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A cognitive radio-based fully blind multihop rendezvous protocol for unknown environments

Saim Ghafoor, Cormac J. Sreenan, and Kenneth N. Brown

***Abstract*—In Cognitive Radio networking, the blind rendezvous problem is when two or more nodes must establish a link, but where they have no predefined schedule or common control channel for doing so. The problem becomes more challenging when the information about the existence of other nodes in the network, their topology, and primary user activity are also unknown, identified here as a fully blind rendezvous problem. In this paper, a novel and fully blind multihop (FBM) rendezvous framework is proposed with an extended modular clock algorithm (EMCA). The EMCA-FBM is a fully blind multihop rendezvous protocol as it assumes the number of nodes, primary radio activity and topology information as unknown. It is shown to work with different Cognitive Radio operating policies to achieve adaptiveness towards the unknown primary radio activity, and self-organization for autonomously handling the rendezvous process by using transmission schedules. It is capable of working without any information of neighbor nodes and terminating the rendezvous process whenever all or sufficient nodes are discovered. The proposed FBM is also shown to work as a general framework to extend existing single hop rendezvous protocols to work as a multihop rendezvous protocol. In comparison with other modified blind rendezvous strategies for multihop network, the combination of the proposed EMCA-FBM protocol and operating policies is shown to be effective in improving the average time to rendezvous (up to 70%) and neighbor discovery accuracy (almost 100%) while reducing harmful interference.**

***Index Terms*—blind rendezvous, cognitive radio networks, disaster response networks, fully blind rendezvous, multihop rendezvous, unknown environments, operating policies.**

I. Introduction

DISASTERS are catastrophic events which cause great damage and require immediate attention. In the aftermath of a disaster, the first responders need to coordinate and victims need to communicate. However, the existing communication network infrastructure might be destroyed completely or partially which makes it difficult to proceed with the response efforts. New and rapidly deployable systems are needed to efficiently coordinate the response efforts and to provide communication services to the victims. Such a system can be deployed to replace a destroyed cellular base station temporarily or can be used independently to form a mesh network to provide services in a larger affected area.

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A. Motivation

In the early hours of a disaster, little may be known about the damage to existing communication systems, the radio environment and physical access, which makes it an unknown environment. A disaster response network is a network which can be deployed in the aftermath of a disaster to provide a response in the form of a temporary network, to replace an existing communication system, or connect two disconnected base stations [1]. For such unknown environments, a cognitive radio (CR) has the potential to provide an efficient and rapidly deployable network by sensing the radio environment, learning from the observed channel information and making decisions about the spectrum usage [1]. Spectrum information is sometimes provided through spectrum databases.

However, in disaster scenarios, the information in these databases is likely to be unreliable and incomplete, or the databases themselves may be unreachable. Therefore, a CR must dynamically sense the available radio channels and use them to establish communication if they are not occupied by a primary radio (PR). A PR in a disaster scenario can be an existing partially destroyed cellular network which still operates on some licensed frequency bands, a nearby radar station or TV station still operational, or some fixed bands for an emergency purpose like an ambulance or public safety service. Figure 1, shows a disaster scenario for a cognitive radio network (CRN) including the cognitive or secondary and primary users. In this figure, different CR mobile base stations are shown to cover the affected areas where the existing communication networks are destroyed. These base stations can communicate with each other in a multihop manner to provide services like voice or data communication. The first responders can then use the CRs to extend the coverage of the service. In any case, the unknown PR activity makes it hard to find a common available channel to establish a rendezvous among nodes.

B. Definitions

We define the Rendezvous process for a CRN as the completion of a handshake mechanism between two secondary radios on a single channel, which assumes that the two radios are within transmission range of each other, that they coincide on the channel for a sufficient time period, and that the channel has no detectable PR activity or excessive interference for the radios over that time period. Achieving a rendezvous in an unknown environment is a difficult task when nodes are not aware of the channel access sequence of the other nodes and when there is no pre-defined schedule or common control channel (CCC) available. A CCC is a pre-defined channel

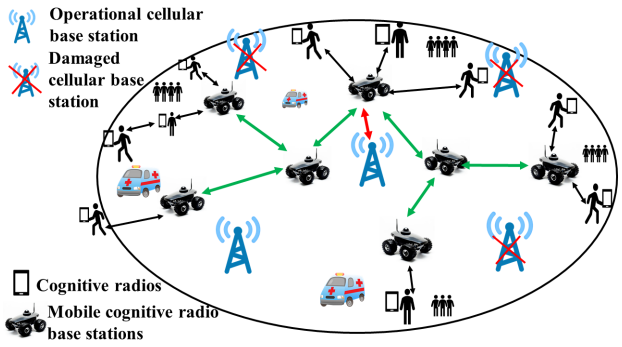


Figure 1: A CR based disaster response network scenario.

known by all nodes to exchange control packets among the network devices to establish communication. However, such CCC can be congested at times when the traffic or node density is high and negotiating a new CCC incurs excessive delays when PR activity is high [2, 3]. Channel hopping (CH) protocols can be used to avoid the use of CCC. Rendezvous can be achieved easily when two nodes follow the same CH sequence and are synchronized with each other in terms of time. The problem arises when nodes are not aware of the CH sequences of the other nodes and their wakeup times. Such problem is known as a blind rendezvous problem [3, 4]. The 'blind' element in that work has been limited to time synchronisation and to unknown channel information. In unknown environments like disasters, the nodes might also be unaware of the other information like the existence of other nodes, their topologies, their wakeup times and PR activity, which is identified here as a fully blind rendezvous problem. It introduces challenges like efficient rendezvous process termination, reliable neighbor information gathering, and synchronization to establish other network services with minimum network set up delay.

C. Prior art

Existing blind rendezvous protocols do not provide an adaptive and self-organized multihop rendezvous protocol. Mostly, PR activity is not considered, and when considered the rendezvous delay is high. Although the existing protocols claim a guaranteed rendezvous within a bounded time, their guarantee remains valid only when the nodes choose different rate values to jump across the CH sequence to select a channel and when the PR remains inactive on a selected channel. For an efficient use of licensed spectrum, the standard bodies have already defined certain operating policies for a CR (IEEE 802.22 [5]). These operating policies suggest to not only vacate a channel on which PR is detected but also to avoid its use for some recommended time. However, the solutions so far do not consider such operating policies and their impact on the performance of a cognitive radio network is still unknown. Further, the need to start again the rendezvous process arises frequently when a PR appears frequently on an available channel. Such a situation of restarting the rendezvous process can be avoided by exchanging schedules for the future meeting point. In addition, a rendezvous process can be terminated easily when a node knows in advance the total number of nodes to discover. It is otherwise challenging when the nodes are not aware initially of the existence of the total number of nodes.

D. Contributions

To address these challenges, our main contributions are summarised as follows:

- A fully blind multihop (FBM) rendezvous framework is proposed for multihop cognitive radio networks.
- The proposed framework is also presented as a general framework to enhance the functionality of existing single hop rendezvous protocol to multihop protocol.
- An extended modular clock algorithm with FBM (EMCA-FBM) is proposed for multihop network as a fully blind rendezvous protocol. which assumes the number of nodes, PR activity, and topology information, as completely unknown.
- EMCA-FBM is shown to work with cognitive radio operating policies to achieve adaptiveness towards unknown PR activity.
- A termination strategy is proposed for unknown number of nodes, to terminate the rendezvous process when all or a sufficient number of nodes are discovered.
- An information exchange mechanism is presented to disseminate a complete network view among all nodes to autonomously handle the rendezvous process and to establish other network services.

The proposed EMCA-FBM is an extension of the work presented in [3], in which only single hop networks with a known number of nodes were considered. In this work an autonomous multihop rendezvous protocol is proposed to handle an unknown number of nodes. The proposed multihop protocol is shown to be adaptive towards the unknown PR activity; self-organized to facilitate new nodes entering or leaving the network; autonomous in handling the rendezvous process; and reliable in gathering the neighbor information. It is shown that the proposed multihop protocol together with cognitive radio operating policies can improve the time to rendezvous by up to 70% and can also achieve almost 100% neighbor discovery accuracy with a reduction in the average number of harmful incidents, in comparison with existing rendezvous strategies. Two operating policies, reactive and proactive, are also shown to be better at improving the rendezvous performance when compared with the basic Listen before Talk approach. For synchronization among the nodes, a reachability factor is shown also to be 100%, i.e., a message can successfully be forwarded to all the discovered nodes.

The rest of the paper is organized as follows. Section 2 discusses the related work of blind rendezvous protocols. The proposed fully blind rendezvous protocol is presented in Section 3 with system model. Section 4 discusses different CR operating policies. In Section 5, the simulation environment is discussed. Section 6 presents the performance evaluation. Finally, in Section 7 the paper concludes.

II. Related work

There exist many rendezvous protocols for CRNs [7, 8] which can be classified as centralized or distributed protocols,

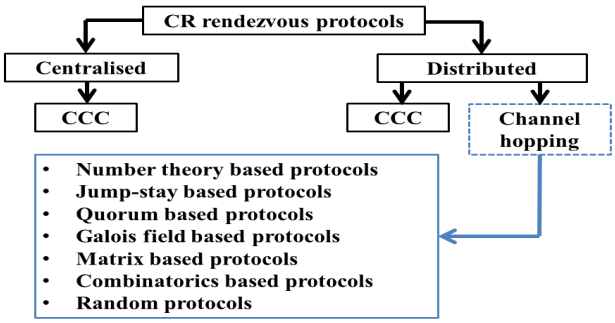


Figure 2: Classification for CR rendezvous protocols.

as shown in Figure 2. The centralized protocols mainly use a central controller or dedicated CCC. In distributed protocols, nodes find the common channel by themselves. The distributed protocols can be further classified as CCC and CH based protocols. The CH protocols are preferable as they avoid the single point of failure which is present in CCC-based protocols [2, 8]. The CH protocols can be further classified into seven categories [8], as shown in Figure 2. This work is mainly focused on distributed CH protocols and uses the Number Theory-based approach [4, 9–12]. The Quorum, Galois, Matrix, and Combinatorics protocols are not used in this work for evaluation because they require some initial information to generate CH sequence (like node IDs and channel information), they are role-based, and their complexity and rendezvous delay are high. For evaluation, we use jump-stay-based protocols [13–17] as they are closely related, and random protocols in which nodes select channels randomly [4]. Further, currently, there is no published work which addresses a fully blind problem for multihop CRNs.

