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Energy-efficient broadcast in multihop cognitive radio networks

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ABSTRACT

Broadcast is an important operation in Cognitive Radio Networks (CRNs). How to achieve broadcast in an energy-efficient way is important since users in CRNs are usually battery-powered. Existing single-channel broadcast mechanisms are not suitable for CRNs because multiple channels can be used in a CRN. Most existing multi-channel broadcast schemes rely on a common control channel (CCC) to support broadcast. However, finding such a CCC in a CRN is difficult because an unlicensed user's available channels are changed over time and space. In this paper, we focus on an environment where no broadcast structure or CCC is established in advance while a node is equipped with one CR transceiver and does not aware of the locations and distances to other nodes. We have defined the one-hop Minimum Multichannel Set Cover (MMSC) problem and the multi-hop Minimum Cost Broadcast (MCB) problem in such an environment. Both problems are NP-hard and we have proposed a heuristic solution, the Energy-Efficient Broadcast (EEB) protocol, to solve them. Considering the uncertain primary user occupancy issue, the EEB protocol features a distributed solution that uses only local information. Simulation results verify that EEB effectively reduces energy consumption and achieves high packet delivery ratio.

1. Introduction

Wireless spectrum is a precious resource because of the increasing requirements of wireless applications. However, a lot of licensed spectrum is underutilized [12], which necessitates a more intelligent allocation scheme to increase spectrum utilization. Utilizing the cognitive radio technology is a possible new spectrum allocation solution in that an unlicensed user (secondary user, SU[1]) can access the licensed spectrum not being used by any licensed user (primary user, PU). In cognitive radio networks (CRNs), SUs are able to recognize spectrum holes and can hop among them to avoid producing PU transmission interruptions. Depending on PU occupancy, the available channels for an SU are changed over time and space. By periodically monitoring all the channels, an SU can estimate the PU occupancy probability for each channel. For different SUs, the estimated PU occupancy probability for the same channel may be different due to their time and space diversity.

Broadcast is an important operation in wireless networks, which has been widely used in route selection, data collection, and information dissemination [5,8,9]. Supporting energy-efficient broadcast is essential in wireless networks since nodes are usually battery-powered. There exist many energy-efficient broadcast schemes for single-channel wireless networks [21,23,24,39,40], but these solutions cannot be applied to CRNs because SUs may reside in different channels. Few CRN broadcast solutions can be found in the literature [2,16,32,36]. A constraint of these solutions is that the available channel set for an SU is fixed, which makes them suitable only for some certain CRNs.

To provide broadcast in a multi-hop CRN, the source node must first broadcast to its one-hop neighbors and then selects some of the neighbors as the forwarders to forward the broadcast packet. The same process is repeated for each forwarder until all the nodes in the network have received the broadcast packet. We consider the one-hop broadcast task is more challenging because the channel availability for an SU is time- and space-dependent. If each node is equipped with one transceiver and is unaware of the available channels of its neighbors, a simple broadcast scheme is to enable the senders to broadcast multiple times in each channel. Such a scheme suffers from high power consumption, long transmission delay, inefficient channel usage, and high transmission collisions. In addition, this solution does not guarantee neighbors to receive the broadcast packet since the neighbors also hop among different channels. Another possible solution is that each node individually switches to a channel that is highly possible to be available from its point of view. The broadcast is achieved in an opportunistic way. A limit of this scheme is that a sender may have little opportunity to broadcast to its receivers when their available channels differ much.

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[1] The terms SU and node may be used interchangeably to represent a secondary user in this paper.

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The delay issue should also be addressed in designing a CRN broadcast solution. In this paper, we consider a constraint, one-hop broadcast delay bound (*HD*), which represents the time interval a forwarder node must rebroadcast after receiving a broadcast packet. This constraint is actually application-dependent. Another issue should be addressed is the PU occupancy. Since PUs may pop up to occupy channels at any time and each PU has a certain interference range, a transmission from a sender using channel i may not be correctly received by neighbors also residing in channel i. In general, a sender relies on acknowledgements from the receivers to determine the receiving status. However, too many receivers replying ACK packets for a broadcast may produce severe contentions and collisions, which is called the ACK implosion problem [15]. To avoid such a problem, in this paper, we consider a node i has received a broadcast packet if the probability for node i to receive the broadcast packet is larger than a predefined threshold, P_{thrd}. The value of P_{thrd} is also application-dependent.

