Chapter 1

Introduction

Recently, with the steep increase in number and type of wireless devices, the unlicensed spectrum becomes increasingly scarce. Studies have shown that large part of licensed bands are unused are under-utilized in time and space domain [1,7,8], resulting in unused holes in the time-frequency grid. As depicted in Figure 1-1, the report by Cabric *et al.* [1] have shown that the spectrum utilization is more competitive and intense at frequencies below 3 GHz whereas in the 3-6 GHz bands the spectrum is highly under-utilized. In a report published by Federal Communications Commission (FCC) [9] has revealed that the traditional fixed spectrum allocation policy results in the temporal and geographic variations in spectrum utilization, ranging from 15% to 85% [8]. On the other hand, fixed spectrum allocation policies do not permit reuse of the unused holes (white space) in licensed spectrum by unlicensed users. To overcome the spectrum scarcity problem, the technique of Cognitive Radio (CR) was coined by J. Mitola III [10] in late 1990. CR is a novel communication technique that enables unlicensed users or called secondary users to opportunistically and dynamically utilize spectrum holes without affecting or degrading the performance of the licensed users also called primary users. A Cognitive Radio Network (CRN) is a network of CR enabled unlicensed users, which compete to access the spectrum and opportunistically operate in spectrum holes. The techniques proposed so far to implement CR communication have proven to be successful in terms of utilizing the spectrum holes opportunistically for wireless transmission. However, it is revealed in the survey by Akyildiz *et al.* [2] that the techniques to perform spectrum sensing, power allocation and channel allocation to make CR communication feasible are quite inefficient to exploit the enormous possibility of the emerging next-generation radio communication technology adopting CR, which need further research initiatives.

The goal of this chapter is to briefly introduce the cognitive radio network (CRN) and describe the problems addressed by this research. The proposed solutions and their innovative aspects are briefly described to highlight the main contributions of this dissertation.
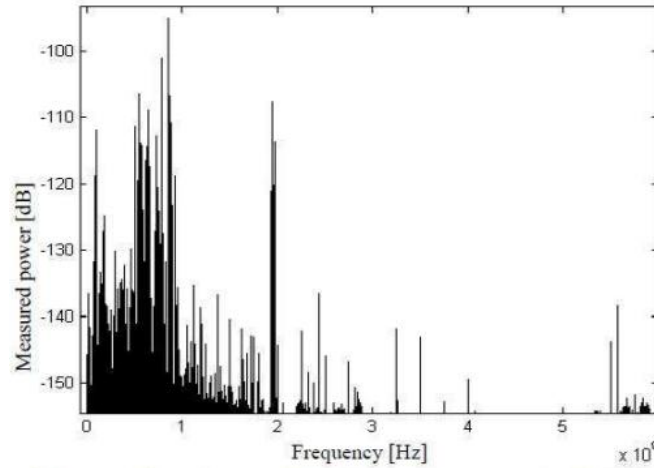
Figure 1-1: Spectrum utilization measurements [1]

1.1   Introduction to Cognitive Radio Network (CRN)

The limited available spectrum and spectrum under-utilization problem have motivated a number of initiatives in the regulatory as well as research communities to develop a new communication paradigm, which can exploit the spectrum bands opportunistically. In addressing the spectrum under-utilization problem, the FCC has recently approved the unlicensed access of the licensed bands [7]. In this context, the term Dynamic Spectrum Access (DSA) has been used to refer to the techniques that implement better spectrum management policies. The key enabling technology that emerges for DSA techniques is the cognitive radio (CR), which is supported by the Software Defined Radio (SDR) technology. CR is usually built upon an SDR platform and is a context-aware intelligent radio, which is capable of autonomous reconfiguration by learning from and adapting to the surrounding communication environment [11]. Formally, the term cognitive radio (CR) can be defined as follows according to FCC [12]:
"A cognitive radio is a radio that can change its transmitter parameters based on interaction with the environment in which it operates".

