Broadcasting in Multichannel Cognitive Radio Ad Hoc Networks

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***Abstract*—Cognitive radio network technology is regarded as a new way to improve the spectral efficiency of wireless networks. It has been well studied for more than a decade and numerous precious works have been proposed. However, very few existing works consider how to broadcast messages in cognitive radio networks that operate in multichannel environments and none of these provides a full broadcast mechanism. Therefore, in this paper, we propose a broadcasting mechanism for multichannel cognitive radio ad hoc networks. Then, we analyze the mechanism regarding the speed of message dissemination, number of transmissions, portion of the users that receive the broadcast message and so forth.**

***Index Terms*—Cognitive radio ad hoc networks, multichannel, message broadcasting**

I. INTRODUCTION

A cognitive radio (CR) network is normally constructed with primary users (PUs) that are licensed to use the specific channels and secondary users (SUs) or cognitive users that are typically not licensed to utilize the channels. The beauty of CR technology is in its allowing the SUs to access the licensed channels without any harmful interference with the PUs' operations [1]. In general, SUs detect the free or idle portions of a channel and access the channel. When the PU appears on the channel that is currently used by SUs, all SUs must defer their transmissions and migrate to other available channels. Channel availability is determined by PU activities, which change dynamically in frequency, space and time; therefore, the set of available channels for each SU might also change dynamically [2]. Thus, at a given time, SUs may operate on different channels independently as shown in Figure 1 [3].

A. Problem Statement

As we all know, broadcasting is essential in many wireless network applications, such as delivering multimedia messages, route discovery in gossip based routing protocols and so on [4]. The problem is how to deliver a message to all users that are currently dwelling on different channels. Since it is a broadcast message, it should be received by all or most of the SUs in the network. Moreover, the message should be delivered to all users within a reasonable time interval. However, no existing protocol for the CR network addresses this problem. This was the main inspiration in our proposing a mechanism that enables broadcasting in multichannel CR ad hoc networks.

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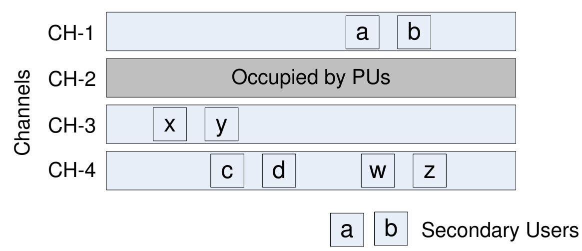

Fig. 1. At any given time, SUs may operate on different channels independently.

B. Related Works

One possible solution to enable broadcasting in a multichannel environment is using a dedicated control channel or broadcast channel [5][6]. In this approach, all users have to tune into a specific channel to receive or transmit the broadcast messages. This approach is applied in many Medium Access Control (MAC) protocols for CR networks because of its simplicity. This dedicated channel is normally called the Common Control Channel (CCC) [7]. This solution is also used in IEEE 1609.4 (standard for wireless access in vehicular environment (WAVE)) [8]. In IEEE standard 1609.4, one out of seven channels is assigned as a control channel (CCH) and the rest are called service channels (SCH). All users switch to the specific channel, the control channel, at a particular time interval, the CCH interval, to transmit and receive the broadcast messages [9]. However, this approach is not applicable in CR networks due to the lack of availability of constantly idle channels. If we assign a channel for broadcasting in a CR network, it will be susceptible to PU activities, because, when PUs appear on the dedicated control or broadcast channel, all SUs must vacate the channel immediately. If the PUs' transmission period is significantly long on the channel, the presence of the PUs may block channel access for SUs. Moreover, the available channel sets in CR networks change dynamically, hindering the establishment of an ever-available channel for all SUs. As an alternative, the authors of [10] proposed enabling broadcasting by using multiradio. Obviously, this is not a cost effective and simple solution since it requires multiple transceivers.

In our proposed mechanism, we use neither a dedicated broadcast channel nor multiple transceivers for message broadcasting. In this mechanism, all SUs just need to collaborate in message dissemination. We present a detailed description in Section II. We analyze the proposed mechanism in Section III. Then, Section IV concludes the paper. Note that, in this paper, we solely focus on message broadcasting in a multichannel network environment.

II. Broadcasting in a Multichannel Environment

A. System Model

We assume the network type is ad hoc without a centralized coordinator and that there are m available channels (CHs), $M = \{CH_1, CH_2, ..., CH_m\}$. We also assume that there are N numbers of SUs in the network and SUs are evenly distributed on available channels. Every SU in the network is equipped with a single transceiver. The channel condition is ideal, which means there are no hidden terminals, and nodes (SUs)[1] are within the transmission range of each other. If a channel is currently used by PUs, this channel is regarded as unavailable for SUs, and SUs dwell only on PU-free channels.

