Continuous Control Message Exchange in Distributed Cognitive Radio Networks

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Abstract
Control message exchange is major job for cognitive radio to exist and use spectrum opportunistically. For this control message exchange they need a common control channel (CCC). Once this channel is affected by a primary user, communication stops until new CCC is setup. This takes substantial time and if they could not get free channel, this halt continues for long time. To prevent such cease of communication, we propose a combination of two networks, namely WLAN and UWB, to let the communication continue. In our proposed idea if the CCC of a certain CR in WLAN is affected, the CR changes its network from WLAN to UWB and keeps the communication because UWB cannot be affected by PU. In the proposed idea every cognitive radio has two transceivers; one for the overlay network (WLAN) and another UWB network. If a primary user is detected in the spectrum of a cognitive radio, it continues exchanging control messages under the UWB network and in parallel negotiates for a new CCC using the WLAN network. This idea solves the communication interruption until new CCC is setup.

Keywords: Cognitive radio, Common control channel, Dynamic Spectrum Access, overlay scheme, underlay scheme, UWB.

1. INTRODUCTION

Since cognitive radios use the primary network opportunistically, they need control message exchange by establishing a common control channel (CCC). While establishing CCC, it is possible to have a dedicated or dynamic CCC. A dedicated CCC is a channel which is commonly available to all network nodes. However, as the number of nodes becomes very large, it may suffer from the control channel saturation. This saturation causes packet collision and throughput degradation. This globally available CCC has additional severe problem which is known as control channel security, it can create a single point failure, once it fails the whole network is affected because the secondary users have no way to communicate and also it is susceptible to jamming attacks. To address these problems, dynamic CCC design approach is proposed. In dynamic CCC, the CCC is changeable according to a given sequence or PU activity. Moreover, the nodes in the network can be divided into many groups, according to the sensing results, so that each group uses its own CCC. This addresses the saturation, packet collision and throughput degradation concerns. However, when the nodes dynamically change the CCC, it may take a considerable time to re-establish a new CCC which causes control message interruption for a certain amount of time until the new CCC is setup.

The remaining sections of this paper are organized as follows; Section II focuses on problem description. The proposed idea is detailed in Section III. In Section IV, we analyze the performance of our proposed idea. We finalize our paper in Section V.

2. BACKGROUNDS

A. Why WLAN and UWB combined?

Control message exchange is major job for cognitive radio to exist and use spectrum opportunistically. For this control message exchange they need a common control channel (CCC). Once this channel is affected by a primary user, communication stops until new CCC is setup. This takes substantial time and if they could not get free channel, this halt continues for long time. To prevent such cease of communication, we propose a combination of two networks, namely WLAN and UWB, to let the communication continue. In our proposed idea if the CCC of a certain CR in WLAN is affected, the CR changes its network from WLAN to UWB and keeps the communication because UWB cannot be affected by PU. Using the spread spectrum technology control messages are transmitted in lower power utilizing short pulses so that they are regarded as noise by the PU.

B. Related works

For control message exchange CCC design comes first. If CCC design is not effective, control message exchange faces severe problems. In this section, we mention some related works with CCC design and their drawbacks which lead us to propose the combined scheme.

In [10], adaptive MRCC-based hopping sequence is proposed. A channel ranking table is first established with channels in the order of increasing PU activity. Then a biased pseudo-random sequence is generated in such a way that the smaller values occur more frequently in the sequence. Finally, by mapping the biased pseudo-random sequence to the channel ranking table, the adaptive hopping sequence is constructed. CR users are synchronized by exchanging packets for synchronization and seed exchange when they rendezvous. The main drawbacks of this scheme are: first, TTR may not be bounded which may take long time for CCC link establishment. Second, CCC coverage is not guaranteed beyond the rendezvoused node pair. As a result control message exchange may be interrupted for considerable time and may not cover larger area.

In [11], spectrum-opportunity clustering (SOC) design is

formulated as a maximum edge bi-clique problem is proposed. A bi-clique is a bipartite graph when an edge connects each node to each channel. In bi-clique, all cluster members have a set of common channels. The drawback of this scheme is two neighbor clusters may not be able to exchange control messages if they have no common channels. Since the UWB transmission is observed as noise in narrowband channels, this scheme can be utilized to send control traffic in UWB channel without harmful interference with the PU traffic in licensed data channels. However, due to the limitation of power, the transmission range is limited and control message cannot be transmitted in large coverage.
To overcome the shortcomings of the previous schemes and to prevent the communication halt, we propose a mixed scheme. In our proposed idea, if PU is detected in a certain SU, the SU lowers its power and continues exchanging control messages under the UWB network. Next section explains our proposed scheme.

