Chapter 1

Introduction

Traditional wireless networks are running with fixed spectrum assignment policies regulated by government agencies. Spectrum is assigned to service providers on a long term basis for large geographical regions. The spectrum is allowed to be used by licensed users. Federal Communications Commission (FCC) measurements have indicated that 15-85% of the time, many licensed frequency bands remain unused while some other bands are highly over-crowded [1]. These overcrowded bands face the issue of spectrum scarcity. In order to better utilize the licensed spectrum, FCC has launched a secondary markets initiative [2], whose goal is to remove regulatory barriers and facilitate the development of secondary markets in spectrum usage rights among the wireless radio services. The inefficient usage of the existing spectrum can be improved through opportunistic access to the licensed bands without interfering with the primary users. This introduces the concept of Dynamic Spectrum Allocation (DSA), which implicitly requires the use of cognitive radios [3] to improve spectral efficiency.

Cognitive radio is an intelligent radio that is aware of its surrounding environment and dynamically adapts to the transmission or reception parameters to achieve efficient communication without interfering with primary users. Thus, a Cognitive Radio Network (CRN) [4] consists of primary and secondary users. The primary users are the licensed users and hence have exclusive rights to access the radio spectrum, whereas the cognitive users are the unlicensed users that can opportunistically access the free spectrum bands, without causing harmful interference to primary users. This introduces cognition and adaptation to physical layer of the network.

These networks work on multi-channel environment with dynamic availability of channels based on primary user activity. These channels can be of different frequencies and/or different bandwidth. The operation of these networks is very different from simple multi-channel environments as different frequencies have different characteristics, like transmit power levels, transmission distance and multi-path effects. This gives new challenges to a variety of stakeholders. For RF equipment vendors, the challenge is to build equipment which can be operated on any spectrum band and capable of doing on the fly changes in the radio transmission parameters. For wireless service providers, the challenge is to use their own resource efficiently and opportunistically use the other bands while maximizing their profit. As other providers can use their band opportunistically, security is also a major concern from
user’s perspective. Ensuring the licensing policies which enable the secondary usage of the spectrum is a challenge for regulatory bodies. Licensing policies should provide benefit to licensed users as well as cognitive users.

To deal with the cognition in radio (i.e. physical) layer, upper layers should also be modified to adapt to the reconfiguration done at physical layer. Thus, adaptation and cognition should also be included at upper layers to achieve the benefits of cognitive radio technology. This makes a network as cognitive network [5,6]. Definition of cognitive network was first presented at IEEE DySPAN conference in 2005.

A cognitive network is a network with a cognitive process that can perceive current network conditions, and then plan, decide and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals.

As cognition should be incorporated in upper layers to effectively utilize the benefits of cognition at physical layer cognitive networks and CRNs are used interchangeably in literature. Cognitive networks can be broadly classified as infrastructure-less cognitive networks and infrastructure-based cognitive networks as shown in figure 1.1. In the infrastructure-based cognitive networks, the cognitive base-station collects the spectrum information acquired locally by the cognitive users and makes the decision. According to this decision, each cognitive user reconfigure its communication parameters. Infrastructure-less cognitive networks or Cognitive Radio Ad Hoc Networks (CRAHNs) [7] require distributed protocols. In CRAHNs, cognitive users need to have the cognitive capabilities and they are responsible for determining the actions based on the local observation. Since cognitive users cannot predict the influence of their actions on the entire network, cooperative schemes are essential. In cooperative schemes, the observed information can be exchanged among cognitive users to broaden the knowledge on the network. Cognitive Wireless Sensor Networks (CWSNs) [8,9] are special class of CRNs which can be deployed as infrastructure based or infrastructure-less networks.

![Diagram of Cognitive Networks](image_url)

**Figure 1.1: Classification of Cognitive Networks**
1.1 Cognitive Network Challenges

1.1.1 Spectrum Management Framework

The functionality of cognitive cycle is the main challenge of the spectrum management framework in cognitive networks. The cognitive cycle builds the spectrum opportunity map identified by the sensing block and schedules the resources dynamically among the cognitive users. Furthermore, the cognitive cycle allows cognitive users to vacate the selected channel when a primary user becomes active on that channel. Following are the main features of spectrum management as shown in figure 1.2.

