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Indoor cognitive radio operation within the broadcast TV protection contour

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ABSTRACT

Although the broadcast television (TV) spectrum is currently open for unlicensed operation in the USA, a considerably large geographic area still remains excluded from the unlicensed operation due to potential interference to the licensed users. However, it might be possible to reuse primary spectrum within the protection contour if the frequency reuse occurs inside a building that shields radio signals and reduces interference to the primary system. Interference to outdoor licensed users from the indoor operations can be minimized if the unlicensed users adjust their transmit power according to their locations in the building. This paper presents an analysis and effectiveness evaluation of a novel cognitive radio (CR) system which enables CRs to access the licensed spectrum inside a building in the area within the protection contour. The system utilizes an indoor sensor network for (i) interference sensing, (ii) CR transmit power control, to limit the interference to the outdoor primary receiving antennas. Power control model of the indoor system has been developed to estimate safe transmit power for the indoor users. Two cases have been considered; single-user single-sensor (single indoor user and single sensor), and multi-user multi-sensor. Based on the power control model, a power control algorithm has been developed and its effectiveness is assessed through simulations. The algorithm is effective in realistic propagation scenarios, e.g. when internal partition walls and multipath fading are present. The outage probabilities in these propagation scenarios are found and the procedure of determining the transmit powers for CRs is presented.

1. Introduction

With the dramatic increase in digital media consumption and the rising popularity of smartphones, more radio spectrum resource will be required to satisfy the current needs for broadband wireless communications. Cognitive radio (CR) has been proposed to explore radio spectrum resources by accessing under-utilized radio frequency bands dynamically [1,2]. While public frequency bands, e.g. industrial, scientific and medical (ISM) radio bands, are becoming heavily used, the licensed bands are much less utilized [3–7]. In the United State of America, CR devices are now allowed to operate in the licensed broadcast television (TV) bands to provide additional broadband data and other services [8]. While the licensed users still remain as the primary users (PUs) of the TV bands, the CR devices are regarded as the secondary users (SUs), and are required to avoid harmful interference to the PUs.

The Federal Communications Commission (FCC) specified a set of rules which adopted two techniques to avoid SUs interfering with the PUs [8]. First is the geo-location database technique. SUs must be aware of their positions and consult a database, which contains information about nearby primary systems (such as their geo-location, transmitting power and frequency), for the availability of the spectrum. This means that the SUs are not allowed to operate in or near the coverage area of the TV broadcast service area, the primary system coverage area (PSCA), in order to avoid interference to the PUs. The second technique is based on spectrum sensing. SUs are required to determine the availability of the primary frequency band by detecting the presence of primary signals. SUs can only access the band if no primary signal is detected.

In the geo-location database technique, the interference can occur to the PUs at the border of the PSCA when SUs operate close to the border. Therefore, a *protection contour* around a primary transmitter (PT) larger than its service area is required to protect the primary system's operation [8]. The area inside the contour is also

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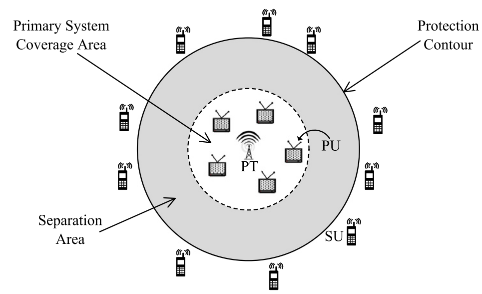

Fig. 1. Geometry of the system model.

referred to as primary exclusive region (PER) at which the primary frequency band is exclusive to the PUs [9]. This creates a separation area (SA) which is used to geographically separate the operations of the SUs from the PUs. In other words, the PER is a union of the SA and the PSCA, as shown in Fig. 1. Although the FCC does not specify the size of the SA, it does define the PSCA to be at the areas where the power of the primary signal is at least −84 dBm. It also specifies a minimum primary signal detection level of −114 dBm for the spectrum sensing technique and that practically defines the border of protection contour. This yields a considerably large SA in which the primary spectrum is not used by both the PUs and SUs; a spectrum hole which can be 2.5 times as large as the PSCA is created as a result [10].

