A Novel Unified Analytical Model for Broadcast Protocols in Multi-Hop Cognitive Radio Ad Hoc Networks

Yi Song, Jiang (Linda) Xie, and Xudong Wang

Abstract—Broadcast is an important operation in wireless ad hoc networks where control information is usually propagated as broadcasts for the realization of most networking protocols. In traditional ad hoc networks, since the spectrum availability is uniform, broadcasts are delivered via a common channel which can be heard by all users in a network. However, in cognitive radio (CR) ad hoc networks, different unlicensed users may acquire different available channels depending on the locations and traffic of licensed users. This non-uniform channel availability leads to several significant differences and causes unique challenges when analyzing the performance of broadcast protocols in CR ad hoc networks. In this paper, a novel unified analytical model is proposed to address these challenges. Our proposed analytical model can be applied to any broadcast protocol with any CR network topology. We propose to decompose an intricate network into several simple networks which are tractable for analysis. We also propose systematic methodologies for such decomposition. Results from both the hardware implementation and software simulation validate the analysis well. To the best of our knowledge, this is the first analytical work on the performance analysis of broadcast protocols for multi-hop CR ad hoc networks.

Index Terms—Cognitive radio ad hoc networks, unified analytical model, network-wide broadcast, channel hopping, non-uniform channel availability

1 Introduction

The rapid growth of wireless devices has led to a dramatic increase in the demand of the radio spectrum. However, according to the Federal Communications Commission (FCC), almost all the radio spectrum for wireless communications has already been allocated. To alleviate the spectrum scarcity problem, FCC has suggested a new paradigm for dynamically accessing the allocated spectrum [1]. Cognitive radio (CR) technology has emerged as a promising solution to realize dynamic spectrum access (DSA) [2]. Unlicensed users (or, secondary users) equipped with the CR technology can form a CR infrastructure-based network or a CR ad hoc network to opportunistically exploit the licensed channels which are not used by licensed users (or, primary users) [3].

In CR ad hoc networks, control information exchange among nodes, such as channel availability and routing information, is often sent out as network-wide broadcasts (i.e., messages that are sent to all other nodes in a network) [4]. Such control information exchange is crucial for the realization of most networking protocols. In addition, some exigent data packets such as emergency messages and alarm signals are also delivered as network-wide broadcasts [5]. Therefore, broadcast is an essential operation in CR ad hoc networks.

Even though the broadcasting issue has been studied extensively in traditional mobile ad hoc networks (MANETs) [6]–[10], research on broadcasting in multi-hop CR ad hoc networks is still in its infant stage. There are a few papers addressing the broadcasting issue in multi-hop CR ad hoc networks [11]–[14]. However, these proposals mainly focus on broadcast protocol designs. The performance analysis of these proposed protocols is simulation-based. Thus, the analytical relationship between these proposals and their performance is not known. More importantly, without analytical analysis, the system parameters in these protocols are not designed to achieve the optimal performance. In fact, analytical analysis is beneficial not only for better understanding the nature of a proposed protocol, but also for better designing the system parameters of a protocol to achieve the optimal performance. It can also provide useful insights to guide the future broadcast protocol designs in CR ad hoc networks. Hence, in this paper, we focus on the analytical analysis of broadcast protocols for multi-hop CR ad hoc networks.

Although a vast amount of analytical works on broadcast protocols in traditional MANETs exist [15]–[19], currently, there is no analytical work on broadcast protocols in multi-hop CR ad hoc networks. More importantly, all the methods proposed for traditional MANETs cannot be simply applied to multi-hop CR ad hoc networks. This is because that in traditional MANETs, the channel availability is uniform for

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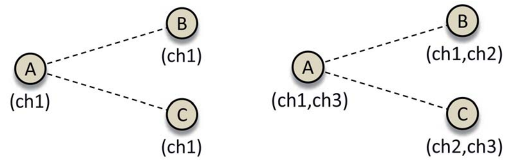

(a) (b)

Fig. 1. Single-hop broadcast scenario. (a) Traditional ad hoc networks. (b) CR ad hoc networks.

all nodes, as shown in Fig. 1(a). However, in CR ad hoc networks, different secondary users (SUs) may acquire different available channel sets, depending on the locations and traffic of primary users (PUs), as shown in Fig. 1(b). This non-uniform channel availability leads to several significant differences and causes unique challenges when analyzing the performance of broadcast protocols in CR ad hoc networks.

First of all, unlike in traditional MANETs, in CR ad hoc networks, the single-hop broadcast is not always successful in an error-free environment. The reason can be illustrated using Fig. 1. If node *A* is the source node, in traditional MANETs, all its neighboring nodes can tune to the same channel to receive the broadcast message. However, in CR ad hoc networks, such a common available channel for all neighboring nodes may not exist [20]–[24]. As a result, the broadcast may fail. More severely, even if a common available channel exists between the source node and its neighboring nodes, they may not be able to tune to that channel at the same time, which will also result in a failed broadcast. In fact, whether the single-hop broadcast is successful depends on the channel availability of each SU which is time-varying and location-varying. Due to the uncertainty of the single-hop broadcast success, the successful broadcast ratio of a network is usually random. Furthermore, since there usually exist multiple message propagation scenarios for all the nodes to successfully receive the broadcast message in a multi-hop CR ad hoc network, it is extremely challenging to identify every possible message propagation scenario for calculating the successful broadcast ratio in a complicated network. An example illustrating this challenge will be given in Section 2.1.

Secondly, different from traditional MANETs where the relative locations of the communication pair do not impact the successful receipt of the message as long as they are within the transmission range of each other, in CR ad hoc networks, the probability that a node successfully receives a broadcast message is affected by the relative locations between the sender and the receiver. This is because that the available channels of a SU are obtained based on the sensing outcome from the proximity of the node. Thus, SU nodes that are close to each other have similar available channels and they may have higher successful broadcast ratio, as compared with the SU nodes far away from each other whose available channels are often less similar. These two differences show that the successful broadcast ratio is affected by various factors and it is random. Currently, there is no straightforward solution to analyze this issue.

Thirdly, the single-hop broadcast delay is usually more than one time slot in CR ad hoc networks, while in traditional MANETs, it is always one time slot. As shown in Fig. 1(a), node *A* only needs one time slot to let all its neighboring nodes receive the broadcast message in an error-free environment. However, in CR ad hoc networks, due to the non-uniform channel availability, node *A* may have to use multiple channels for broadcasting and may not be able to finish the broadcast within one time slot. In fact, the exact broadcast delay for all single-hop neighboring nodes to successfully receive the broadcast message in CR ad hoc networks relies on various factors (e.g., channel availability and the number of neighboring nodes) and it is also random. Moreover, since there may exist multiple message propagation scenarios, to identify which node is the last node in a network to receive the message is very difficult. Thus, the multi-hop broadcast delay is extremely difficult to obtain.

Finally, broadcast collisions are complicated in CR ad hoc networks. Unlike in traditional MANETs where nodes use a common channel for broadcasting, in CR ad hoc networks, nodes may use multiple channels for broadcasting. Without the information about the channel used for broadcasting and the exact delay for a single-hop broadcast, to predict when and on which channel a broadcast collision occurs is extremely difficult. Hence, to mathematically analyze broadcast collisions is very challenging for multi-hop CR ad hoc networks under practical scenarios.

In summary, due to the randomness of the single-hop successful broadcast ratio and broadcast delay, the broadcast performance of a multi-hop CR ad hoc network is extremely challenging to analyze. Currently, no existing work on CR ad hoc networks addresses these challenges. Moreover, due to the above explained differences, the analytical methodology for broadcast protocol analysis in tradition MANETs cannot be extended to CR ad hoc networks. Specifically, the existing performance analytical papers on broadcasting in traditional multi-channel ad hoc networks cannot reflect the unique features (e.g., non-uniform channel availability and channel rendezvous schemes) in multi-hop CR ad hoc networks because: 1) a common control channel is used for broadcasting [25]–[29]; 2) only single-hop scenario is considered [25],[27],[30]; 3) a centralized entity is needed to schedule the broadcast [30]; and 4) multiple radios are used [31]. Therefore, in this paper, we study the performance analysis of broadcast protocols for multi-hop CR ad hoc networks. A novel unified analytical model is proposed to analyze the broadcast protocols in CR ad hoc networks with any topology. Specifically, in this paper, we propose to decompose an intricate network into several simple networks which are tractable for analysis. We also propose systematic methodologies for such decomposition. The main contributions of this paper are given as follows:

1) *An algorithm for calculating the successful broadcast ratio* (i.e., the probability that all nodes in a network successfully receive a broadcast message) is proposed for CR ad hoc networks. The proposed algorithm is a general methodology that can be applied to any broadcast protocol proposed for multi-hop CR ad hoc networks with any topology.
2) *An algorithm for calculating the average broadcast delay* (i.e., the average duration from the moment a

broadcast starts to the moment the last node in the network receives the broadcast message) is proposed for CR ad hoc networks under grid topology.

3) *The derivation methods of the single-hop performance metrics*, successful broadcast ratio, average broadcast delay, and broadcast collision rate (i.e., the probability that a single-hop broadcast fails due to broadcast collisions), for three different broadcast protocols in CR ad hoc networks *under practical scenarios* (e.g., no dedicated common control channel exists and the channel information of any other SUs is not known) are proposed.

4) *A hardware system is developed to implement different broadcast protocols* in multi-hop CR ad hoc networks and validate our proposed unified analytical model.

To the best of our knowledge, this is the first analytical work on the performance analysis of broadcast protocols for multi-hop CR ad hoc networks.