From the above definition, the two major characteristics of CR can be defined as given by Haykin *et al.* [13] as: the cognitive capability and reconfigurability. The cognitive capability refers to the ability of the radio component to capture (using techniques such as autonomous learning and action decision) or sense information (the temporal and spatial variations in the radio environment and the interference level generated to other users) from its surrounding radio environment, which uses the cognitive cycle as defined by Akyildiz *et al.* [2] as shown in Figure 1-2. On the other hand, the reconfigurability refers to the ability to enable the transmitter parameters to be dynamically programmed and modified according to the dynamics of radio environment.

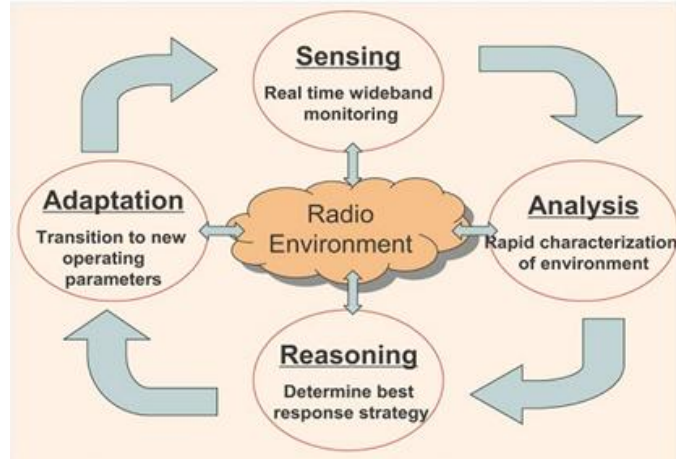Therefore, a CR enabled node in the network adapts dynamically to re-
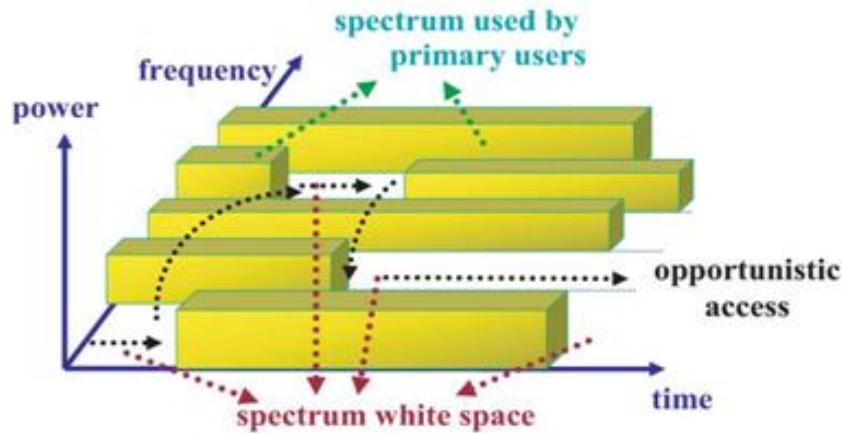
Figure 1-2: Cognitive Cycle [2]

Figure 1-3: Opportunistic Usage of Spectrum Holes [2]

configure several parameters such as the operating frequency (to take advantage of detected spectrum holes on different frequency bands), modulation and channel coding (to adapt to the requirements of application and the instantaneous conditions of channel quality), transmission power (to control the possible generated interference), and communication technology (to adapt to specific communication needs). Depending on the characteristics of the detected spectrum holes, as shown in Figure 1-3, the CR enables to switch to different spectrum bands opportunistically [2], while the transmitter and receiver parameters are reconfigured accordingly.