Although most of the existing blind rendezvous strategies in the literature provide a rendezvous guarantee, their rendezvous guarantee is conditional and depends upon choosing either different rates, different prime numbers, CH sequences or node role assignments. In [4], a rendezvous guarantee is provided using a modular clock algorithm (MCA) based on number theory. In MCA, a node hops on the available channels using a rate (the step length) for a duration of a rendezvous cycle i.e., $2P$ timeslots and selects a new rate when a rendezvous does not occur within its one full rendezvous cycle. The guarantee is provided when two nodes select their rate values differently. It assumes the channels are available all the time with no PR activity. However, a PR can appear at any time and can abandon a rendezvous guarantee. A modified MCA (MMCA) is also proposed in [4] for the asymmetric channels case. A similar assumption that all channels are always available is made in [9]. In [10, 11], although PR activity is considered, their time to rendezvous (TTR) increases with increasing PR activity and are not adaptable towards the unknown PR activity. In [9–11], each node is assigned with a role as a sender or receiver, which is unrealistic as when two nodes are assigned with similar roles, they can not achieve a rendezvous. In [11], rendezvous guarantee is given only when the nodes pick different prime numbers, and in [12] ID information is required to generate CH sequences. In [4] to [12], the node information is assumed to be known in advance, without which the rendezvous process cannot be terminated.

A Jump-Stay based rendezvous technique is presented in [13], in which each node jumps over the available channels for $2P$ timeslots and then stays on a channel for P timeslots. A multihop strategy is presented also in [13], in which the users with lower IDs follow the CH sequence of nodes with higher IDs. However, the number of nodes is assumed to be known in advance and channels are assumed with no PR activity. The rendezvous guarantee is given only when both nodes select different rate values. An extension of JS is proposed in [14], to improve the maximum TTR with $4P$ as a rendezvous cycle length. The role-based JS rendezvous protocols are presented in [15, 16]. Another extension of JS is presented in [17], by randomly replacing the channels, in which Random is shown as better only for asymmetric channels case due to its better expected TTR.

In [18], a Randomised Quorum and Latin Square based distributed CH protocol is presented, which uses the concepts of Quorum system, Latin Square, and Pseudo-random number generator, to generate CH sequences. However, the drawback is that each secondary user needs to know the IDs and timeslot offset of its neighbors to switch to any global channel and the roles are picked randomly. Another role based Symmetric\Asymmetric Quorum-based CH protocols are presented in [19], in which the randomly replaced channels are copied in different sub-columns to increase the rendezvous success rate which is a biased condition as all channels might not be same among different nodes. In [20], a matrix-based approach is used which requires ID information of other nodes to generate the CH sequences in a matrix form. A greedy channel selection algorithm is proposed in [21] for single/multi-hop CRNs, in which the nodes pass the channel switching order to the nodes with higher IDs. It assumes global channels are accessible to all nodes with no PR activity and assumes a known number of nodes. In [22], secondary user is used as a brige to facilitate rendezvous between a pair of CRs. In [23, 24], rendezvous using multiple radios are presented.

The existing blind rendezvous strategies cannot be directly applied to an unknown environment like disaster scenarios due to some limitations, which include a conditional rendezvous guarantee; fixed role based node operation (as a sender or receiver); the requirement of initial information (e.g., ID information) to generate CH sequences; higher time to rendezvous; and longer rendezvous cycles. Most of the existing papers do not consider the PR activity and if they do consider it, their TTR increases with increasing PR activity and are not adaptive. None of the work provides a rendezvous guarantee in presence of unknown PR activity. The CR operating policies [5] is the main part of CR operation, which directs the CR behavior on detection of a PR activity. Although it is recommended that a CR vacates a channel and avoids its use for some time after PR detection, none of the work shows the impact of this on the rendezvous performance. The work in [12, 18, 20], requires some initial information (IDs) to generate channel hopping sequences, due to which they remain not completely blind. Most importantly, the existing work on blind rendezvous does not provide a multihop rendezvous solution

for unknown nodes, topology and PR activity information. The works in [13, 21] considers a multihop scenario, but only for a known number of nodes.

In summary, the existing work does not address a fully blind rendezvous problem for the unknown environment. A rendezvous protocol for an unknown environment should be adaptive, cooperative, self-organized and should work without any initial information like the number of nodes, topologies or PR activity. Therefore, a fully blind multihop rendezvous protocol is considered in this paper, which focuses on challenges like efficient termination of the rendezvous process, adaptiveness towards unknown PR activity, autonomous rendezvous process management and gathering of reliable neighbor information.

III. A fully blind Rendezvous protocol for Multihop network

In this Section, the proposed EMCA-FBM rendezvous protocol is presented for multihop network. First, we present the system model, followed by the core extended modular clock algorithm (EMCA) from [3] (based on [4]), which we then further extend for multihop networks with unknown numbers of nodes.

A. System Model

We assume N CRs located in an LxL area. Each CR i (where $1 \leq i \leq N$) is equipped with a single wireless interface and can operate on only one channel at a time.

We assume perfect channel sensing for the discussion and justification of the methods; we evaluate the impact of imperfect sensing in the experiments section.

A time-slotted system is assumed with a fixed timeslot (TS) duration for the rendezvous algorithm. The CR nodes are not synchronized with each other or with PRs and are unaware of the starting times of all other nodes. Rendezvous is possible between two nodes only when their TSs overlap for a sufficient amount of time to exchange beacons. For beacon transmissions, a broadcast transmission is adopted where each node broadcasts its beacon to attempt a rendezvous.

B. Extended Modular Clock Algorithm (EMCA)

EMCA follows the number theory based technique to select the next channel and attempt rendezvous. It is based on Modular Clock Algorithm [4] and modifies MCA by reducing its rendezvous cycle length, remapping unavailable channels randomly while considering PR activity. Its main operation and differences with other existing protocols are mentioned below. Its operation is also shown in Algorithm 1. The main notations for EMCA algorithm are:

- r_i (rate), is the step length for channel hopping.
- m_i, is the total number of channels in ACS_i.
- P_i, represents the duration of a rendezvous cycle and is the lowest prime number greater than or equal to m_i.
- j_i, is the index value or label of a channel.
- $c_{i,j}$, is the channel at index j of node i's ACS.

Algorithm 1 Extended Modular Clock Algorithm [3].

Input: m_i and P_i
choose initial $j_i^{t_i} = rand[0, m_i)$
choose initial r_i from $[0, P_i)$ randomly
Initialize, $t_i = 0$
while node i not rendezvous with all nodes **do**
  if $t_i \geq P_i$ **then**
    choose r_i from $[0, P_i)$ randomly
    $t_i = 0$
  end if
  $j_i^{t_i+1} = (j_i^{t_i} + r_i)$ mod P_i
  if $j_i^{t_i+1} < m_i$ **then**
    $c = c_{i,j_i^{t_i+1}}$
  else
    $c = c_{i,rand([0,m_i))}$
    c is the selected channel for t_i
  end if
  Sense channel c for PR activity.
  if channel c is occupied **then**
    Do not attempt rendezvous on c.
  else
    Attempt rendezvous on c by sending beacon with neighbour information.
  end if
  wait for timeslot to end
  $t_i = t_i + 1$
end while

1) EMCA Operation: The EMCA algorithm initializes by choosing an initial index and rate value (r_i) randomly, as shown in Algorithm 1. The rate value remains the same for the duration of a rendezvous cycle with length P_i timeslots, whereas in MCA the rendezvous cycle length is $2P$ timeslots. If rendezvous does not occur within P_i timeslots, then a new rate will be selected again randomly from $[0, P_i)$. At each iteration, the next index value j_i will be calculated using $mod(P_i)$. If the new channel index j_i is within m_i then that channel $c_{i,j}$ will be selected, which is the channel at index j_i on node i's ACS. Otherwise, if the next index value is greater than $m_i - 1$, than the index value will be remapped randomly (out of m_i) to select a channel from ACS_i. The index can exceed $m_i - 1$ due to the gap between m_i and P_i.

For a successful rendezvous, two nodes must complete a handshake process. A beaconing mechanism is presented, in which nodes embed into the beacon a list of neighboring nodes they have overheard. If two nodes find their own IDs in each other's beacons, then it is assumed that rendezvous has been completed, which can result in a faster rendezvous. For example, when Node B receives a beacon from A it will send an ACK. A now knows that B has received its beacon, and adds B to its neighbor list. If B receives A's next beacon, it will discover its own ID in the list. It knows that A has received its ACK, and can add A to its neighbor list.

2) Difference with existing approaches: The main advantages of EMCA and its difference with existing blind rendezvous strategies are,

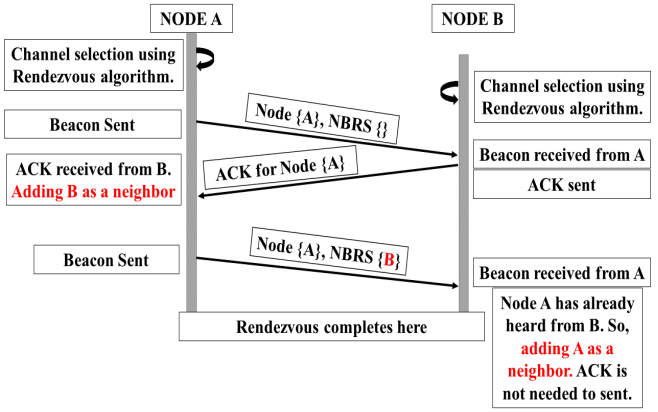
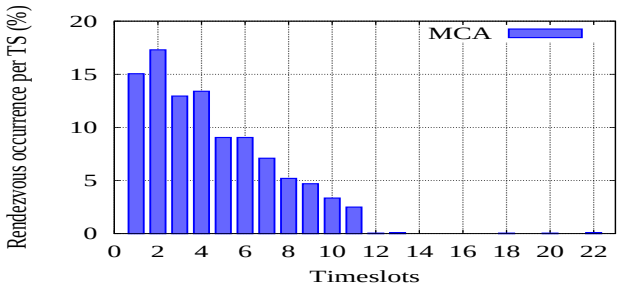


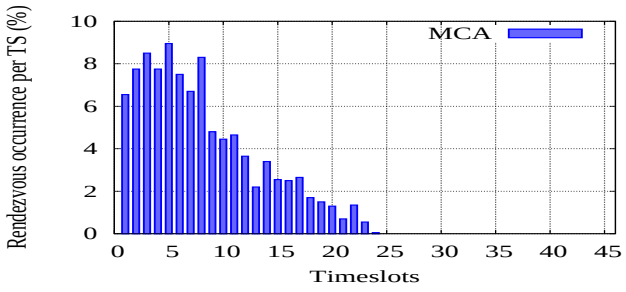
Figure 3: Handshake and information exchange mechanism.