- **Spectrum sensing**: The cognitive users are allowed to use the unused portion of spectrum. Therefore, a cognitive user should monitor the available spectrum bands to detect spectrum opportunities. Spectrum sensing can be done by the cognitive users or a trusted third party. In case of third party sensing, third party shares the geo-location database of spectrum with the cognitive users. Some efforts are already taken by companies to provide geo-location database of spectrum. FCC has approved Spectrum Bridge Inc.’s for providing spectrum database services for television white spaces in USA since January 26, 2012. Google is also working with industry and regulators for TV whitespaces database [10].

- **Spectrum decision**: Once the available spectrum bands are identified, cognitive users select the most appropriate band according to their QoS requirements.

- **Spectrum handoff**: If primary user presence is detected in the specific portion of the spectrum in use, cognitive user should vacate that spectrum and continue their communication in some other vacant band. Spectrum handoff process needs to communicate with spectrum sensing process to find the vacant band.
• Spectrum sharing: As multiple cognitive users may be looking for the spectrum at the same time, transmission between cognitive users should be coordinated to avoid collisions. This spectrum sharing capability is taken care by spectrum sharing process. Spectrum sharing can be classified as centralized spectrum sharing and distributed spectrum sharing. Spectrum sharing can also be classified as cooperative spectrum sharing and non-cooperative spectrum sharing. In cooperative sharing, communication effect to other cognitive users is considered while selecting the channel. While in non-cooperative sharing, channel is selected based on local policies. For networks where centralized infrastructure is present, spectrum sharing is done through the base-station and hence comes under cooperative sharing. For infrastructure-less networks, where the controlling infrastructure is not present, spectrum sharing is done based on local policies.

1.1.2 MAC layer in the Cognitive Networks

Functionality of the cognitive cycle discussed above is the main challenge of MAC layer in cognitive radio networks. Classifications of cognitive MAC protocols based on various factors are listed in the figure 1.3. Based on spectrum access method, MAC protocols can be classified into contention based protocols, TDMA based protocols, hybrid protocols and OFDMA based protocols. To avoid interference to primary user in TDMA based spectrum access method, all secondary users should be synchronized and should follow the same timeslot division as of the primary user. Thus, TDMA based approach cannot be used for more than one kind of primary user. In cooperative spectrum allocation based MAC protocols, the cognitive user also considers requirements from other cognitive users and fairly uses the channels. While in Non-cooperative spectrum allocation based MAC protocols, the cognitive user only considers its own requirement and voraciously access the channel whenever available. The MAC protocols can be classified into underlay spectrum sharing model based MAC protocols, overlay spectrum sharing model based MAC protocols and Interweave spectrum sharing model based MAC protocols.
according to spectrum sharing models. In the underlay spectrum sharing model based MAC protocols, a cognitive user can operate in the primary user's band if the interference caused to the primary user is below some threshold. Cognitive user is restrictive to short distance communication because of interference constraint of such protocols. In the overlay spectrum sharing model based MAC protocols, the cognitive user has access to the primary user codebook. Primary user codebook information is used at the cognitive receiver to cancel the interference caused by the primary user. Overlay and underlay spectrum sharing model based MAC protocols allow cognitive user and primary user to transmit simultaneously. Interweave spectrum sharing model based MAC protocols use primary spectrum band in spectrum opportunities.

MAC protocols for cognitive networks should support multi-channel operation. In cognitive networks, availability of channels is dynamic and also the channels are heterogeneous, i.e. they could be of different bandwidth and different frequencies with different propagation characteristics. In multi-channel networks, MAC layer is responsible for channel assignment and medium access control. Due to the dynamic nature of cognitive networks some other challenges also arise in the design of MAC layer. Below are the main issues related to the MAC layer of cognitive networks, details about these issues are discussed in chapter 3.