1.1.1 Cognitive Radio Paradigm

The opportunistic spectrum access by the cognitive radio can be performed in three different modes [2]: underlay, interweave and overlay. The mode of spectrum access can be decided depending on protection of the non-cognitive radio (i.e. primary) from interference produced due to secondary communication by the CR nodes. In underlay mode of CR communication the CR users coexists with primary
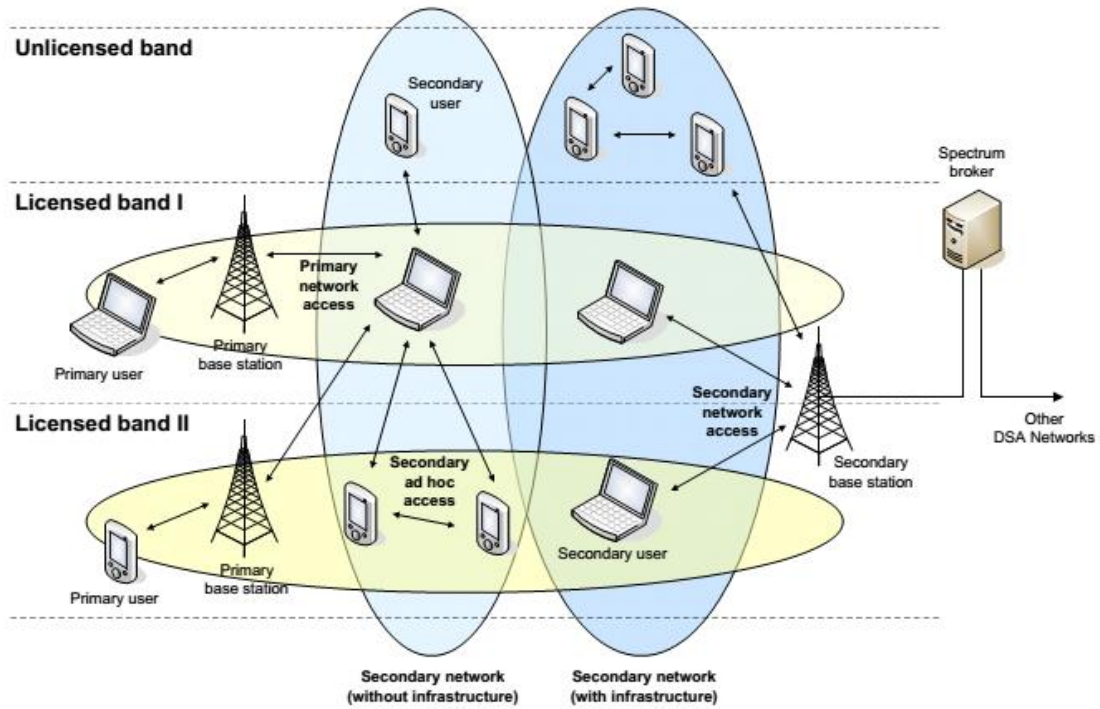
Figure 1-4: Cognitive Radio Network Architecture [2]

such that the cognitive radios constrained to cause minimal interference to primary user or non-cognitive radios. In case of interweave category, cognitive radios find and exploit unused spectral holes to avoid interfering with non-cognitive radios. In overlay mode of communication CR user utilizes the knowledge of primary signal, where cognitive radios overhear and enhance non-cognitive radio transmissions (e.g. using Network Coding).

1.1.2   CR Network Architecture

The possible architecture of a CR network as defined by Akyildiz *et al.* [2] is shown in Figure 1-4. The components of such a CR network architecture can be classified into two groups as *primary network* and *secondary network* (i.e. cognitive radio network).

- *Primary network:* A primary network is referred to an existing network infrastructure, where the nodes called primary users (PUs) have authorized license for exclusively accessing a certain frequency band. Examples of such networks include the cellular and the TV broadcast networks. Primary user (PU) activities are controlled through the primary base-stations in infrastructure based the primary network. Since the PUs have their priority in spectrum access, the operations of PUs should not be affected by any other unlicensed or secondary users.

- *Secondary network:* A secondary or unlicensed network is referred to a network, with fixed infrastructure or based on ad hoc communication principle, without license to operate in a desired licensed band. Hence, to share the licensed spectrum band with primary networks, the additional functionalities are used by the nodes called CR users/secondary users (SUs). The infrastructure based secondary networks are equipped with a central entity called CR base station, which implements a single-hop connection to SUs. On the other hand, the secondary ad-hoc networks have no infrastructure backbone and a SU can communicate with other SUs through the ad-hoc connection on both licensed and unlicensed spectrum bands. Furthermore, secondary networks may include spectrum brokers, which can play a role in sharing spectrum resources among different secondary networks.