B. Message Broadcasting

The basic message broadcasting scheme is as follows. When an SU receives a broadcast message from upper layer applications, it will broadcasts the message by embedding a counter (r) with the message on the current operation channel, CH_i. All message transmissions follow the principle of the Distributed Coordination Function (DCF) of IEEE 802.11 [11]. Any neighboring SU that receives the broadcast message checks the counter and, if the counter is non-zero, it will retransmit the message after decreasing the counter by one. If an SU receives the same message with a different counter value, the counter value will be updated with a lower value. The message will be retransmitted until its counter reaches zero. Since SUs are evenly distributed on different channels independently, if a node transmits the broadcast message on a channel, say CH_i, only a portion of the neighbor nodes, which are currently dwelling on CH_i, will receive it. However, the message should be broadcast on every channel at least once in order to be delivered to all neighbors. Therefore, instead of the source SU transmitting the message on every channel, neighbor SUs need to collaborate in message dissemination.

When an SU broadcasts a message on CH_i with counter, r, some neighboring SUs which are currently dwelling on CH_i will receive it. When an SU receives the broadcast message on CH_i, first, it chooses one of the available channels, $CH_j \in M, i \neq j$, randomly. Then, it switches to CH_j and detects the presence of the PUs. If it detects the channel is free, it will retransmit the message after decreasing r by one. If the selected channel is occupied by PUs, it will choose another available channel. Neighbor nodes on CH_j perform the same way. They choose one of the available channels randomly and transmit the broadcast message and so on. If a channel is chosen by more than one node, nodes need to contend to broadcast the message. If a node successfully transmits the message, the rest will switch to other available channels to retransmit the message. An SU can participate more than once in message dissemination. For example, if an SU receives the same message after transmitting, and if the counter is non-zero, it will participate again by retransmitting the message. For example, if an SU receives the same message after transmitting, and if the counter is non-zero, it will participate again by retransmitting the message. Figure 2 shows message broadcasting in a multichannel environment.

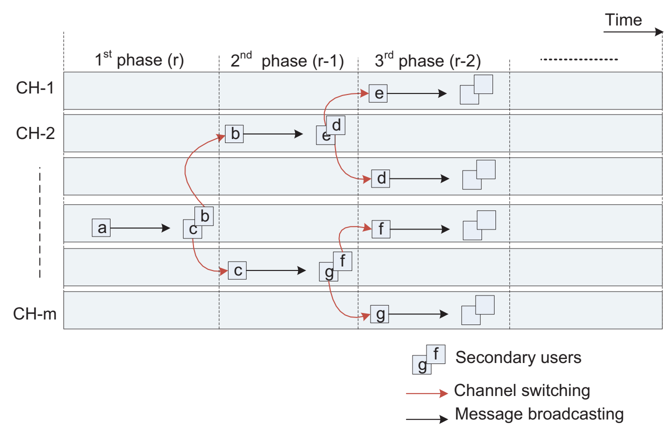

Fig. 2. Message broadcasting procedure.

C. Selecting the Counter Values

A large counter value can increase the number of users that receive the broadcast message or the probability that the broadcast message is received by all users. However, the large counter value may cause undesirable transmission overheads. If we choose a small counter value, message broadcasting will be terminated within a short time and it might not be delivered to a significant portion of users. It is not straight forward to set the counter for the messages.

As we mentioned above, if a node transmits a message successfully on CH_i and all neighbor nodes on CH_i receive it, then each node chooses one of the channels randomly for retransmission. Consider the worst case, suppose all nodes on CH_i choose the same channel ($CH_j \in M, i \neq j$) and switch to CH_j for the retransmission. Then, there will be, at most, one retransmission on CH_j in the second phase. Again, all nodes choose the same channel ($CH_k \in M, k \neq j, i$) and there will also be only one retransmission on CH_k in the third phase and so on. In order to transmit the message on

[1] In this paper, we use the terms, node and secondary user interchangeably.

every CH, the counter value should be m, since m is the total number of channels. Consider again the best case scenario as neighbor nodes choose different channels for retransmission. For example, node b chooses CH_k and c chooses CH_j, where $k \neq j$, as shown in Figure 2. Therefore, in the second phase, there will be n retransmissions on n different channels, where n is the average number of neighbor nodes on CH_i and it can be estimated as $n = N/m$. Again, if the nodes that receive the broadcast message choose totally different channels, there will be $min(n^2, m)$ retransmissions on $min(n^2, m)$ different channels and so on. Thus, the message will be transmitted on every channel within $(log_n m)$ phases. Then we can choose the counter value for the broadcast message transmissions as

$$\lceil log_n(m) \rceil < r \leq m, \tag{1}$$

where $\lceil x \rceil$ is the smallest integer not less than x.

