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Spread spectrum-based coordination design for spectrum-agile wireless ad hoc networks

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ABSTRACT

Cognitive radios (CRs) have been proposed to improve spectrum utilization by enabling opportunistic and dynamic spectrum access for unlicensed users. To enable efficient CR communications, a reliable control channel (CC) for exchanging control information is needed. In this paper, a direct sequence spread spectrum (DSSS)-based underlay CC design for distributed coordination in CR networks (CRNs) is proposed. The proposed design provides immunity to licensed primary radio (PR) interference (reliable communication), low transmission power (PR users' protection) and predefined-required transmission rate and range (network connectivity). The Proposed design ensures that both narrow-band data and wide-band control transmissions can be simultaneously proceeded while protecting the performance of PR users. To ensure reliable CR control communications, a closed-form expression is derived for the minimum required transmission power for control packet transmissions such that required transmission range and rate are achieved. Based on the derived expression, the maximum allowable transmission power for CR data transmissions is computed such that an enforced power mask constrain over the PR channels is not violated. Simulation results indicate that the proposed CC design enables efficient CR communications without relying on the existence of a dedicated CC.

1. Introduction

Recent reports by the FCC and other agencies have reported that the licensed spectrum is heavily allocated, but vastly underutilized (FCC, 2002; Bany Salameh and Krunz, 2009; Song et al., 2014; Cacciapuoti et al., 2015). At the same time, the unlicensed frequency spectrum (e.g., the ISM bands) is heavily utilized due to the widespread acceptance of the unlicensed wireless services and applications. This calls for a new opportunistic and dynamic spectrum access (DSA) policy to efficiently utilize the available spectrum. For this purpose, cognitive radios (CRs) have been proposed as the key enabling technology to allow for such opportunistic DSA for unlicensed users. In an environment where a network of CR users coexists with several legacy primary radio (PR) networks, CR users should efficiently exploit the underutilized portion of the PR spectrum in a distributed manner. In this case, the crucial challenge is the need for a reliable control channel (CC) mechanism for exchanging control information without relying on the existence of a dedicated CC (Bany Salameh and Krunz, 2009).

Control channel design for CRNs can be generally classified into three different categories: (1) a predetermined narrow-band dedicated CC (e.g., Petracca et al., 2011; Bany Salameh et al., 2010, 2014; Jung and Yoo, 2005), (2) dynamic in-band common CC within the PR bands (e.g., hopping-based CC Bian et al., 2011; Bian and Park, 2013 and cluster-based CC Bany Salameh and El-Attar, 2015; Nishra et al., 2005; Liu et al., 2012, and (3) underlay CC, where a spread spectrum (SS) technique is adopted to establish a common CC (e.g., Wasden et al., 2012; Gardellin et al., 2013; Perez-Salgado et al., 2013). The dedicated CC can be implemented as a fixed dedicated out-of-band licensed channel (e.g., Chen et al., 2011), an underlay unlicensed UWB channel (e.g., Petracca et al., 2011), or a sub-channel in an unlicensed frequency band (ISM band) (Bany Salameh et al., 2010, 2014; Bany Salameh and Badarneh, 2013). While using such dedicated CC designs (when available) is simple and guaranteed, they have major design issues that make their practicality questionable. Specifically, using UWB limits the maximal distance between neighboring CR users (since the throughput of UWB decreases heavily with distance). Using a fixed narrow-band dedicated licensed/unlicensed CC can cause a single-point-of-failure (SPOF) and raise security issues (Bany Salameh and Krunz, 2009). Worse yet, using a dedicated licensed CC contradicts the opportunistic nature of the CRNs. On the other hand, dynamic in-band common CC can provide an effective coordination mechanism and solves the issues associated with the

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previous design approaches. However, implementing such an approach in a multi-hop ad hoc CRN is daunted with three main deployment challenges: (1) guaranteeing PR protection, (2) achieving CR coordination stability (e.g., minimizing the frequency of CC migration due to PR activities), and (3) minimizing the latency in establishing a new CC (time to rendezvous) whenever the current CC is reclaimed by the PR users. It is noted here that creating and maintaining a connected CRN using an in-band PR CC in a distributed and fully self-organized manner while addressing the aforementioned deployment challenges is still an open issue.