- Its rendezvous cycle is short (i.e., P timeslots), for which a node hops among available channels.
- It remaps channels randomly from m_i, to avoid biased channel selection from the initial order.
- It considers channels with PR activity and transmits only on a free channel.
- It contains a handshake and information exchange mechanism for a successful rendezvous, as shown in Figure 3.

Short rendezvous cycle: The rendezvous cycles of existing blind rendezvous strategies are long, which is to achieve a rendezvous guarantee. The MCA case is considered here, in which rendezvous is guaranteed (if $r_1 \neq r_2$) and rendezvous cycle length is set to $2P$ timeslots due to possible different starting times of two radios. Since they assume channels with no PR activity, the PR effect is not accounted for. The rendezvous opportunity can be missed, if a PR appears on that channel at that particular time, which also breaks the rendezvous guarantee. In such a case, following the same rate value for $2P$ timeslots results in higher TTR values. Therefore, the limit of $2P$ is reduced to P in EMCA for a faster rate re-selection in the hope of a faster rendezvous completion. As we are giving away half of the rendezvous cycle length, it is important to determine how often rendezvous occurs in the second half of $2P$ timeslots (i.e., last P timeslots) of MCA. A scenario is simulated using 2 nodes and 10 channels (simulation setup will be discussed in Section V in detail), to find out the rendezvous occurrence distribution in each half of $2P$ timeslots (rendezvous cycle length of MCA). Figure 4a illustrates the results, which show that for 10 channels 99.45% times rendezvous occurred in the first half of $2P$ timeslots and only 0.55% times they occurred in the second half of $2P$ timeslots, which we propose to compromise. For 10 channels (m_i) the P value is 11 timeslots and $2P$ is 22 timeslots. For 20 channels P is 23 and $2P$ is 46 timeslots. Figure 4b shows the results for 20 channels, and the percentage ratio appeared again in favor of first half of $2P$ timeslots with 99.95% times rendezvous occurred in the first half of $2P$ timeslots. Thus, since the presence of unknown PRs removes the guarantee of MCA, we reduce the period by 50% to P, which allows us to select a new rate value more quickly, and hence should reduce TTR.

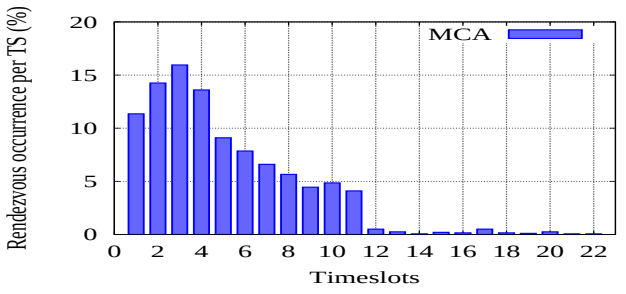


(a) 10 channels

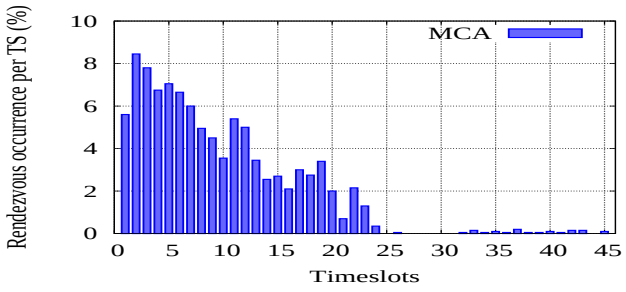


(b) 20 channels

Figure 4: Rendezvous occurrence distribution among $2P$ timeslots of MCA rendezvous cycle length.



(a) 10 channels



(b) 20 channels

Figure 5: Rendezvous occurrence distribution among $2P$ timeslots of MCA rendezvous cycle length with random channel remap.

Random remapping of channels: Depending on the total number of channels m_i, there can be a gap between m_i and P_i, because P_i is selected as a prime number larger than or equal to m_i (For example, if m_i is 8 then P_i will be 11). Due to next index calculation in Line 10 of Algorithm 1, the resulting index can exceed the $m_i - 1$ limit of channel

indexes. To overcome this situation and to wrap it again within the $m_i - 1$ limit, MCA remaps the index with another mod function (as $j_i^{t_i+1} mod(m_i)$) between 0 and $m_i - 1$, which results in biased channel selection from the initial order of ACS_i. Using the mod function means that only channels 0 to $P_i - m_i$ will be selected in remapping, which biases the channel selection. If those channels are not equally accessible, or if PR activity concentrates on those channels, this will affect the TTR. In EMCA the channels are remapped randomly from ACS_i, when the resulting index value exceeds the $m_i - 1$ limit. The test for rendezvous occurrence distribution per timeslot is repeated with the random remap, to see the effect on rendezvous occurrence distribution in each half of $2P$ rendezvous cycle length. The results show that for 10 channels case (Figure 5a) 97.75% times rendezvous occurred in the first half of $2P$ timeslots and only 2.25% times they occurred in the second half. Similarly, for 20 channels case (Figure 5b) about 98.50% times rendezvous occurred in the first half and only 1.50% times rendezvous occurred in the second half. This shows that even with random replacement, the rendezvous occurrence within first P timeslots is not affected as compared to the results without channel.

C. A Fully Blind Multihop rendezvous framework (FBM)

In the proposed multihop protocol framework, each node works in different phases to achieve the rendezvous with all neighbors and to terminate their algorithms. At every rendezvous attempt, a node embeds into its beacon two lists of neighbors, a Directly connected neighbors list (DNL) and an Indirectly connected neighbors list (INL). DNL contains a list of neighbors to which a node can talk directly and are within one hop distance, whereas INL contains the list of those neighbors which are known to exist but with which a node can not directly communicate or are at more than one hop distance. As nodes are unaware of N, nodes do an estimation of N by comparing their DNLs and INLs, to proceed with the rendezvous process and its completion. The flowchart is shown in Figure 6. To achieve rendezvous among the nodes and to terminate the rendezvous process successfully, a node will progressively move from Rendezvous to the Termination phase. These phases include a Rendezvous, Transition, and Termination Phase, and are discussed below;

1) Rendezvous Phase: Nodes attempt to discover a common understanding of their reachable network.

In this phase, nodes start their rendezvous process normally using a rendezvous algorithm, without any time limit. In this phase, the nodes will try to achieve rendezvous with their one-hop neighbors and shares information about their direct and indirect neighbors including the channels information. However, when a node find its neighbor list same as sender's neighbor list, it will move to the Transition phase and sends an ACK to tell the other node to do so also. While comparing the DNLs and INLs, the nodes with which the receiver has not talked directly will be added to the INL of the receiver node. However, if the neighbors are not equal, then the node will continue its rendezvous phase. The nodes will also exchange a scheduling point by exchanging a particular timeslot and

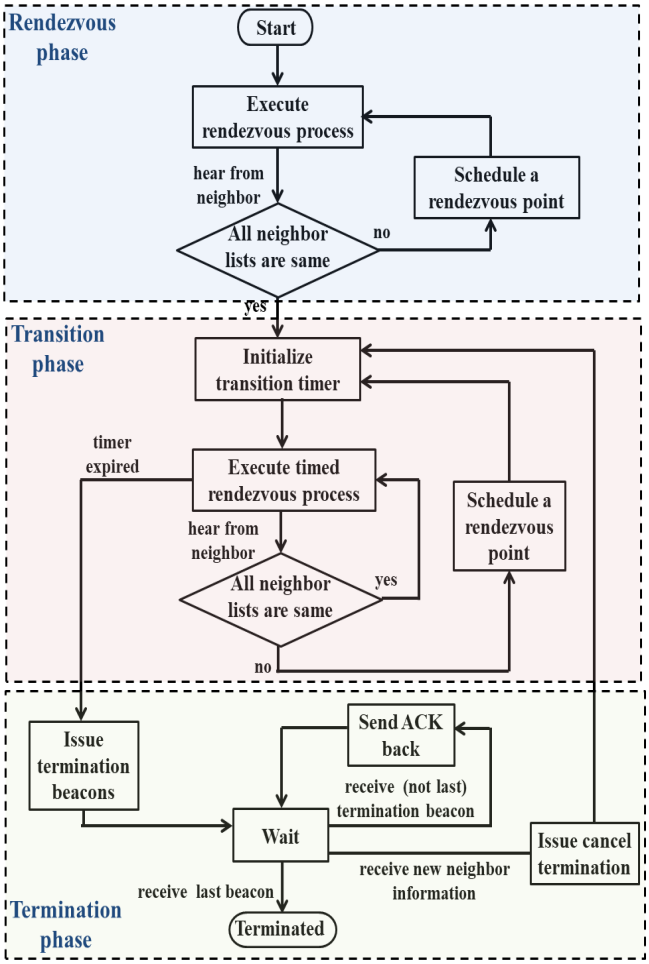


Figure 6: FBM rendezvous framework flowchart.

a channel, to meet at a future time to share and update their neighbor information. Once the receiver encounters a rendezvous with any node that already exists in its INL, it will move it from its INL to the DNL. Once a node moves from the Rendezvous phase to the Transition phase, it will not go back to it.

2) Transition Phase: Nodes wait to see if new nodes or new links are reachable, until a time limit passes with no new information.

