

MAC AND ROUTING PROTOCOLS FOR MULTI-HOP COGNITIVE
RADIO NETWORKS

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MAC AND ROUTING PROTOCOLS FOR MULTI-HOP COGNITIVE
RADIO NETWORKS

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THESIS ABSTRACT

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RADIO NETWORKS

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Cognitive radio networks that allow dynamic spectrum access are considered spectrally more efficient than networks using fixed spectral allocation. These networks are characterized by dynamically changing channel sets at each node. *Multi-hop cognitive radio network* is a cooperative network in which cognitive users take help of their neighbors to forward data to the destination. Control signals used to enable cooperation are communicated through a *common control channel* (CCC). Such a usage introduces conditions like channel saturation which degrades the overall performance of the network. Thus, exchanging control information is a major challenge in cognitive radio networks. Moreover, the graph theoretic approach used in traditional multi-hop networks fails to efficiently model multi-hop cognitive radio networks and capture the required information for optimal routing. Hence, conventional graph-based routing protocols such as DSR or AODV cannot be used directly, for route discovery in such networks.

Two ideas are proposed in this thesis as a solution to the above problems. Firstly, a MAC protocol for multi-hop cognitive radio networks is proposed to avoid a common control channel. The scheme is applicable in heterogeneous environments where channels have different bandwidths and frequencies of operation. It inherently provides a solution to issues like CCC saturation problem, Denial of Service attacks (DoS) and multi-channel hidden problem. The proposed protocol is shown to provide better connectivity and higher throughput than a CCC based protocol, especially when the network is congested.

Secondly, a unique *multi-edge planar graph model* for routing is proposed which can efficiently represent a multi-hop cognitive radio network. The model is quite simple and could be used in conjunction with any conventional graph-based routing protocol. The model is validated through simulations and the complexity of the model is shown to be lesser than an earlier layered graph model.

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CHAPTER 1

INTRODUCTION

Guglielmo Marconi's first Radio Broadcast was a point-to-point communication. With the emerging radio technologies such as Wi-Fi, WiMax, Bluetooth, ZigBee and the growing panoply of cellular and satellite communication, we need to pack the radio waves to accommodate each of these services. To minimize interference, each of these technologies is restricted to specific bands of the spectrum. If we tried imposing this sort of regime on road transportation, we might wind up with a system in which buses, cars and trucks were each restricted to their own separate roadways.

Radio spectrum allocation is rigorously controlled by regulatory authorities through licensing processes. Most countries have their own regulatory bodies, though regional regulators do exist. In the U.S., regulation is done by the Federal Communications Commission (FCC). Spectrum has long been allocated in a first-come, first-served way. According to the FCC [1], temporal and geographical variations in the utilization of the assigned spectrum range from 15% to 85% [2]. If radios could somehow use a portion of this unutilized spectrum without causing interference, then there would be more room to operate and exploit. Cellular telephony and other important services would then be a lot cheaper and would be a lot faster as well. To manage such feats, cellphone handsets would have to be able to shift their frequency of operation on demand without packing in lots of extra hardware. The key technology which enables dynamic spectrum access is a Software-defined Radio [3]. A bigger goal is a

wireless device that is smart enough to analyze the radio environment and decide for itself the best spectral band and protocol at the lowest level of power consumption. The name of such a device is “Cognitive Radio”, and some have already emerged from the laboratory to be field tested by the U.S. military.

1.1 Cognitive Network

A cognitive network is an opportunistic network. The basic premise of a cognitive network is that the owner of a licensed spectrum may not be using the spectrum always. Hence, this unused and licensed spectrum can be utilized by other users who have a need for the same. The licensed owner of a frequency band is called a *primary user* and the one who utilizes spectrum opportunities for communication is called a *secondary user*. Networks built using this concept are called cognitive radio networks.

The part of spectrum, allocated to a user for communication, is referred to as a *channel*. A channel is temporarily available to a secondary user when the primary user of that channel is not using it at that instant of time. Every secondary user is assumed to have the capability of sensing a channel for the presence of primary user using a cognitive radio i.e. every secondary user is assumed to have a cognitive PHY layer. Thus, a secondary user may have a set of free channels (*available channels*) for communication. One of the available channels is chosen for communication. An important constraint on the choice of the channel is that, both the sender and receiver should be on the same channel for possible communication. If the receiver is not in communicating range of the sender, the communication has to be set up through

several intermediate nodes. Such types of networks are called *Multi-hop Cognitive Radio Networks* (MHCRN).

1.2 Multi-Hop Cognitive Network

A MHCRN is, in many ways, similar to a multi-channel network. In both networks, each user has a set of channels available for communication. When two users want to communicate, they negotiate via a common control channel (CCC) to select a communicating channel. Two major differences in these two network environments are:

- The number of channels available at each node is fixed in a multi-channel network whereas it is a variable in a MHCRN. It is possible that a user has no available channel at all due to the complete occupancy of the spectrum by primary users.
- In general, the channels in a multi-channel environment have equal transmission ranges and bandwidths unlike in a MHCRN in which the environment is heterogeneous. Thus, a MHCRN is a combination of a multi-hop and a multi-channel network.

While the MHCRN concept appears attractive, there are many complexities introduced not only due to the frequency shifting in the PHY layer but also due to multi-hop characteristics of these networks. Some of them are:

- Since the available channels for communication vary with primary user's traffic, the cognitive PHY layer is dynamic in nature.

- Due to the multi-hop nature, the choice of a channel for each secondary user is now constrained by the available channel set at every user along the route. A route is possible only if every pair of users along the route have at-least one common channel available at their respective locations.
- After a communication path is established through a set of intermediate nodes, still the route may fail due to the dynamic nature of the PHY layer at each node. A new route has to be discovered with the new set of available channels.

Due to the abrupt failure in communications and delays caused in discovering a new route, traditional routing protocols in the network stack are either not applicable or very inefficient on MHCRNs. Similarly the MAC protocols used in multi-channel networks cannot be applied to a MHCRN due to the above mentioned differences in the two networks. However, the issues and challenges related to these networks apply to a MHCRN as well. For example, CCC and multi-channel hidden terminal problems [4] which are related to a multi-channel network are common to a MHCRN.

This work addresses two of the problems associated with MHCRNs. Firstly; it addresses the impact of the cognitive PHY layer on the network (routing) layer of the protocol stack. Routing operations in MHCRN are analyzed using a multi-edge planar graph model. Such a model is general enough to be applied to well known routing protocols such as AODV [5], DSDV [6], and DSR [7].

Secondly, a new MAC protocol for MHCRNs is proposed which avoids the need of a dedicated CCC and solves the multi-channel hidden terminal problem [4]. The main idea is to divide total time into fixed-time intervals, each representing one of the available channels. At the beginning of each time slot, all nodes in the network listen

to a channel which the time slot represents for exchanging control signals. Thus, all nodes in the network are synchronized.

1.3 Organization

The work is divided into two parts. The first part discusses about the MAC layer issues and protocol and the second part discusses the Routing layer issues and protocol. The related work and the introduction required for the respective topics are discussed before the idea is presented. As a result, a separate literature review section is obviated.

CHAPTER 2
MAC LAYER ISSUES
IN MULTI-HOP COGNITIVE NETWORKS

In this chapter, we describe the common control channel (CCC) problem and briefly explain the multi-channel hidden terminal problem [4] in the context of a MHCRN.

2.1 The Common Control Channel problem

As discussed earlier, two users in a MHCRN are connected if they have a common channel for communication. It is possible that each user has a choice of more than one channel. In that case, the sender and the receiver need to agree upon a common communicating channel which is available to both. The initial handshake signals to negotiate the choice of a common channel are called control signals. But such negotiations require communication over a common signaling channel. This is called the common control channel problem. This problem is illustrated in more detail using Fig. 2.1. A cognitive user is referred to as a ‘node’ in the rest of the work.

Suppose Node A has channels 1, 3 and 4 available and node B has 1, 2 and 4 available as shown in Fig. 2.1. These available channels form the channel set of the respective pair of nodes. Also, suppose that A is unaware of B’s channel set and vice versa. It can be seen from the figure that channels 1 and 4 are common among the two nodes. When node A wants to transmit to node B, A and B should:

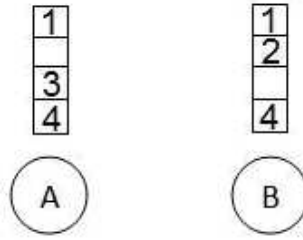


Figure 2.1: Two cognitive nodes with a set of free channels.