The underlay CC technique has been proposed to solve the aforementioned issues. According to this technique, the control signal is spread over a large PR frequency band with a very low transmission power level that is below the background noise level. Consequently, with a proper design, an efficient underlay, CC design can be implemented using SS with minimal impact on the performance of PR users. In this paper, an *underlay* distributed coordination design for a CSMA/CA-based CRN is designed without relying on the availability of a dedicated overlay (licensed or unlicensed) fixed CC. The proposed design is based on the direct sequence spread spectrum (DSSS) technology. According to the proposed design, the control packets are transmitted at a very low power density (in Watt/Hz) by spreading the control signal over a large portion of the spectrum (an entire PRN band). Therefore, its impact on the performance of PR users will be very small. The proposed design allows simultaneous narrow-band data and wide-band control transmissions to proceed simultaneously without interfering with each other while meeting an imposed power mask constraint over the PR channels. Unlike dynamic in-band CC designs, the proposed design introduces no delay in establishing the CC as the DSSS-based CC is always available, irrespective of the time-varying nature of PR activities. Specifically, a closed-from expression for the required transmission power over the DSSS-based CC is obtained for given network connectivity requirements (i.e., required transmission range and minimum control transmission rate). Numerical results indicate that the required control transmission rate and range can be achieved with a very low transmission power level. To ensure the enforced CR-to-PR power mask, a closed-form expression for the maximum permissible transmission power for CR data transmissions over the narrow-band PR channels is determined based on the computed CC transmission power. According to the proposed CC design, the control signals are spread across a wide bandwidth, making them very difficult to intercept, demodulate, and intercept. This provides low probability of intercept and better CR communication security. In addition, the spread of energy over a wide band (resulting in a very low power-spectral density) makes the DSSS CR control signals less likely to interfere with narrow-band PR transmissions. This significantly reduces the CR-to-PR interference and provides PR users' protection. On the other hand, the narrow-band PR communications introduce little-to-no interference to the DSSS-based control transceivers because the DSSS-based receiver effectively spreads out the PR narrow-band interference over the receiver's total SS bandwidth. Thus, the proposed DSSS-based CC design can provide reliable CR communications and robust connectivity under different PR traffic loads.

To evaluate the performance of the proposed DSSS-based CC design, simulations are conducted over a dynamic CRN that uses a CSMA/CA-based random access strategy to access the DSSS CC. Simulation results show that the proposed design provides reliable CR communications, PR users protection, and robust network connectivity. The results also indicate that compared to dedicated narrow-band *overlay* CC designs, the issues associated with such designs are significantly mitigated with minor degradation in the overall CRN performance.

The rest of the paper is organized as follows. In Section 2, a brief overview of related work is presented. Section 3 introduces the network model and assumptions. In Section 4, the proposed DSSS-based CC design is presented. The transmit power analysis is given in Section 5. Section 6 presents the simulation results comparing the proposed design with a dedicated channel-based coordination one. Section 7 concludes this paper.

2. Related work

One of the vital challenges in enabling efficient CR communications is the need for a reliable mechanism for exchanging control information (channel assignment and route selection decisions, sensing information exchange, etc.). Recently, several attempts were made to develop CC designs for CRNs (e.g., Jung and Yoo, 2005; Nishra et al., 2005; Bany Salameh and El-Attar, 2015; Gardellin et al., 2013; Bian et al., 2011; Bian and Park, 2013; Wasden et al., 2012; Chen et al., 2011; Bany Salameh and Badarneh, 2013; Perez-Salgado et al., 2013; Liu et al., 2012). Existing work on CC designs can be classified according to their spectrum access technique (underlay or overlay) and spectrum allocation strategy (dedicated or non-dedicated).

The coordination scheme in IEEE 802.22 WRAN selects the CC for CR handshaking from the currently available narrow-band PR channels. Such an approach can result in high failure rate when the availability of PR channels are dynamically changing (Saleem and Rehmani, 2014). In Jung and Yoo (2005), the authors investigated the rendezvous problem in a centralized CRN. They proposed a resource-aware rendezvous algorithm which is based on a spectrum-hole management scheme. In Bian et al. (2011), the authors presented four quorum-based channel-hopping (QCH) CC designs in CRNs that can effectively tolerate the appearance of PR users (two synchronous QCH designs under the assumption of global synchronization, and two asynchronous channel hopping designs, where no global synchronization is required). However, the proposed designs only support a very limited number of distinct rendezvous CCs between any two communicating CR users, which can negatively affect the CRN performance in case of PR users' appearance in one or more of the limited rendezvous CCs. In Bian and Park (2013), the authors developed an asynchronous channel hopping (ACH) CC scheme that attempts at maximizing the rendezvous diversity of any communicating pair in a distributed CRNs without imposing clock synchronization. ACH attempts at reducing rendezvous failures caused by the appearance of PR users. The authors in Bany Salameh and El-Attar (2015) proposed a spectrum-aware cluster-based coordination mechanism with multi-packet multi-channel OFDM technology for CRNs. The proposed mechanism employs a CSMA/CA mechanism to asynchronously organize neighboring CR users with similar views to spectrum into virtual clusters, and coordinate their communications using locally available common CCs. In Nishra et al. (2005), a universal CC is used by all CR users for coordination and local CCs are used by neighboring CR users to exchange control information and enable CR data communications.

The authors in Wasden et al. (2012) provided a CC design for CRNs based on a filter bank multi-carrier spread spectrum (FBMC-SS) system. A hardware implementation of the proposed FBMC-SS CC design using FlexRIO FPGA module was also reported. The use of two different types of underlying CCs were proposed in Gardellin et al. (2013), one for global coordination and the other for local coordination. The proposed design in Gardellin et al. (2013) employs code division multiple access (CDMA) with adaptive frequency hopping in order to protect PR users and achieve reliable CR communications. It is worth noting that most of the previously proposed underlay CC designs (e.g., Wasden et al., 2012; Gardellin