The Transition phase is different from the Rendezvous phase, as it runs with a time limit. The Transition phase time limit is set according to the time required to achieve a rendezvous between one-hop neighbors in a worst case scenario (i.e., the High PR activity). It is meant to provide extra time to a node to achieve rendezvous with the nodes in its INL and to which a node could not talk while in the Rendezvous phase due to the unknown PR activity. If a node encounters a rendezvous in this phase with a new neighbor or finds new information about any indirectly connected neighbor, the transition phase will start again. At every beacon reception, a node in the Transition phase compares and matches the DNL and INL IDs; and starts again if they are not equal. A rendezvous point is also scheduled, if not scheduled already between any pair of direct neighbors, to be sure that none of

the nodes have missed any neighbor entry. This will help out in distributing a complete network view across a network and to achieve synchronization among nodes. After the expiry of the Transition phase, the nodes will automatically move to the Termination phase and start their Termination process.

3) Termination Phase: Nodes attempt to terminate the rendezvous process, to get ready for network operation.

In the Termination phase, the nodes will move towards the termination of the rendezvous process by exchanging messages and confirming with each other about their termination stage. Once a node receives a beacon which confirms the start of the Termination stage of the sender, the receiving node will update the sender node's status as Terminated, and inform the sender about its status by sending an ACK (provided the receiver is also in the Termination phase). The sender on reception of an ACK will change the receiver's status also to Terminated. A node will wait until it receives from all of its directly connected neighbors, a beacon with a termination request or an ACK which confirms their Termination decision, after which it can terminate its rendezvous process. While Terminated, the nodes will not send any rendezvous beacons to attempt a rendezvous. However, if they receive any beacon with a request from the sender about the Termination, the node will send back an ACK message, to confirm their Terminated status. If any new information is found during that time, the nodes will move back to the Transition phase and cancel their Terminated status. This will facilitate the information dissemination of any new neighbor arrival, even after the rendezvous process has terminated.

After the completion of the Termination phase, a node can stop its rendezvous process and can start establishing other network services like routing or data dissemination. The rendezvous process can also be carried out periodically to update the neighbor information and can trigger the rendezvous process from the transition phase if a new information is found.

IV. Cognitive Radio operating policies

The operating policies are intended to protect a PR system from harmful interference and to specify the next course of action when a PR is detected on a channel. These policies can be integrated with rendezvous strategies to handle the PR activity and to achieve the design and performance goals. On detection of a PR activity, a CR should not only vacate the channel but also avoid its use for some time. These recommendations are described in [5] as channel availability check (CAC) and channel non-occupancy period (CNP). CAC is the time during which a channel should be checked for the presence of a PR. CNP is the period during which a CR should avoid transmission on a channel which is already detected as occupied. Each node maintains its blacklisted channels list (BLC), in which channels detected with PR activity will remain until their CNP time expires, at which point they can be used again. A CR can also learn to assist the spectrum policy decision in parallel with spectrum sensing. These policies are presented below and also shown in Figures 7 to 10.

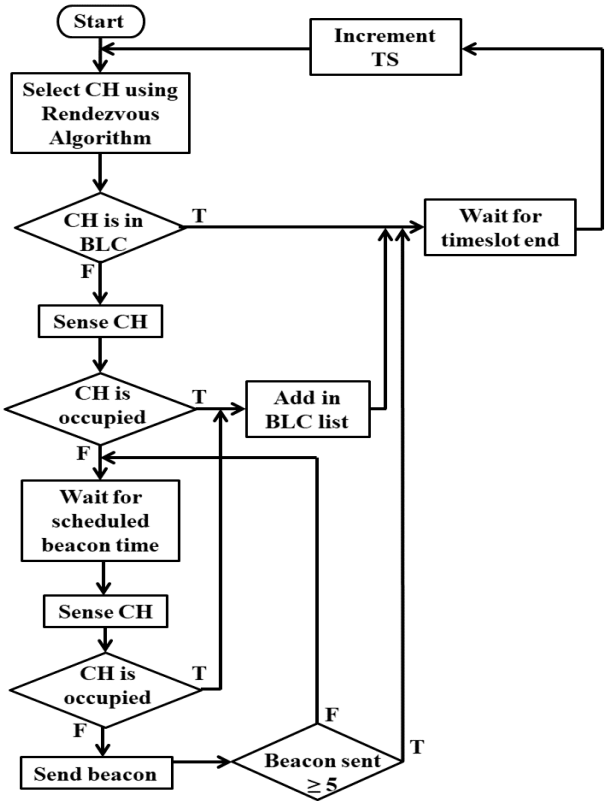


Figure 7: Normal operating policy.

A. Listen Before Talk (LBT)

In LBT, a channel status will be checked before every beacon transmission, and rendezvous will be attempted only when a channel is sensed as free (i.e., no PR activity is detected on a channel). However, it has its own drawbacks,

- It violates the standard's recommendations by continuing to probe on a channel, detected with a PR activity.
- It wastes time by staying on a channel detected with a PR, which may cause harmful interference.

B. Normal Policy

In this policy, we modify LBT so that when a PR is detected on a channel the CR is using, it stops beaconing on that channel, adds the channel to its BLC, and waits for the next timeslot. Figure 7, shows the working of a Normal operating policy. In Normal policy, the selected channel will be checked for a possible PR activity or presence in the BLC list at the start of a timeslot. Rendezvous can only be attempted when the channel is found free. Otherwise, the node will remain silent for the rest of the timeslot. If at any level during a beacon transmission phase, the channel is detected with PR, then it will be added in the BLC and node will remain silent for the rest of the timeslot.

C. Reactive Policy

The Normal policy wastes time by staying silent on a channel detected with PR activity. To avoid this, the Reactive policy immediately starts searching for a free channel using

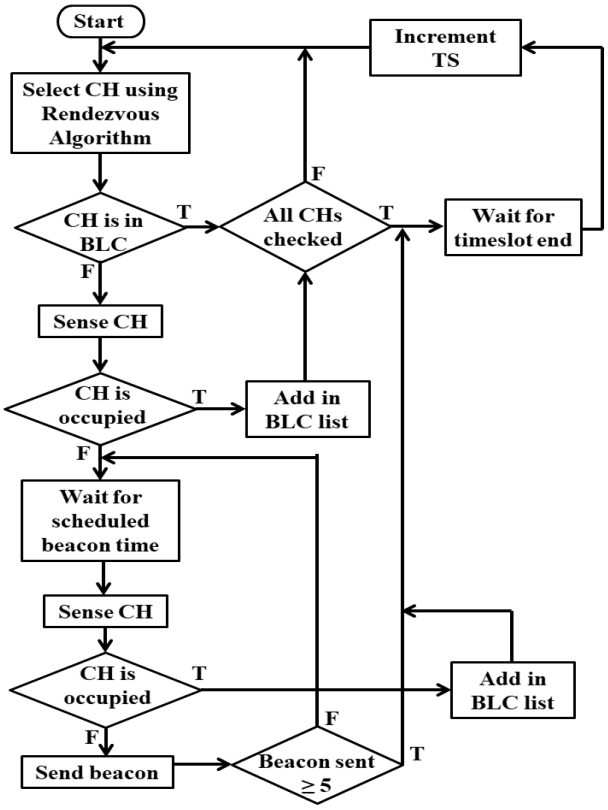


Figure 8: Reactive without timeslot truncation operating policy.

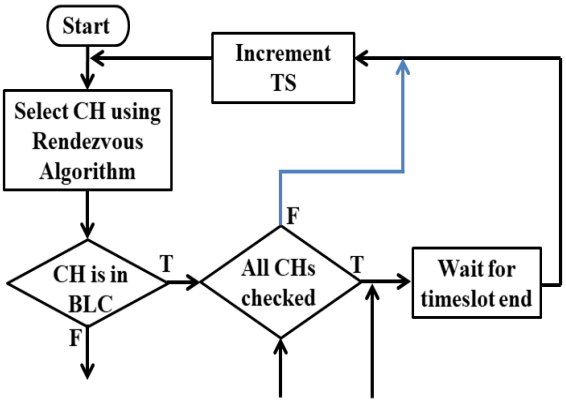


Figure 9: Reactive with timeslot truncation operating policy.

the rendezvous algorithm. The CR operating limitations are as before, where LBT is followed with CAC/CNP checks. There are two variations, depending on whether or not the timeslot is truncated on PR activity detection at the beginning of the timeslot. Maintaining the timeslot structure keeps any time synchronization between nodes while starting a new timeslot means that a node will reach the P timeslots limit faster (in real time), and so if needed can change its rate more quickly.

1) Reactive without Timeslot Truncation (RwoT): The RwoT is close to IEEE 802.22 in selecting the next channel immediately, however, the difference is that in IEEE 802.22 the channel is selected by using a spectrum database whereas in

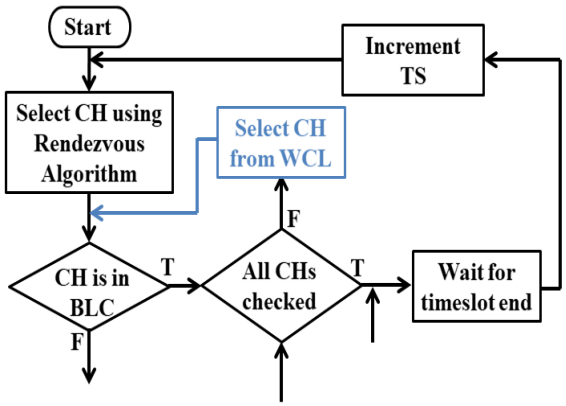


Figure 10: Proactive operating policy.

RwoT the node will select a free channel using an independent channel sensing. Initially, the node will select a channel using a particular rendezvous algorithm. If occupied by a PR or found in BLC, the next channel will be selected using the existing rendezvous algorithm. The process will continue until a free channel is found or all channels are examined. If a free channel is found, then the node will start its beacon transmission phase. Otherwise, the node will remain quiet until the end of the timeslot. The channel will be selected by using a rendezvous algorithm every time, however, the rate parameter (the channel hopping factor) will be updated only when a node completes its rendezvous cycle (i.e., P timeslots). The flowchart is shown in Figure 8.

2) Reactive with Timeslot Truncation (RwT): In RwT, a node searches for the free channel in a reactive manner as in RwoT. However, with every channel selection, the timeslot will also increase. By doing this, not only will the node truncate the current timeslot and start the new timeslot for the new channel, but will also reach the P limit faster to select the new rate value. The flowchart is shown in Figure 9, where the rest of the flow is similar as in Figure 8.

