Probabilistic Selective Broadcast for energy-saving communications in Cognitive Ad Hoc Networks

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Abstract. Cognitive radio, as a promising technology, plays an important role in ad hoc network communications, leading to more reasonable and orderly utilizations of wireless spectrum resources. It is not only an opportunity but also a challenge for wireless mobile communications. In cognitive radio ad hoc networks, the non-uniform channel arrays available for secondary users make it difficult to the application of broadcasting technologies, concentrating on common channel selection and broadcast collision. In this paper, a probabilistic selective broadcast, called pSB, is proposed, aiming at economy and energy-saving distributed wireless communications. The protocol adopts an intelligent channel selection policy with a probabilistic forwarding strategy to alleviate collisions caused by redundant message exchanges. Consequently, the proposed pSB outperforms other methods in terms of higher message reach rates and fewer broadcast collisions evaluated by simulations under different parameter configurations.

1. Introduction
A cognitive radio ad hoc network (CRAHN) collects the licensed users, defined as primary user (PU), the unlicensed users, defined as secondary user (SU) and a large number of spectrum resources with different access permissions together for efficient and reliable distributed communications. Since PUs may stay in any of licensed channels at unpredictable moment, SUs will first sense and determine which channels and when they are free to access. The capability of SUs makes better spectrum utilizations. Generally, each SU maintains its own channel set for data acquisition and the available channels may be the same or different from others. Assume that SUs equip with a single radio so that they can access one channel at a time. In other words, communication succeeds only if the transceivers are operating on the same channel at the same time. Therefore, a hard problem is how to find such common channel and guarantee the successful transmissions.

There are various elements involved in decision makes of channel selection, such as transmission rate, communication timeline, nodes’ states, topology, spectrum status and so on. Particularly, a trade-off between delay and reachability is actually important for broadcasting design in CRAHNs. Authors in [1] provided a speedy policy to get the channel selection, but the fuzzy logic method does not contribute to increase successful delivery ratio. Moreover, Sureshkumar et al. categorized the popular approaches concerning broadcast issues in the field [2]. Random broadcast scheme is flooded with randomicity in channel selections and thus is at great risk to find a common channel. Full broadcasting
scheme [3] represented another extreme case. Message transmissions are performed by sending and listening through all allocated channels sequentially. Although the message reachability is guaranteed, this method causes a fairly high broadcast delay, especially when the number of SUs and available channels is large. On balance, an intelligent solution is to construct a subset of channels from the total available ones of each SU, i.e. selective broadcast scheme [4] and minimum broadcast scheme [5], taking into account the global network topology and spectrum status of every node. Neighbour information is helpful for channel negotiation to balance the successful rate against the delay even though the information is hard to be maintained during the ad hoc broadcasting.

There are many literatures state "beacon" for coordinating the coming radios to the first radio to synchronize their tx and rx frequencies into a same channel. Oh et al. [6] summarized the possible access techniques in CR including beacon and others. A beacon based neighbor discovery method was put forward in [7] to get one-hop neighbour information. Every CR node classifies its channels based on neighbor information and a joint transmitter-receiver channel selection method is proposed to increase the reliability and the reachability of data dissemination. Kondareddy et al. in [4] proposed a neighbor graph to track channel information of neighbours. Some other papers investigate method without any neighbor information and most of them are based on channel hopping. In [8], two channel hopping algorithms called generated orthogonal sequence (GOS) algorithm and modular clock (MC) algorithm were proposed. However, both algorithms have limitations. GOS is only suitable when two users have the same available channel sets and MC introduces unpredictable delay in different cases. A common control channel design for CR ad hoc networks was proposed, called as adaptive multiple rendezvous control channel (AMRCC) based on frequency hopping in [9]. But the scheme cannot guarantee rendezvous in a finite time. Although a jump-stay based channel-hopping algorithm was proposed for guaranteed delay in [10], the expected delay increases exponentially along with the total number of channels. Also, a broadcast protocol under blind information for multi-hop CR ad hoc networks was proposed in [3] to provide QoS (success rate and average delay) support.