In the context of network architecture, the spectrum management functionalities are implemented by different entities. For instance, in infrastructure based architecture, the spectrum broker is responsible for coordinating the tasks of spectrum sensing, decision and management (sharing and mobility), while in ad-hoc architecture, CR nodes themselves are responsible for spectrum sensing, decision and management. The former requires a dedicated control channel whereas in infrastructure less architectures use of dedicated control channel is optional.

1.1.3   Cognitive Radio Network Functionalities

The CR concept is envisaged through the efficient implementation of spectrum access using a set of specific functions, which can broadly be summarized as stated by Akyildiz *et al.* [2] as: *spectrum sensing, spectrum decision, spectrum sharing and spectrum management.* During spectrum sensing, CR nodes detect the unused spectrum and presence of the primary radio nodes in that portion of the spectrum. In spectrum decision, CR nodes select the best available channel. CR nodes can coordinate access to the best selected channel with other CR nodes during the spectrum sharing. During spectrum mobility, CR nodes maintain seamless communication and vacate the current channel whenever a licensed node (or PU) is detected on that channel.

1.2   Motivation of the Research

Spectrum sensing and power allocations for communication by the secondary users are considered to be the two key functions for successful deployment of CRNs using dynamic spectrum allocation (DSA) and sharing. The system model used in this thesis is the dynamic channel allocation and sharing. Spectrum sensing is used to detect spectrum holes at physical layer whereas spectrum sensing at medium access control (MAC) layer is used to decide how often and in which order to sense those channels. On the other hand, the cognitive communication using the detected holes can be made possible by adopting an efficient power alloca-

tion technique. It has been revealed from literature that the traditional spectrum sensing techniques face challenges [2, 14] in terms of sensing efficiency due to their inabilities to exploit the inherent spatial diversity [15–22]. Allowing the cooperation [3] among the secondary users is the way to tackle this problem, which can improve the overall detection reliability and performance by utilizing the inherent diversity. In this direction, a number of cooperative sensing approaches [3] have been attempted by researchers. Unfortunately, these approaches could not improve the sensing performance beyond a certain limit. The majority of the approaches do not consider the cost of cooperation due to reporting time and reporting energy. Also they do not consider estimating the sensing thresholds based on SUs distances from the primary user. Accordingly, the cooperative spectrum sensing [3] framework needs to consider the cooperation constraints, which can use coalitional game theoretic [23, 24] formulation for improving the performance. Similarly, utilizing the detected holes by means of maximization of capacity rate requires optimal power allocation. It is found that the traditional water-filling [25] based power allocation approaches face challenges [13, 26–28] in terms of ensuring strict primary user protection and the computation overhead to find the water level for optimal solution. Furthermore, the schemes based on iterative water-filling for multiuser power allocation to maximize the capacity rates suffer from the issue of convergence. A number of approaches have been proposed by the researchers to address these problems . However, optimizing the power allocation on the channels with technique to relax the expensive search to find water level is not applied to CRN. Further, in presence of average interference power (AIP) [29] constraint of primary user this problem of power allocation is more challenging. In multiuser environment, the majority of approaches fail to determine convergence behavior. Accordingly, the power allocation problem needs to be addressed as optimization problem to achieve the capacity rate improvement. For multiuser environment, game theory [23, 24] based techniques are formulated. The protocol level decision about the availability of opportunities in the licensed spectrum is taken at MAC level sensing [30]. The task of the MAC level sensing is to decide about the channel to be used for secondary communication. Taking the decision about the availability of a channel, the estimation of channel usage pattern of primary user is challenging. In this direction, researches have proposed techniques to predict the channel availability using Hidden Markov Model (HMM) [31] for interweave access. However, developing a model to predict channel availability for underlay access is challenging and not addressed so far. Accordingly, secondary users need to estimate channel usage pattern of primary user for underlay access and to predict availability of the concerned channel for future transmission. The key issues and difficulties for cooperative spectrum sensing, power allocation and channel usage pattern estimation and modeling in cognitive radio networks that have motivated this research are as follows.

- Cooperative spectrum sensing requires dynamic interaction among the secondary users, which leads to cooperation overhead in terms of reporting time and reporting energy.

- Issues due to spatial diversity of the secondary users and selection of sensing threshold which has the influence of distances of secondary users from the

primary affect sensing performance of cooperative spectrum sensing.