D. Proactive Policy

The Proactive policy attempts to learn the behavior of the primary users. For each channel, it maintains a channel weight C_w^i, which approximates the channel's probability of being unoccupied (or OFF), as shown in Eqn 1. The flowchart of proactive policy is shown in Figure 10, where the rest of the flow is similar as in Figure 8. The policy starts by selecting a channel in each timeslot as normal, using a rendezvous algorithm. However, if the channel is occupied or exists in BLC then the Weighted Channels list (WCL) will be used to pick another channel in proportion to the weights in the WCL. The intention is to augment an existing channel selection algorithm by temporarily returning to channels most likely to be free, rather than staying silent during a slot when PR activity is detected. Besides, the channel selection, it follows the same process for the beacon transmissions as in the reactive policy, where LBT was followed with CNP/CAC checks. At any instance, if a channel is detected with a PR activity, the nodes blacklist the channel and avoid its usage for CNP time.

$$C_w^i(weight) = \frac{(P_{PSM} + P_{FA})}{(P_{PSM} + P_{NSM} + P_{FA} + P_{MD})} \quad (1)$$

At each channel selection, the channel's randomly estimated state (ES) and actual observed state (OS) are matched for its weight calculation. The channel state matching is defined as positive successful match (PSM) (ES=0, OS=0), negative successful match (NSM) (ES=1, OS=1), false alarm (FA) (ES=1, OS=0) and miss detection (MD) (ES=0, OS=1). MD occurs when a node declares an occupied channel as unoccupied and FA occurs when a node declares an unoccupied channel as occupied. Each node maintains these probabilities or channel's predictive conditions like PSM, NSM, MD, and FA, and updates only the particular condition when they occur. These accuracy test values are then used in Eq. 1 to determine the rank or C_w^i, which appears between 0 and 1, where 1 means the channel has the highest probability of being in OFF state. Using the C_w^i values, each node then maintains a sorted WCL and selects a channel from WCL when required. The WCL is updated every time a node selects a channel and the time a node takes to select a channel from WCL is negligibly small compared to channel selection in LBT policy. Note that any other learning mechanism could be inserted into this policy.

V. Simulation environment

In this section, the simulation platform is discussed.

A. Primary Radio Activity Model

A lot of work has been done already on PR activity traffic models [26, 27]. The main function of these models is to simplify the real spectrum environment to provide a tractable and realistic representation of the spectrum so that they can be used in analytical studies and computer simulations. Different PR activity models are discussed in [26, 27] and mainly classified into Markov process, Queuing theory, time series and ON/OFF models. Among different PR activity models, Markov chain based PR activity models are widely used in the literature [26–30] and also followed in this paper.

For CR systems, the occupancy pattern of a PR can be modeled as a two-state Markov chain, where the two states are ON and OFF. ON means the channel is busy and should not be used while OFF shows that the channel is free or idle and can be used by a CR. The continuous time alternating ON/OFF Markov Renewal Process is used in [28–31] to model PR activity. This model is also been used for the performance evaluation of CRN [31–33], and used for public safety bands [34]. This model makes the following assumptions when the current state of a channel is i.

- the time will be exponentially distributed until the next channel state transition and it will be independent of the past history of the previous channel-state.
- the next state will be j with probability P_{ij} and it will also be independent of the previous state and process until next transition.

In this model, the duration of ON/OFF states of a channel i is denoted as T_{ON}^i and T_{OFF}^i. The renewal period $Z_i(t)$ will occur when one ON/OFF period is complete [28, 29], where,

$$Z_i(t) = T_{ON}^i + T_{OFF}^i \quad (2)$$

where the channels ON/OFF periods are both exponentially distributed [28–30] with p.d.f.,

$$f_X(t) = \lambda_X \times e^{-\lambda_X(t)} \qquad \text{for ON state, and} \quad (3)$$

$$f_Y(t) = \lambda_Y \times e^{-\lambda_Y(t)} \qquad \text{for OFF state} \quad (4)$$

The duration of time in which channel i is in ON state i.e. U^i is given as [29],

$$U^i = \frac{E[T_{ON}^i]}{E[T_{ON}^i] + E[T_{OFF}^i]} = \frac{\lambda_Y}{\lambda_X + \lambda_Y} \quad (5)$$

where $E[T_{ON}] = 1/\lambda_{ON}$ and $E[T_{OFF}] = 1/\lambda_{OFF}$ are the means of exponential distribution and λ_X and λ_Y are the exponential distribution rate parameters. The probability of channel i being in ON or OFF state at time t can be calculated as below, where $P_{ON}(t) + P_{OFF}(t) = 1$.

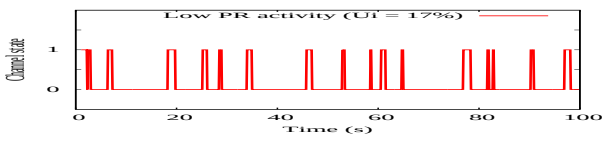
$$P_{ON}(t) = \frac{\lambda_Y}{\lambda_X + \lambda_Y} - \frac{\lambda_Y}{\lambda_X + \lambda_Y} e^{-(\lambda_X + \lambda_Y)t} \quad (6)$$

$$P_{OFF}(t) = \frac{\lambda_X}{\lambda_X + \lambda_Y} + \frac{\lambda_Y}{\lambda_X + \lambda_Y} e^{-(\lambda_X + \lambda_Y)t} \quad (7)$$

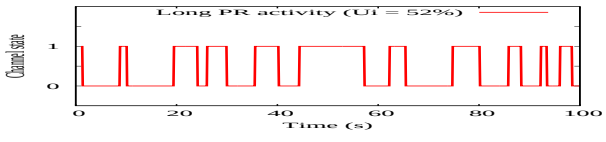
Different PR activity patterns can be generated using this model and adjust the exponential distribution rate parameters (i.e., λ_X and λ_Y) for ON and OFF periods.

These rate parameter values (λ_X and λ_Y) shown in Table I are provided as an input for PR activity modelling in the simulator, where PR module calculates the probabilities of channel occupancy and availability (P_{ON} and P_{OFF}) at any given time t and channel utilization (U_i, which is time for which the channel i remains occupied), and assigns the PR activity on each channel. These rate values were also measured in [29].

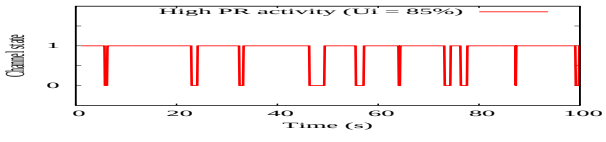
In disasters, the PR traffic remains unknown, and each link can have different traffic patterns with low occupancy or high occupancy. For example, when a disaster occurs near a coastal area the radar bands may have ongoing communication, and when it occurs near an urban area than TV or cellular bands may be occupied. In fact, disasters can occur at any place and time, and depending on the locations the PR occupancy can be different. Therefore, these rate values are adjusted carefully to generate different PR activity traffic patterns, and are shown in Figure 11 and Table I, to analyze the performance of rendezvous protocols over different PR activities. These PR activity traffic patterns include zero (0%), low (10-20%), long (45-60%), high (70-85%) and intermittent (40-60%) PR. A mix PR activity is also used in which each channel is given a different PR traffic pattern randomly. For example, a first responder might be using their own network for walkie-talkie based voice communication which can result in partial channel occupancy. A news agency might be using channels for their own transmissions with live video streaming. The partially destroyed cellular base stations might still be in service, providing voice communications on cellular bands.



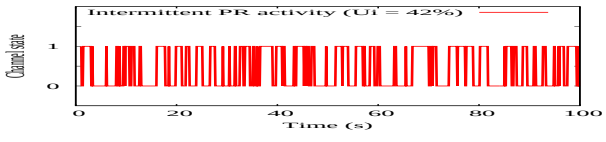
(a) Low PR Activity



(b) Long PR Activity



(c) High PR Activity



(d) Intermittent PR Activity

Figure 11: Different PR activity patterns.

Table I: Rate parameters values for channel states used in the simulations

	HIGH PR ACTIVITY			MIX PR ACTIVITY		
Ch ID	λ_X	λ_Y	U_i	λ_X	λ_Y	U_i
1	0.25	0.93	0.79	10000	0	0
2	0.3	1	0.77	1.03	0.3	0.23
3	0.25	1.03	0.8	0.22	0.31	0.58
4	0.23	1.45	0.86	0.22	1.2	0.85
5	0.22	1.1	0.84	1.33	1.2	0.47
6	0.25	0.64	0.72	10000	0	0
7	0.22	1.41	0.87	1.28	0.28	0.18
8	0.23	1.59	0.87	0.23	0.49	0.68
9	0.32	0.64	0.66	0.25	0.93	0.79
10	0.21	1.45	0.87	1.79	1.3	0.42

B. Cognitive Radio Simulator

A Cognitive Radio Cognitive Network patch [35] of NS-2 is used to implement a CRN which is also used in [31, 32] for the performance evaluation. It has three main functional layers i.e., Network, MAC, and Physical layer. A simple collision and contention-based MAC protocol (maccon.cc) is extended with a PR activity model, which is responsible for the channel based PR activities i.e., channels ON/OFF periods over the simulation time. The Network layer contains the rendezvous protocols, cognitive radio operating policies block for channel selection and decision block. The selected channel will then be passed to the lower layers for channel sensing output, based on which it decides to continue on a particular channel or contact the rendezvous algorithm or particular policy for next channel selection. The neighbor information is encapsulated in the packet header and then passed on to the lower layers. The MAC layer has the channel status check or sensing mechanism which contacts the PR activity block

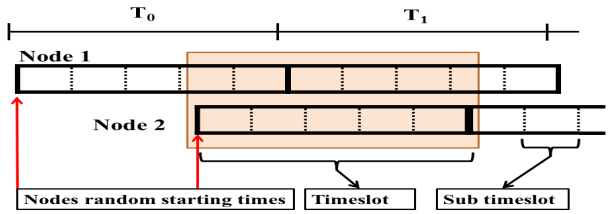


Figure 12: Overlapping of timeslots.

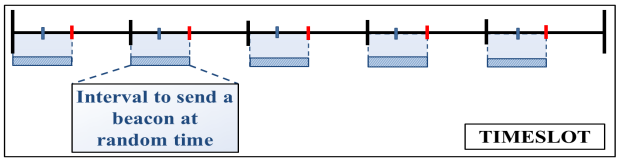


Figure 13: Timeslot structure and beacon transmissions.