- Negotiate their channel sets and
- Exchange ‘Request to Send’ (RTS) and ‘Clear to Send’ (CTS) messages to reserve a channel for communication in a manner similar to IEEE 802.11 Distributed Coordination function (DCF). These control messages in turn have to be negotiated via a channel.

Intuitively, a separate dedicated channel for control signals would seem a simple solution. But a dedicated CCC has several drawbacks as discussed in [8]. Firstly, a dedicated channel for control signals is wasteful of channel resources. Secondly, a control channel would get saturated as the number of users increases similar to a multi-hop network as identified in [4]. Thirdly, an adversary can cripple the dedicated control channel by intentionally flooding the control channel. This is the Denial of Service (DoS) attack as discussed in [9].

Another solution to exchange control messages is to choose a channel among the available channels as the control channel. For example, in Fig. 2.1, channel 1 or 4 can be chosen as the control channel. When the primary user of that channel returns, a new channel which is available to all users is chosen. This approach is not feasible because the probability that a particular channel is available to all users is small. Moreover, the available channels may vary in the frequency of operation, bandwidth

and transmitting range. Due to such heterogeneity in the transmission range, the connectivity and scalability of the network varies with the control channel because a channel with shorter transmission range may not cover all the areas covered by a channel with a longer transmission range. Thus, there is a need for a better protocol which avoids the use of a CCC and which takes heterogeneity into account while choosing a channel for communication.

2.2 Multi-channel hidden terminal problem in MHCRNs

The multi-channel hidden terminal problem was identified in [4] for multi-channel networks. The same problem is extended to a cognitive network environment in [10]. It is briefly explained below.

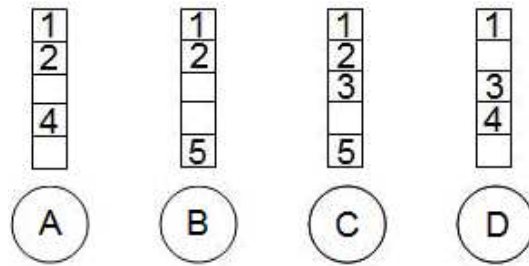


Figure 2.2: Four nodes with respective available channels.

Fig. 2.2 represents 4 nodes with their respective channel sets. Suppose that only adjacent nodes are in transmitting range. Since channel 1 is available to all nodes, suppose that channel 1 is chosen as the control channel and that node C and D are already communicating using channel 3. When node A wants to transmit a packet to node B in channel 2, it sends an RTS to B on the control channel (channel 1 in this case). B sends a CTS proposing channel 2 for data communication. Node A sends a confirmation message to B and to its neighbors that channel 2 is reserved for data

communication. But since C was communicating in channel 3, it did not receive the CTS from B. So C assumes that channel 2 is free and might initiate a communication with node B in channel 2 resulting in a collision. This is called the multi-channel hidden terminal problem. In [10], this problem is addressed by allocating special slots. In these time slots the communicating pair of nodes gets updated from its neighboring nodes about any potential hidden terminals in their vicinity. Though, the problem is solved successfully using this method, a CCC is still used for control signal exchange.

To avoid the above mentioned disadvantages, a MAC protocol which does not need a pre-allotted control channel and which solves the multi-channel hidden terminal problem, is proposed in this work.

2.3 Literature review

Considerable number of MAC-protocols have been proposed for cognitive networks previously [11, 12, 13, 14, 15, 16, 17, 18, 19]. But most of these assume a Common Control Channel (CCC) which limits the robustness of the network in many ways as pointed out earlier. [11, 12] assume a CCC which is one among the available channels. Similarly [13, 14, 15] also assume a CCC for the purpose of exchanging control signals. There are a few proposals which solve the problem of CCC partially. Since the probability that a CCC is available at every node is small, [16] proposes a method in which a group of users which are close together form a sub-ad hoc network and select a channel for communicating control information. If the primary user of the channel returns, a different channel which is available to everyone in the sub-group

is chosen. It is assumed that one of the members of the group has the capability to connect to the neighboring groups. Though it is an indirect solution to the problem of availability of a CCC, it does not completely eliminate the dependency on a CCC. There is still a possibility that a user can pose a DoS [17] attack. Moreover, the group head that is responsible for sharing of the information between two groups gets a chance to act selfishly on its data. [10] solves multi-channel hidden node problem but still uses a CCC for control signal exchanges.

Though the MAC layer misbehaviors have been pointed out in [9], there is no existing protocol which considers the control channel saturation problem, multi-channel hidden terminal problem and heterogeneity of channels simultaneously. Compared to the above proposals, our protocol does not require a separate control channel for the purpose of control signal exchange. Instead it requires synchronization among all nodes. Though it is an extra requirement on the network, it will be shown in next chapter that it achieves better throughput and network connectivity than maintaining a separate control channel.

2.4 Synchronized MAC Protocol

In this chapter, the proposed scheme is presented. Before that, the assumptions are summarized below.

- Every node is assumed to be equipped with two radios. One of the two radios is used for just listening (*listening radio*) to the control signals and the other for both receiving and transmitting data (*data radio*).

- The maximum number of channels at each node is N , but the channels available at each node may vary with the primary user's traffic.

The proposed protocol will be referred to as Synchronized MAC (SYN-MAC) [20] from now on.

2.4.1 Network initialization state

Initially, when there are no cognitive users (*nodes*) to form a network or when the new user wants to form a sub-group independent of the existing users, the network is said to be in the initialization state.

In the network *initialization state*, a node checks whether it is the first node or not by listening in each channel for $N \times Tc$ seconds. If it hears no beacons then it is considered the first node. The first node divides time into N number of equal time slots of fixed duration Tc , since there are N possible channels. Each time slot is dedicated to one channel for control signal exchange. The node then beacons in all its available channels at the beginning of the corresponding time slots. The following nodes choose one of the channels and listen for beacon messages to synchronize their listening radios. Since the first node broadcasts in all its available channels, the following nodes can choose any channel and be sure to receive a beacon message within $N \times N \times Tc$ seconds. After it receives a message, the nodes exchange information about their channel sets. If it did not receive a beacon, then it is considered to be the first node.

At the end of the *network initialization state*, all nodes are synchronized and every node has the information about its neighbors and their respective channel sets.

Nodes being synchronized mean that at the beginning of every slot, the listening radio of every node tunes to the respective channel which the slot represents and listens in that channel. It is analogous to passing a token among the channels and every node is listening to that particular channel at a given time. The continuous scanning (listening) of channels is necessary for three reasons, which are:

1. To keep track of primary user's presence,
2. For exchanging control signals and
3. To avoid multi-channel hidden node problem.

2.4.2 Exchange of control signals and data

When a node wants to start a communication, it should exchange the required control signals. To exchange the control signals it chooses one of the channels common between itself and its neighbor. It then waits for the time slot which represents the chosen channel. Since all nodes will be listening to that channel in that slot duration, it will start exchanging its control signals with its neighbor.

Unlike the exchange of control signals which need to be exchanged only at the beginning of specified time slots, the data is exchanged after exchanging the control signals. So exchange of data occurs in an un-synchronized fashion using the second radio (*data radio*). Control signals or information is exchanged among the nodes whenever an event occurs. These events are called information events. There are 4 information events (IEs) which are:

- IE-1: When a new node enters the network, it should notify its arrival to its neighboring nodes.

- IE-2: When the available channel list at a node changes due to the primary user traffic, the node's neighbors have to be updated about its new channel list.
- IE-3: When a node starts, stops or changes its channel of communication, the information is forwarded to its neighbors to enable them to know whether the data packets can be forwarded through the communicating node.
- IE4: When a node wants to communicate with its neighbor, it sends a set of control signals to inform its intent to start a communication in a particular channel. This event is followed by an acknowledgement by the neighbor to convey its acceptance/denial. On acceptance, data transfer takes place on the negotiated channel without any delay.