The rest of this paper is organized as follows. The algorithm for calculating the successful broadcast ratio is proposed in Section 2. The proposed algorithm for approximating the average broadcast delay is presented in Section 3. In Section 4, three existing broadcast protocols for multi-hop CR ad hoc networks under practical scenarios and the derivations of their single-hop performance metrics are introduced. The proposed algorithms are validated in Section 5, followed by the conclusions in Section 6.

2 Calculating the Successful Broadcast Ratio

In this section, we present the proposed algorithm for calculating the successful broadcast ratio of a broadcast protocol in multi-hop CR ad hoc networks. We first introduce a unique challenge of calculating the successful broadcast ratio. Then, the details of the proposed algorithm are presented. In addition, an example is given to show the process of the proposed algorithm. For simplicity, we assume that the wireless channels are error-free (i.e., the white noise of the channels is ignored). However, the probability that a broadcast fails due to the channel noise can be easily added in our analysis, if necessary. In the rest of the paper, we use the term "sender" to indicate a SU who has just received a broadcast message and will rebroadcast the message. In addition, we use the term "receiver" to indicate a SU who has not received the broadcast message yet.

2.1 The Unique Challenge

Let $G(V, E)$ denote the topology of a CR ad hoc network, where V is the set of all SU nodes in the network and E is the set of all links in the network. The problem of calculating the successful broadcast ratio is described as: given a CR ad hoc network $G(V, E)$, from the source node v_s, every other node follows a certain rule to rebroadcast (e.g., simple flooding or the broadcast scheduling algorithm used in the distributed broadcast scheme in [14]), what is the successful broadcast ratio of $G(V, E)$?

As mentioned in Section 1, the single-hop successful broadcast ratio may not always be one in CR ad hoc networks due to various reasons. Therefore, a SU may not be able to receive the broadcast message from its direct parent node. However, during the broadcast procedure, it may receive the message from other nodes via different paths in the network. This is different from the broadcast schemes in traditional MANETs, where nodes usually receive broadcast messages from their parent nodes. This feature imposes a special challenge of calculating the successful broadcast ratio for the whole CR ad hoc network. That is, there exist multiple message propagation scenarios for all the nodes to successfully receive the message. The overall successful broadcast ratio is the sum of the successful broadcast ratio of all these propagation scenarios. However, it is extremely challenging to calculate the successful broadcast ratio for every message propagation scenario when the network topology is complicated.

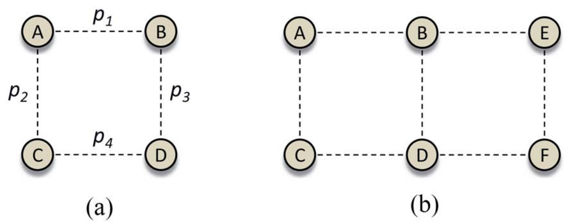

Fig. 2. Example for showing the unique challenge when calculating the successful broadcast ratio. (a) 2×2 grid network. (b) 2×3 grid network.

To further illustrate this challenge, we consider a simple 2×2 grid network shown in Fig. 2(a), where node A is the source node. There are four links in the network, where the successful broadcast ratio over each link is given. The single-hop successful broadcast ratio depends on the specific broadcast protocol used. The method to obtain the single-hop successful broadcast ratio may be different for different protocols. We will explain the methods for calculating the single-hop successful broadcast ratio for various protocols in Section 4. If simple flooding is used to propagate the message, there are totally seven different scenarios for all nodes to successfully receive the message. They are: 1) $A \to B \to D \to C$; 2) $A \to B \to D$ and $A \to C$; 3) $A \to B$ and $A \to C \to D$; 4) $A \to C \to D \to B$; 5) $A \to B \to D$, $A \to C \to D$ and B, C do not have a collision at D; 6) $A \to C \to D \to B$, $A \to B$ and A, D do not have a collision at B; and 7) $A \to B \to D \to C$, $A \to C$ and A, D do not have a collision at C. Accordingly, since the broadcast events to different SU nodes are independent, the successful broadcast ratio for these seven scenarios is: $p_1(1-p_2)p_3p_4$, $p_1p_2p_3(1-p_4)$, $p_1p_2(1-p_3)p_4$, $(1-p_1)p_2p_3p_4$, $p_1p_2p_3p_4-p_{q1}$, $p_1p_2p_3p_4-p_{q2}$, and $p_1p_2p_3p_4-p_{q2}$, where p_{q1} is the probability that B and C fail to broadcast to D due to broadcast collisions and p_{q2} is the probability that A and D fail to broadcast due to broadcast collisions. The probability that two nodes have a collision also depends on the specific broadcast protocol used. Therefore, the overall successful broadcast ratio is the sum of the successful broadcast ratio of these seven scenarios, that is,

$$P_{succ}=p_1(1-p_2)p_3p_4+p_1p_2p_3(1-p_4)+p_1p_2(1-p_3)p_4+(1-p_1)p_2p_3p_4+(p_1p_2p_3p_4-p_{q1})+2(p_1p_2p_3p_4-p_{q2}). \quad (1)$$

Then, we increase the dimension of the grid network to 2×3, as shown in Fig. 2(b). If simple flooding is used, the total number of message propagation scenarios is 40. The

TABLE 1
Notations Used in the Proposed Algorithm 1

$E(v)$	The set of all the links that connect to node v
$e(v,u)$	The link that connects node v and u
$P(v,u)$	The successful broadcast ratio from node v to u
$P(G(V,E))$	The successful broadcast ratio of the network $G(V,E)$
$P_q(v,u,k)$	The probability that node v and u fail to broadcast to node k due to broadcast collisions
$\lvert\cdot\rvert$	The number of elements in a set

overall successful broadcast ratio is the sum of the successful broadcast ratio of all these 40 message propagation scenarios. Note that although only 2 additional nodes and 3 additional links are added, the total number of propagation scenarios increases significantly. Moreover, if the grid network size is 2×4, the total number of message propagation scenarios is 252. If we further increase the dimension of the grid network to 3×3, it is almost impossible to obtain the successful broadcast ratio of every possible message propagation scenario. Therefore, when the number of nodes and links increases in a CR ad hoc network, the total number of message propagation scenarios increases exponentially. It is extremely challenging to identify every possible message propagation scenario and calculate the successful broadcast ratio for each scenario in a complicated network.

2.2 The Proposed Algorithm

We develop an iterative algorithm to address the above challenge. The main idea of the proposed algorithm is to decompose a complicated network into a few simpler networks so that the successful broadcast ratio of these simpler networks is straightforward to obtain and the complexity of the original network can be reduced. Then, the successful broadcast ratio of the overall network can be acquired. The notations used in the proposed algorithm are listed in Table 1. The pseudo-codes of the proposed algorithm for calculating the successful broadcast ratio is shown in Algorithm 1.

Under the proposed algorithm, at each iteration round, a link that connects to the source node is randomly selected. Based on whether the broadcast over this link is successful or not, the network is decomposed into two simpler networks. If the broadcast over this link is successful, all links that connect to the other node of the selected link will connect to the source node. If the broadcast over this link fails, this link is simply removed from the network. The successful broadcast ratio over each remaining link is updated accordingly after each iteration. The process terminates when only two nodes are left in the remaining networks.

2.3 An Illustrative Example

We use an example to illustrate the process of the proposed Algorithm 1. As shown in Fig. 3(a), the original CR ad hoc network consists of 4 nodes and 5 links. Based on Algorithm 1, since the source node v_s has two links, we randomly select one of these two links (e.g., link $e(v_s,v_2)$). In the first iteration, if the broadcast over the link $e(v_s,v_2)$ is successful, all nodes that are originally connected to v_2 are connected to the source node, as shown in Fig. 3(b). In addition, the successful broadcast ratios of the new links are updated. That is, $P(v_s,v_3)=P(v_2,v_3)=p_5$ and $p'_1=1-(1-p_1)(1-p_3)-P_q(v_s,v_2,v_1)$ because the message propagation scenarios in the original network for v_1 to successfully receive the message directly from v_s or

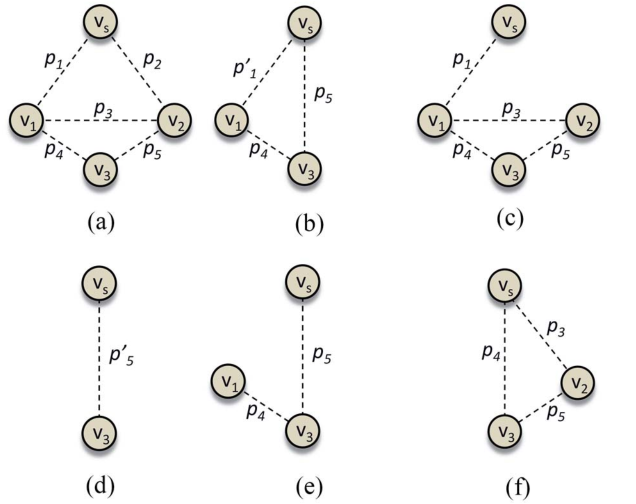

Fig. 3. Process of the proposed Algorithm 1 for a 4-node CR ad hoc network. (a) original network. (b) Link $e(v_s,v_2)$ is successful. (c) Link $e(v_s,v_2)$ is failed. (d) Link $e(v_s,v_1)$ is successful after (b). (e) Link $e(v_s,v_1)$ is failed after (b). (f) Link $e(v_s,v_1)$ is successful after **??**.

Algorithm 1: The proposed algorithm for calculating the successful broadcast ratio.