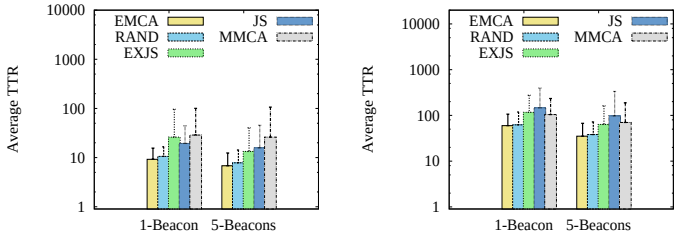
for acquiring the channel sample at a particular simulation time for channel occupancy by a PR. On receiving a channel occupancy status as ON, a channel hand-off signal is sent back to Network layer's decision block, which then initiates a new channel selection. No transmission occurs when a channel hand-off mechanism is initiated. The channel status prediction module works in parallel to calculate the channel's weight and prediction. Physical layer has the Transmission power, SNR, propagation model etc. Each module implemented are shared using a common information sharing layer.

C. Simulation Setup

The network area is set to 1000 x 1000 square meters. For the experiments, the number of nodes is either 2, 3, 10, or 100. The number of channels is 7 or 14, which are selected randomly from a set (G) of 10 and 20 channels respectively. The channel non-occupancy period or blacklisting time is 3 timeslots. An actual CNP time of 10 mins or 600 TSs is also simulated for the analyses. Nodes are static, and each node is only aware of its own starting time. Each node is initially unaware of the total number of nodes, their topology, and the PR activity.

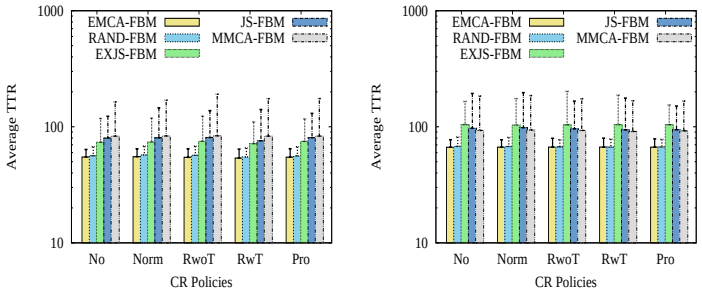
D. Timeslots structure and multiple beacon transmissions

Each node starts its rendezvous process at random times within a window of one timeslot, as shown in Figure 12. Due to different starting times, the timeslots of different nodes can overlap with each other in different proportions. As shown in Figure 12, the first timeslot of Node 1 is overlapped with first TS of Node 2 by nearly 40%, similarly the second TS of Node 1 is overlapped with first TS of Node 2 by approximately 60%. Sending multiple beacons in a TS gives more opportunities to a node to achieve rendezvous with each other, than just by sending one beacon in each TS. Therefore, a TS is further divided into sub-timeslots, as shown in Figure 13, in which a beacon is scheduled to be transmitted at random times within the first half of each sub timeslot. A comparison of sending multiple beacons is shown in Figure 14, for zero and high PR activity, in which each rendezvous strategy is simulated



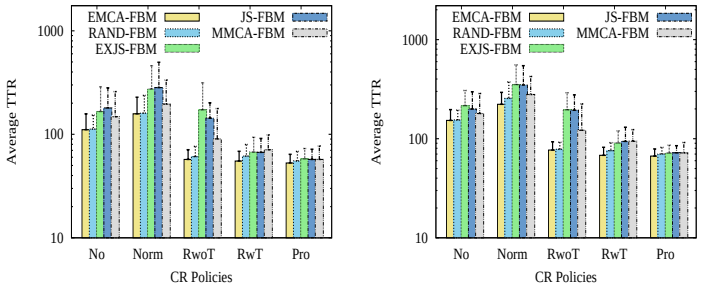
(a) Zero PR activity (b) High PR activity

Figure 14: Multiple beacons transmissions (2 nodes and 7 chs).



(a) 3 Nodes (b) 10 Nodes

Figure 15: Average TTR for Zero PR activity (7 channels).



(a) 3 Nodes (b) 10 Nodes

Figure 16: Average TTR for High PR activity (7 channels).

for sending 1 and 5 beacons. The number of the channel is used as 7 (asymmetric) for 2 nodes. The figures show that by increasing the number of beacons transmissions, an improvement in the ATTR can be achieved.

E. Performance Metrics

EMCA-FBM and other blind rendezvous strategies are evaluated over different PR activity patterns and policies, using the following evaluation metrics.

1) **Average Time to Rendezvous (ATTR):** the time from when the first node starts its rendezvous process to the time when the last node terminates its rendezvous process (for an unknown number of nodes).
2) **Average Harmful Interference (HI):** the average number of times when interference is caused by a CR towards a PR, which occurs when a CR transmits its beacon while a PR is active.
3) **Average Neighbour Discovery Accuracy (NDA):** the average number of nodes discovered by each node from the actual number of nodes.
4) **Reachability:** the percentage of the total number of nodes which receives a copy of the message forwarded after the rendezvous process has finished.

VI. Performance Evaluation

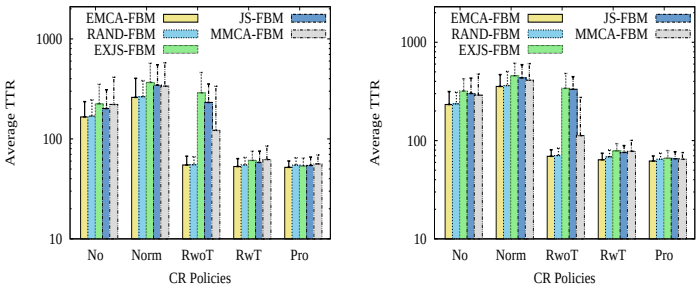
The proposed multihop rendezvous protocol EMCA-FBM is evaluated over different CR operating policies and PR activity patterns. Since there is no work on multihop rendezvous with an unknown number of nodes, the existing blind rendezvous strategies are modified with the proposed FBM rendezvous framework. EMCA-FBM is compared against the modified multihop versions of MMCA [4], JS [13], Random, and EXJS [13] rendezvous protocols, which are named here as MMCA-FBM, JS-FBM, RAND-FBM, and EXJS-FBM. These existing strategies are also integrated with the presented CR operating policies. As in proposed EMCA-FBM, the rendezvous cycle is reduced to P to pick a new rate value in case the rendezvous does not occur. The rendezvous cycle length of JS is also reduced to $2P$ from $3P$ for a fair comparison and we named it as EXJS. In Random strategy, each node selects a channel in a random manner. The policies are compared against the basic LBT approach, as there are no published results using policies for evaluation.

A. Unknown number of nodes for multihop networks

It is assumed that the nodes are not aware of the existence of other nodes in the network and their topologies. A random topology is generated for every simulation run. The results are the average of 100 simulation runs, where each node stops its rendezvous process when it receives a termination confirmation from all of its one-hop neighbors. For clarity, the results are shown in log scales.

1) Average Time to Rendezvous: The ATTR results for each multihop rendezvous protocol for 3, 10 and 100 nodes, are shown in Figures 15 to 21 (for 7 and 14 channels). Only the Zero, High and Mix PR activities are discussed here.

The policies do not apply to zero PR activity and therefore do not affect the TTR for both 3 and 10 nodes, as shown in Figure 15. With increase in the PR activity, the effect of policies is clearer, as shown in Figures 16 and 19, for High and mixed PR activities. The Normal policy is found to be worst in terms of the average TTR among all the policies, as it blacklists the channel on which PR is detected for CNP time (channel blacklisting time) and stays silent for the whole time slot. Due to the immediate search of a free channel, the reactive and proactive policies utilize this wasted time more efficiently, and therefore the TTR is significantly less in comparison with both LBT and Normal approaches. The RwoT policy only searches for a free channel, however, the RwT policy not only searches for a free channel but also increments the timeslot to select a new rate faster, due to which EMCA-FBM with shorter rendezvous cycle achieves more than 70% improvement over the LBT and Normal policy.



(a) 3 Nodes (b) 10 Nodes

Figure 17: Average TTR for High PR activity (14 channels).

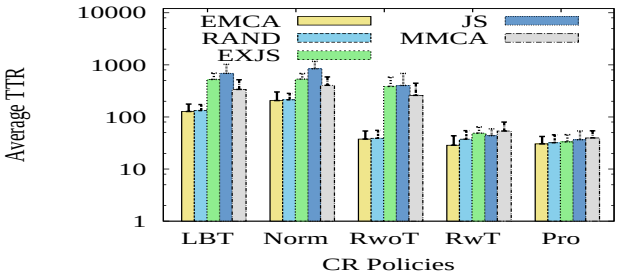


Figure 18: Average TTR for Single-Hop (10 nodes, 7 ch, and High PR activity) [3].

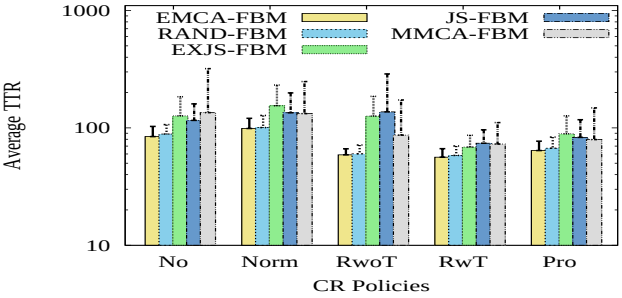


Figure 19: Average TTR for Mix PR act. (7 Ch, 10 nodes).

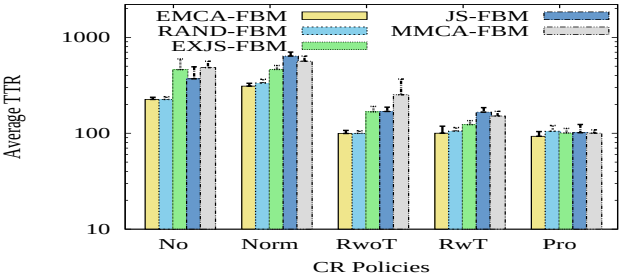


Figure 20: Average TTR for multihop (100 nodes, 7 ch, 3 BL TSs and High PR activity).