- Power allocation on channels using water-filling based technique for underlay communication requires strict primary protection, which leads to the capacity rate maximization problem, while facing the computational overhead in terms of searching delay to find optimal water level.

- Distributed power allocation on channels for multiuser underlay communication scenario with strict primary protection leads to the capacity rate maximization problem. Achieving the convergence state in such a multiuser underlay communication scenario is challenging.

- Higher layer protocols requiring MAC layer sensing to discover spectrum opportunities in the licensed channel need to estimate and derive the channel usage pattern of primary user, while tolerating interference from secondary users.

1.3   Research Objective

This research is largely motivated by the observations that for effective cognitive radio communication, SUs need to be equipped with efficient mechanisms for opportunity detection and channel allocation.

The broad objectives of this research work are to develop techniques for - (i) cooperative spectrum sensing taking reporting time and reporting energy as cooperation constraints and deciding adaptive sensing threshold for the SUs, (ii) power allocation on channel for underlay communication and game theoretic approach for multiuser communication and (iii) primary user's channel usage pattern modeling for MAC level sensing decision. The tasks respective to the objectives of the research work are outlined as follows:

- Designing a constraint based cooperative spectrum sensing technique

  - To address the pitfalls of individual spectrum sensing by the secondary users due to multi-path fading, shadowing, hidden node and user uncertainty problem
  - To incorporate dynamic behavior of secondary users using game theoretic formulation
  - To reduce cooperation overhead due to reporting time and reporting energy

- Designing a threshold adaptive cooperative spectrum sensing technique

  - To model a distributed scheme to address the issues of spatial diversity of the secondary users using coalitional game theory
  - To improve the sensing performance with incorporation of distance based adaptive sensing threshold estimation

– To reduce the cooperation overhead due to the error in the reporting channel and the reporting energy

- Designing a power allocation technique for underlay communication

  – To maximize the power allocation on OFDMA sub-channels for a secondary transmitter, keeping the average interference power (AIP) to the primary receiver within the permissible limit

  – To propose a scheme to find water level for optimal solution without resorting to the iterative search mechanism.

  – To optimize the capacity rate for underlay communication

- Designing a distributed power allocation technique for multiuser underlay communication scenario

  – To propose a distributed power allocation scheme to maximize the capacity rate of the secondary users by modeling the problem using potential game theory

  – To incorporate the primary user receiver protection using the average interference power (AIP) constraint

  – To study the Nash Equilibrium (NE) state of the game for convergence behavior

- Designing a channel usage model for MAC layer sensing decision

  – To estimate and model the channel usage pattern of primary user while tolerating interference from secondary users using Hidden Markov Model (HMM)

  – To discover opportunities in the licensed channels based on learnt channel usage patterns

  – To develop a channel selection scheme to decide and select the best channel to be used by a secondary user for future communication

Keeping the above broad objectives in mind, the works done in this dissertation are outlined in the next section 1.4 (Dissertation Contributions).

1.4   Dissertation Contributions

The main contributions of the dissertation can be divided into five parts. The following subsections briefly outline the major contributions of the dissertation.