Input: The topology of the network $G(V,E)$, the source node v_s.
Output: $P(G(V,E))$.
if $|V|>2$ **then**
  if $|E(v_s)|>1$ **then**
    $E_1\leftarrow E$; $V_1\leftarrow V$; /* initialization */
    $E_2\leftarrow E$; $V_2\leftarrow V$;
    Randomly select $e(v_s,v_i)\in E(v_s)$;
    foreach $v_k, e(v_i,v_k)\in E(v_i)$ **do**
      $E_1\leftarrow E_1+e(v_s,v_k)$; /* original link to v_i is connected to v_s */
      if $e(v_s,v_k)\in E(v_s)$ **then**
        $P(v_s,v_k)\leftarrow$
        $1-(1-P(v_i,v_k))(1-P(v_s,v_k))-P_q(v_s,v_i,v_k)$;
        /* update the link success ratio */
      else
        $P(v_s,v_k)\leftarrow P(v_i,v_k)$;
    $E_1\leftarrow E_1-E(v_i)$; /* remove all links to v_i */
    $V_1\leftarrow V_1-v_i$; /* remove v_i */
    $E_2\leftarrow E_2-e(v_s,v_i)$; /* remove $e(v_s,v_i)$ */
    $P(G(V,E))\leftarrow$
    $P(v_s,v_i)P(G_1(V_1,E_1))+(1-P(v_s,v_i))P(G_2(V_2,E_2))$;
    /* calculate the successful ratio from the two simpler networks */
    return $P(G(V,E))$;
  else if $|E(v_s)|=1$ **then**
    $E_1\leftarrow E$; $V_1\leftarrow V$;
    select $e(v_s,v_i)\in E(v_s)$;
    foreach $v_k, e(v_i,v_k)\in E(v_i)$ **do**
      $E_1\leftarrow E_1+e(v_s,v_k)$;
      $P(v_s,v_k)\leftarrow P(v_i,v_k)$;
    $E_1\leftarrow E_1-E(v_i)$;
    $V_1\leftarrow V_1-v_i$;
    $P(G(V,E))\leftarrow P(v_s,v_i)P(G_1(V_1,E_1))$;
    return $P(G(V,E))$;
else if $|V|=2$ **then**
  select $e(v_s,v_i)\in E(v_s)$;
  return $P(v_s,v_i)$; /* iteration terminates */

Fig. 4. Example for showing the randomness of the single-hop broadcast delay in CR ad hoc networks. (a) B is on channel 1. (b) B is on channel 5.

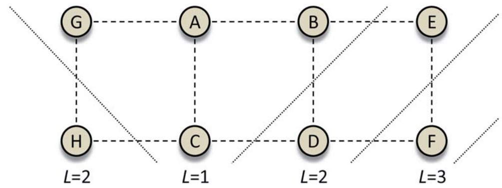

Fig. 5. Example of a 8-node CR ad hoc network with the levels of SUs.

v_2 are: 1) $v_s \rightarrow v_1$ only; 2) $v_s \rightarrow v_2 \rightarrow v_1$ only; and 3) $v_s \rightarrow v_1, v_s \rightarrow v_2 \rightarrow v_1$ and v_s, v_2 do not have a collision at v_1. The probability $(1-p_1)(1-p_3)$ in calculating p_1' is the probability that both v_s and v_2 fail to broadcast to v_1. In addition, the probability that node v_s and v_2 fail to broadcast to node v_1 due to broadcast collisions $P_q(v_s, v_2, v_1)$ will be calculated in Section 4. On the other hand, if the broadcast over the link $e(v_s, v_2)$ fails, this link is simply removed from the network, as shown in Fig. 3(c). The successful broadcast ratio of the original network can be obtained from the successful broadcast ratio of the two simpler networks, as shown in Fig. 3(b) and (c). In the second iteration, these two simpler networks can be further decomposed following the same procedure. For the network shown in Fig. 3(b), assume that we select the link $e(v_s, v_1)$. Similar to the process of the first iteration, this network is further decomposed into two networks, as shown in Fig. 3(d) and (e), where $p_5' = 1-(1-p_4)(1-p_5) - P_q(v_s, v_1, v_3)$. Then, the successful broadcast ratio of the network shown in Fig. 3(b) can be obtained from the successful broadcast ratio of these two new networks shown in Fig. 3(d) and (e). For the network shown in Fig. 3(c), since the source node has only one link, this link must be successful for other nodes to receive the message. Thus, this network is reduced to the network shown in Fig. 3(f) and the successful broadcast ratio of this network can be obtained from the successful ratio of the network shown in Fig. 3(f). Therefore, if we repeat this process, the complexity of the networks from the second iteration can be further reduced. Finally, the original network can be decomposed into several single-hop networks. Then, the procedure of the proposed Algorithm 1 terminates. Therefore, the successful broadcast ratio of the original network can be expressed as

$$\begin{aligned} P_{succ} = {} & p_2\{[1-(1-p_1)(1-p_3)-P_q(v_s,v_2,v_1)][1-(1-p_4) \\ & (1-p_5)-P_q(v_s,v_1,v_3)]+[(1-p_1)(1-p_3)+P_q(v_s,v_2,v_1)]p_4p_5\} \\ & +(1-p_2)p_1\{p_3[1-(1-p_4)(1-p_5)-P_q(v_s,v_2,v_3)]+(1-p_3)p_4p_5\}. \end{aligned} \quad (2)$$

3 Calculating the Average Broadcast Delay

In this section, we introduce the proposed algorithm for calculating the average broadcast delay of a broadcast protocol. Similar to the previous section, we first present the unique challenge of calculating the average broadcast delay for a CR ad hoc network. Then, the detailed algorithm is given. Furthermore, an example is shown to illustrate the process of the proposed algorithm.

3.1 The Unique Challenge

As mentioned in Section 1, since the single-hop broadcast delay depends on various factors, such as the channel availability of the communication pair and specific broadcast protocol, the single-hop broadcast delay is random. Fig. 4 illustrates the randomness of the single-hop broadcast delay in CR ad hoc networks. In Fig. 4, node A is the sender and broadcasts the message on each available channel sequentially. In addition, node B is the receiver and constantly listens on the channel shown in the bold font. Since node B does not have any information about the sender before a broadcast starts, the channel it stays on is randomly selected. It is shown that, even though the channel availability of node B is the same in the two scenarios shown in Fig. 4(a) and (b), the single-hop broadcast delay is quite different (i.e., it takes 1 time slot for a successful broadcast in Fig. 4(a), while it takes 5 time slots for a successful broadcast in Fig. 4(b)). Hence, due to this randomness, to obtain the single-hop broadcast delay in CR ad hoc networks is challenging. Moreover, if the number of senders and receivers is larger than one, it is even more difficult.

3.2 The Proposed Algorithm

Since to obtain the closed form expression of the average broadcast delay for arbitrary network topology is extremely complicated, in this paper, we focus on the grid topology. However, the proposed methodology can be applied to any network topology. We define the level of SUs as h if they are h hops to the source node (denoted as $L = h$). Fig. 5 shows an example of an 8-node CR ad hoc network with the levels of SUs where A is the source node. Then, the original network is decomposed into H_m levels, where H_m is the distance from the source node to the furthest node in the network. To make the derivation process tractable, we first make two assumptions. First of all, we assume that the broadcast message is propagated from the source node to the furthest node sequentially based on the relative distance to the source node. This means that, we assume that the nodes who are closer to the source node receive the message sooner than the nodes who are farther away from the source node. Based on this assumption, we categorize the SUs based on their relative distances to the source node. We further justify this assumption using simulation. We apply the broadcast protocol proposed in [13] to the network shown in Fig. 5. Fig. 6 shows the simulation results of the average delay for different nodes to receive the broadcast message in the network shown in Fig. 5. It is shown that nodes at a higher level (e.g., nodes D and E at the second level) receive the broadcast message later than the nodes at a lower level on average (e.g., nodes B and C at the first level), which justifies our first assumption. The second assumption is that only the nodes that are at the highest level or have a path leading to the furthest node (excluding the source node) contribute to the overall average broadcast delay. Other nodes will be removed from the network for calculating the average broadcast delay.

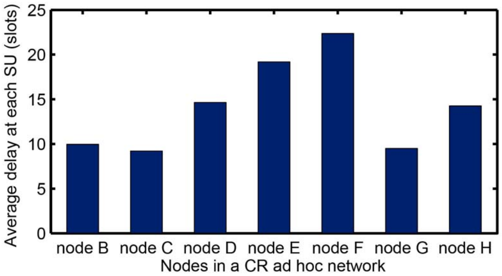

Fig. 6. Average delay for different nodes to receive the broadcast message in the network shown in Fig. 5.

This assumption is straightforward since those nodes are independent of the message propagation path to the nodes at the highest level. For instance, in Fig. 5, nodes G and H do not contribute to the message propagation to node F. Thus, they can be removed when calculating the average broadcast delay of the network.

The main idea of the proposed algorithm is that the overall average broadcast delay is the sum of the average broadcast delay at each level. At each level, it is a simple network whose average broadcast delay can be obtained. That is, $\Gamma = \sum_i^{H_m} D_i$, where Γ is the overall average broadcast delay and D_i is the average broadcast delay of the nodes at level i.