III. Performance Evaluation

A. Message Dissemination Rate

We ran simulations to show the message dissemination rate based on the r value and the number of neighbor nodes on each CH. We assigned the number of channels as $m = 6$. Figure 3 (a) shows the portion of channels to which the nodes choose to transmit and (b) shows the ratio of users currently dwelling on the selected channels to the total users of the network. In other words, it shows the number of users that can receive the broadcast message.

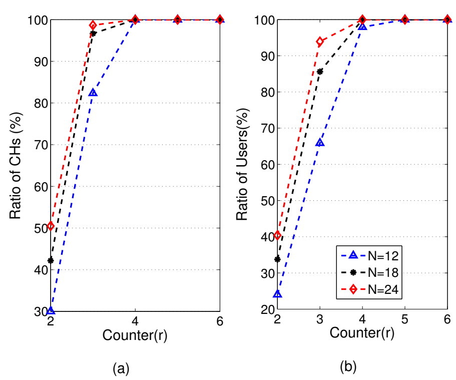

Fig. 3. (a) Portion of channels chosen for retransmission and (b) ratio of users that receive the message based on the r value.

Obviously, the message dissemination rate is totally dependent on the number of nodes in the network. If we evaluate in terms of phases, we can say that the denser the network, the faster the message dissemination. However, on the other hand, if there are many users in the network, each user has less chance to seize the channel for transmission. It can cause long transmission delays which we discuss in detail later.

B. Number of Message Transmissions

According to the proposed mechanism, the source node (the node that generates the broadcast message) transmits the broadcast message with counter value r on its current operating channel, CH_i. Any node on CH_i that receives the message chooses one of the available channels for retransmission. Let Y be the number of channels that are chosen for retransmission. Then, the probability that all neighbor nodes on CH_i choose the same channel (only one channel) is

$$P(Y = 1) = \frac{m}{m^n}. \tag{2}$$

Here, m^n represents the number of permutations with repetition of m things taken n at a time. The probability of all nodes choosing two channels for retransmission is

$$P(Y = 2) = \frac{m.(m-1).2^{n-2}}{m^n}. \tag{3}$$

Then we have a probability mass function as,

$$P(Y = y) = \frac{m(m-1)(m-2)...(m-(y-1))y^{n-y}}{m^n} = \frac{\frac{m!}{(m-y)!}y^{n-y}}{m^n}, y = 1, 2, 3, ..., n. \tag{4}$$

Let T be the number of transmissions on different channels. Generally, the expected number of T can be expressed as

$$E[T] = \begin{cases} \frac{1}{n}\sum_{i=1}^{n} i.\frac{\frac{m!}{(m-i)!}i^{n-i}}{m^n} & ,n < m \\ min(m, \frac{1}{n}\sum_{i=1}^{n} i.\frac{\frac{m!}{(m-i)!}i^{n-i}}{m^n}) & ,n \geq m. \end{cases} \tag{5}$$

According to the proposed broadcasting mechanism, the number of transmissions is exponentially increased based on r. Thus, we have the total expected number of transmissions based on r as follows.

$$\begin{aligned} E[T_{tot}] &= 1 + min(m, n^0.\frac{1}{n}\sum_{i=1}^{n} i.\frac{\frac{m!}{(m-i)!}i^{n-i}}{m^n}) \\ &+ min(m, n.\frac{1}{n}\sum_{i=1}^{n} i.\frac{\frac{m!}{(m-i)1}i^{n-i}}{m^n}) + ... \\ &+ min(m, n^{r-1}.\frac{1}{n}\sum_{i=1}^{n} i.\frac{\frac{m!}{(m-i)!}i^{n-i}}{m^n}) \\ &= 1 + \sum_{k=0}^{r-1} min(m, n^k.(\frac{1}{n}\sum_{i=1}^{n} i.\frac{\frac{m!}{(m-i)!}i^{n-i}}{m^n})) \end{aligned} \tag{6}$$

C. Average Delay for Each Broadcast Message

Here, we define the average delay as the necessary time for successful transmission of a broadcast message on every channel. We have assumed that all message transmissions follow the principle of DCF. Therefore, at a given time slot, an SU will transmit the broadcast message with probability τ. If more than one node transmits at the same time, it causes collision with probability p and we have,

$$p = (1 - (1 - \tau)^{n-1}), \tag{7}$$

where $0 < p < 1$ and $0 < \tau < 1$. The variables τ and p can be solved by the numerical method as in [11].