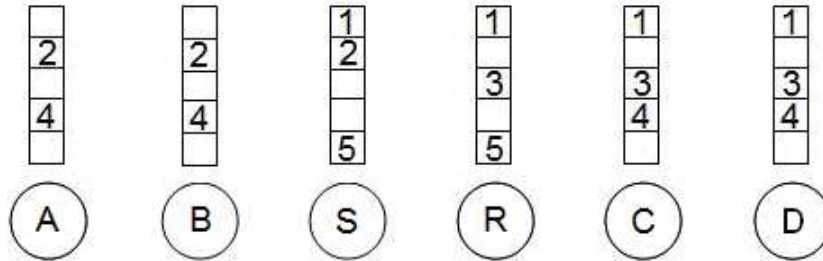


Figure 2.3: Six cognitive nodes with a set of free channels at each node.

The complete process of starting a communication is illustrated with an example shown in Fig. 2.3.

Consider a network of 6 nodes as shown in Fig. 2.3. There are a total of 5 possible channels among them. The array of blocks above each node represents the available channels at that node. Since the total number of channels is 5, time is divided into 5 slots and the listening radio of the nodes keep listening to successive channels at the beginning of the respective slots. Now, suppose *Sender* (S) wants to

start a communication with *Receiver* (R). Since the nodes know the available channel sets of their neighbors, node S sees that it has channels 1 and 5 in common with node R. It chooses one of these channels for communicating with node R. If channel 1 is chosen, then node S waits for a random back off time (shown using solid shading in Fig. 2.4) and starts its negotiations, similar to IEEE 802.11 DCF. Once the negotiation is successful the data transfer takes place in channel 1 immediately. This is shown in Fig. 2.4.

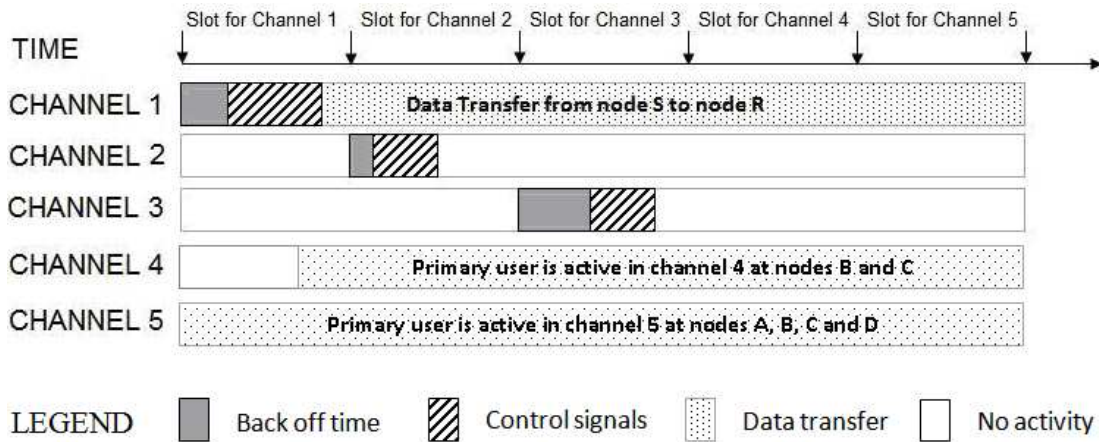


Figure 2.4: Five channels with the control and data transfer events in their respective time slots.

Now, suppose that node B observes that primary user of channel 4 has returned. So, it generates an IE2 which contains its new channel set. Since node B knows that it can reach its neighbors through channel 2, it waits for the time slot which represents channel 2, backs off for a random time and then transmits its information (IE2). Nodes S and A, on receiving this information learn that node B will not be available on channel 4. Similarly, when node C sees that primary user of channel 4 has returned, it waits till the slot representing channel 3 and then broadcasts the

information to nodes R and D. All activities described above are summarized in Fig. 2.4.

With the above explanation, we will demonstrate the advantages of the protocol over CCC based protocols now. We will also show how different issues discussed in chapter 2 are solved using our protocol.

Firstly, it should be clear by now that there is no dedicated CCC for control signals, so there would be no concept of control channel saturation. It will be shown in the next section that there is a significant benefit in terms of throughput from not having a CCC in a MHCRN. Also, in Fig. 2.3, it is seen that there is not even one channel common at all of the six nodes and hence control signal exchange could not have been possible using the CCC based protocols. But in SYN-MAC communication could be established as discussed.

Secondly, observe that when node S wanted to transmit to R, it chose channel 1 and sent an RTS to R and node R sent CTS back to S. Suppose that nodes C and D are already communicating over channel 3. Though nodes C and D are busy communicating data in channel 3, since the listening radio of C is listening to channel 1, it receives the CTS sent by node R and hence notes that channel 1 will be busy for the ‘*Network Allocation Vector*’ (NAV) amount of time. But for the synchronization and the extra radio (*listening radio*), multi-channel hidden terminal problem could not be avoided.

Thirdly, suppose the transmitting range of channel 1 is so short that node S can’t reach R through that channel and that of channel 5 is long enough to reach its adjacent node. This is an example of heterogeneous environment. When node S wants to send a packet to R as discussed, S chooses channel 5 now, instead of channel 1 and

starts its negotiations in the fifth time slot. Hence maximum connectivity is possible in a heterogeneous environment also. In the following section, the effectiveness of the proposed protocol is demonstrated using simulations.

2.5 Simulation results

In this section the SYN-MAC protocol is compared with the CCC based protocol proposed in [11] for throughput performance and network connectivity.

2.5.1 Throughput performance

NS2 with CMU wireless extensions is used for this part of simulations. A multi-hop network with 80 nodes, randomly placed in a 1000m 1000m area is considered. 40 nodes are chosen randomly as the sources and the other 40 nodes as destinations. The transmission range of each node is set to 250m. A set of three channels is chosen, each of which is available at each node with a probability of $p = 80\%$. The primary users are accounted for using this probability. The flow rate is varied for each connection to increase the network traffic and the throughput performance of CCC-MAC and SYN-MAC is compared. Each point in the graph in Fig. 2.5 is an average of 100 simulations.

Fig. 2.5 shows the aggregated throughput of both the protocols as the network traffic is increased. The throughput of SYN-MAC is significantly higher than that of CCC-MAC. The major reason for this behavior is that a CCC among all the nodes is not always available and so many times a connection is not established. Due to these failures the throughput is significantly lower in CCC-MAC. It can also be observed that when the traffic is very high, the throughput of CCC-MAC starts dropping.

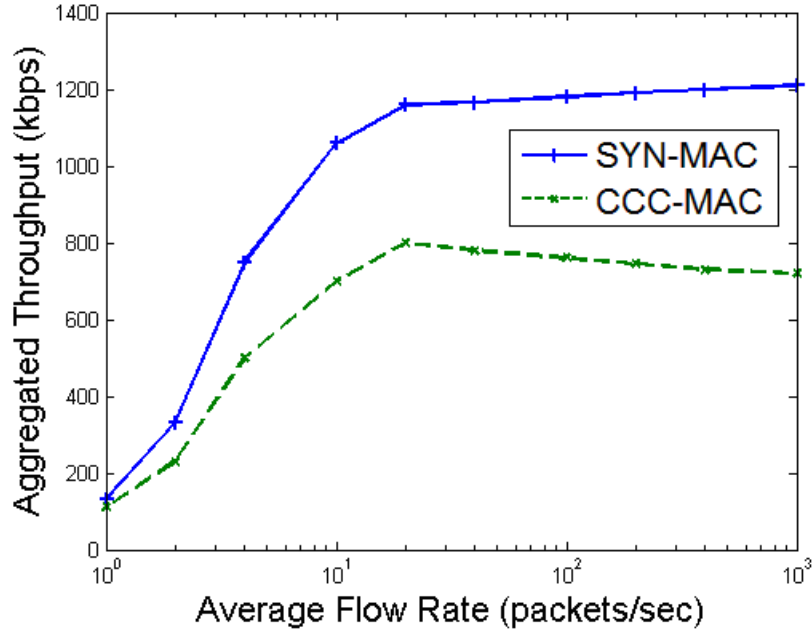


Figure 2.5: Average Throughput vs. Flow Rate. Packet size is 512 bytes.

This is because a single channel is used for control signal exchange. With increased traffic, contention of control packets increases and throughput degrades. Whereas, in SYN-MAC the control signal traffic is shared among all available channels and there is lower contention and hence, better throughput.

2.5.2 Network Connectivity

Network connectivity is defined as the percentage of nodes in the network which are connected together either directly or through several hops.