Then, we calculate the average broadcast delay at level i, D_i. Based on the number of parent nodes, there exist only two scenarios of the single-hop broadcast in a grid topology network. The first scenario is that a SU only has one parent node (denoted as Scenario I, as shown in Fig. 7(a)), while the second scenario is that a SU has two parent nodes (denoted as Scenario II, as shown in Fig. 7(b)). We further prove that the maximum number of parent nodes for a node in grid topology networks is two. The proof is: if there are more than two parent nodes (say, three), these three nodes should be at the same level. However, for any node that is the parent node of any two of those parent nodes (exactly 1-hop away), it needs more than two hops to reach the third parent node. That is, these three nodes cannot be at the same level. Therefore, only the two single-hop broadcast scenarios shown in Fig. 7 exist. We assume that for the nodes at the same level, there are α Scenario I and β Scenario II.

If the current level, level i, is not the highest level, the average broadcast delay at level i is the mean of the single-hop average broadcast delay of the nodes at level i. That is, $D_i = (\alpha\tau_1 + \beta\tau_2)/(\alpha+\beta)$, where τ_1 and τ_2 are the single-hop average broadcast delay of Scenario I and II, respectively. Denote the probabilities that the single-hop broadcast is successful at time slot k as $P_I(k)$ and $P_{II}(k)$ for Scenario I and II, respectively. $P_I(k)$ and $P_{II}(k)$ can be obtained based on a specific broadcast protocol, which is explained in Section 4. Given a successful broadcast, we first obtain the conditional probability that the single-hop broadcast is successful at time slot k for the two scenarios:

$$P_1(k) = \frac{P_I(k)}{\sum_j P_I(j)},$$
$$P_2(k) = \frac{P_{II}(k)}{\sum_j P_{II}(j)}. \tag{3}$$

Fig. 7. Two single-hop broadcast scenarios in a grid topology network. (a) Scenario I. (b) Scenario II.

Therefore, we have $\tau_1 = \sum_{k=1}^{T_m} kP_1(k)$ and $\tau_2 = \sum_{k=1}^{T_m} kP_2(k)$, where T_m is the maximum length of time slots the sender uses for broadcasting.

If the current level is the highest level, the calculation method for D_i is different. Since the probability that the broadcast is successful at time slot k is different in the two broadcast scenarios, we need to consider two cases: the last SU node at level i successfully receives the broadcast message is under Scenario I or Scenario II. Therefore, we first assume that the last SU node successfully receives the broadcast message at time slot d is under Scenario I and no other SU receives the message at time slot d under Scenario II. Thus, we have the probability that the single-hop broadcast delay is d at level i as

$$P'(D_i = d) = \binom{\alpha}{1} P_1(d) \left[\sum_{k=1}^{d} P_1(k)\right]^{\alpha-1} \left[\sum_{k=1}^{d-1} P_2(k)\right]^{\beta}. \tag{4}$$

Next, we assume that the last SU node successfully receives the broadcast message at time slot d under Scenario II and no other SU node receives the message at time slot d under Scenario I. Thus, we obtain

$$P''(D_i = d) = \binom{\beta}{1} P_2(d) \left[\sum_{k=1}^{d-1} P_1(k)\right]^{\alpha} \left[\sum_{k=1}^{d} P_2(k)\right]^{\beta-1}. \tag{5}$$

Last, we assume that under both scenarios, at least one node receives the broadcast message at time slot d. Hence, we have

$$P'''(D_i = d) = \binom{\alpha}{1}\binom{\beta}{1} P_1(d) P_2(d) \left[\sum_{k=1}^{d-1} P_1(k)\right]^{\alpha-1} \left[\sum_{k=1}^{d-1} P_2(k)\right]^{\beta-1}. \tag{6}$$

Therefore, the probability that the single-hop broadcast delay is d at level i can be written as

$$\Pr(D_i = d) = P'(D_i = d) + P''(D_i = d) + P'''(D_i = d). \tag{7}$$

Then, the average broadcast delay at level i is

$$D_i = \sum_{d=1}^{T_m} d \Pr(D_i = d). \tag{8}$$

3.3 An Illustrative Example

We use the example shown in Fig. 5 to illustrate the proposed algorithm for calculating the average broadcast delay. From Fig. 5, there are three levels of nodes in the network. As explained above, according to our second

Tx	1	3	4	1	5	4	3	4	5	3	5	2
Rx	3	1	2	4	3	2	1	2	4	3	2	1

Fig. 8. Example of the random broadcast scheme.

assumption, we first remove nodes G and H for the consideration of average broadcast delay. Then, at the first level, since both nodes B and C are under Scenario I, for D_1, we have

$$D_1 = \tau_1 = \sum_{k=1}^{T_m} \frac{kP_I(k)}{\sum_j P_I(j)}. \quad (9)$$

That is, the average broadcast delay at level 1 is the same as the single-hop broadcast delay under Scenario I. At the second level, nodes D and E are under different scenarios. Therefore, we have

$$D_2 = \frac{\tau_1 + \tau_2}{2} = \frac{1}{2}\left[\sum_{k=1}^{T_m} \frac{kP_I(k)}{\sum_j P_I(j)} + \sum_{k=1}^{T_m} \frac{kP_{II}(k)}{\sum_j P_{II}(j)}\right]. \quad (10)$$

Finally, for D_3, since this is the highest level, D_3 can be obtained using (8), where $\alpha = 0$ and $\beta = 1$. That is,

$$D_3 = \sum_{d=1}^{T_m} d \frac{P_{II}(d)}{\sum_j P_{II}(j)}. \quad (11)$$

By summing up the average broadcast delay of these three levels, the overall average broadcast delay for the network shown in Fig. 5 can be written as $\Gamma = \sum_{i=1}^{3} D_i$.

4 BROADCASTING IN CR AD HOC NETWORKS

In this section, we first introduce several existing broadcast designs, i.e., the random scheme and the schemes proposed in [13],[14], for CR ad hoc networks under practical scenarios. Since the broadcast schemes proposed in [11] and [12] are based on impractical assumptions (i.e., a dedicated common control channel for the whole network is employed and the available channel information of all SUs are assumed to be known), we exclude these proposals in this paper. In addition, we propose the derivation methods to calculate the single-hop broadcast performance metrics (i.e., successful broadcast ratio, average broadcast delay, and broadcast collision rate) for each protocol.

4.1 Random Broadcast Scheme

The first broadcast scheme is called the *random broadcast scheme*. Since a SU is unaware of the channel availability information of other SUs before broadcasts are executed, a straightforward action for a SU sender is to randomly select a channel from its available channel set and broadcasts a message on that channel in a time slot. If the channel selected by the receiver is the same as the channel selected by the sender, the broadcast message can be successfully received. Fig. 8 illustrates the procedure of the random broadcast scheme, where the shaded part represents a successful broadcast.

4.1.1 Single-Hop Successful Broadcast Ratio for the Random Broadcast Scheme

We first calculate the single-hop successful broadcast ratio for the random broadcast scheme. Without loss of generality, in the rest of the paper, the sender and the receiver of the single-hop link is denoted as A and B. We further denote the numbers of available channels for the single-hop communication pair as N_A and N_B, respectively. The number of common channels between A and B is Z_{AB}. Therefore, the probability that the single-hop broadcast is successful in a time slot is

$$p_r = \binom{Z_{AB}}{1} \frac{1}{N_A} \frac{1}{N_B} = \frac{Z_{AB}}{N_A N_B}. \quad (12)$$

Therefore, if the length of the time slots that the sender uses for broadcasting is S_r, the single-hop successful broadcast ratio for the random broadcast scheme is

$$P_{rand} = 1 - \left(1 - \frac{Z_{AB}}{N_A N_B}\right)^{S_r}. \quad (13)$$

4.1.2 Single-Hop Average Broadcast Delay for the Random Broadcast Scheme

Next, we calculate the single-hop average broadcast delay for the random broadcast scheme. In this paper, since we focus on grid topology for the broadcast delay, we only need to consider the two single-hop broadcast scenarios shown in Fig. 7. For Scenario I, since the sender and the receiver randomly select a channel in a time slot, the probability that the single-hop broadcast is successful at time slot k is $P_I(k) = (1-p_r)^{k-1} p_r$, where p_r is given in (12). For scenario II, since there are two senders, we denote the other sender as C and the number of available channels of C is N_C. In addition, the number of common channels between B and C is Z_{BC}. Thus, similar to (12), the probability that the single-hop broadcast is successful between C and B in a time slot is $p_m = \frac{Z_{BC}}{N_B N_C}$. Hence, the probability that the single-hop broadcast is successful under Scenario II in a time slot is $p_{r2} = [1-(1-p_r)(1-p_m)] - p_{q1}$, where p_{q1} is the probability that nodes A and C have a broadcast collision at node B in a time slot. The derivation of p_{q1} is given in Section 4.1.3. Hence, the probability that the single-hop broadcast is successful at time slot k can be expressed as

$$P_{II}(k) = (1-p_{r2})^{k-1} p_{r2}. \quad (14)$$

Then, based on (3), given the single-hop broadcast is successful, the conditional probability that the receiver successfully receives the broadcast message at time slot k for both scenarios under the random broadcast scheme, $P_1(k)$ and $P_2(k)$, can be obtained.