3. PROPOSED SCHEME

A. Overview

SUs can operate in two networks, WLAN and WPAN. WLAN is wireless local area network which two or more devices use wireless distribution method and usually provide a connection through an access point (AP) to the wider Internet. Because stations are based on IEEE 802.11 standards, they operate in both the 2.4 GHz and 5.0 GHz bands. However, WPAN is wireless personal area network which can be used for communication among the personal devices themselves, or for connecting to a higher level network and the Internet. This network is carried over wireless network technologies such as IrDA, Wireless Bluetooth, ZigBee, and UWB (Ultra-wideband).
In this paper, we consider UWB as WPAN technology. WLAN with IEEE 802.11 has much larger coverage area, i.e., 1 Km, than WPAN with UWB, i.e., 2 – 100 m (using low control data rate). After this section we call WLAN as overlay network using IEEE 802.11 and WPAN as WPAN using UWB.
In WLAN network, when the assigned CCCs are affected by PU activity, CR users must vacate the channel and negotiate for new CCC. Because data communication is suspended until they setup a new CCC, the reestablishment should be fast and reliable. If most of the spectrum is occupied by the licensed users, searching for new CCC becomes very difficult and it takes long time. If there are no spectrum holes and the SUs could not find a new CCC, communication may halt.

Network Change from WLAN to UWB

To prevent this communication halt, we let the affected SU to change its network from WLAN to UWB and continue control message exchange being on the UWB network. When an SU detects a PU on the spectrum it is operating, it sends a control message to the cluster head (CH) indicating it has detected a PU and is going to change its network from WLAN to UWB. The CH sends back a confirmation and the affected node starts using the UWB.

B. System Model

In order to coordinate each SU, it should be equipped with more than two transceivers. In this paper, we consider an SU with two transceivers, one for WLAN and another for WPAN. Without loss of generality, a spectrum band can be divided into several channels to use spectrum resources elastically and efficiently. In this paper, we consider N channels in operating spectrum band. These channels are characterized by discrete time Markov chains (DTMCs) model and can be used for WPAN and WLAN. WPAN and WLAN have the number of channels, i.e., NWPAN and NWLAN, and distance of transmission, i.e., RUWB and RCH. The number of SUs in each WPAN and WLAN, i.e., NUWB and Novly can be changed dynamically along with proposed scheme.
When PU is detected on the spectrum of one or more SU(s) the affected SUs lower their transmission power and switch to the UWB network. When the affected SUs use the UWB network, it is expected that the coverage of each UWB user decreases. In this case some unaffected overlay SUs serve as multi-hop relays. For instance, as shown in figure 4, UWB A and B and E are affected by PU activity while Overlay C and D are not affected. Since UWB A and B cannot reach the cluster head (CH), they have to use Overlay C and/or D as relays depending on their coverage area.

Synchronization of the Heterogeneous Networks

Because the WLAN and WPAN are different networks synchronization needs to be considered. Synchronizing heterogeneous networks using voter model is proposed in [12]. Assume network 1 and 2 are separately synchronized to time T1 and T2 in advance, and the two networks co-locate in the same area. The goal is eliminating the gap of timing between two networks in a distributed manner.
To prevent the influence of error timing comes from uncontrolled nodes, one possible solution is that the minority timing should follow the majority timing. So they proposed that the network with smaller size should follow the timing of network with larger size. The interaction rules of voter model contain two steps:

(i) Randomly pick up a node

(ii) The chosen node adopts the state of a random neighbor

Initially, each node has an initial state chosen from {0, 1}. After some steps of interaction, the network will be synchronized to one of states, all nodes in state 0 or 1. The probability of reaching state-1 synchronization is given by:

$$E_1(w) = w \equiv \frac{1}{N\mu}\sum_i k_i x_i(0)$$

Where k_i is degree of node i (number of nodes that node i connects to), $x_i(0)$ is the initial state of node i, and is the average degree. ω is defined as the degree- weighted average state, which is also the probability of reaching state-1 synchronization.
For the interaction they assume that each node holds an independent Poisson clock with rate 1 per unit time, the node do the interaction rule when the clock expires.