The network connectivity of CCC-MAC and SYN-MAC protocols are compared in this subsection using MATLAB simulations. A network of 10 nodes randomly deployed in a $500m \times 500m$ area is considered. Each node is assigned a set of channels. Each channel is available at a node with a probability of $p=80\%$. Fig. 2.6 shows the percentage of network connectivity as a function of the number of channels. It can

be observed that the SYN-MAC protocol assures higher connectivity than the CCC-MAC approach. As the number of channels is increased the probability that a common channel is found among all nodes increases. The rate of increase in SYN-MAC is higher than that of CCC-MAC. The SYN-MAC assures nearly 100% connectivity while the CCC-MAC provides only 65% connectivity for a group of 10 nodes and a set of 10 channels.

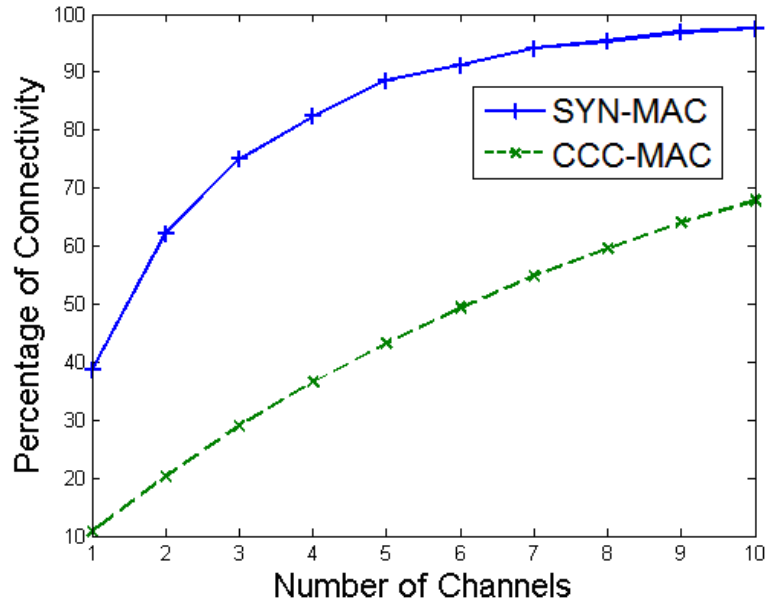


Figure 2.6: Percentage of network connectivity as the number of channels are varied for a group of 10 nodes.

Fig. 2.7 shows the percentage of network connectivity versus the number of nodes. It is observed that for a fixed number of channels, as the number of nodes is increased, the connectivity of both the approaches drop. But the fall in the CCC approach is very steep. This is due to the fact that as the number of nodes increases, the probability that a common channel is available at all the nodes decreases. For a network of just 10 nodes, the percentage connectivity of CCC-MAC fell to nearly 65%

and that of SYN-MAC is 93%. So, it can be concluded that the proposed protocol provides higher network connectivity than the CCC approach.

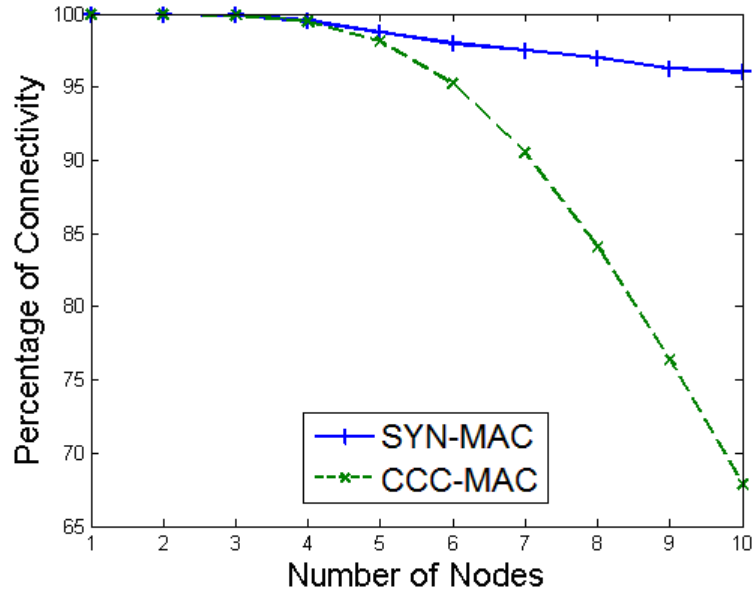


Figure 2.7: Percentage of network connectivity as the number of nodes is varied for a set of 10 channels.

Till now, we have discussed the MAC layer issues and a solution to these problems in MHCRNs by introducing a MAC protocol which avoids the need for a common control channel for the entire network. In the following chapters routing issues will be discussed and a innovative solution will be proposed.

CHAPTER 3
ROUTING ISSUES
IN MULTI-HOP COGNITIVE NETWORKS

Routing in multi-hop networks has been extensively studied in the literature. Several protocols have been proposed among which AODV [5], DSDV [6], DSR [7] are some of the widely used ones. Most of these protocols are graph based protocols, wherein a network is represented as a *graph*. *Nodes* in the graph represent the users and *edges* are used to join two nodes which can communicate with each other. The edges are assigned weights which generally represent the distance from one node to another. Protocols, mentioned above use this graph based information and find routes between nodes using various metrics, like DSDV finds a route based on the shortest distance or hop count. Hence, the graph theoretic approach is very efficient in modeling traditional networks and provides sufficient information for route discovery.

Traditional wireless networks make two general but fundamental assumptions.

- Fixed spectrum allocation i.e., pair of nodes communicate over a fixed band of spectrum (channel) and
- That the fixed channel is always available for communication.

This means that the physical layer and its fundamental characteristics like bandwidth, and channel of operation do not change and are static both in space and time. As a

result of these general assumptions, the graph model mentioned above is sufficient to represent traditional networks.

In a MHCRN, as discussed earlier, secondary users scan for the channels in which the primary users are inactive. Among the set of free channels, a suitable channel is used by the secondary user and when the primary user returns, a new free channel is located which may have different physical characteristics like bandwidth, power constraints and interference levels. This basic characteristic differentiates a MHCRN from traditional networks.

For a MHCRN:

- The channel of communication is not fixed
- A particular channel is not always available for communication and depends on primary user's traffic.

Thus, PHY layer of a MHCRN may vary both in space and time and is dynamic in nature. If a route discovery has to be initiated in such networks, a series of steps have to be followed in which, scanning for available channels at each node, deciding on a common channel for each pair of neighbors are most important ones. If there is more than one common channel between a pair of nodes, then an optimal channel has to be chosen based on various criterion such as interference level, bandwidth etc. Moreover, FCC regulations may specify different limits on the maximum allowed transmission power for different frequency bands. As a result, different channels may support varied transmission ranges [21] due to which a node reachable in one channel may not be reachable in another. Hence, the neighbor set of a node may depend on the type of channel used for communication. Due to lack of consideration of important

information like available channel set at each node, possible routes to other nodes and neighbor set in each channel, traditional graph model is insufficient to model MHCRNs. For example, DSR [7] was used in a multi-radio multi-hop single channel network [22] to find an efficient route. If the network were characterized by multiple channels which keep varying, the routing would not have been possible using simple DSR since, the graph model can represent only one fixed channel.

3.1 Related Work

A layered graph model was proposed as a solution to this problem in [23]. Fig. 3.1 shows a multi-layered graph model representing a 4 node network with three possible channels for communication. In this graph model, each channel or frequency of operation is represented by a layer of the graph. Since, there are three possible channels, the graph contains three layers. Each layer is a graph containing nodes representing users and edges joining any two nodes if they are in the transmission range of each other through that particular channel. For example, node pairs A-B and B-C are reachable to each other in channel 1, but node 4 is not in the communicating range of any other node through channel 1 and hence is shown isolated in the layer. Communication among the nodes across layers is possible through inter-layer links. Such inter-layer communication is not shown to keep the model simple.

Using this graph model, a routing strategy was built to find a near optimal route [23]. The disadvantages of this graph model are that the model is complex to represent and most importantly since, traditional routing protocols like AODV [5],

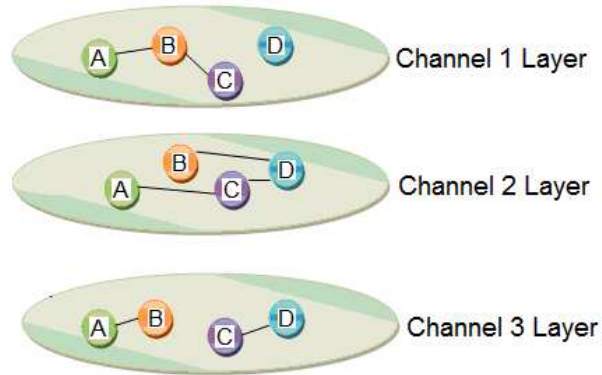


Figure 3.1: Example layered graph model representing a 4 node network with 3 possible channels.