- Selection of transmission channel
- Neighbor discovery
- Control information sharing
- Channel synchronization
- Medium access coordination
- Multi-channel hidden node problem
- Channel scheduling

1.1.3 Routing in Cognitive Networks

Khalife et al [11] argues that no general routing protocol can be proposed for cognitive networks. According to the paper, cognitive networks can be classified into three categories based on primary user activity models; each requiring specific routing solutions as shown in figure 1.4. In the case of a static primary user activity model, traditional routing algorithms can be used as primary user activity and inactivity is for longer periods like in case of TV broadcasts. In the case of a dynamic primary user activity model, specific routing protocols for cognitive networks should be developed. While in case of highly dynamic primary user activity model, the availability of such frequency bands for the whole communication duration becomes an unrealistic assumption. Therefore, complete opportunistic routing protocol, where every packet can be forwarded opportunistically over available channels with no route
setup, constitutes a potential solution. This thesis considers dynamic primary user activity model for routing.

![Routing Diagram](image)

**Figure 1.4: The primary band holding time and its effect on routing**

Figure 1.5 lists the challenges for designing effective routing metrics for cognitive networks. Some of the challenges are inherited from traditional networks. Opportunistic spectrum availability, interruption time due to channel switching if primary user comes back and signaling and deafness problem also known as multi-channel hidden node problem are some of the challenges specific to cognitive networks.

<table>
<thead>
<tr>
<th>Inherited from Traditional Networks</th>
<th>Spectrum Availability</th>
<th>Interruption Time</th>
<th>Signaling and Deafness Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic set of challenges inherited from traditional networks that a routing metric for cognitive networks should address.</td>
<td>Assign different weights to different channels based on their availability and the interruption probability.</td>
<td>Take into account the channel switching time that needs to be paid when a channel switching decision is taken.</td>
<td>The solution of deafness problem affects the choice of the routing metric and the performance of the routing protocol in general.</td>
</tr>
</tbody>
</table>

**Figure 1.5: Routing metric design challenges**

In literature, various routing algorithms have been proposed. Papers [12, 13] provide a survey of routing metrics used in cognitive networks. The routing metrics are classified as follows:
• Delay
• Hop Count
• Power Consumption
• Location based
• Spectrum Availability
• Route Stability
• Probabilistic
• Route bandwidth capacity
• Route closeness
• Dead Zone Penetration

• Metrics that capture secondary user interference

Delay, hop count, power consumption, location based and probabilistic routing metrics are inherited from traditional networks. Spectrum availability, route stability, route bandwidth capacity, route closeness, dead zone penetration and metrics that capture secondary user interference are specific to cognitive networks. The routes closeness metric [14] favors routes that are far away from each other. Selecting non-close routes makes them less vulnerable to primary user’s activities as it would be difficult for an active mobile primary user to interrupt all the routes at the same time. The Dead Zone Penetration metric (DZP) [15] is a route maintenance metric and can be used in conjunction with any of the existing routing. This metric uses multipath routing to penetrate active primary user’s zones by using the relay to cooperatively send data to the next hop.

These different metrics perform differently in different network conditions and/or requirements. Chapter 2 discusses routing protocols from literature. Most of the presented protocols were inherited from traditional routing protocols, i.e. the routing metrics are old metrics like hop-count or delay, and algorithms send data only in spectrum opportunities. The goals for routing in cognitive networks are:

• Use spectrum opportunities effectively to benefit secondary users without causing harmful interference to primary users.

• Save energy of nodes to increase the network lifetime.

• Minimize end-to-end delay.

• Increase throughput.