Collision is an along-standing problem in terms of broadcasting. It may occur frequently because the unnecessary replicated messages are rebroadcast; or because there are multiple SUs attempting to use a same channel for rebroadcasting. There are very limited papers addressing the collision issue in CRAHNs. A typical example was found in [11][12] that the authors managed to overcome transmissions at the same time. This paper may make contributions to the issue by adopting a probabilistic forwarding strategy in selective broadcast, called pSB. It challenges the conventional selective broadcast scheme (SB), which presents a wise channel selection method for transmissions but suffers from serious broadcasting collisions resulting in the low success rates of message deliveries. Simulation outcomes provide proof of higher communication performances regarding message reach rate and broadcast collisions in various simulation scenarios.

Following the introduction, Section 2 formulates problems in details. For the problem of redundant broadcasts, further discussions and corresponding simulation findings are given afterwards. Meanwhile, the performance of pSB is verified by comparing with the numerical results obtained by implementing FB, SB, acSB protocols. Finally, we conclude the paper.

2. Problem formulation
In a CRAHN system, there are $N_P$ PUs and $N_S$ SUs randomly distributed in a fixed-size area, sharing totally $M$ system channels. PUs may release channels at any moment leading to unpredictable amount of free channels. Referring to the birth-death process [13], the probability ($\rho$) of the $i^{th}$ PU being active is given as formula (1).

$$\rho^i = \frac{\lambda_i}{\lambda_i + \mu_i}, i \geq 1, \mu_0 = 0$$

where $\lambda_i$ and $\mu_i$, as the expectation of random variables, indicate birth rate and death rate of the $i^{th}$ PU respectively. Then, a probability ($P$) that PU is active can be obtained by formula (2). The lower $P$ implies the more idle channels that are available for SUs.
\[ P = \prod_{i \in \text{ESC}} p^i \]  

2.1. Problem 1: Multi-channel broadcast in CRAHNs

In a traditional ad hoc network, there is a common control channel defined for nodes’ broadcasting, but not in a CRAHN. In such system, SUs can sense an idle channel set (ICS) of the system before communications. The available channel sets (aCS) with aCS \( \subseteq \) iCS are allocated depending on their conditions such as position, mobility, energy and so on. Generally, aCS \((i)\) could be of different sizes and elements. As shown in [9], \( S_1 \) and \( S_2 \) with aCS(1) = \{c_1, 5\} and aCS(2) = \{5, c_2\} respectively. \( c_i \) and \( c_j \) represent a different size of channel IDs that \( 5 \notin c_i \), \( 5 \notin c_j \), \( c_i \cap c_j = \text{null} \) and \( c_k, c_l \in \mathbb{N} \). The communication succeeds only if both SUs choose the 5th channel. Consequently, a vexed problem emerges that how to determine a same channel connecting sender SU and its neighbors at the same time.

To solve this problem, a simplest method is to apply full broadcast (FB) policy in CRAHNs. As mentioned in the previous section, this approach can guarantee a high ratio of message transmissions but it has to pay for that by very large delays [14]. An improved protocol, selective broadcast (SB), is primarily put forward by Kondareddy et al. [4] and the advantage of this method has been proved via a 1000-run simulation in an aspect of smaller delays (38.7s less) along with good reachability of messages (97.5%) between SB and FB, as in Table 1.

Table 1. Average Data by SB and FB protocols

| Protocol | **TD (s)** | RR (%)  | BC (%) |
|----------|------------|---------|--------|
| SB       | 8.13       | 97.5    | 22.29  |
| FB       | 46.83      | 96.4    | 35.71  |

\( *M \): total number of channels; \( P_{iC} \): idle channel probability; \( N_{5} \): the ratio of SUs' neighbors; \( N_{S} \): the number of SUs; **TD**: transmission delay; **RR**: message reach rate; BC: broadcast collision.