4.1.3 Single-Hop Broadcast Collision Rate for the Random Broadcast Scheme

Next, we calculate the single-hop broadcast collision rate for the random broadcast scheme. We first derive the probability that nodes A and C have a broadcast collision at node B in a time slot, p_{q1}. p_{q1} is equivalent to the

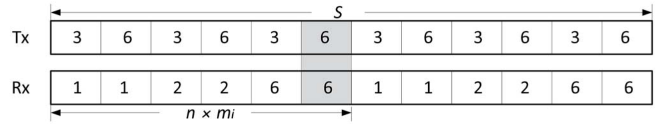

Fig. 9. Example of the QoS-based broadcast scheme.

probability that all the three nodes select the same channel. Denote the number of common channels among the three nodes as Z_{ABC}. Thus, we have

$$p_{q1} = \frac{Z_{ABC}}{N_A N_B N_C}. \tag{15}$$

Since the length of the time slots that the sender uses for broadcasting is S_r, the probability that a single-hop broadcast fails due to broadcast collisions for the random broadcast scheme can be written as

$$P_q(A, C, B) = \sum_{l=1}^{S_r} \binom{S_r}{l} p_{q1}^l \left[(1-p_r)(1-p_m)\right]^{S_r - l}, \tag{16}$$

where l is the number of time slots when nodes A and C have a broadcast collision at node B.

4.2 QoS-Based Broadcast Scheme

The second scheme is called the *QoS-based broadcast scheme* [13],[32]. The main idea of the QoS-based broadcast scheme is to let the sender broadcast on a subset of its available channels in order to reduce the broadcast delay. In addition, the channel hopping sequences of both the sender and the receiver are designed for guaranteed rendezvous, given that the sender and the receiver have at least one channel in common in their hopping sequences. Fig. 9 shows an example of the QoS-based broadcast scheme. For each sender, it randomly selects n channels from its available channel set. Then, it hops and broadcasts periodically on the selected n channels for S time slots. The values of n and S are determined by the QoS requirements of the network (i.e., the successful broadcast ratio and the average broadcast delay). On the other hand, for each receiver, it first forms a random sequence that consists of its every available channel with a length of n time slots for each channel. Then, it hops and listens following this sequence periodically.

4.2.1 Single-Hop Successful Broadcast Ratio for the QoS-Based Broadcast Scheme

We continue to use the notations for calculating the single-hop performance metrics in the random broadcast scheme for the QoS-based broadcast scheme. Denote the number of channels in the n channels selected by node A which are also in the available channel set of node B as y. We assume that the length of time slots that the sender uses for broadcasting, S, is a multiple of n. Thus, the single-hop successful broadcast ratio for the QoS-based broadcast protocol is

$$P_{qos} = \sum_{y=y^*}^{y^{**}} H(y), \tag{17}$$

where $y^* = \max(1, n + Z_{AB} - N_A)$, $y^{**} = \min(n, Z_{AB})$, and $H(y)$ is written as

$$H(y) = \begin{cases} \frac{\binom{Z_{AB}}{y}\binom{N_A - Z_{AB}}{n-y}}{\binom{N_A}{n}} \frac{\binom{N_B}{y} - \binom{N_B - \frac{S}{n}}{y}}{\binom{N_B}{y}}, & \text{if } y < N_B - \frac{S}{n} \\ \frac{\binom{Z_{AB}}{y}\binom{N_A - Z_{AB}}{n-y}}{\binom{N_A}{n}}, & \text{if } y \geq N_B - \frac{S}{n}, \end{cases} \tag{18}$$

where $\frac{\binom{Z_{AB}}{y}\binom{N_A - Z_{AB}}{n-y}}{\binom{N_A}{n}}$ is the probability that there are y common channels between the sender and the receiver in the selected n channels by the sender. (18) indicates that when S is large enough (the case when $y \geq N_B - \frac{S}{n}$), the single-hop successful broadcast ratio is independent of S.

4.2.2 Single-Hop Average Broadcast Delay for the QoS-Based Broadcast Scheme

Secondly, we calculate the single-hop average broadcast delay for the QoS-based broadcast scheme. Similar to the random broadcast scheme, we first calculate the probability that the single-hop broadcast is successful at time slot k. Based on the broadcast protocol shown in Fig. 9, one cycle of the broadcasting sequence of the receiver consists of N_B sections, where each section includes the same channel repeated for n times. If the channel in a section is the first appearing common available channel of nodes A and B, the single-hop broadcast is successful within that section. Denote the sections of one cycle of the broadcasting sequence of the receiver as $[f_1, f_2, \ldots, f_{N_B}]$. We calculate the probability that for a particular y, the channel in f_i is the first appearing common available channel, $\Pr(f_i)$, $i \in [1, N_B - y + 1]$. This probability is equal to the probability that the first

$$P_I(k) = \begin{cases} \sum_{y=y^*}^{y^{**}} \frac{\binom{Z_{AB}}{y}\binom{N_A - Z_{AB}}{n-y}}{\binom{N_A}{n}} \frac{\binom{N_B - \lfloor \frac{k-1}{n} \rfloor - 1}{y-1}}{n\binom{N_B}{y}}, & \text{if } k \leq n(N_B - y) \\ \sum_{y=y^*}^{y^{**}} \frac{\binom{Z_{AB}}{y}\binom{N_A - Z_{AB}}{n-y}}{\binom{N_A}{n}} \frac{1}{n\binom{N_B}{y}}, & \text{if } n(N_B - y) < k \leq n(N_B - y + 1) \\ 0, & \text{if } k > n(N_B - y + 1). \end{cases} \tag{19}$$

$$P_{II}(k) = \begin{cases} \sum_{y=y^*}^{y^{**}} \sum_{x=x^*}^{x^{**}} \sum_{q=0}^{q^*} \frac{\binom{Z_{AB}}{y}\binom{N_A - Z_{AB}}{n-y}}{\binom{N_A}{n}} \frac{\binom{N_B - \lfloor \frac{k-1}{n} \rfloor - 1}{2y-2q-1}}{n\binom{N_B}{2y-2q}} \Pr(x)\Pr(q), & \text{if } k \leq n(N_B - 2y + 2q) \\ \sum_{y=y^*}^{y^{**}} \sum_{x=x^*}^{x^{**}} \sum_{q=0}^{q^*} \frac{\binom{Z_{AB}}{y}\binom{N_A - Z_{AB}}{n-y}}{\binom{N_A}{n}} \frac{1}{n\binom{N_B}{2y-2q}} \Pr(x)\Pr(q), & \text{if } n(N_B - 2y + 2q) < k \leq n(N_B - 2y + 2q + 1) \\ 0, & \text{if } k > n(N_B - 2y + 2q + 1). \end{cases} \tag{20}$$

ball is in the i-th box if y balls are randomly put in N_B boxes. Therefore, $\Pr(f_i) = \frac{\binom{N_B - i}{y-1}}{\binom{N_B}{y}}$. Since time slot k is in the $(\lfloor \frac{k-1}{n} \rfloor + 1)$-th section, the probability that the single-hop broadcast is successful in $f_{\lfloor \frac{k-1}{n} \rfloor + 1}$ is $\frac{\binom{N_B - \lfloor \frac{k-1}{n} \rfloor - 1}{y-1}}{\binom{N_B}{y}}$. On the other hand, given that the first appearing common available channel is in $f_{\lfloor \frac{k-1}{n} \rfloor + 1}$, since the channels in the broadcasting sequence of the sender is evenly distributed, the conditional probability that the broadcast is successful in time slot k is $\frac{1}{n}$. Therefore, for Scenario I, the probability that the single-hop broadcast is successful at time slot k is expressed in (19).

For Scenario II, for simplicity, we assume that both the two senders have the same number of common available channels with the receiver (i.e., $Z_{AB} = Z_{BC}$). In addition, the numbers of channels that are also available for the receiver in the selected n channels by the two senders are the same (denoted as y). Denote the number of channels in the available channel sets of the two senders that are also available for all three nodes as x. Therefore, the probability that there are x channels that are available for all three nodes in their selected available channel sets is $\Pr(x) = \left(\frac{Z_{ABC}}{Z_{AB}}\right)^x \left(1 - \frac{Z_{ABC}}{Z_{AB}}\right)^{y-x}$, where Z_{ABC} is the number of channels that are available for all three nodes. Therefore, the probability that the single-hop broadcast is successful at time slot k under Scenario II is written in (20), where $\Pr(q)$ is the probability that there are q channels out of x channels appearing in the same time slots. In addition, $x^* = \max(0, y - Z_{AB} + Z_{ABC})$, $x^{**} = \min(y, Z_{ABC})$, and $q^* = \min(x, y-1)$. Thus, $\Pr(q)$ is written as

$$\Pr(q) = \begin{cases} \frac{\binom{x}{q}[(n-q)! - \sum_{j=1}^{x-q} (-1)^{(j+1)} \binom{x-q}{j} (n-q-j)!]}{n!}, & \text{if } 0 \le q < x \\ \frac{(n-q)!}{n!}, & \text{if } q = x. \end{cases} \quad (21)$$

Then, based on (3), given the single-hop broadcast is successful, the conditional probability that the receiver successfully receives the broadcast message at time slot k for both scenarios under the QoS-based broadcast scheme, $P_1(k)$ and $P_2(k)$, can be obtained.

4.2.3 Single-Hop Broadcast Collision Rate for the QoS-Based Broadcast Scheme

Then, we calculate the single-hop broadcast collision rate for the QoS-based broadcast scheme. The probability that two senders have a broadcast collision is equivalent to the probability that all the common channels selected by the two senders appear in the same time slots. Therefore, using (21), the probability that a single-hop broadcast fails due to broadcast collisions for the QoS-based broadcast scheme is

$$P_q(A, C, B) = \sum_{y=y*}^{y^{**}} \frac{\binom{Z_{AB}}{y}\binom{N_A - Z_{AB}}{n-y}\binom{Z_{ABC}}{y}}{\binom{N_A}{n}\binom{Z_{AB}}{y}^2} \frac{(n-y)!}{n!}. \quad (22)$$

4.3 Distributed Broadcast Scheme

The third broadcast scheme considered in this paper is called the *distributed broadcast scheme* [14],[33]. In this scheme, all SU nodes in the network intelligently select a subset of available channels from the original available channel set for broadcasting. The size of the downsized available channel set is denoted as w. The value of w needs to be carefully designed to ensure that at least one common channel exists between the downsized available channel sets of the SU sender and each of its neighboring nodes. Fig. 10 gives an example of the broadcasting sequences of the distributed broadcast scheme. For a SU sender, it hops periodically on the w available channels for w cycles (one cycle consists of w^2 time slots). For each receiver, it stays on one of the w available channels for w time slots. Then, it repeats for every channel in the w available channels.