• Improve route stability.
1.1.4 Transport layer in Cognitive Networks

The performance of TCP depends on the packet loss probability and the round trip time (RTT). Link errors, packet loss probability and RTT depend on the access technology, interference level, channel bandwidth and frequency of the channel in wireless communication. Thus, the performance of transport protocol is dependent on the physical layer parameters. Therefore, the transport protocols that are designed for existing networks cannot be used in cognitive networks. The spectrum sensing results, activity of the primary users, large-scale bandwidth variation based on spectrum availability, and the channel switching process should be considered in the transport protocol design. Chowdhury et al [16] propose a window-based transport protocol for cognitive networks, TP-CRAHN, which distinguishes each of these events by a combination of explicit feedback. This protocol closely interacts with the physical layer channel information, link layer spectrum sensing and buffer management, and a predictive mobility framework that is developed at the network layer to achieve desired TCP rate.

1.1.5 Need for Cross Layer Design

In the traditional OSI model of communication, strict boundaries between layers are enforced and meta-data for layers are kept unavailable to other layers. While in cross layer design strict boundaries are removed and exchange of meta-data is permitted across the layers. The layered OSI model for communication was build for wired communication and later adapted to the wireless communication. Issues with wireless links and opportunistic behavior of cognitive networks are the main motivations for cross layer design in cognitive networks. In cognitive wireless environment, several problems cannot be handled by layered communication. Below we discuss specific needs for cross layer design with respect to network layer and transport layer.

- **Need for cross layer design with respect to network layer**: In cognitive networks, physical layer parameters should be changed based on the available spectrum. This change in the channel parameters may affect the QoS of the path selected. For example, an optimized MAC protocol may provide the best channel/power/rate assignment for a particular link but such an assignment can be quite inefficient for end-to-end path of the flow. This necessitates that the decisions at network layers should consider and reflect the parameters of lower layer. Hence, lower layer optimization without considering network layer protocols can lead to sub-optimal solution. This necessitates the use of cross layer protocols with hybrid routing metrics.

- **Need for cross layer design with respect to transport layer**: Link unavailability due to the primary user activity could be mistaken as network congestion by transport layer protocol. In case of TCP as a transport layer protocol, this may cause to increase the size of congestion window. As discussed earlier, the performance of TCP depends on bandwidth and frequency of spectrum. In cognitive networks, bandwidth changes with the spectrum switching at MAC layer. The size of contention window should also be updated with the change in transmission spectrum bandwidth.
Thus, appropriate changes are needed in the design of transport layer for cognitive networks which takes feedback from lower layers.

Srivastava et. al. [17] also shows that the cross layer protocols are more effective than layered protocols where dynamic adaptation of parameters is required. Cognitive networks use spectrum opportunities for communication where dynamic adaptability to the transmission or reception parameters is required. For cross layer design of the network, objectives from different layers should be combined to one optimization problem to ensure QoS at each layer.

1.2 Thesis Statement

The objective of the research project is to study, evaluate and propose cross layer protocols for various design challenges in cognitive mobile ad hoc networks and cognitive wireless sensor networks. As discussed earlier, cognitive users need to have the cognitive capabilities and they are responsible for determining the actions based on the local observations in cognitive mobile ad hoc networks. Also, cognitive users act as a router for data forwarding in cognitive mobile ad hoc networks. Thus, energy efficiency is one of the main concern in the design of protocols for cognitive mobile ad hoc networks. Cognitive wireless sensor networks uses cognitive capabilities to solve the spectrum scarcity issue in ISM band. CWSNs can be deployed either as an infrastructure based networks or as an infrastructure-less networks. Sensor nodes are small low cost devices with limited power. These nodes act as a data collector and a data router. Sensor networks get very less human interaction once they are deployed and hence energy efficiency is more crucial while designing the protocols for such networks.

The resulting protocols/solutions should ensure better utilization of communication and computation resources as well as increase the lifetime of the network by increasing energy efficiency. The scope of the current research is to study and give cross layer protocols that deal with the following problems:

- Routing
- MAC layer issues
- Spectrum allocation
- Power control
- Representation of network architecture
- Localization of primary users

The proposed protocols should conserve energy at all the nodes in the network which in turn will affect the lifetime of the whole network. Detailed study of physical layer issues are out of the scope of this research project.
1.3 Contributions and Layout of the thesis

This thesis proposes cross layer protocols for routing, spectrum allocation, spectrum access, and power control in cognitive networks.