DSDV [6] and DSR [7] assume planar structured graphs, a direct application of these protocols on layered graph model is not possible.

Hence a new ‘*Multi-Edge Planar Graph Model for Routing in MHCRNs*’ is proposed in this work. Such a model is simpler and accurate as it takes into account various radio channel related parameters in determining edge weights. The next chapter discusses the model and its performance evaluation.

3.2 Multi-Edge Graph Model

As the name implies, this graph model, unlike the traditional graph models used in routing, has multiple edges between a pair of nodes. This added feature of the graph accounts for the modeling of extra characteristics of MHCRNs such as available channel set, possible routes to other nodes through various channels and neighbor set of each channel. Unlike in layered graph model where layers represent different channels, multi-edged graph model takes advantage of extra edges to represent the channels and weights of these edges to represent the channel’s characteristics. Due to this characteristic of multi-edged graph model, a layered structure is obviated and is

reduced to a planar structure. It can be argued that the layer complexity is shifted to edge complexity in the multi-edge planar graph model. But it will be demonstrated later in this chapter that edge complexity of the new model is much lower than layered graph model. The following section explains the proposed model in detail.

3.2.1 Graph Topology Formation

In MHCRN, routing depends on the available channels which in turn depend on the primary user's traffic. This means that for an optimal choice of the route, the routing layer should be provided with information about the available channel set at each node by the PHY layer. Additionally, the total number of interfaces available at each node is also important for optimal choice of the route. A node with a single radio (interface) cannot communicate simultaneously over two different channels. Hence, to avoid choosing routes which violate the interface constraint, knowledge of the number of interfaces is necessary for the routing layer. So a cross layer design is necessary to keep the routing layer updated about the changes in the PHY layer. It is assumed in the rest of the paper that the information about the total number of interfaces and available channels at each node is provided to the routing layer of the nodes in question.

In the *Multi-Edge planar graph* model, each user is represented as a *Node* in the graph. Each channel is represented by an *Edge*. Let graph G denote the multi-edged graph, N denote the set of nodes and C denote the set of all possible channels. So a pair of nodes can have 2 edges if they can use two different frequencies (channels) for communication unlike conventional graph models where each pair of nodes has only 1 channel in common as in [22]. For example, if nodes A and B have two channels to

communicate, then it is represented as shown in Fig. 3.2. A and B can communicate through channel 1 and channel 2. Therefore, nodes A and B are connected by two edges. $W1$ and $W2$ represent the weights of the edges in each channel which can be simple distance or a complex combination of different factors like interference, energy etc. Every channel is assigned a channel ID. For example Channel 1 is assigned '1' as channel ID.

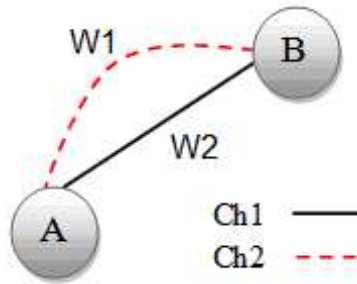


Figure 3.2: Nodes A and B linked by 2 edges.

Now, consider a graph with 4 nodes and 3 different channels. Each node may have different channels available with it. Two nodes in this graph are connected if they have a common channel in their channel sets. Graphical representation of these 4 nodes in a traditional network with fixed channel allocation is shown in Fig. 3.3. Since all the nodes can communicate in only one channel in such networks, there is only one edge between every pair of nodes which can communicate with each other. The numbers on the edges represent the weights of the edges which in this case are distances.

A cognitive network where each node has varying number of channels available with it is shown in Fig. 3.4. In this graph, the node pairs A-D, D-C, and B-C have channels 1 and 2 in common but the node pair A-B has channels 1, 2 and 3 in common

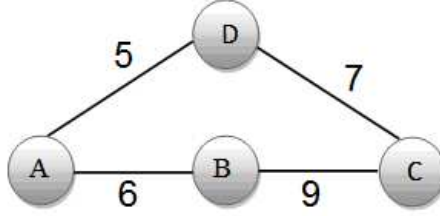


Figure 3.3: Graphical representation in traditional network.

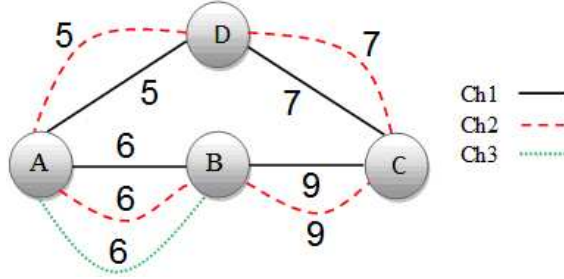


Figure 3.4: Graphical representation in cognitive network.

consequently having three edges between them. All edges between every pair of nodes are assigned the same weight because, the weights represent distance between pair of nodes and it does not vary with type of channel. So, any routing protocol such as AODV [5], DSDV [6], and DSR [7] gives the shortest route as an optimal route.

Algorithm 1 is used for the construction of the Multi-Edged graph model.

Algorithm 1 Construction of Multi-Edged graph model

- Add a node N_i to the graph G for each user in MHCRN.
 - Add an edge between between node N_i and node N_j if they are potential neighbors through channel C_i for all $N_i, N_j \in N$ and $C_i \in C$.
 - Assign weights for each edge between nodes N_i and N_j using a weight assignment algorithm for all $N_i, N_j \in N$.
-

3.2.2 Weight assignment and Routing in Multi-Edged Graph Model

All graph based protocols, find a route based on the weights of the edges of the graph. If the weights of the edges represent the distance between the nodes, a graph based protocol like DSDV would choose the shortest path route. If the weights were a function of interference then the route with lowest interference is chosen. Therefore weight assignment is a very important step in building a graph model. In the multi-edged graph model a problem of interface constraint arises due to the multi-edged nature of the graph. The problem is explained below and solved by modifying the weights of the edges. Finally, the weights of all edges are added with a cognitive cost function which is explained later.

A node can have a single or multiple radios. Each radio (interface) is capable of changing to a required frequency (channel) to communicate. Switching the interface between channels is feasible in a classical wireless network, though it requires fine synchronization between neighboring nodes and introduces overhead. But in a cognitive environment where the channels are not bound to 2.4 GHz ISA band, this type of switching might not be feasible. Moreover, the channels in a cognitive network are distributed across a large spectrum and the channels may be separated with a large band. In such a scenario, it might not be practical to switch channels at packet granularity. A method to avoid the choice of routes in which switching occurs, is proposed below.

Interface constraint

Now let us consider Fig. 3.4. If the weights are a simple function of distance, then all the edges between a fixed pair of nodes would weigh the same as explained earlier. For example, weights of channels 1, 2 and 3 are the same between nodes A and B. In this case, distance vector routing might choose channel 1 between A, D and channel 2 between D, C as shown in Fig. 3.5. Channel used from A to D is different from D to C in this route. If node D were have having a single radio it should switch the interface (radio) between channels 1 and 2 for carrying on the communication. As mentioned above, it might not be always feasible, though faster radios are promised by the growing technology. Hence, there should be a way for the routing protocol to avoid choosing different channels if a node has a single available radio and when switching is not allowed.

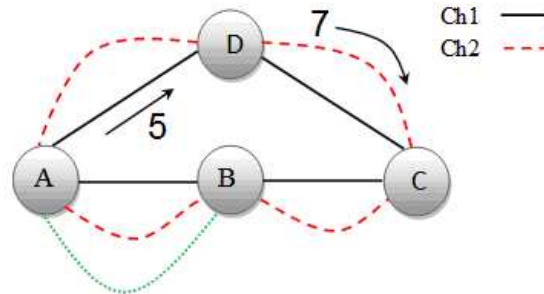


Figure 3.5: Path taken if only weights were considered.