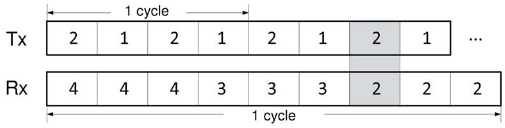

Fig. 10. Example of the broadcasting sequences of the distributed broadcast scheme.

4.3.1 Single-Hop Successful Broadcast Ratio for the Distributed Broadcast Scheme

Similar to the previous schemes, we first calculate the single-hop successful broadcast ratio for the distributed broadcast scheme. As discussed above, the size of the downsized available channel set, w, has significant impact on the performance of the distributed broadcast scheme. If w is given, the single-hop successful broadcast ratio is equivalent to the probability that the sender and the receiver have at least one channel in common in their downsized available channel sets. That is, $P_{dist} = 1 - \Pr(Z(0, i) = 0)$, where $\Pr(Z(0, i) = 0)$ is the probability that the sender and the receiver do not have any common channel in their downsized available channel sets. The derivation process of $\Pr(Z(0, i) = 0)$ is the same as the method proposed in [14].

4.3.2 Single-Hop Average Broadcast Delay for the Distributed Broadcast Scheme

Then, we calculate the single-hop average broadcast delay for the distributed broadcast scheme. For simplicity, we assume that the w obtained by the receiver is the same as the w of the sender. In addition, we denote the number of common channels between the sender and the receiver as z. We calculate the probability that the single-hop broadcast is successful at time slot k under Scenario I. Based on the broadcast protocol proposed in [14], the broadcasting sequence of a receiver consists of w sections where each section includes the same channel repeated for w times. Similar to the QoS-based broadcast scheme, the probability that for a particular z, the channel in $t_{\lfloor \frac{k-1}{w} \rfloor + 1}$ is the first appearing common available channel in the downsized available channel set of the sender is expressed as $\Pr(t_{\lfloor \frac{k-1}{w} \rfloor + 1}) = \frac{\binom{w - \lfloor \frac{k-1}{w} \rfloor - 1}{z-1}}{\binom{w}{z}}$.

In addition, given that the first appearing common available channel is in $(\lfloor \frac{k-1}{w} \rfloor + 1)$-th section, the conditional probability that the broadcast is successful in time slot k is $\frac{1}{w}$. Therefore, for Scenario I, the probability that the single-hop broadcast is successful at time slot k is expressed as

$$P_I(k)=\begin{cases}\sum_{z=1}^{w}\frac{\binom{w-\lfloor\frac{k-1}{w}\rfloor-1}{z-1}}{w\binom{w}{z}}\Pr(z), & \text{if } k\le w(w-z)\\ \sum_{z=1}^{w}\frac{1}{w\binom{w}{z}}\Pr(z), & \text{if } w(w-z)<k\le w(w-z+1)\\ 0, & \text{if } k>w(w-z+1),\end{cases} \tag{23}$$

where $\Pr(z)$ is the probability that there are z common channels in the downsized available channel sets between the sender and the receiver. The derivation process of $\Pr(z)$ is given in [14].

Then, for Scenario II, denote the numbers of common available channels that the two senders have with the receiver in the downsized available channel sets as z_1 and z_2, respectively. In addition, denote the number of channels in the downsized available channel sets of the two senders that are available for all three nodes as x. Since the available channels are evenly distributed in the spectrum band, the probability that there are x channels that are available for all three nodes in their downsized available channel sets is $G(x)=\binom{z^*}{x}P_A^x(1-P_A)^{z^*-x}$, where P_A is the probability that a channel is available for all three nodes and $z^*=\min(z_1,z_2)$. In addition, P_A can be obtained from [14]. Therefore, similar to the QoS-based broadcast scheme, the probability that the single-hop broadcast is successful at time slot k under Scenario II is expressed in (24), where $U(q)$ is the probability that there are q channels out of x channels appearing at the same time slots. In addition, $q^*=\min(x,z^*-1)$. Using (21), $U(q)$ can be written as

$$U(q)=\begin{cases}\frac{\binom{x}{q}\left[(w-q)!-\sum_{j=1}^{x-q}(-1)^{(j+1)}\binom{x-q}{j}(w-q-j)!\right]}{w!}, & \text{if } 0\le q<x\\ \frac{(w-q)!}{w!}, & \text{if } q=x.\end{cases} \tag{25}$$

Then, based on (3), given the single-hop broadcast is successful, the conditional probability that the receiver successfully receives the broadcast message at time slot k for both scenarios under the distributed broadcast scheme, $P_1(k)$ and $P_2(k)$, can be obtained.

4.3.3 Single-Hop Broadcast Collision Rate for the Distributed Broadcast Scheme

Finally, we calculate the single-hop broadcast collision rate for the distributed broadcast scheme. Note that in [14], a broadcast collision avoidance scheme is proposed. If this scheme is used, broadcast collisions can be avoided. However, it involves significant changes to the broadcasting sequences of the senders shown in Fig. 10. To make the analysis tractable, in this paper, we do not consider the broadcast collision avoidance scheme. Therefore, similar to the QoS-based broadcast scheme, the probability that a single-hop broadcast fails due to broadcast collisions for the distributed broadcast scheme is

$$P_q(A,C,B)=\sum_{z=1}^{w}\frac{(w-z)!}{w!}P_A^z\Pr(z). \tag{26}$$

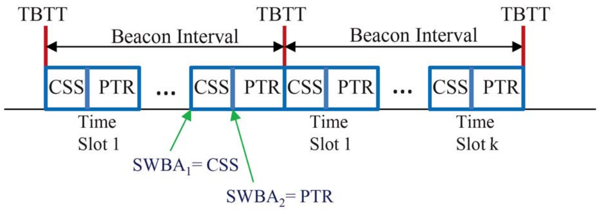

Fig. 11. Synchronized time slots for IEEE 802.11 chipsets.

5 Performance Evaluation

In this section, we validate our proposed unified analytical model using both hardware implementation and simulation in order to prove its correctness.

5.1 Validating Analysis Using Hardware Implementation

The considered broadcast schemes have been implemented in embedded wireless radios. Each radio contains a Qualcomm Atheros IEEE 802.11 a/b/g chipset, and MADWIFI is used as the medium access control (MAC) driver. The three broadcast schemes are implemented as sub-functions of the MAC driver.

5.1.1 Time Slot and Synchronization

To support synchronized transmission of broadcast messages in different time slots, we first need to implement timing events that are synchronized among all communication nodes [34]. In order to minimize the impact by the software in the driver, a hardware register called software beacon alert (SWBA) is utilized to generate timing events. To support different timing events, the value in the SWBA register must be set into the time interval between the current timing event and the next expected timing event. Based on this mechanism, the time-line of each communication node is split into consecutive time slots each consisting of two portions: channel switching (CSS) and packet transmission/reception (PTR), as shown in Fig. 11.

To synchronize time slots among all nodes, we adopt two mechanisms of IEEE 802.11 [35]: target beacon transmission time (TBTT) and timing synchronization function (TSF). Within each beacon interval, the first time slot must be aligned with TBTT, as shown in Fig. 11. Through TSF, the time in the TSF register of different nodes is synchronized. Since TBTT is determined based on the timing value of the TSF register, the time slots of different nodes are synchronized accordingly.

$$P_{II}(k)=\begin{cases}\sum_{z_1=1}^{w}\sum_{z_2=1}^{w}\sum_{x=0}^{z^*}\sum_{q=0}^{q^*}\frac{\binom{w-\lfloor\frac{k-1}{w}\rfloor-1}{z_1+z_2-2q-1}}{w\binom{w}{z_1+z_2-2q}}\Pr(z_1)\Pr(z_2)G(x)U(q), & \text{if } k\le w(w-z_1+z_2+2q)\\ \sum_{z_1=1}^{w}\sum_{z_2=1}^{w}\sum_{x=0}^{z^*}\sum_{q=0}^{q^*}\frac{1}{w\binom{w}{z_1+z_2-2q}}\Pr(z_1)\Pr(z_2)G(x)U(q), & \text{if } w(w-z_1+z_2+2q)<k\le w(w-z_1+z_2+2q+1)\\ 0, & \text{if } k>w(w-z_1+z_2+2q+1).\end{cases} \tag{24}$$

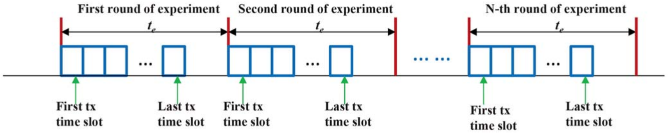

Fig. 12. Repeating experiments.

5.1.2 Packet Transmission/Reception and Channel Selection

In a source node, a broadcast message is generated in the PTR portion of a time slot and is then sent in a selected channel. This process repeats for S time slots. Other nodes in the network attempt to receive the broadcast message from its neighboring nodes and then rebroadcast it. Due to slot-by-slot operation, when a broadcast message is received, it is rebroadcast in the next time slot in the selected channel. This process is also repeated for S time slots. Since the same message may be received for multiple times, a sequence number is added into each broadcast message to avoid redundant broadcast messages. It should be noted that the channel selection for packet transmission and reception follows the rules set by the specific broadcast schemes developed in this paper. The channel set in each node reflects the activities of primary nodes and is determined according to off-line simulations.