Chapter 2 proposes a new cross layer routing protocol for cognitive networks, called cognitive cross-layer multipath probabilistic routing (CCMPR). It also performs power control, spectrum selection and node selection. This work calculates the transmit power level for each hop in the routing path based on history of the channel. This protocol introduces cognition to network layer. To define the routing metric, multi-objective optimization is used. It is shown that the defined routing metric gives a Pareto optimal solution.

Chapter 3 discusses MAC layer issues and existing protocols from literature. The MMAC-CR protocol provides solution to most of the issues but it seems to suffer from spectrum wastage. As discussed above, the selection of spectrum should be done by upper layers to improve the end-to-end performance. This chapter also proposes a cognitive cross-layer multi-channel MAC protocol (CCM-MAC). MMAC-CR protocol is modified to support high throughput and spectrum decisions at upper layer in CCM-MAC. CCM-MAC also provides spectrum sensing support such that cognitive user data is not mistaken as primary user data. It also provides solution for the multi-channel hidden node problem. The MAC and routing protocols are implemented such that the combined cross layer protocol gives solution to routing, MAC layer issues, spectrum allocation and power control.

Several proposals about cognitive MAC protocols based on traditional IEEE 802.11 can be found in the literature. None of the previous works talks about performance analysis of cognitive MAC protocols with exponential backoff procedure using Markov Model. Bianchi [18] proposed a Markov model for single channel IEEE 802.11, providing results about the throughput of the protocol. This work can be extended to provide performance analysis of IEEE 802.11 based MAC protocols in cognitive multi-channel networks. MMAC-CR and CCM-MAC protocol proposed in chapter 3 are the examples of such protocols. Chapter 4 develops a Markov model for the performance analysis of these MAC protocols under ideal channel and saturation conditions. The developed analytical model is defined as a three state model for Distributed Coordination Function (DCF) mode of operation which can be used for ad hoc networks. The analysis is done for data frame transmission together with the corresponding Ad hoc Traffic Indication Messages (ATIM) frame transmission. Performance analysis is done to analyze the channel capacity, MAC layer throughput and average MAC layer delays. This analysis can be used to select the design parameters of the protocols based on different user and/or network characteristics.

Chapter 5 focuses on CWSNs. Wireless sensor networks (WSNs) are used to perform distributed sensing in order to have a better understanding of the behavior of monitored entity for the occurrence of a set of possible events, so that proper action may be taken whenever necessary. Most WSN operate in unlicensed frequency bands which are also used by other wireless applications, such as Wi-Fi and Bluetooth. This makes unlicensed bands overcrowded. The capabilities of cognitive networking can be applied to any of the current wireless systems with adaptability to existing spectrum allocation in the deployment field, and hence improve overall spectrum utilization. These features can also be used to
meet many of the unique requirements and challenges of WSNs. Thus, CWSNs work with the cognitive network principles by adaptively changing the system parameters. CWSNs are special kind of cognitive networks, but bit different from cognitive ad hoc networks in the following sense:

- The number of sensor nodes in a CWSN can be several orders of magnitude higher than the nodes in a cognitive ad hoc networks.
- Sensor nodes are small low cost devices limited in power. And each node in CWSNs plays the dual role of data collector and data router.
- CWSNs usually get deployed in field at random unknown locations (like forest) and it is impractical to recharge sensor nodes once they are deployed. This makes energy efficiency more important in CWSNs.
- One or few nodes acts as data sink(s) in CWSNs and all the sensed data should be forwarded to the predefined sink(s) unlike cognitive ad hoc networks which support any node pairs for routing. This makes a need for specific routing protocol for sensor networks.
- CWSNs can also be deployed as infrastructure based networks.

CWSN specific protocols for energy efficient network architecture, routing, spectrum access and localization of primary users are proposed.

Finally, chapter 6 presents the conclusions of the thesis.