In this paper, we define the one-hop Minimum Multichannel Set Cover (MMSC) problem and the multi-hop Minimum Cost Broadcast (MCB) problem. To solve the problems, we design an Energy-Efficient Broadcast (EEB) protocol for a CRN in which no broadcast structure or CCC is established in advance. Furthermore, a node needs only one transceiver and does not need the information of its location or the distance to any other node. Given the PU occupancy probability for each channel and one-hop broadcast delay bound *HD*, nodes running EEB can individually determine their own broadcast schedules based on their one-hop neighbor information. To enable a transmission in a CRN, a sender and its receiver must have a rendezvous which means that both nodes switch to the same channel at the same time. Providing rendezvous guarantee is an important MAC problem in CRNs. We focus on designing an energy-efficient broadcast protocol which can be built on many rendezvous-guaranteed CRN MAC protocols. That is, EEB is independent from the MAC protocol being used. There exist several CRN MAC protocols that rely on a common control channel (CCC). However, finding and maintaining a common control channel in CRNs is difficult because the availability of the dedicated control channel may change over time. These protocols also suffer from the CR longtime blocking problem: the control message cannot be successfully exchanged among SUs when a PU occupies the CCC for a long time [35]. Besides, periodically updating channel availability information produces a lot of overhead and a single CCC usually becomes a bottleneck. Many solutions use some kind of channel hopping mechanism to provide rendezvous without using a CCC [3,4,18,22,44]. In such solutions, each SU changes channels according to a predefined channel hopping sequence. Two SUs have a rendezvous when they tune to the same available channel at the same time. In most of these channel hopping solutions, each SU has a fixed channel hopping sequence and thus the time to rendezvous for any two SUs is proportional to the number of channels. This implies that accomplishing a broadcast requires longer delay and more energy consumption. QLCH is a solution that enables each SU to hop to different channels based on the intended recipient's channel hopping sequence [7]. In QLCH, the expected time to rendezvous between any two SUs is a constant (≒2). To facilitate our protocol description, we use QLCH to demonstrate the operation of EEB because it provides rendezvous guarantee without using a CCC and performs well in CRNs.

The contribution of the paper can be listed as follows.

1. Define the one-hop MMSC problem and the multi-hop MCB problem and prove them to be NP-hard (Section 3).
2. Design a distributed broadcast protocol that does not rely on any pre-established broadcast structure (a broadcast tree or broadcast paths) to solve the MMSC and the MCB problems. Without using pre-established broadcast structure enhances the robustness of the proposed solution in a network with mobile nodes or unexpected node failures (Section 4).
3. The proposed EEB scheme performs close to the optimal broadcast solution in terms of arrival rate and power consumption (Section 5.1). EEB is also a practical scheme (Section 5.2).

2. Related work

According to the topology information a node need to maintain, existing broadcast solutions for wireless networks can be classified into four categories:

- Class 1: No neighbor information is needed [26,38].
- Class 2: One-hop neighbor information is needed [6,20,21,42].
- Class 3: Two-hop neighbor information is needed [10,11,14,19,20,23–25,30,31,36,37,39–41].
- Class 4: The whole network topology is needed [2,16,32].

Since few CRN broadcast solutions exist in the literature, we also review some broadcast solutions for traditional wireless networks.

A typical mechanism in Class 1 solutions is to flood the broadcast packet since no neighbor information is available. A node rebroadcasts each received unduplicated broadcast packet. Such a mechanism is simple but suffers from the broadcast storm problem [26]. Several probability-based broadcast schemes have been proposed to reduce the number of redundant rebroadcasts with the same core concept: a node rebroadcasts with a probability of p [33]. A major concern of probability-based broadcast scheme is that finding the optimal value of p is difficult. Note that a probability-based broadcast scheme is reduced to the flooding mechanism when p is equal to one. Some distance-based and location-based enhancements for probability-based solutions have also been proposed to reduce the number of rebroadcasts when the distance/location information is available [38].

For solutions belonging to the other three categories, a node is aware of its one- or two-hop neighbors or the whole network topology by, for example, HELLO packet exchanges. A major task for solutions in these categories is to find the set of forwarders to rebroadcast packets. Some protocols use the concept of connected dominating set (CDS) to select forwarders [11,14,39,40]. A dominating set (DS) is a set of nodes wherein a node in the network is either in the set or is adjacent to at least one member in the set. A CDS is a DS wherein all the nodes in the DS are connected. The CDS concept is useful for forwarder selection and hence it is used in the broadcast operation in traditional wireless networks. However, in a CRN, a sender and its neighbors may reside in different channels and thus a single transmission is not enough to achieve a one-hop broadcast. Without considering this issue, the selected CDS may not be a proper forwarder set and hence the traditional CDS-based broadcast solutions do not apply to CRNs.

Besides the CDS-based solutions, there are two types of forwarder selection strategies depending on where the forwarding node selection is made: sender-based ones [19–21,23,24,31] and receiver-based ones [10,25,30,37]. In the sender-based schemes, the source node and the forwarders are responsible for selecting the next hop forwarders. The selection result is attached in the broadcast packet so that the next hop forwarders know they are selected. In the receiver-based schemes, a node receiving a broadcast packet determines by itself if it should act as a forwarder. In general, a node should be a forwarder if any of its neighbors has not received the broadcast packet. We are more interested in the sender-based solutions because they achieve broadcast with less number of forwarders [15].

Several sender-based schemes belonging to Class 2 have been proposed. To achieve a competitive performance when compared to Class 3 schemes, a sender in these schemes also needs each neighbor's location information. A typical strategy of these Class 2 schemes is to enable a sender to select a set of neighbors that cover the largest