The Proactive policy is found to be better, as it brings down the TTR for all the rendezvous strategies close to the level of EMCA-FBM (Figure 16). The proactive policy learns the behavior of the channel and assigns weight to each channel (based on its occupancy), and therefore allows each node to converge to the best channel (in terms of the availability). This improves the chance to achieve a rendezvous earlier regardless of their longer rendezvous cycles. For Mix PR activity (Figure 19), the TTR is found to be slightly better than the High PR activity case, which is due to different PR activities at different channels, as shown in Figure 11.

With an increase in the number of channels to 14, the TTR increases as well for the LBT and Normal policies, as shown in Figure 17, and compared to 7 channels (Figure 16). However, for the Reactive and Proactive policies, the TTR is dropping on average, similar as in 7 channels case (Figure 16). The proactive policy is found to be better in the higher number of channels case, as it converge to best channels, as shown in Figure 17. Overall, increasing the number of channels does not affect the time to rendezvous very much when reactive and proactive policies are used.

In comparison with single hop case (Figure 18 [3]), the TTR in the multihop case (Figure 16b) is slightly higher, because in single hop case each node is aware of the total number of nodes in the network and can terminate the rendezvous process. However, for the multihop case the TTR is considerably higher, due to the time spent in different phases to estimate the number of nodes and to terminate the rendezvous process.

The proposed multihop protocol EMCA-FBM, spends time in each different phase to receive a good estimate of the neighbor nodes, before terminating the rendezvous process, completely. The EMCA-FBM outperforms all the other multihop blind rendezvous protocols and RAND-FBM is found to be only marginally slower, under different PR activity traffic patterns and operating policies. The other protocols appear as much slower because of their longer rendezvous cycles. When the number of nodes are increased to 10, the TTR increases under High and Mix PR activity, as shown in Figures 16b and 19. The TTR increased further for 100 nodes, as shown in Figure 20, compared to 10 nodes (Figure 16b). The overall pattern remains similar, and the proactive policy performed better in reducing the TTR for all rendezvous strategies.

With an increase in the channel blacklisting time (or CNP time) which is mainly intended to reduce the harmful interference, the ATTR also increases due to less number of free channels availability. With the increase in the CNP time to 600 timeslots (i.e., 10 minutes, as suggested by IEEE 802.22), the ATTR is found to be significantly higher compared to 3 timeslots which is due to the longer duration of channel blacklisting (Figure 21). The Normal policy is found to be worst. The reactive and proactive policies manage to bring down the average TTR, but still, the TTR is found to be significantly higher, compared to the aggressive channel blacklisting times (3 BL TSs). LBT shows no effect, as it does not involve channel blacklisting.

Overall, with an increase in the PR activity, the ATTR is increasing. However, the reactive and proactive policies are found to be helpful in bringing down the TTR.

2) Average Harmful Interference: The average number of incidents of harmful interference are shown in Figures 22 to 27 for the same experiments shown in Figures 15 to 21 for ATTR. For Zero PR activity, no harmful interference is observed,

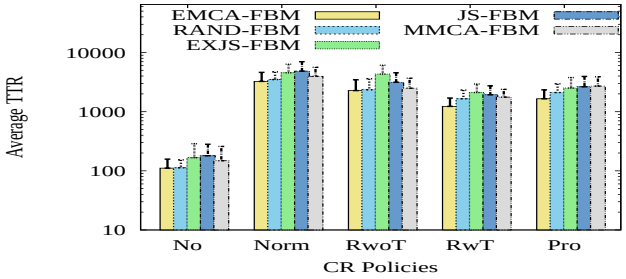


Figure 21: Average TTR for High PR activity (3 nodes and 600 BL TSs).

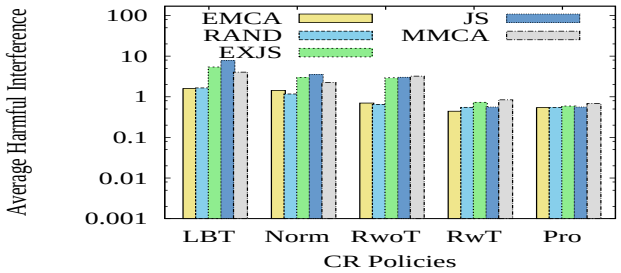
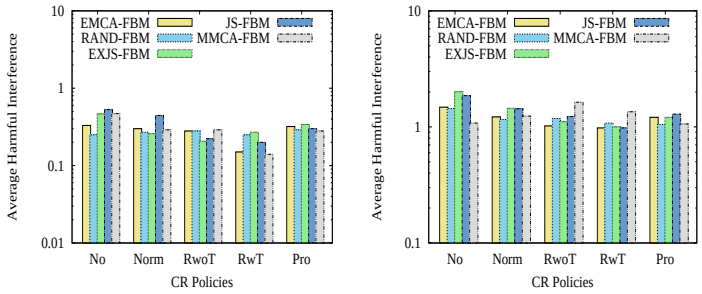


Figure 23: Average HI for Single-Hop (10 nodes, 7 ch, and High PR act) [3].



(a) 3 Nodes (b) 10 Nodes

Figure 22: Average HI for High PR activity (7 channels).

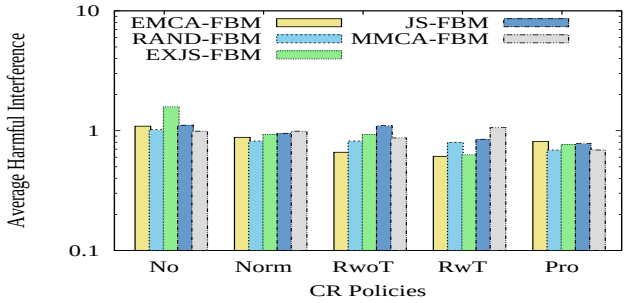


Figure 24: Average HI for Mix PR act. (7 Ch, 10 nodes).

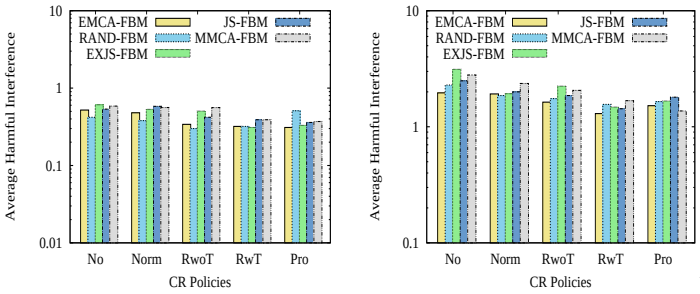
as there is no PR activity. However, when PR activity is increased, the harmful interference is observed.

The higher incidents are observed for LBT and Normal policies, but the reactive and proactive policies are found to be helpful in reducing the average number of incidents, as shown in Figures 22 and 24. For high PR activity, the HI appears to be higher, as shown in Figure 22. The average HI is found to be below 0.5 incidents for 3 nodes and 1.1 incidents on average for 10 nodes (high PR activity), for different multihop rendezvous protocols. The average incidents compared to a single hop case (Figure 23) are slightly higher. When the number of nodes increases to 100, the HI count increases, as shown in Figure 26, due to the increased TTR and the increased number of beacons being emitted across the network in each time slot. For Mix PR activity (Figure 24), the number of incidents is observed less than 1 incident on average when different policies are applied, compared to the high PR activity case. The MMCA-FBM, JS-FBM, and EXJS-FBM are mostly observed with higher HI values, due to their higher TTR values. For higher number of channels (i.e., 14), as shown in Figure 25, no significant difference is observed for 3 nodes case, compared to 7 channels case. However, a marginal increase is observed for the 10 nodes case. With the increase in the channel blacklisting time to 600 timeslots, as suggested by the IEEE 802.22 and shown in Figure 27, the HI is found to be below 0.1 incidents on average for 3 nodes, however at the cost of significantly higher ATTR.

3) Neighbour Discovery Accuracy: Neighbor discovery accuracy is the average accuracy of discovered nodes by each node. The multihop rendezvous framework is designed to work in phases and terminates also at some point, with an estimation of the number of nodes. As the nodes are not aware of the total number of nodes, it is possible that some nodes might not get a chance to discover all its neighbors, due to the unknown PR activity. Therefore, the average neighbor discovery accuracy of different multihop rendezvous protocols is quantified to evaluate the fully blind multihop rendezvous protocols performance. The average neighbour discovery accuracy results are shown in Figures 28 to 33. Only the last 5% values (i.e., 95 to 100%) are shown in these figures for the clarity.

For Zero PR activity, the NDA is found to be 100%, as shown in Figure 28a (for 3 nodes). However, for 10 nodes case (Figure 28b), it drops to only 98%. The drop is because some nodes terminate their rendezvous process earlier without waiting for all nodes to be discovered, and that happens only a few times in 100 simulation runs. The policies do not take part here due to the zero PR activity and therefore the accuracy drops for all the policies is almost same (i.e., about 98%). The MMCA-FBM, JS-FBM, and EXJS-FBM are found to be less accurate than EMCA-FBM and RAND-FBM. For high PR activity, the RwT and Proactive policies are found to be better than the LBT, Normal and RwoT policies, as they provide 100% NDA for all rendezvous strategies. These policies show benefits for the Mix PR activity also, as shown in Figure 30, by obtaining an average accuracy of more than 99%. For higher number of nodes i.e., 100 the NDA is found to be 100%, as shown in Figure 32. For higher number of channels (14 channels), as shown in Figure 31 for High PR activity, no significant difference is observed, compared to 7 channels case.

For channel blacklisting time as 600 timeslots, as shown in Figure 33, the NDA is found to be less for the Normal policy,



(a) 3 Nodes (b) 10 Nodes

Figure 25: Average HI for High PR activity (14 channels).

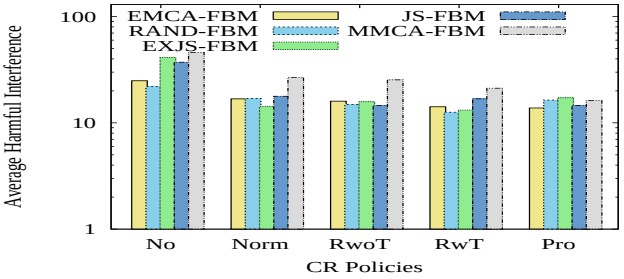


Figure 26: Average HI for High PR act. (100 nodes, 7 ch, 3 BL TSs).