5.1.3 Performance Measurement

Two performance metrics are used in our implementation: the successful broadcast ratio and the average broadcast delay. The former metric measures the probability that a broadcast message can be successfully received by all nodes in a network, and the latter one records the average delivery time from the source node to the last node. In order to get stable performance results, we repeat the experiments for N measurements as shown in Fig. 12. Within t_e seconds, one round of experiment is conducted. t_e is selected large enough so that all non-source nodes finish the process of receiving/rebroadcasting messages within the same period. In our experiments, we set t_e to be 3 seconds for a multi-hop CR ad hoc network under Topology 1 as shown in Fig. 13(a).

Fig. 14 shows comparisons between analytical results and experimental measurements for the random and QoS-based broadcast schemes. The comparisons for the distributed broadcast scheme are depicted in Fig. 15, where two cases are considered: 1) Case 1: all nodes have the same w (i.e., $w(A) = w(B) = w(C) = w(D) = 5$) and 2) Case 2: some nodes have different w (i.e., $w(A) = w(B) = w(D) = 5$ and $w(C) = 4$). As we can see from Figs. 14 and 15, the implementation results fit the analytical results fairly well.

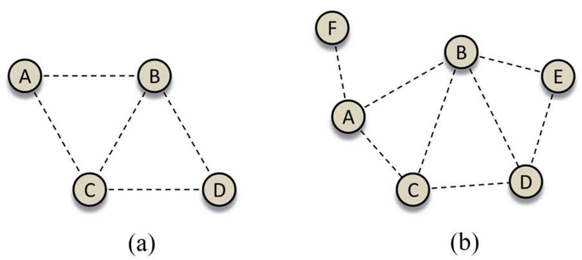

Fig. 13. Topology 1 and 2 considered in the performance evaluation. (a) Topology 1. (b) Topology 2.

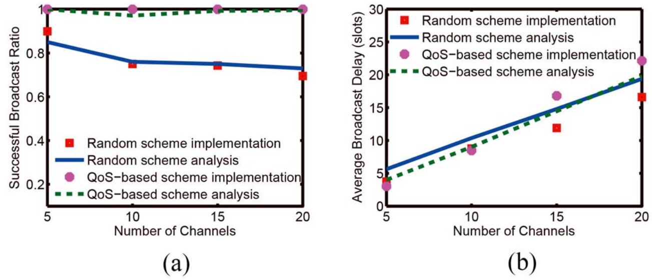

Fig. 14. Analytical and implementation results using the random and QoS-based broadcast schemes under Topology 1. (a) Successful broadcast ratio. (b) Average broadcast delay.

5.2 Validating Analysis Using Simulation

Due to the constraint on the total number of channels for hardware testing, we also use simulations to validate our proposed analytical model when the number of channels varies from 10 to 40. The side length of the simulation area L_s=10 (unit length). PUs are evenly distributed within this area. The total number of PUs is denoted as $K = 40$. The total number of channels is denoted as M. Furthermore, each SU has a circular transmission range with a radius of r_c. The SUs within the transmission range are considered as the neighboring nodes of the corresponding SU. In addition, each SU also has a circular sensing range with a radius of r_s. That is, if a PU is currently active within the sensing range of a SU, the corresponding SU is able to detect its appearance. Moreover, we consider the PU traffic model used in [36], where the PU packet inter-arrival time follows the biased-geometric distribution [37],[38]. In fact, our proposed algorithms do not rely on specific PU traffic models. We assume that the probability that a PU is active is fixed (i.e., $\rho = 0.9$). Each PU randomly selects a channel from the spectrum band to transmit one packet. Since the available channels for each SU depends on the sensing outcome in its sensing range, we use the values from the simulation as the input for the proposed analytical model (e.g., the number of common available channels between nodes A and B, Z_{AB}). In addition, we assume that the SU channel availability is stable during a broadcast duration.

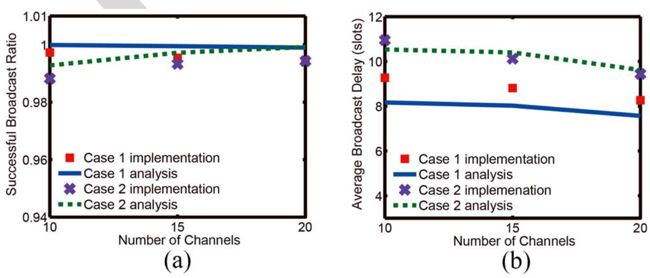

Fig. 15. Analytical and implementation results using the distributed broadcast scheme under Topology 1. (a) Successful broadcast ratio. (b) Average broadcast delay.

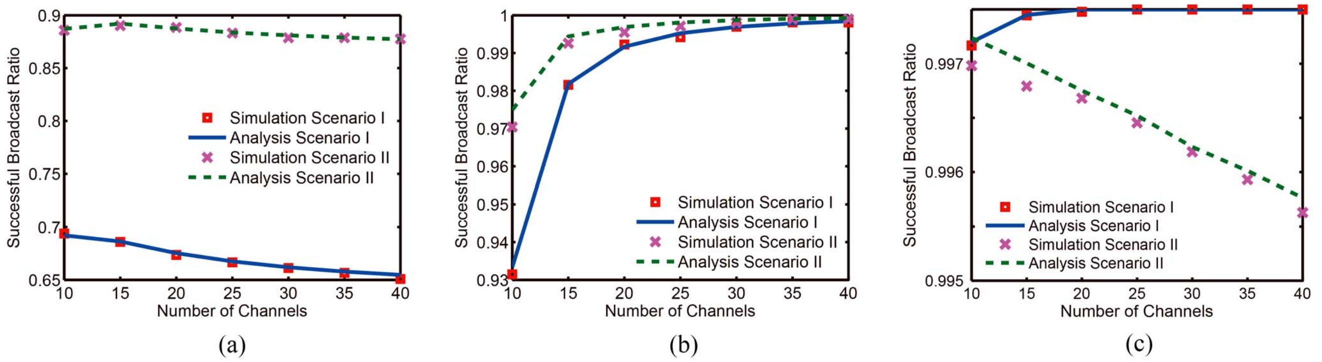

Fig. 16. Analytical and simulation results of the single-hop successful broadcast ratio using the three broadcast schemes under Scenario I and II. (a) Random broadcast scheme. (b) QoS-based broadcast scheme. (c) Distributed broadcast scheme.

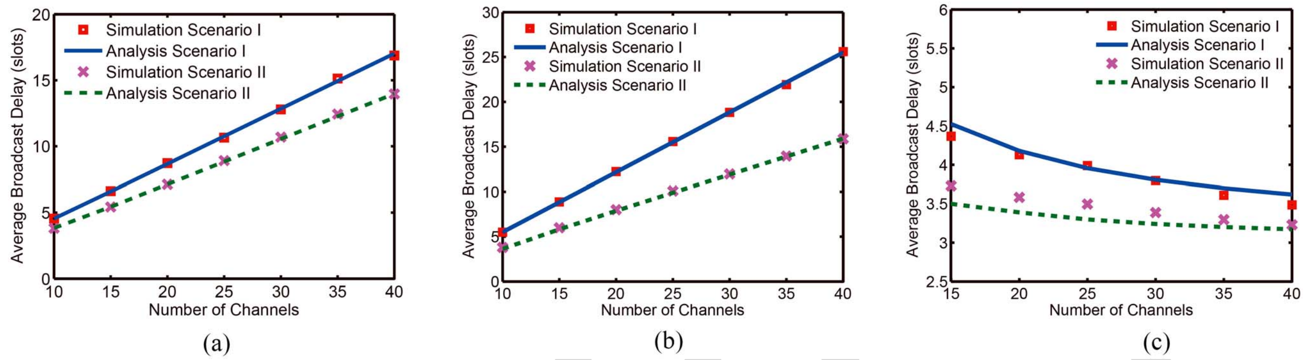

Fig. 17. Analytical and simulation results of the single-hop average broadcast delay using the three broadcast schemes under Scenario I and II. (a) Random broadcast scheme. (b) QoS-based broadcast scheme. (c) Distributed broadcast scheme.

5.2.1 Single-Hop Performance

We first investigate the single-hop performance of each broadcast protocol considered in this paper, because this performance is the foundation of the multi-hop performance evaluation. We study the two single-hop broadcast scenarios shown in Fig. 7. In our study, the nodes are at the border of each other's sensing range. Fig. 16(a) to (c) show the analytical and simulation results of the single-hop successful broadcast ratio using the three considered broadcast schemes under Scenario I and II. For the random broadcast scheme, S_r is set to be the same as the number of channels, M. For the QoS-based broadcast scheme, $n = 2$ and $S = 2M$. In addition, for the distributed scheme, $w = 5$. It is shown that the simulation and analytical results match very well with the maximum difference of 0.4%, 0.5%, and 0.7% for the three schemes, respectively. The figure indicates that the distributed broadcast scheme can achieve the highest single-hop successful broadcast ratio.

In addition, Fig. 17(a) to (c) illustrate the analytical and simulation results of the single-hop average broadcast delay using the three considered broadcast schemes under Scenario I and II. It is also shown that the simulation and analytical results match very well with the maximum difference of 1.4%, 3.7%, and 5.5% for the three schemes, respectively. The distributed broadcast scheme results in the lowest single-hop average broadcast delay among the three schemes.