1.4.1 A Constraint based Cooperative Spectrum Sensing Technique

In CR communication, spatial diversity of spectrum band affects the individual spectrum sensing performance of secondary users (SUs), which has impact on the detection performance. In general, SUs use Energy Detection (ED) [15] for their local sensing for its low computational and implementation complexity. The Cooperative Spectrum Sensing (CSS) [3,32,33] has proven to be an emerging scheme, which can significantly improve spectrum sensing performance by exploiting the spatial diversity of the SUs. CSS involves additional overheads due to cooperation, which pose as constraints in the effectiveness of CSS scheme. Reporting time and reporting energy are two dominant sources of overhead incurred to share the individual sensing information among the nodes. In this part of the research work, the problem faced in the design of CSS for an ad-hoc CRN have been investigated to incorporate the issues of cooperation overhead in terms of reporting time and reporting energy. A game theory [23, 24] based coalitional model for CSS has been proposed by formulating the game as a non-transferable coalitional game, where the utility/payoff function of the game collects the total revenue to be optimized while considering the cost due to reporting time as constraint. The revenue is collected in terms of average throughput per SU by means of minimizing the probability of false alarm of a coalition. The throughput is measured in terms of transmission rate achieved by each SU in the coalition. The minimization of probability of false alarm of the coalition establishes the fact that with the increase in number of SUs in a coalition the throughput also increases. On the other hand, the cost of reporting energy is minimized by adopting a policy for adaptively selecting the head of a coalition while playing the game. In a coalition, an SU having its position at the minimum average distance from all other SUs is selected as the head. Experimental results show that the average throughput of the SUs increases while reducing the probability of false alarm. It is also observed that taking optimal size of coalition can significantly improve the performance of CSS in terms of throughput. Furthermore, the correct selection of coalition head reduces the overall energy consumption by a coalition. Comparing the performance with non-cooperative sensing, it is found that the CSS model enhances the average throughput of the SUs significantly. The detection performance of the CSS can further be enhanced by taking the location/position of the SUs into consideration, which will allow the SUs to choose the ED sensing threshold adaptively, which is addressed in the next work of this dissertation.

1.4.2 A Threshold Adaptive Cooperative Spectrum Sensing Technique

Most of the CSS techniques found in literature [3, 32, 33] assumes a fixed Energy Detection (ED)[15] threshold and the same probability of false alarm for the secondary users. The accuracy of detection can be improved by taking the ED sensing threshold adaptively depending on the location/position of individual SUs. Spectral diversity plays an important role in sensing performance of an individual

SU, which is dependent on the location or position of the SU. In this part of the research work, the problem of CSS is reinvestigated with both distance adaptive individual ED threshold and probability of false alarm, which address the issues of cooperation overhead. The cooperation overheads considered are the cost incurred due to reporting error and reporting energy involved during sharing of individual sensing information among the SUs. A coalitional game theoretic model is proposed for distributed threshold adaptive CSS (TACSS), by formulating the game as a non-transferable coalitional game for an ad-hoc CRN. The proposed model implements a collaborative framework for spectrum sensing, which partitions the CRN into coalitions using merge and split operations autonomously. This gives rise to an optimization problem, where the game decides either to form or break coalitions to optimize the utilities of coalitions in terms of detection probability. The utilities of coalitions are evaluated taking the cost of coalitions, which is derived considering the distance adaptive individual false alarm and reporting error of the SUs. Experimental results have shown that the proposed model can significantly improve the detection quality and throughput of the SUs compared to the method by Saad *et al.* [34]. Furthermore, the proposed model outperforms the model by Saad *et al.*[34] in terms of probability of false alarm and probability of miss detection. With the enhanced detection performance of this CSS scheme, the next task is to make the efficient use of the detected opportunities for maximizing the capacity rate for SUs, which is addressed in the next work.

1.4.3   A Power Allocation Technique for Underlay Communication

The maximization of capacity rate for SUs while ensuring primary protection in underlay communication is a challenging task, and the power allocation techniques used in legacy wireless networks do not work in such a scenario. This part of the research work investigates the power allocation problem for capacity rate maximization using OFDMA mode of channel access for underlay communication, where a single pair of SUs is assumed. The proposed technique uses a water-filling (WF) [25] based scheme in presence of channel state information (CSI) [13, 26] to maximize the power allocation leveraging the capacity rate optimization for transmission. The algorithm used handles the issue of computational complexity of classical WF to search the water level without resorting to the binary search mechanism. Using theoretical analysis of the classical water-filling framework, the proposed technique directly computes the final solution considering the AIP constraint of primary user. Experimental results show that the proposed algorithm runs much faster compared to the existing classical [25] based algorithms for varying number of sub-channels. The result show that while the interference tolerance power, constrained by the AIP remains within the total transmission power limit of the SU, the proposed algorithm achieves the optimal spectral efficiency in terms of capacity rate. When interference tolerance power value increases close to total transmission power limit of the SU, the capacity rate further improves significantly. For multiuser scenario, the optimization of power allocation for capacity rate maximization is more challenging due to presence of additional constraint as

self-interface among SUs, which is addressed in the next work.