This is done by adding an *Interface Constraint term* to the weights of outgoing edges of single radio nodes only as shown below:

$$\text{Let Interference Constraint term (IC)} = |x - y| \infty$$

Where:

W - Weight of the edge

X - Channel ID of the incoming channel

Y - Channel ID of the outgoing channel

D - Distance Metric

Since X and Y are channel ID's, if a same channel is chosen for incoming and outgoing communication, then the value of X and Y will be equal and their difference is zero. As a result the interference constraint term is zero and the weight, W of the edge will just be distance, D . Suppose different channels are chosen for the incoming and outgoing communications, then mod of the difference of X and Y will be a positive non-zero value. The interference constraint term will now be infinity and the final weight, W would also be infinity. Hence, this option will not be considered as a successful route.

Now consider the same graph as in Fig. 3.4 and let us assume that node D has a single radio and it cannot communicate over two different channels. Suppose the routing protocol chose channel 1 from A to D. The weights for the next hop would be as shown below and the path followed is shown in Fig. 3.6.

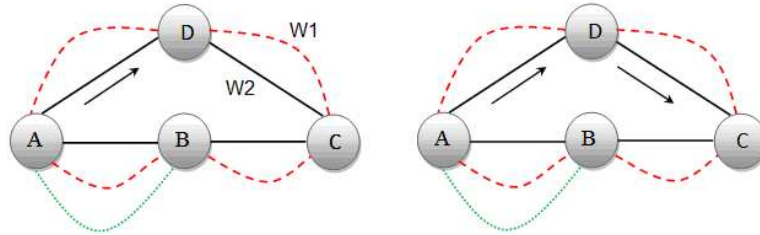


Figure 3.6: Path followed as the new weights are calculated.

$$W1 = |1 - 2|\infty + 7 = \infty$$

$$W2 = |1 - 1|\infty + 7 = 7$$

It is seen from Fig. 3.6 that the protocol would choose channel 1 in the second hop since the weight of the edge through channel 2 ($W1$) is infinity. So, by adding an *interface constraint term*(IC) to the weights of outgoing edges of the single radio nodes which cannot switch, the possibility of choosing two different channels by the protocol at that node is avoided.

Cognitive cost function

The nodes in a MHCRN have the capability to sense the channels using cognitive radio. This capability of the nodes can be used to find better routes in terms of interference. This can be done by adding an additional term to the weights of the edges, *cognitive cost function* (CF). A routing cost function incorporating measurements of the instantaneous behavior of the external world, as represented for example by current network status in terms of interference suffered by overlaid networks was proposed in [24]. The cost function accounted for various terms, of which, power, multi-user interference, reliability of the channel, traffic in the channel and delay factor are important. This cost function is added to the weights of the edges to incorporate cognitive routing.

Now that we have an unlabeled graph, an algorithm to assign the weights to the edges of the graph is needed. Algorithm 2 is used for weight assignment and routing in MHCRN.

In the following section the performance and complexity of the multi-edged graph model is studied.

Algorithm 2 Weight assignment and Routing

- Assign distance D as the weight for the edge connecting nodes N_i and N_j for all $N_i, N_j \in N$.
 - Add the *Interference constraint term* (IC) to outgoing edges of nodes N_i if N_i has a single radio for all $N_i \in N$.
 - Add the *Cognitive cost function* (CF) to the weights of all edges connecting nodes N_i and N_j for all $N_i, N_j \in N$.
 - Use the graph G for route discovery using any graph based routing protocols like distance vector routing.
-

3.3 Simulation results

A custom simulator written in C is used to simulate the multi-edge graph. The graph model is tested using DSDV protocol. A grid topology is considered with varying number of nodes from 2×2 to 10×10 . The channels available at each node are randomly selected. The probability that a particular channel is available at a node is p . The value of p is chosen to be 0.5. Maximum number of channels (channel set) at each node is varied from 2 to 10. The connectivity from the first node to the last node in the graph is examined for and the percentage of successful routes is plotted. Each point on the graphs is an average of 100 simulations.

Two sets of simulations were carried out. The first set of simulations assume that all the intermediate nodes in a route can switch between channels to communicate with their two neighbors and the second set of simulations assume that no intermediate node can switch between channels in a communication. Though these assumptions are unrealistic, they serve two purposes.

- They help us verify the proposed model intuitively.

- They act as upper and lower bounds respectively.

In practice, results will lie in-between these results.

Fig. 3.7 shows the variation of percentage of successful routes with the number of nodes in the networks in which switching the interface between the channels is allowed and not allowed respectively.

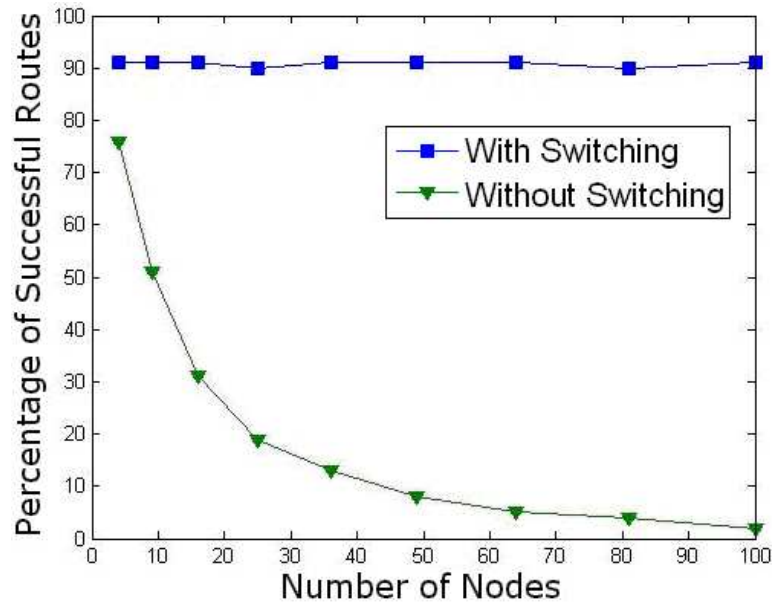


Figure 3.7: Comparison of percentage of successful routes as a function of number of nodes with and without switching interfaces.

It is observed that there is a success rate of 90% with switching. When switching is not allowed, a node cannot communicate in two different channels simultaneously. This constraint, limits all nodes in the route to communicate using the same frequency (Channel). Because it is less probable that all nodes in the route have a common channel, the success rate is lower in such a network. When switching is possible, a route is possible if there is at least one channel between every pair of nodes along

the route. As a result the percentage of successful routes is far better with switching than without switching.

It is also observed that as the number of nodes increases, the success rate decreases. This is because of the fact that with the increase in the number of nodes, the probability of finding a route with a common channel between every pair of nodes along the route decreases.

In Fig. 3.8, percentage of successful routes is plotted against the maximum number of channels (channel set). From this graph it is seen that with an increase in the number of channels, the success rate of the routes increases drastically to nearly 100% with switching. This is obvious from the fact that the probability of finding at least one available channel between a pair of nodes increases with the number of channels. Whereas, the probability that a common channel is found among all the nodes with increase in number of channels increases marginally.

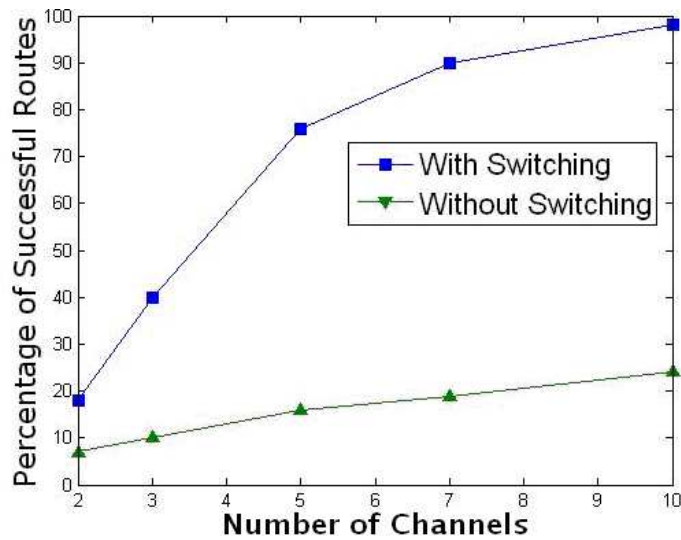


Figure 3.8: Comparison of percentage of successful routes as a function of number of channels with and without switching.

In a real world scenario a network consists of heterogeneous nodes. Some nodes might have single interface and some have more than one interface. When the nodes have more than one interface, they can use one interface for each incoming and outgoing channel in which case, the percentage of success rate is similar to the network in which switching is possible. So, the practical success rate lies in-between the results shown above.