5.2.2 Successful Broadcast Ratio of Multi-hop CR Ad Hoc Networks

Next, we investigate the multi-hop performance. For the successful broadcast ratio, we study the two topologies shown in Fig. 13(a) and (b). The coordinates of nodes in Topology 1 are $A(4,4), B(6,4), C(5,2.28)$, and $D(7,2.28)$. On the other hand, note that Topology 2 is a 6-node network under arbitrary topology. Moreover, the coordinates of nodes in Topology 2 are $A(4,4), B(5.8,4.8), C(5,3), D(6.6,3)$, $E(7,4.5)$, and $F(3,5)$. The parameters of each broadcast scheme are set to be the same as in the single-hop performance evaluation. In all topologies considered in the performance evaluation, node A is the source node. Fig. 18(a) to (c) show the analytical and simulation results of the broadcast ratio using the three considered broadcast schemes under Topology 1 and 2. It is shown that the simulation results fit the analytical results well with the maximum difference of 2.1%, 4.6%, and 0.4% for the three schemes, respectively. The distributed broadcast scheme still has the best performance of successful broadcast ratio among the three schemes.

5.2.3 Average Broadcast Delay of Multi-hop CR Ad Hoc Networks

For the average broadcast delay, we investigate two grid topology networks: 1) a 3×3 grid network (denoted as Topology 3); and 2) a 4×4 grid network (denoted as

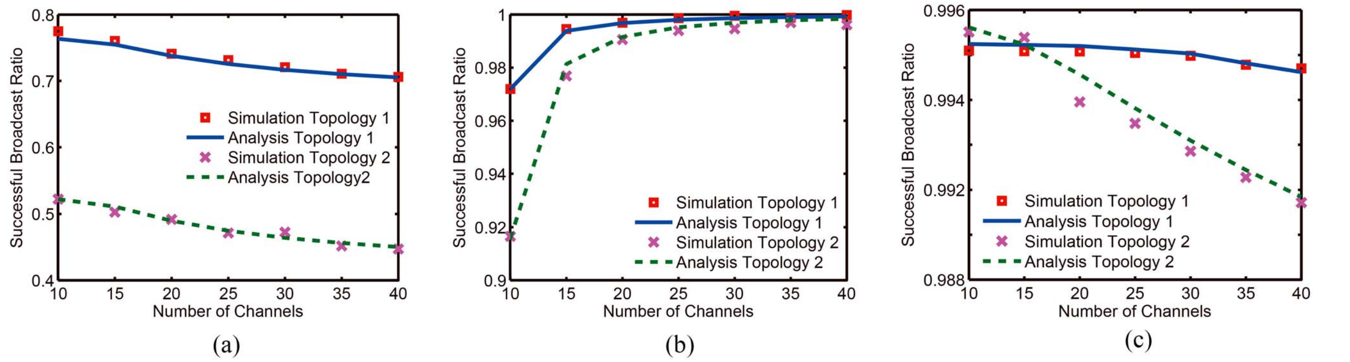

Fig. 18. Analytical and simulation results of the successful broadcast ratio using the three broadcast schemes under Topology 1 and 2. (a) Random broadcast scheme. (b) QoS-based broadcast scheme. (c) Distributed broadcast scheme.

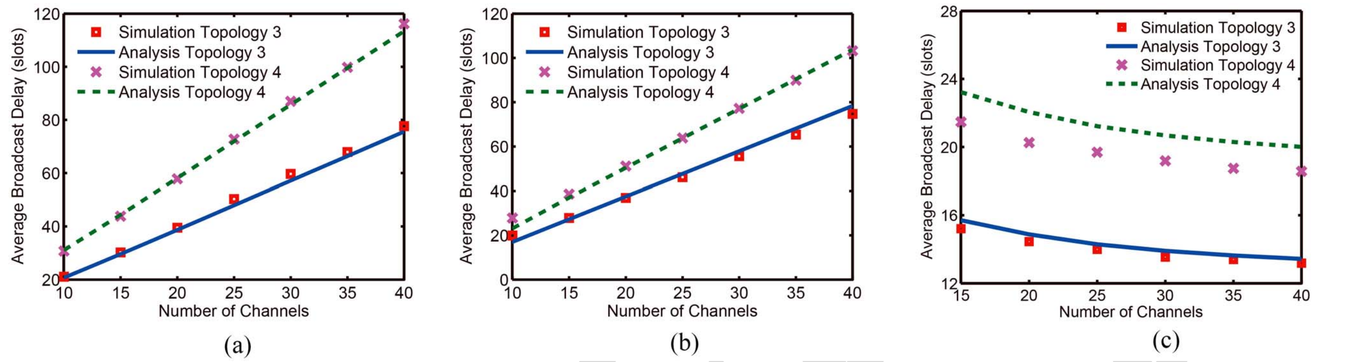

Fig. 19. Analytical and simulation results of the average broadcast delay using the three broadcast schemes under Topology 3 and 4. (a) Random broadcast scheme. (b) QoS-based broadcast scheme. (c) Distributed broadcast scheme.

Topology 4). Fig. 19(a) to (c) depict the analytical and simulation results of the average broadcast delay using the three considered broadcast schemes under Topology 3 and 4. It is shown that the simulation and analytical results coincide with each other well with the maximum difference of 4.9%, 9.4%, and 6.5% for the three schemes, respectively. Again, the distributed broadcast scheme has a much lower average broadcast delay, as compared to the other two schemes.

5.3 System Parameter Design Using the Proposed Analytical Model

As explained in Section 1, the system parameters of the proposed broadcast protocols in [11]–[14] are not designed to achieve the optimal performance due to the lack of analytical analysis. In this paper, we investigate the system parameter design of the random broadcast scheme using the proposed analytical model. In the random broadcast scheme, the length of time slots that the sender uses for broadcasting, S_r, is crucial to the performance of the broadcasting. Note that there exists a trade-off when determining S_r. If S_r is large, the successful broadcast ratio is high. However, the average broadcast delay is also long. On the other hand, if S_r is small, the average broadcast delay is short. However, the successful broadcast ratio is low. Hence, to design an optimal S_r is essential to the performance of the random broadcast scheme. We use an example to illustrate the process of the system parameter design. Consider a CR ad hoc network under Topology 1 shown in Fig. 13(a). We assume that the single-hop successful broadcast ratio over each link is the same, which can be obtained from (13) (denoted as p). Thus, using the proposed algorithm for calculating the successful broadcast ratio, the successful broadcast ratio for the random broadcast scheme under Topology 1 is

$$P_{succ}=p[1-(1-p)^2-P_q]^2+p^3\{1-[1-(1-p)^2-P_q]\} \\ +(1-p)p^2[1-(1-p)^2-P_q]+(1-p)^2p^3, \quad (27)$$

where P_q is given in (16). It is known that P_{succ} is a function of S_r.

On the other hand, we calculate the average broadcast delay under Topology 1, where node A is the source node. Since there are two levels in the network, we need to obtain the average broadcast delay of each level. Thus, using the proposed algorithm for calculating the average broadcast delay, we have

$$\Gamma = \sum_{d=1}^{S_r} dP_1(d) + \sum_{d=1}^{S_r} dP_2(d), \quad (28)$$

where $P_1(d)$ and $P_2(d)$ can be obtained from Section 4.1.2 and (3). Note that Γ is also a function of S_r. Define the objective function of a broadcast protocol, Θ, as the rate between the successful broadcast ratio and the average broadcast delay. Therefore, we have $\Theta = \frac{P_{succ}}{\Gamma}$. Thus, the optimization problem of the protocol design becomes finding the optimal S_r that maximizes the objective function, Θ. Then, using certain numerical method, the optimal S_r can be obtained. Fig. 20 shows the numerical results of the objective function under various S_r. It is shown that a proper S_r exists

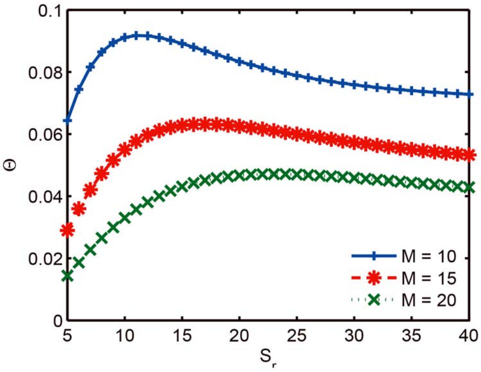

Fig. 20. Numerical results of the objective function under various S_r.

to achieve the optimal performance of a broadcast protocol. For instance, when $M = 10$, the optimal S_r is 11. The corresponding successful broadcast ratio is 81.25% and the average broadcast delay is 8.85 time slots.

6 Conclusion

In this paper, the performance analysis of broadcast protocols for multi-hop CR ad hoc networks is studied. Due to the non-uniform channel availability in CR networks, several significant differences and unique challenges are introduced when analyzing the performance of broadcast protocols in CR ad hoc networks. A novel unified analytical model is proposed to address these challenges and analyze the broadcast protocols in CR ad hoc networks with any topology. Specifically, two algorithms are proposed to calculate the successful broadcast ratio and the average broadcast delay of a broadcast protocol. In addition, the derivation methods of the single-hop performance metrics for three different broadcast protocols in CR ad hoc networks under practical scenarios are proposed. Results from both the hardware implementation and software simulation validate the analysis well. To the best of our knowledge, this is the first analytical work on the performance analysis of broadcast protocols for multi-hop CR ad hoc networks.

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