1.4.4 A Distributed Power Allocation Technique for Multiuser Underlay Communication

In multiuser environment, secondary users compete to use the available channels for transmission. A distributed solution is desirable to address both the equilibrium condition and maximization of power allocation, while optimizing the capacity rate. Toward this direction, this part of the research work proposes a potential game theoretic [23, 24] framework in modeling the optimization problem of distributed power allocation (DPA) for multiuser ad-hoc underlay communication scenario. The proposed framework is based on iterative water-filling (IWF) [13, 35] scheme, where the potential function developed incorporates noise variance, and interference from the primary user as well as other SUs. Using the framework improves the capacity rate for underlay communication while the game reaches the Nash Equilibrium (NE), proving the convergence behavior of the game according to the potential game model. Experimental results show that the game reaches the NE, and at the NE state, the capacity rate depends on the number of secondary transmitters and receivers. Compared to the centralized approach, the proposed technique is found to be more robust to accommodate the dynamic behavior such as interference tolerance and adaptive power allocation of the SUs. Providing channel access to SUs on detected available spectrum while protecting PU is done through proper power allocation technique. The sensing overhead and quality of such detected spectrum determines the transmission efficiency. To reduce sensing overhead for underlay mode of channel access, the estimation and modeling of primary user's channel usage pattern to predict channel availability at MAC is required, which is addressed in the next work.

1.4.5 A Channel Usage Model for MAC Layer Sensing

Learning about the channel usage pattern of PUs to predict future channel availability can help alleviate the sensing overhead problem of proactive sensing [30] at MAC layer. In this part of the work, two important issues of MAC-layer sensing have been investigated for underlay mode CRNs. These are - i) how to estimate and model the channel usage pattern of PUs, while tolerating interference from SUs, and ii) how to use learnt channel usage patterns for discovery of opportunities. Accordingly, a Hidden Markov Model (HMM) [31] based channel usage pattern of PUs is proposed for use by the SUs to predict the spectrum opportunity. The proposed model uses estimated IPC [36, 37] in determining the effect of interference due to the presence of SUs to protect the PUs from harmful interference. Using the model, a formulation deriving the availability metric (AM) for a license channel is developed, which helps in deciding and selecting the best channel by an SU for its transmission needs. Experimental results show that the trained HMMs are statistically stable and accurate, which can be used for predicting future channel availability, provided the same IPC condition prevails for a

certain period. It is also observed that the availability metric (AM) of the channel sequences generated by the trained HMMs are effective in selecting a suitable channel for transmission. Furthermore, using the proposed channel usage model a distributed medium access control protocol for data dissemination (DMDD) is proposed, which can be used for underlay mode data dissemination by SUs.

1.5   Dissertation Organization

The rest of the dissertation is organized as follows.

- Before going to discuss our contributions, a state of the art literature survey on spectrum sensing, cooperative spectrum sensing, power allocation and MAC layer sensing in cognitive radio networks is presented in **Chapter 2**.

- A coalitional game theoretic framework for cooperative spectrum sensing is presented in **Chapter 3**. It discusses the problem of minimizing the cooperation overhead in terms of reporting time and reporting energy to improve the sensing performance.

- A coalitional game theoretic modeling and framework proposed for distributed threshold adaptive cooperative spectrum sensing is presented in **Chapter 4**. It addresses handling of spectral diversity of the secondary users with incorporation of cooperation constraint due to reporting error and reporting energy.

- **Chapter 5** presents a power allocation technique for underlay communication using OFDMA mode channel access. It describes a water-filling (WF) based scheme to maximize the power allocation leveraging the capacity rate optimization.

- A potential game theoretic framework is proposed for distributed power allocation (DPA) in multiuser underlay communication scenario in **Chapter 6**. It describes how an iterative water-filling (IWF) based scheme can be adopted to maximize the power allocation while maintaining the interference tolerance limit of primary user.

- A Hidden Markov Model (HMM) based model to estimate and model the channel usage pattern of primary users is presented in **Chapter 7**. It discusses how the model helps to discover opportunities in the licensed channel while tolerating the interference power constraint (IPC) for MAC level policy.