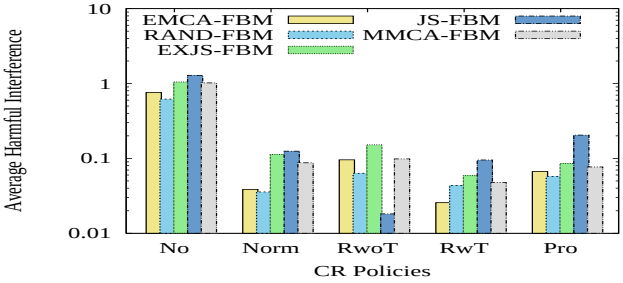
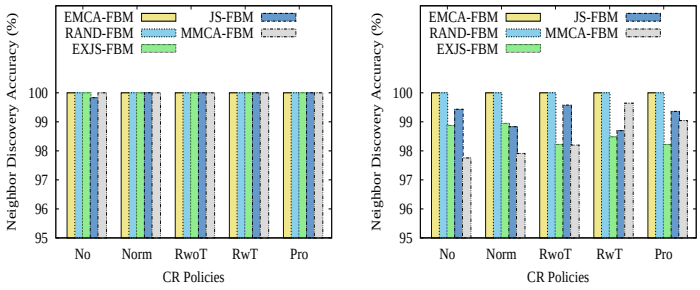


Figure 27: Average HI for High PR act. (3 nodes, 600 BL TSs).



(a) 3 Nodes (b) 10 Nodes

Figure 28: Average NDA for Zero PR activity (7 channels).

however, the average NDA improves and reaches above 99% for both the RwT and Proactive policies.

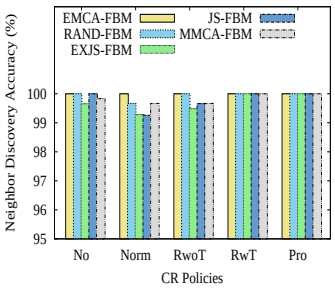
4) Summary and discussion: With the increase in the PR activity and nodes, the ATTR and harmful interference increase as well, when LBT and Normal policies are used. However, the reactive and proactive policy is found to be adaptive towards the unknown PR activity, as it not only reduces the ATTR and harmful interference but also improves the neighbor discovery accuracy (almost 100%). The rendezvous performance was found to be better when aggressive CNP time (3 TS) is used. When suggested CNP time (600 TS) is used, although the interference was less, the TTR increases significantly. This setting is mainly for the environment where spectrum databases assist the network operation. However, when such databases might not be available, blacklisting the channels for a longer period can degrade the rendezvous performance. It is possible that due to PR activity, some nodes might not be discovered when the nodes finish their rendezvous process. However, the multihop framework is capable of restarting the rendezvous process (from the transition phase again), whenever a new node information is found by any node, even after a rendezvous process has finished.

B. Imperfect sensing

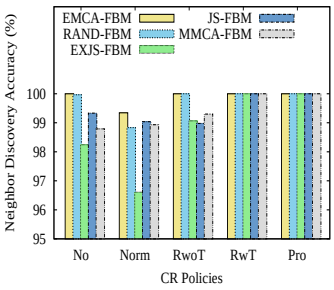
For the experiments discussed so far, a perfect channel sensing model is assumed. However, an imperfect sensing is also considered, in which due to limited sensing capabilities, a CR can sense in an imperfect way. For example, it can claim an available channel as occupied (False alarm) or consider an occupied channel as an available opportunity (Miss detection). When a radio claims an unoccupied channel as occupied, the rendezvous cannot be attempted which results in increased TTR. Similarly, when a radio cannot detect a PR activity due to its low signal strength, it attempts a rendezvous by sending a beacon, which results in the increased harmful interference. Figure 34, shows the results of ATTR with imperfect sensing for multihop scenario (unknown number of nodes). The error probabilities (i.e., miss detection and false alarm) are fixed to 0.1 (or 10%), for 3 nodes (multi-hop) and 7 channels under High PR activity. The results in Figure 34 shows only marginal increases in the ATTR, as compared to the results in Figure 16a.

C. Synchronization and reachability

The rendezvous is mainly to discover the nodes and to establish synchronization among the discovered nodes to establish other network services, without re-running the rendezvous process. We simulate a scenario, in which after completion of a rendezvous process, a randomly selected node sends a message to all its directly connected neighbors at their scheduled time and channel until received by all of them. The node which will receive that message will send an ACK to its sender confirming the reception of the message and start forwarding the copy of the message to their directly connected neighbors, excluding the node from which it has received a message. The objective is to check the reachability of a message, by using those already agreed schedules. Table II shows the results of the reachability and the time it takes to deliver a message from the randomly selected node to the last discovered node. The results are shown in Table II for the zero and high PR activity, shows

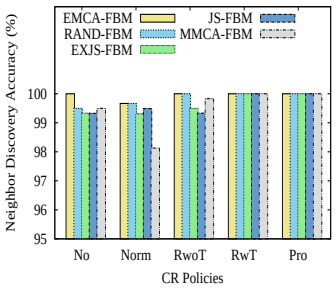


(a) 3 Nodes

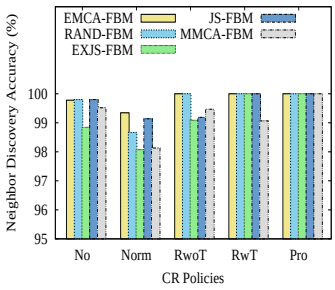


(b) 10 Nodes

Figure 29: Average NDA for High PR activity (7 channels).



(a) 3 Nodes



(b) 10 Nodes

Figure 31: Average NDA for High PR activity (14 channels).

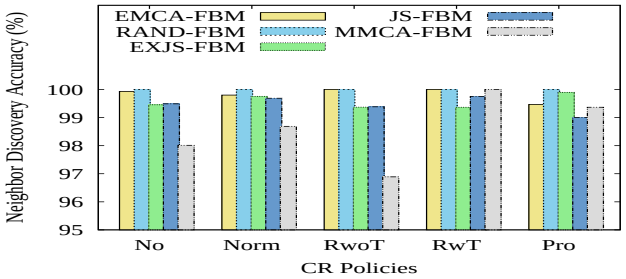


Figure 30: Average NDA for Mix PR activity (7 Ch, 10 nodes).

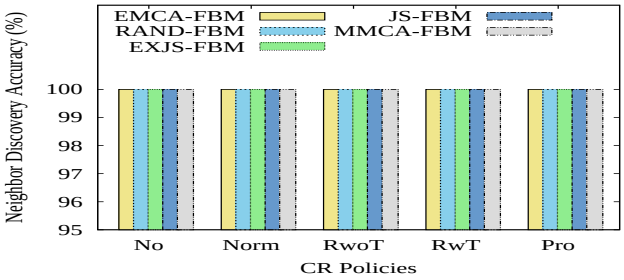


Figure 32: Average NDA for multihop (7 ch, 100 nodes, 3 BL TSs and High PR activity).

the nodes have achieved a perfect synchronization (100%). However, the delay increases, when the number of nodes is increased to 10 nodes due to the gap between the scheduled time among different nodes; and when the PR activity is increased to High (85% PR activity) which is because of the frequent re-schedules among the nodes. Note: Our focus is only on showing the reachability of the nodes and not on improving the performance of a message forwarding scheme.

VII. Conclusion

A fully blind multihop framework (FBM) is proposed for extended modular clock algorithm (EMCA-FBM) with different cognitive radio operating policies. The proposed multihop rendezvous protocol EMCA-FBM is a fully blind rendezvous protocol which assumes that nodes are not aware of the total number of nodes in the network, PR activity and topology. A termination strategy is also proposed to stop the rendezvous process when all or sufficient number of nodes are discovered. It is also presented as a general framework to accommodate and extend existing blind rendezvous protocol for single hop network and known number of nodes. The proposed protocol with operating policies is shown to be adaptive towards the unknown PR activity; self-organized by autonomously handling the rendezvous process and the new neighbor arrival, and cooperative by disseminating the neighbor information among all nodes. A scheduling mechanism is also introduced to achieve synchronization among the nodes, to avoid the re-running of rendezvous process and to establish other network services. The proposed protocol is evaluated over different primary user traffic patterns and operating policies. It is shown that the EMCA-FBM together with reactive and proactive operating policies can improve the time to rendezvous up to 70% in comparison with existing modified blind rendezvous strategies with a reduction in the average harmful interference; can achieve almost 100% neighbor discovery accuracy, and can terminate the rendezvous process even when the number of nodes and their topology information is unknown.

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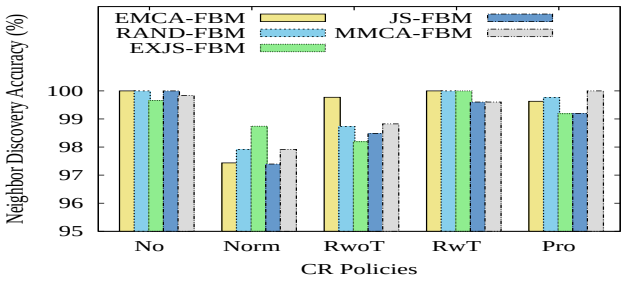


Figure 33: Average NDA for High PR activity (3 nodes and 600 BL TSs).

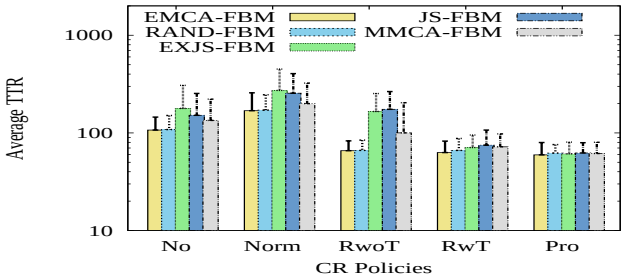


Figure 34: Average TTR with imperfect sensing (3 nodes, High PR activity).

Table II: Performance of synchronization and reachability among the discovered neighbours

	Zero PR activity		High PR activity	
	3 Nodes	10 Nodes	3 Nodes	10 Nodes
Reachability (%)	100	100	100	100
Delay (timeslots)	7.44	61.41	120.98	1396.54

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