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Number of channels (m)	6
Data rate (B)	2 Mbps
Broadcast packet length	1024 bytes
Time Slot	$9\mu s$
SIFS	$16\mu s$
DIFS	$SIFS + 2.TimeSlot$

In every time slot, the packet will be successfully transmitted with probability p_{sus}, the packet collision occurs with probability p_{col}, or the channel is idle or busy with probabilities p_{idle} and p_{busy}. Here, let us apply some results from [12], and then we have

$$
\begin{aligned}
p_{idle} &= (1-\tau)^n \\
p_{busy} &= 1 - p_{idle} = 1 - (1-\tau)^n \\
p_{sus} &= n\tau(1-\tau)^{n-1} \\
p_{col} &= p_{busy} - p_{sus} = 1 - (1-\tau)^n - n\tau(1-\tau)^{n-1}.
\end{aligned} \quad (8)
$$

Let T_{data} denote the time for transmission of a broadcast message. T_{idle}, T_{col} and T_{sus} represent the duration of channel idle, the duration of packets collision and the duration for a successful packet transmission. Then we have,

$$
\begin{aligned}
T_{idle} &= aTimeSlot \\
T_{sus} &= T_{col} = T_{data} + DIFS. \\
T_{data} &= \frac{Data_L}{B}.
\end{aligned} \quad (9)
$$

$Data_L$ represents the total packet length of broadcast message and B denotes the data rate. Suppose, X is the time interval from channel access contention to the time when a message is successfully broadcast on a channel, then the mean of time interval X is given as

$$E[X]^2 = \frac{T_{idle}}{p_{sus}} + p_{col}\frac{T_{col}}{p_{sus}} + T_{sus}. \quad (10)$$

Then, the average delay for each broadcast message is going to be

$$E[Delay] = r.E[X]. \quad (11)$$

We ran simulations to illustrate the average delay for each broadcast message while PU activities are taken into consideration. Table 1 represents the simulation parameters we used. Broadcast packet arrivals follow the Poisson distribution and, again, all message transmissions follow the principle of IEEE 802.11 DCF [11]. In the simulations, PU appearance is random and can occur on any channel at any time. When a PU appears on a channel, we assume that this channel is no longer available for SUs and all SUs vacate to other available channels. As shown in Figure 4, the average delay is slightly increased while the number of PUs in the network increases. This is because high PU activities can decrease the number of available channels for SUs. SUs need to share less available channels. Thus, SUs require more time on contention to seize the channels for message broadcasting. It increases the value of $E[X]$. On the other hand, if the network has fewer available channels, it will require a small counter value for broadcasting, as discussed in Section II. Nonetheless, for simplicity, we used $r = 4$ in our simulations.

[2]Detailed proof for E[X] can be seen in [12].

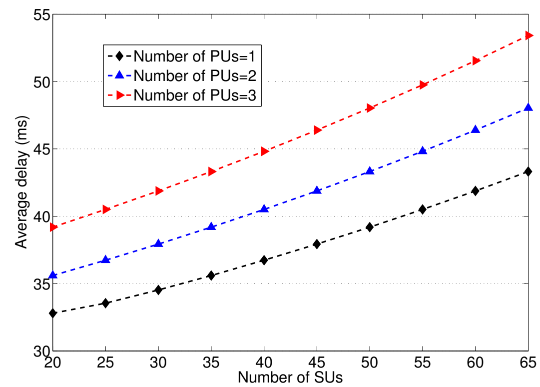

Fig. 4. Average delay for message broadcasting.

We also evaluated our mechanism regarding the message delivery ratio, the proportion of the successfully transmitted messages to the number of total messages which arrive. The message delivery ratio is also slightly affected by PU activities and the numerical result can be seen in Figure 5. Similarly to the previous results, high PU activities cause less channel access time for SUs and degrade the packet delivery ratio of the secondary network.

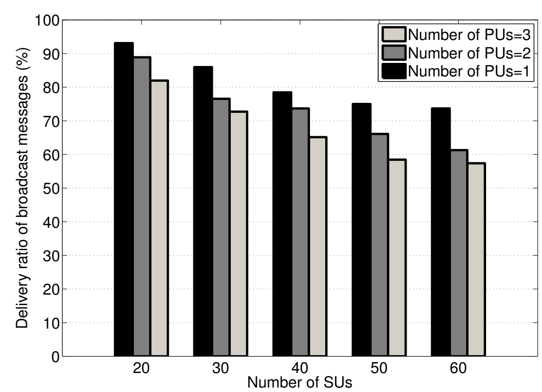

Fig. 5. Successful packet delivery ratio

IV. CONCLUSION

We have presented a broadcasting mechanism for multichannel CR ad hoc networks. This mechanism enables broadcasting in multichannel environments without using a dedicated broadcast channel or multiple transceivers. Then, we showed the average time necessary for broadcasting a message over a multichannel environment. In future works, we will analyze our proposal in more depth, considering the PU actives on each channel.

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