The corresponding calculations are given by formula (3) and (4):

\[ TD = M^* \times T \]  

\[ RR = \frac{N_{5}}{N_{S}} \times 100\% \]  

SUs organize their neighbor graphs (NG) in which neighbor SUs and their communicating channels are included and thus lower transmission delays by reducing the number of broadcasting channels. For example, a SU \( S_i \) with assigned channels \{1, 2, 3\} maintains its NG with neighbors \( \{S_i, S_2, S_3\} \) and using channels \{1, 2\}, \{2, 3\} and \{1\} separately. In such case, the degrees of channel 1, 2 and 3 used by SU pairs are \{2, 2, 1\}, constructed in minimal neighbor graph (mNG) as DC. From DC, SUs can find their essential channel set (ECS) for broadcasting. In DC, both channel 1 and 2 have been used twice. Then, channel 1 is selected as the first element of ECS. Since only channel 3 left in the DC, it is added to ECS(1), where ECS(1) = \{1, 3\}. Finally, \( S_i \) broadcasts the message following ECS(1) sequentially.

This project makes an intensive study on SB policy to seek high matching rates of transmission channels from unequal aCSs of SUs and their neighbors in CRAHNs. However, this may not be enough, we have to pay more attention to another urgent and persistent problem which particularly belongs to distributed communications.

2.2. Problem 2: Redundant broadcast for a CRAHN message

Without broadcast collisions, ideally, the SB approach can lead to 100% percentage of message delivery in CRAHNs. However, they are just hard to be evaded. There are many reasons, such as simultaneous
rebroadcast under a same channel [12] and redundant broadcast for the same message. In this project, we specially explore a solution for the latter.

Redundant broadcast implies copying behaviors for a same message by CRAHN nodes. Taking an example from Figure 2, $S_1$ has neighbors $\{S_2, S_3, S_4, S_5, S_6\}$. At time $T_0$, $S_1$ communicates its neighbors using channels $\{1, 2, 3, 4, 5\}$ separately. Next $S_2$, $S_3$, $S_4$ broadcast the same message to $S_7$ on the 3rd channel at time $T_1$; meanwhile $S_4$ and $S_5$ broadcast the message to $S_8$ via channel 2 and 4 and $S_6$ broadcasts the message to $S_9$ by the 6th channel. Although the message reaches at all SUs finally, every $S_i$ has to consume energies. From the views of economic and energy consumption, it is unnecessary to broadcast a same message by all neighbors, especially in a network that a SU has a large number of neighbors. Once again, the same result can be obtained by using one of $S_2$, $S_3$, $S_4$ and one of $S_5$ and $S_6$, namely 33% of the total amount of original broadcasters.

![Figure 1. An example of redundant broadcast](image)

**Algorithm 1. Probabilistic Broadcast**

| Input: $ECS(i)$, $\alpha$, $aCS(j)$ |
|--------------------------------------|
| Output: $BS(S_j)$                     |

$S_j$ receives a message from $S_i$ with $ECS(i)$;

$\alpha = \{aCS(j) \notin ECS(i)\}$;

Obtain $P_r(S_j)$ by formula (3);

IF $P_r(S_j) > \mu$

$BS(S_j) = TRUE$;

ELSE

$BS(S_j) = FALSE$;

END

A probabilistic broadcast scheme which limits the amount of rebroadcasts is introduced into the original SB method as Probabilistic Selective Broadcast ($pSB$). It challenges for alleviating detrimental effects of broadcasting events caused by message redundancy. As described in Algorithm 1, once $S_j$ receives a message from its parent SU $S_i$, it should consider whether or not it is a rebroadcast candidate. Firstly, $S_j$ invokes its assigned channel set $aCS(j)$. The elements those are different from the elements of $ECS(i)$ of $S_i$ will be inserted into a set $\alpha$. After that, a probability of $S_j$ is given by the formula (5), where $L$ means the size of a channel set. $P_r(S_j)$ compares with a preset threshold value $\mu$. If and only if $P_r(S_j)$ is greater than $\mu$, where $\mu \in (0,1)$, $S_j$ is a qualified forwarding candidate.

