence, if $N_s = N$, the system becomes the traditional CR with LBT; When all these three parameters are employed, this system supports bi-directional communication while sensing, but the interference is quite complicated among the antennas.

5.2 Centralized Scenarios

In the centralized scenarios, an access point (AP) establishes the connection with the mobile users, which are served in the coverage area.

Full-Duplex Cognitive Access Point System*:* Fig. 5 shows a simple secondary AP system consisting of a FD cognitive OFDM-AP with 2 antennas and a number of SUs [11]. One antenna in the AP senses the PU's spectrum, and the other antenna provides wireless service for the SUs, in which the downlink transmission brings the RSI to the sensing results. Hence, how to assign SUs to the proper subcarriers and adjust the transmit power becomes essential for the system performance.

Full-Duplex Cognitive Relay System*:* By equipping the relay node with a FD radio, the relay can receive and retransmit signals simultaneously, and thus spectral efficiency can be improved, compared to the traditional HD relay. Fig. 6 illustrates a simple FD cognitive relay system consisting of one source, one destination, and one FD relay node. Both the source and relay nodes use the same time-frequency resource and the relay node works in the FD mode with 3 antennas (one for spectrum sensing, one for reception, and one for transmission). The communication process can be briefly described below:



Secondary

Fig. 5.Full-Duplex Cognitive Access Point System

- The source transmits signals to the FD relay;

- At the same time, the FD cognitive relay performs spectrum sensing;
- And the relay forwards the signals received in the previous time slots to the destination.

Note that different from traditional HD relay, the FD relay uses two antennas to receive data from the PU for sensing and the source for data forwarding. Thus, since FD works in the same frequency band, these two receive antennas actually have a combination of the PU, source, and RSI signals.

VI. CONCLUSIONS

This article presents a new paradigm for future CR by exploring the FD technology to allow the SUs to simultaneously sense and access the vacant spectrum. Novel protocol design have been explained in depth. Both it is indicated that the proposed LAT protocol can efficiently improve the spectrum utilization. Feasible applications with FD enabled CR have been elaborated into centralized and distributed scenarios.Future work may further study the scenario with multiple PUs and SUs in CRNs, and introduce basic economic theories as a tool to study and analyze.

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