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A survey of common control channel design in cognitive radio networks

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ABSTRACT

Cognitive radio networks have been recognized as a promising paradigm to address the spectrum under-utilization problem. To improve spectrum efficiency, many operations such as sharing data in cooperative spectrum sensing, broadcasting spectrum-aware routing information, and coordinating spectrum access rely on control message exchange on a common control channel. Thus, a reliable and "always on" common control channel is indispensable. Since the common control channel may be subject to primary user activity, the common control channel design in cognitive radio networks encounters unprecedented challenges: cognitive radio users are unable to negotiate a new control channel when the original one is occupied by primary users. In this paper, the problem of common control channel design is presented by its classification, design challenges, design schemes, and its applications in network protocol layers. The issues of control channel saturation, robustness to primary user activity, limited control channel coverage, control channel security are identified as design challenges. Moreover, the major control channel design schemes such as sequence-based, group-based, dedicated, and ultra wideband approaches are presented. Lastly, the relation of the common control channel with radio interface, cooperative sensing, medium access control, and routing are discussed.

1. Introduction

The recent skyrocketing growth of the research on cognitive radio (CR) networks has shown the promises of the CR paradigm as the enabling technology to the spectrum under-utilization problem [1,2]. CR users improve spectrum efficiency by opportunistic spectrum access when the licensed spectrum is not occupied by the primary users (PUs). CR users also need to sense the spectrum and vacate the channel upon the detection of the PU's presence to protect PUs from harmful interference. To achieve these fundamental CR functions, CR users usually coordinate with each other by using a common medium for control message exchange. This common medium is known as a common control channel (CCC) [1–3].

A CCC in CR networks facilitates a variety of operations from transmitter–receiver handshake, neighbor discovery, channel access negotiation, topology change and routing information updates, to the cooperation among CR users [1,2]. Specifically, CR users show their existence by broadcasting control messages on the CCC for neighboring users in the proximity to maintain the contact and the network's connectivity. Moreover, CR users can cooperate and share their spectrum sensing data with each other by using the CCC to improve the detection of PUs [4]. More importantly, CR users need to inform each other on the changes of PU activity, spectrum availability, and network topology so as to improve the CR throughput and spectrum efficiency. Therefore, it is essential to devise CCC schemes that can reliably establish and efficiently maintain CCCs in CR networks.

The CCC design in CR networks is originated from the medium access control (MAC) in multi-channel wireless networks. In multi-channel environments, one channel commonly available to all network nodes is used for exchanging control messages to reserve data channels for data transmission. Such a dedicated CCC facilitates the handshake between the transmitting and receiving nodes.

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However, it may suffer from the *control channel saturation* problem when a large number of nodes access the control channel causing high control packet collisions and throughput degradation [5]. To address this problem, many multi-channel MAC protocols and CCC allocations schemes were proposed for multi-channel wireless networks [6]. As a result, these early CCC studies for legacy wireless networks pave the way for the CCC design in CR networks.

Although the concept of CCC is not new, the CCC design in CR networks faces several new challenges. The challenges arise in the following two aspects: *PU activity* and *spectrum heterogeneity*. First, unless the CCC can be allocated in the frequency band free from PUs, a CCC is susceptible to PU activity and can be occupied by PUs at any given time. Upon PU's return to the CCC, CR users face the difficulty in establishing a new CCC because they are unable to use the original CCC to negotiate a new one. Since this problem significantly complicates the CCC design in CR networks, the *robustness to PU activity* is one of CCC design challenges. Second, unlike multi-channel wireless networks where all channels are at the disposal of all users, CR users usually observe different sets of available channels, each of which is a subset of the set of all licensed channels. Due to this spectrum heterogeneity in CR networks, it is unlikely to find a channel commonly available to all users as the CCC. As a result, the area where CR users share the same CCC, called *CCC coverage*, is limited to a neighborhood in a CR network. Since it affects the efficiency of a control message broadcast and the incurred signaling overhead, CCC coverage is also a CCC design challenge. Even if a dedicated CCC is available to all users in the CR network, the globally available CCC can create a single point of failure and is susceptible to control channel jamming attacks. This raises another design challenge in *control channel security*.