$$P_r(S_j) = \frac{L(\alpha)}{L(aCS(j))}$$  \hspace{1cm} (5)

3. Discussion and proof

3.1. Discussion 1: The larger size of $N_{nb}D$ leads to the higher possibility of redundancy transmissions. Let $N_{nb}D$ denote as neighbor density, which means the amount of neighbours around each SU, expressed as a percentage. In an area with a fixed dimension and parameters such as $M$ and $P$, cases in Figure 3 can be formulae as follows: 1) all SUs are the neighbour of each other, then $N_{nb}D = 1$ (Figure...
3 a); 2) SUs own a certain number of neighbours, then $N_{nb} \in (0, 1)$ (Figure 3b&3c); 3) all SUs are not the neighbour of each other, then $N_{nb} = 0$ (this situation is not considered here).

Now, a concerning point is whether or not the proposed broadcast protocol pSB could provide a high ratio of successful message delivery even though any of SUs are surrounded by neighbor nodes.

![Figure 2. Neighbor density: dense, moderate, sparse](image)

3.2. Discussion 2: the larger value of $\mu$ leads to the less rebroadcast candidates.

Maintaining $P_r$ of a SU fixed in one observation period, high value of $\mu$ could control the number of redundant broadcasts within a satisfactory range. In other words, forwarding activities are carried out by conditional SUs only.

Now, a key point becomes whether or not pSB could provide a high ratio of successful message delivery by only SUs who satisfies criteria $P_r > \mu$.

To observe and study above discussions and then validate the effects of pSB in collision controls, simulations over 1000 runs are carried out with the number of channels $M=50$, the number of SUs $N_S \in (20, 50)$, the probability of active PU $P \in (0, 1)$ % and neighbor density $N_{nb} \in (0.1, 1)$ % subsequently.

As seen in 3, RR and BC are observed by giving different threshold value $\mu$. It is noticed that $\mu=0.8$ is a turning point that the reachability of messages decreases for all cases of neighbor density. Particularly, when $\mu$ is between 0.7 and 0.8, collisions start to fall (3b) and meanwhile the reach rates of messages keep stable (3a), even though $N_{nb}D$ is up to 100%. These results are in consistent with theoretical predictions that pSB can find a proper $\mu$ to select forwarders who satisfies the criteria $P_r > \mu$ and thus minimize unnecessary broadcast collisions.

![Figure 3. RRs and BCs of pSB with given $\mu$](image)

Further simulations work on SB, acSB [12] and pSB protocols, observing the average ratio of successful transmissions. Simply, acSB is a protocol adopting SB principles for channel selection and utilizing an asynchronous rebroadcast mechanism to deal with the problem of broadcast collisions. In Figure 5, when $N_{nb}D$ reaches to be 100%, SB obtains the lowest reach rate. In addition, pSB with 0.9 of $\mu$ provides a linear growth of RRs without obvious advantages. However, acSB and pSB with 0.5 of $\mu$
outperform others. Their RRs sharply increase to be 100% from the original average data of 77% and stay in 100% level afterwards ($N_{nb}D > 0.2$). Apparently, $pSB$ with a certain $\mu$ requires less consumption of energy and resources during transmissions when compared with $acSB$.

![Figure 4. RRs among SB, acSB and pSB protocols](image)

4. Conclusion
This paper proposes a probabilistic selective broadcast scheme, $pSB$, to perform efficient common channel selection among non-uniform available channel sets of SUs and, significantly, to weaken broadcast collisions caused by redundant broadcasting in dense CRAHNs. The numerical results support for several concerning discussions. Firstly, communications in a dense network or an area with dense surrounding neighbors can maintain a high ratio of message exchanges (up to 100%). Besides, the use of a certain value of $\mu$ (such as 0.5) can properly prevent duplicate message forwarding. In conclusion, $pSB$ not only obtains results as good as those collected by an advanced anti-collision protocol, $acSB$, but also makes economy and energy-saving communications be possible.

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