To further improve the spectrum utilization efficiency in today's CR paradigm, the primary spectrum can still be accessed by SUs in the SA. There exists an opportunity for SUs to access the primary spectrum in the SA, while controlling the interference at PUs, if the SUs are inside buildings [11]. The interference to the PUs at the edge of the coverage area can be reduced by an additional propagation loss provided by the building structures. Indoor spectrum reuse can be found in femtocell technology. However, the femtocell and the indoor CR systems have distinct properties. Firstly, femtocells operate inside the coverage area of the macrocell system whereas the indoor CR system is designed to operate outside the PSCA. Therefore the interference between the femtocells and the macrocells can occur in both directions. In contrast, there is little or no interference to the indoor CR system from the primary system. In addition, the interference to the PUs is considerably smaller in the indoor CR system than in the system with the femtocell system. It is due to the fact that the SUs are geographically separated from the PUs. Secondary, femtocells are designed to be used as auxiliary systems to the macrocell systems. They are part of a mobile network and provide services to the same users, i.e. mobile users. However, CR systems are designed to explore unused spectrum opportunistically and use the spectrum as secondary users. They do not provide services to the PUs of the spectrum.

The primary contribution of this paper is that we develop a transmit power control system based on application of a sensor network which controls indoor CR system. The is designed to operate in buildings in the SA that is currently excluded for secondary operations. This system takes the advantage of the additional penetration loss from building structures to limit the interference at PUs. The sensor network is used to measure the interference level produced by the indoor SUs and regulate their transmit power in order to control the interference at outdoor locations. Two radio propagation properties, i.e. correlated shadowing and path-loss reciprocity, are explored for the power control in the over all system. As the secondary contribution, the paper presents a performance evaluation of a power control algorithm designed specifically for the sensor network controlled indoor CR system [12]. The evaluation is done by accessing the outage probability of outdoor PUs in different cases. The first two cases compare the performances of the algorithm when SUs start with high and low initial transmit powers. The third case investigates and compares the system performances in four different scenarios which consider a building (i) without both internal walls and fast fading, (ii) with internal walls and no multipath fading, (iii) without internal walls but with multipath fading, and (iv) with both internal walls and fast fading.

The reminder of this paper is organized as follows. Related works are first discussed in Section 2. In Section 3, the system model and interference control strategy are presented. This is followed by a description of the power control algorithm in Section 5 and its effectiveness evaluation in Section 6. Section 8 concludes the paper.

2. Related work

Reuse of spectrum under indoor environment has been used in femtocell technology. Femtocells, also referred to as home base stations (BSs), are low-cost, low power mobile network BSs which are used to increase the capacity and coverage of macrocell systems [13]. The macrocell mobile systems often have poor signal strength in some indoor environments or at the cell edge, which typically results in the system service outage. The system can be improved by adding femtocells in these areas. Since the femtocells operate at the same frequency bands as the macrocells, interference between the two systems will occur and is one of the main development challenges [13]. Different interference avoidance techniques, such as sectoring antennas [14] or adaptive power control [15], have been proposed to tackle these issues.

Authors in [16] considered a sensor-network-aided cognitive radio system in which the sensor network is a part of the spectrum sensing functionality. Sensor nodes sense primary spectrum cooperatively to provide a more accurate spectrum hole information for SUs. Authors in [17] discussed a concept of using sensor network in CR system, SENDORA, in which the main objective of the sensor network was to provide a reliable detection of spectrum holes. The sensors in both papers are used to detect primary signal and relay the measured information to SUs. SUs then can use the spectrum optimally from a more accurate and detailed spectrum hole information.

We have recognized that the control of interference level to primary systems should be the top priority of CR systems. Hence, instead of using sensor network for spectrum sensing, we will use it for *interference sensing* and controlling the SU's transmit power by feeding back the measured information. The sensors in the proposed system are required to measure SUs' signal strengths and broadcast beacons. These functionalities have been used in the infrastructures of indoor wireless communication systems such as the WLAN routers. Moreover, since that using sensor network to assist CR systems has been proposed in the literature, and also due to the fast technology development, we expect that the cost of using sensor network for the indoor CR system will not be prohibitively high.

3. System model

3.1. Indoor cognitive radio system in the separation area

In the SA, the primary signal strength is assumed to be below the noise floor of primary receivers so no PUs are able to operate in this area. Consider a scenario that a number of SUs are transmitting in the primary spectrum inside a building which is in the SA. The building is assumed to be an idealized single storey and square-shape structure with the size of 30 m by 30 m by 3 m as show in Fig. 2. The SUs are randomly and uniformly distributed in the building with the same antenna height of 1.5 m.

For any outdoor location with a distance D away from the building walls, the outdoor interference perimeter (OIP) around