3.3.1 Analytical Model

To verify these results an analytical model is needed to determine variation of the probability of a successful route with the number of nodes and the maximum number of channels is varied.

Probability of a successful route is derived below:

Consider a path along a chain of n nodes. Probability that there exists a route between the first node and the last node if a channel is available at a particular node with a probability of p is derived. Let the total number of possible channels be c .

Where:

n - Number of nodes in the route

c - Number of possible channels at each node

p - Probability that a particular channel is available at a node

P - Probability that a route exists between the first node and the last node

In a non-switching radio network, each radio can communicate over only one channel at a time. So a route is possible only if all nodes in the path have at least one common channel available.

Probability that one common channel exists among n nodes

$$= p^n.$$

Probability that one common channel does not exist

$$= 1 - p^n.$$

Probability that no common channel exists among all c possible channels

$$= (1 - p^n)^c.$$

Probability that at least one common channel exists among all possible channels

$$= 1 - (1 - p^n)^c.$$

$$\text{Thus } P = 1 - (1 - p^n)^c.$$

In a switching radio network, each node can receive and send along different channels. So, a route is possible if there is at least one common channel between the two nodes along every hop. To calculate this probability we consider each hop separately.

Probability that one common channel exists between two nodes

$$= p^2$$

Probability that a common channel does not exist between 2 nodes

$$= 1 - p^2$$

Probability that no common channel exists between two nodes along c possible channels

$$= (1 - p^2)^c$$

Probability that at least one common channel exists between two nodes

$$= 1 - (1 - p^2)^c$$

Probability that at least one common channel exists between every hop

$$= (1 - (1 - p^2)^c)^{n-1}$$

$$\text{Thus, } P = (1 - (1 - p^2)^c)^{n-1}$$

Since, the probability of a successful route along a path is known; the results from the graph model can be verified. The model is used to find the route possibility along the shortest path. Since grid topology was used in simulating the graph model, the shortest path would be along the diagonal. This will be a pessimistic value because, there can be other routes possible and hence the actual probability is expected to be higher. Results from the graph model and analytical model are plotted in Figs. 3.9 and 3.10.

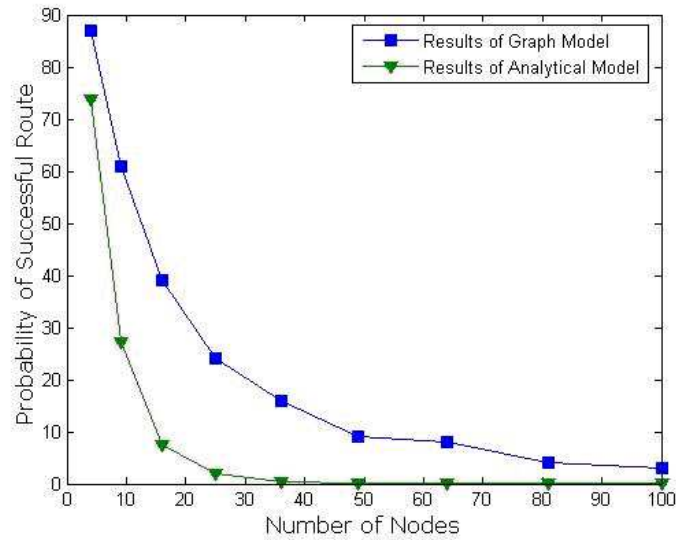


Figure 3.9: Comparison of Practical Results and Theoretical Results for a switching radio network as the number of nodes are varied for a set of 10 channels.

It is seen from the simulations that the results from the graph model match the results from the analytical model. Hence, the proposed graph model is demonstrated to be valid in modeling MHCRN. Since the multi-edged graph can model the MHCRN and provide sufficient information for routing, all graph based protocols can use this graph to find the routes in a MHCRN. In the above simulations, DSDV has been used for this purpose.

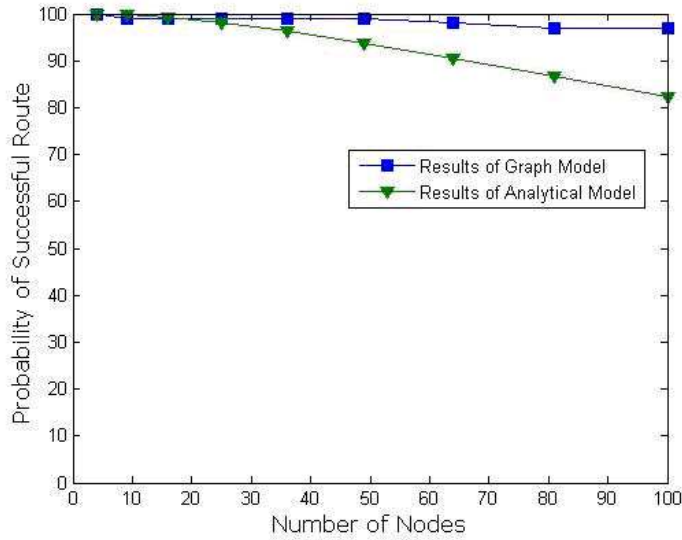


Figure 3.10: Comparison of Practical Results and Theoretical Results for a non-switching radio network as the number of nodes is varied for a set of 10 channels.

3.3.2 Complexity

A graph model, while modeling the network correctly should be simple. In the following discussion the complexity of the graph model is compared with the layered graph model proposed in [23]. A sample 4 node network represented using layered graph model is reproduced from [23] in Fig. 3.11. Node A has not been shown by the author for demonstration purpose. The same network is represented using multi-edged graph model in Fig. 3.12. It can be said that multi-edged graph model is simpler compared to layered graph model just by visual observation. Moreover it can be observed that the layered graph model contains many unidirectional edges which add to the complexity of the graph; unlike in multi-edged model where all edges are assumed bidirectional and this is more realistic since wireless medium is bidirectional.

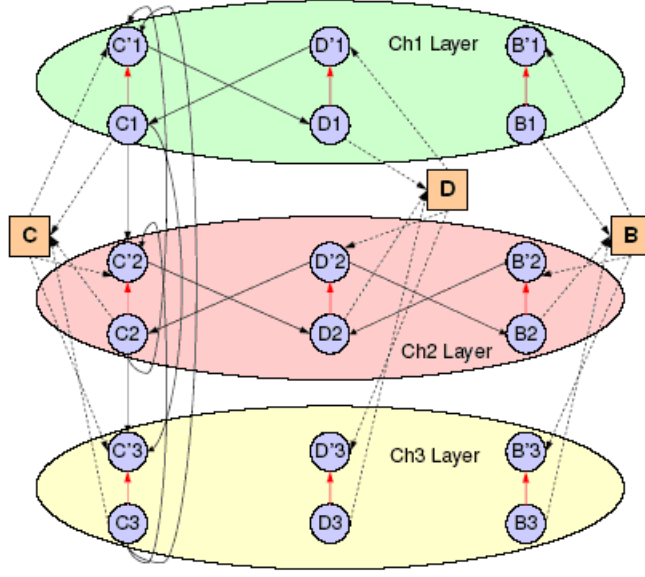


Figure 3.11: Layered Graph model representing a sample 4 node network.

Node complexity and edge complexity of the two models is given below. To understand the derivation of the complexity of the layered graph model the reader is referred to [23].

Let $A_{n \times n \times c}$ be a three dimensional matrix, with two dimensions representing the pair of nodes and the third dimension represents the channel in which each pair can communicate. This matrix represents all possible node pairs in all channels. The value of an element $A(x, y, z) = 1$ means that nodes x and y can communicate using channel z .