Due to the unique CCC characteristics and challenges in CR networks, a CCC in a CR network is defined as a medium temporarily or permanently allocated in a portion of licensed or unlicensed spectrum commonly available to two or more CR users for control message exchange. Based on this definition, a CCC in CR networks may not be unique and may not always available. Notice that, with the definition, a CCC exists in all MAC or channel allocation schemes in CR networks. For those existing schemes [7–9] claiming that a CCC is not required or needed in the literature, the CCC is more appropriately termed *dedicated CCC*. In this paper, the problem of CCC design in CR networks is addressed first by identifying CCC design challenges. The CCC design schemes and their requirements are then introduced to demonstrate the strong relation between the CCC design challenges and the CR performance. Lastly, the applications of the CCC in different network protocol layers are discussed to show the universal usage of the CCCs in CR networks. The contribution of this paper is summarized as follows.

- *Identify CCC Design Challenges*: The CCC design challenges in CR networks are identified and comprehensively discussed. The primary challenges include control channel saturation, robustness to PU activity, CCC coverage, and control channel security.
- *Analyze CCC Design Schemes*: The design requirements of existing CCC schemes are introduced to provide the insights into the tradeoff between CR performance and CCC establishment overhead and how these schemes address the aforementioned design challenges.

The remainder of this paper is organized as follows: in Section 2, existing CCC design schemes are classified. In Section 3, the challenges and the requirements in CCC design are identified. In Section 4, major CCC design approaches and their performance are presented. In Section 5, the relation of CCCs with different network protocol layers are discussed. Finally, the survey is concluded in Section 6.

2. Classification of common control channel design

The classification of CCC design is the best place to understand the CCC design in CR networks from the bird's-eye view. The CCC design schemes have been classified in several ways in the literature. In [10,11], the authors divide CCC schemes into four categories: *dedicated control channel*, *common hopping*, *split phase*, and *multiple rendezvous control channel* (MRCC) according to the classification of multi-channel MAC protocols [6]. In [2], the CCC design approaches are classified as *in-band* and *out-of-band* based on whether or not data channels are shared by both control and data transmission. In each category, CCC solutions are further classified based on the area covered by the allocated CCCs. Moreover, in [3,12], the CCC designs are classified as *group/cluster-based*, *sequence-based*, and *dedicated* CCC depending on how CCCs are established in CR networks.

The classification based on multi-channel MACs is not suitable for the CCC designs in CR networks for the following reasons: (1) Split-phase approaches result in inefficient spectrum utilization because all nodes are tuned to one channel and most channels are idle during the control phase. These schemes are unlikely to be used in CR networks. (2) Common hopping requires the tight synchronization of all network nodes, which is unlikely to be achieved in a CR network with a large number of nodes. (3) Except for the dedicated CCC cases, CR users are likely to rendezvous on different CCCs owing to spectrum heterogeneity. As a result, multiple rendezvous is not appropriate to categorize a specific type of CCC schemes in CR networks. Therefore, in this paper, we extend the classifications in [2,3,12] and present the comprehensive classification of CCC designs in CR networks to include the overlay schemes and the subcategories in major CCC design approaches based on how CCCs are established.

As shown in Fig. 1, the CCC design classification is first divided into overlay and underlay CCC schemes. This first-level categorization reflects two primary spectrum sharing approaches in the CR paradigm. Contrary to the overlay approaches where the majority of CCC designs are centered, the underlay CCC schemes mainly utilize the ultra-wideband (UWB) transmission technology. Overlay approaches are then divided into in-band and out-band schemes as in [2]. In terms of CCC coverage, in-band approaches are local while the out-of-band schemes are mainly global. The in-band schemes are further classified