Control message exchange in the UWB network

We assume that the UWB CCC is implemented using the Impulse-radio UWB (IR-UWB) transmission technique [3]. All network nodes periodically transmit a Hello message over the UWB CCC, using the common spreading code which is randomly selected by the exchange initiator out of a set of available codes. A Hello includes the sender's identifier (ID), and then every CR device knows the nodes with which it can directly communicate over the UWB channel. When a CR changes its operating network from WLAN to UWB, it listens and waits for Hello messages from nearby nodes. If it does not hear any Hello message within a given time, it broadcasts a relay request message (RLY_RQ) using the common spreading code. This message includes sender ID and common spreading code because it is the initiator.

Then any CR user within its coverage replies ACK message after a random time since the RLY_RQ reception, so as to avoid collisions among different replies; it carries the list of nodes. According to this message exchange, a CR node can get or update the structure of network topology.

Switching failure probability

There is a case where switching problem may face. If a CR user switches to UWB network but cannot get any Overlay CR user in its UWB coverage, UWB E in this case, it faces switching failure. From this problem we define a probability called switching failure probability.

In this analysis, we use the switching failure probability metric. This metric is defined as the probability that overlay-UWB switching cannot be used when switching is required. This probability (PSF) can be written as follows.

$$P_{SF} = 1 - \frac{N_{UWB\_use}}{N_{UWB\_need}}$$

Where N_{UWB_need} is the number of CR users which need UWB communication and N_{UWB_use} is the number of CR users which can continue UWB communication (which have WLAN relays in their coverage) among N_{UWB_need} CR users.

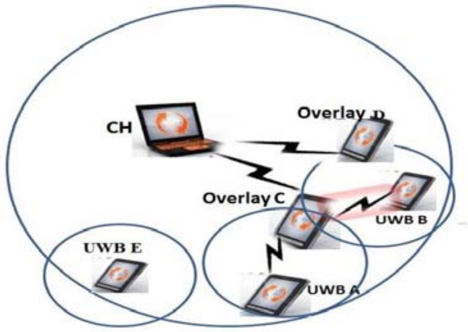

Figure 1 WLAN and UWB cooperative system

If some SUs switch from overlay to UWB, all may not be able to success in continuing communication with all cluster members. Some of the UWB users may fail if there is no, at least one, overlay CR user within their UWB coverage. To calculate the switching failure probability, we consider the following cases.

1. *Only one user tends to use UWB network*

Assume the number of Overlay CR users within the cluster is N_{ovly} and out of these overlay CR users only one user switches to UWB network. This user may fail due to the absence of overlay CR relay within its UWB coverage area. Considering uniform distribution of users in the cluster, the switching failure probability is given as follows:

Let R_{UWB} and R_{CH} be the radius of UWB user and the cluster head (CH) respectively.

The coverage area of this UWB user in the cluster is: $A = \pi R_{UWB}^2$

The probability of getting a WLAN relay in this area coverage is:

$$P_{get\_relay} = \frac{R_{UWB}^2}{R_{CH}^2} \tag{1}$$

Now the switching failure probability of system is given by:

$$P_{SF\_1} = \left(1 - \frac{R_{UWB}^2}{R_{CH}^2}\right)^{N_{ovly}} \tag{2}$$

2. *Two users tend to use UWB network*

Here we consider that there are two users which switch to UWB network. In this case we may have two conditions; (1) if both are far to each other or they do not overlap, (2) if both are close to each other and overlap. Now for the first case, the probability that the UWB users do not overlap, P_{no_ovlp}, is given as follows:

$$P_{no\_ovlp} = 1 - \frac{(2R_{UWB})^2}{R_{CH}^2}$$

For these non-overlapping UWB users, the switching failure occurs if there are no overlay CR relays in each UWB user coverage or when overlay relays present in only one of them, only one of them fails. Then the switching failure probability when there is no overlap is provided by:

$$P_{SF\_1} = \left(1 - \frac{2R_{UWB}^2}{R_{CH}^2}\right)^N + \sum_{k=1}^{N}\binom{N}{k}\left(1 - \frac{2R_{UWB}^2}{R_{CH}^2}\right)^{N-k}\left(\frac{R_{UWB}^2}{R_{CH}^2}\right)^k \tag{4}$$

In equation (4), the first term is the probability both do not have relays. The other term is the probability that only one user can have relay (divided by half).

If the UWB users are close to each other and overlap, the total coverage area of both UWB users will be smaller than those of non-overlapping. The switching failure probability of the system in this case is:

$$P_{SF\_2} = P_{SF\_no\_ovlp} + (1 - P_{no\_ovlp}) \times \left(\int_0 (P_0 + P_1) \cdot \frac{d\Delta d}{2R_{UWB}^2}\right) \tag{5}$$

Where P_0 and P_1 are the switching failure probabilities in which none of them has overlay CR relay and one of them has overlay CR relay respectively.