Let $B_{n \times c}$ be a two dimensional matrix representing the available channels at each pair of nodes. $B(n, c)$ is 1 if n^{th} node has channel c available. For a group of n nodes and a total of c possible channels, let X and Y be two variables defined as follows:

$$X = \sum_{i=1}^n \sum_{j=1}^n \sum_{k=1}^c A(i, j, k)$$

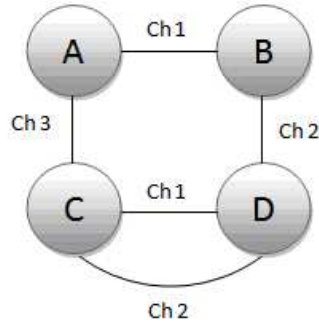


Figure 3.12: Planar Graph model representing a sample 4 node network.

$$Y = \sum_{j=1}^c B(i, j)$$

Using these variables the *layered graph model* has:

$$\text{Number of Nodes} = 2nc + n.$$

$$\text{Number of Edges} = X + \sum_{i=1}^n {}^Y C_2 + 3nc.$$

The *planar graph model* has:

$$\text{Number of Nodes} = n.$$

$$\text{Number of Edges} = X.$$

In the planar graph model, the elements of matrix A represent the edges since $A(x, y, z)$, represents a possible communication between node pairs x and y through channel z . Hence, sum of all elements in matrix A , which is defined as X , is equal to the number of edges in multi-edged graph model. The number of nodes is equal to n since there is only one layer. For example, in a set of 5 possible channels and 10 nodes, the layered graph model has 110 nodes and 258 edges whereas, the multi-edged graph model has only 10 nodes and 30 edges. Thus, the multi-edged graph model is much simpler than the layered graph model.

From the above discussion the clear advantages of the multi-edge graph model are:

- Planar structure as in traditional graph models.
- Lower node and edge complexity.
- Bidirectional edges.
- Graph based routing protocols like AODV, DSDV, DSR can be adopted. .

CHAPTER 4

CONCLUSION

In the first part of this work, a MAC protocol for MHCRNs is presented which avoids the need for a common control channel for the entire network. This automatically eliminates the control channel saturation problem and DoS attacks. The multi-channel hidden terminal problem is solved by introducing synchronization into the protocol. The protocol is also applicable to heterogeneous channels. NS2 simulation results show that SYN-MAC achieves higher throughput than CCC based protocols. It was also demonstrated through MATLAB simulations that SYN-MAC offers higher network connectivity than CCC-MAC.

In the second part, a multi-edged graph to model a MHCRN is presented. Using such a graph to model an MHCRN enables the direct use of traditional routing protocols for route discovery. The graph model is validated using a custom simulator built in C. DSDV routing protocol is used in the simulations. Finally, the node and edge complexity of the proposed model was demonstrated to be lesser than layered graph model. In the future, the feasibility of our model will be further tested by using different graph based protocols like DSR and AODV.

As a future work, we plan to combine the two concepts and study the simulated results. Experimenting with practical Software Defined Radios and implementing these protocols on them is the ultimate goal.

BIBLIOGRAPHY

- [1] FCC, ET Docket No 03-222 Notice of proposed rulemaking and order, December 2003.
- [2] Akyildiz, Ian F. ,Lee, Won-Yeol, Vuran, Mehmet C, Mohanty, Shantidev, “NeXt generation dynamic spectrum access cognitive radio wireless networks: A survey,” *Computer Networks*, v 50, n 13, Sep 15, 2006, p 2127-2159.
- [3] Joseph Mitola and G. Q. Maguire. “Cognitive radio: making software radios more personal,” *IEEE Personal Communications*, 6(4):1318, 1999.
- [4] J. So, N. Vaidya; “Multi-Channel MAC for Ad Hoc Networks: Handling Multi-Channel Hidden Terminals Using A Single Transceiver,” *Proc. ACM MobiHoc* 2004.
- [5] C. E. Perkins, E. M. Royer, and S. R. Das, “Ad Hoc On-Demand Distance Vector (AODV) Routing,” IETF Mobile Ad Hoc Networks Working Group, IETF RFC 3561.
- [6] C. E. Perkins and P. Bhagwat, “Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers”. In *Proceedings of the ACM Special Interest Group on Data Communications (SIGCOMM)*, August 1994, pages 234-244.
- [7] D. B. Johnson, D. A. Maltz, and Y-C Hu, “The Dynamic Source Routing Protocol for Mobile Ad Hoc Networks (DSR),” IETF Mobile Ad Hoc Networks Working Group, Internet Draft, work in progress, 24 February 2003.
- [8] J. Zhao, H. Zheng, G.-H. Yang, “Distributed coordination in dynamic spectrum allocation networks,” in: *Proc. IEEE DySPAN 2005*, pp. 259-268, November 2005.
- [9] K. Bian and J.-M. Park, “MAC-layer misbehaviors in multi-hop cognitive radio networks,” 2006 US - Korea Conference on Science, Technology, and Entrepreneurship (UKC2006), Aug. 2006.
- [10] Hao Nan, Sang-jo Yoo and Tae-In Hyon, “Distributed Coordinated Spectrum Sharing MAC Protocol for Cognitive Radio,” *IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, pp. 240-249, April 2007.

- [11] S. Krishnamurthy, M. Thoppian, S. Venkatesan, and R. Prakash, "Control Channel-based MAC-layer Configuration, Routing and Situation Awareness for Cognitive Radio Networks," in: MILCOM 2005, Atlantic City, NJ, October 2005.
- [12] C. M. Cordeiro and K. Challapali, "C-MAC: A Cognitive MAC Protocol for Multi-Channel Wireless Networks," in IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, April 2007.
- [13] S.-L. Wu , C.-Y Lin , Y.-C. Tseng , J.-P. Sheu, "A New Multi-Channel MAC Protocol with On-Demand Channel Assignment for Multi-Hop Mobile Ad Hoc Networks," Proceedings of the 2000 International Symposium on Parallel Architectures, Algorithms and Networks (ISPAN '00), p.232, December 07-07, 2000.
- [14] Thoppian, M.; Venkatesan, S.; Prakash, R.; Chandrasekaran, R., "MAClayer scheduling in cognitive radio based multihop wireless networks," World of Wireless, Mobile and Multimedia Networks, 2006.
- [15] Q. Zhao, L. Tong, and A. Swami, "Decentralized cognitive MAC for dynamic spectrum access," in Proc. of IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, Nov. 2005.
- [16] Q. Zhao, L. Tong, A. Swami, and Y. Chen, "Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework", submitted to IEEE Journal on Selected Areas in Communications, February, 2006.
- [17] Pradeep Kyasanur , Nitin H. Vaidya, "Selfish MAC Layer Misbehavior in Wireless Networks," IEEE Transactions on Mobile Computing, v.4 n.5, p.502-516, September 2005.
- [18] Q. Zhao, L. Tong, and A. Swami, "A Cross-Layer Approach to Cognitive MAC for Spectrum Agility," in Proc. of Asilomar Conference on Signals, Systems, and Computers, Nov. 2005.
- [19] Athanassios V. Adamis, Konstantinos N. Maliatsos, Philip Constantinou, "A New MAC Protocol with Control Channel Auto-Discovery for Self-Deployed Cognitive Radio Networks," in Program for European Wireless 2007.
- [20] Y. Kondareddy and P. Agrawal, "Synchronized MAC Protocol for Multi-Hop Cognitive Radio Networks," IEEE ICC, Beijing, China, May 2008.
- [21] Pradeep Kyasanur, Nitin H. Vaidya, "Protocol Design Challenges for Multi-hop Dynamic spectrum Access Networks," Proc. IEEE DySPAN 2005, November 2005, pp. 645- 648.

- [22] Bing Qi, Saad Biaz, Shaoen Wu, Yiming Ji, "An interference-aware routing metric in multi-radio multi-hop networks," ACM Southeast Regional Conference 2007: 549-500.
- [23] Chunsheng Xin, Bo Xie, Chien-Chung Shen, "A novel layered graph model for dynamic spectrum access networks," Proc. IEEE DySPAN 2005, November 2005, pp. 308-317.
- [24] L. De Nardis and M.-G. Di Benedetto, "Cognitive routing in UWB networks," invited paper at the IEEE International Conference on UWB 2006 (ICUWB2006), September 24 - 27 2006.
- [25] Dipankar Raychaudhuri and Xiangpeng Jing, "A spectrum etiquette protocol for efficient coordination of radio devices in unlicensed bands," in: 14th IEEE PIMRC2003, September 2003.
- [26] P. Pawelczak, R.V. Prasad, Xia Liang, I.G.M.M. Niemegeers, "Cognitive radio emergency networks - requirements and design," Proc. DySPAN, Nov. 2005, pp. 601- 606.
- [27] Srinivasan Krishnamurthy, Mansi Thoppian, Srikant Kuppa, R. Chandrasekaran, S. Venkatesan, Neeraj Mittal and Ravi PrakashM, "Time-efficient layer-2 auto-configuration for cognitive radios," In IASTED International Conference on Parallel and Distributed Computing and Systems (PDCS), pages 459-464, November 2005.