- **Chapter 8** concludes the dissertation by summarizing the overall contribution and identifies some future directions of research in this area.
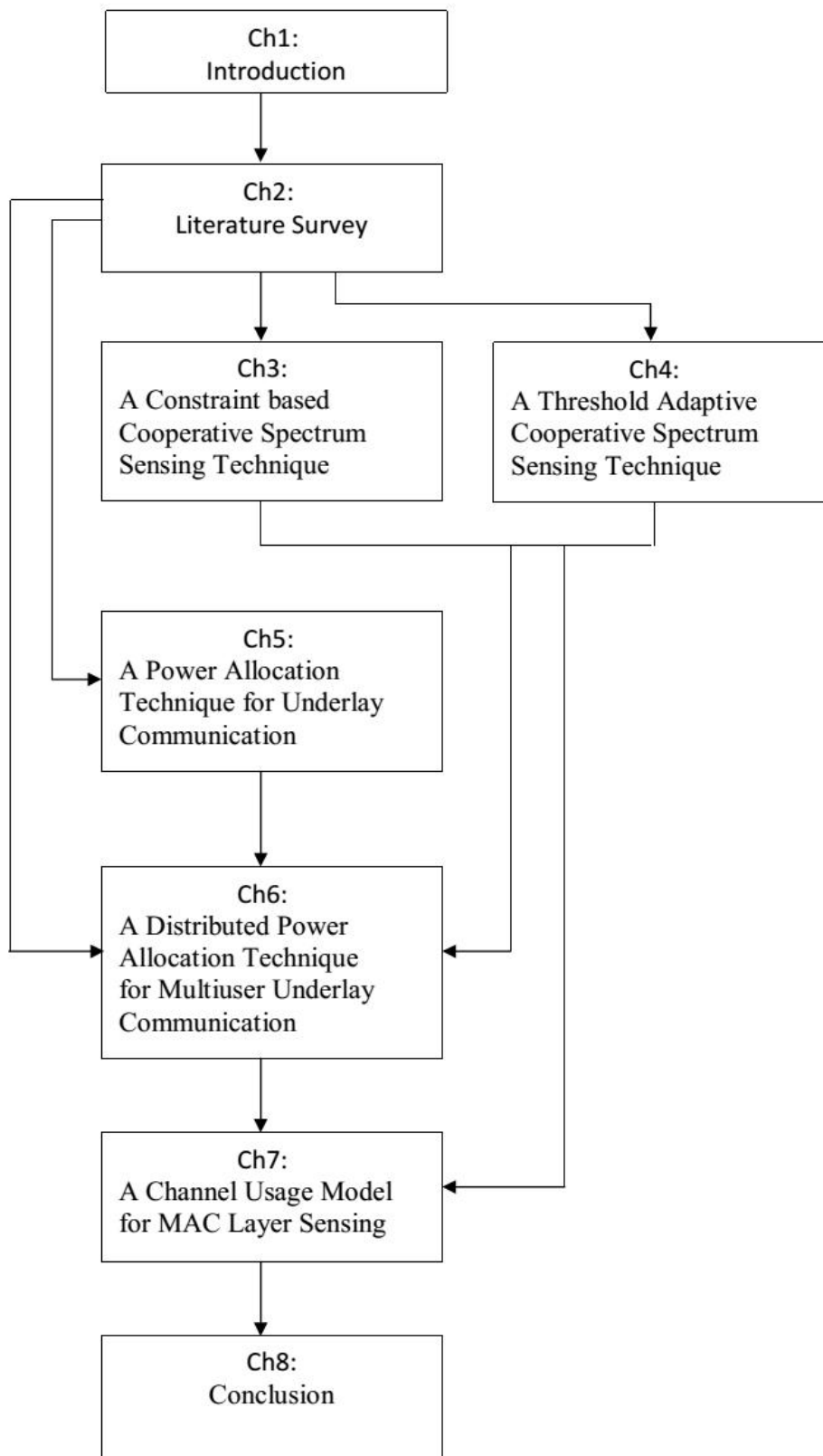
Figure 1-5: Relation of chapters demonstrating the contributions