3. *more than two users tend to use UWB network*

In this case, there may be more than two users which switch to UWB network. Here it is difficult to formulate the switching failure probability because of many overlaps and many overlay CR relays may exist in many of these UWB users. But we can easily calculate the switching failure probability using some approximations. If there are many UWB users, we can ignore the overlaps because they are very small compared to the coverage of the cluster head. Then the approximated switching failure probability when there are NUWB users exist in the UWB network is given by:

$$P_{SF\_aprx}(N_{ovlp}, N_{UWB}) = \left(\frac{R_{CH}^2 - N_{UWB} \times R_{UWB}^2}{R_{CH}^2}\right)^{N_{ovlp}} \tag{6}$$

4. PERFORMANCE ANALYSIS

A. Simulation Environment

For our simulation, we use MATLAB R2012b simulation tool. Switching failure probability is used as simulation metric. We use the cluster head coverage area, R_{CH} 500m and

1km. And the UWB user coverage area, R_{UWB}, is used as 10m, 30m and 50m. These variations help us to understand how the cluster head and UWB radii affect the switching failure probability. We also take the overlay users that can be used as relays, N_{UWB}, from 1 to 300.

B. Simulation Results

As shown in figure 3 and 4, when the radius of UWB user is small, the switching failure probability is high. This indicates the probability of getting an overlay relay within this small area is low. On contrary, when the UWB radius is large, the switching failure probability is small as the probability of getting overlay relay users is high; compare R_{UWB} 10m and 50m.

However, when the radius of the cluster head, R_{CH}, increases the switching failure probability of the same RUWB increases, compare when R_{UWB} is 50m in figure 3 and 4, because the distance between nodes becomes large and the probability of getting overlay relay decreases. On contrary, if R_{CH} is small, the switching failure probability decreases as the number of overlay relays are dense in this small area. Therefore, to decrease the switching failure probability, we have to increase R_{UWB} and decrease R_{CH}.

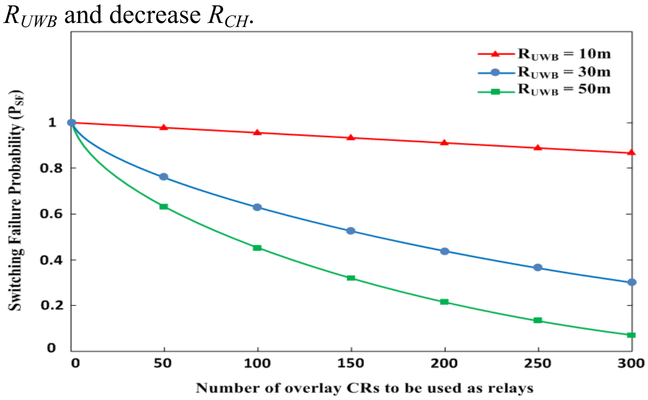

Figure 2, Switching failure probability N_{UWB} = 30 and R_{CH} = 500m

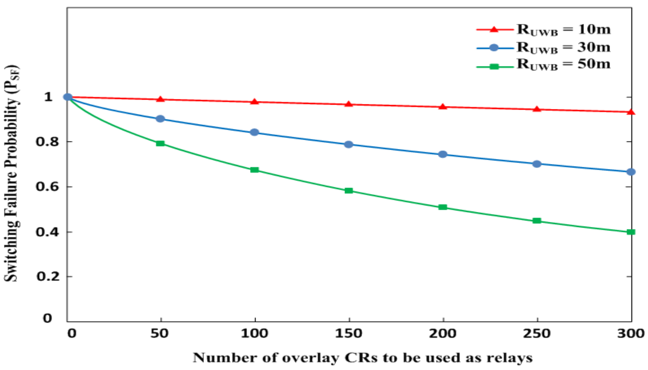

Figure 3, Switching failure probability N_{UWB} = 30 and R_{CH} = 1000m

5. CONCLUSION

In this paper we proposed a continuous control message exchange in distributed cognitive radio networks. In our proposed scheme, when PU is detected on a certain spectrum the affected CR user does not quit communication with the cluster members rather it switches to UWB and continues control message exchange until it gets spectrum hole on the overlay network. We used switching failure probability as simulation metric to solve the failure in continuing communication under the UWB network. Our simulation results showed that by decreasing R_{CH} and increasing R_{UWB}, we can decrease the communication failure in UWB. Compared to previous works of WLAN or UWB alone, our proposed scheme has enabled to have unterminated control message exchange even though PU is detected.

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