Chapter 1

Introduction

The wireless devices has experienced an unprecedented surge in recent decades, owing to the rapid advances in technology [41]. The widespread utilization of wireless devices has resulted in a need for large radio spectrum bands to accommodate a wide range of bandwidth-intensive services. According to reports [1, 5], the number of mobile devices will reach 13.1 billion by 2023 across the globe, and the total global mobile data traffic (excluding traffic generated by fixed wireless access) is estimated to reach around 288EB per month by 2027. Such an exponential increase in mobile devices/services and the escalating need for bandwidth have resulted in a scarcity of radio resources. The conventional fixed allocation strategy for assigning radio spectrum to existing wireless services, as mentioned in [49], has resulted in shortcomings within current frequency bands, which cannot meet the growing demand for future wireless applications. This scarcity of spectrum poses a significant challenge, impeding the adoption and advancement of next-generation wireless technologies, including 5G cellular communications, Internet of Things (IoT), vehicular communications, virtual reality, and augmented reality.

The traditional fixed spectrum allocation policy, employed by government-authorized bodies assigns licensed bands to service providers based on geographical regions. However, this approach has a significant drawback [49]: if the licensed users fail to utilize their assigned bands, those bands remain idle and unavailable for use by other users, such as unlicensed users. Consequently, a substantial portion of the licensed spectrum is underutilized both spatially and temporally, leading to inefficiencies in spectrum usage. An investigation by the Federal Communications Commission (FCC) [36, 37] reveals that a considerable proportion of the allocated spectrum in the United States remains unused by licensed users. This inefficiency results in the emergence of spectrum holes or white spaces, which

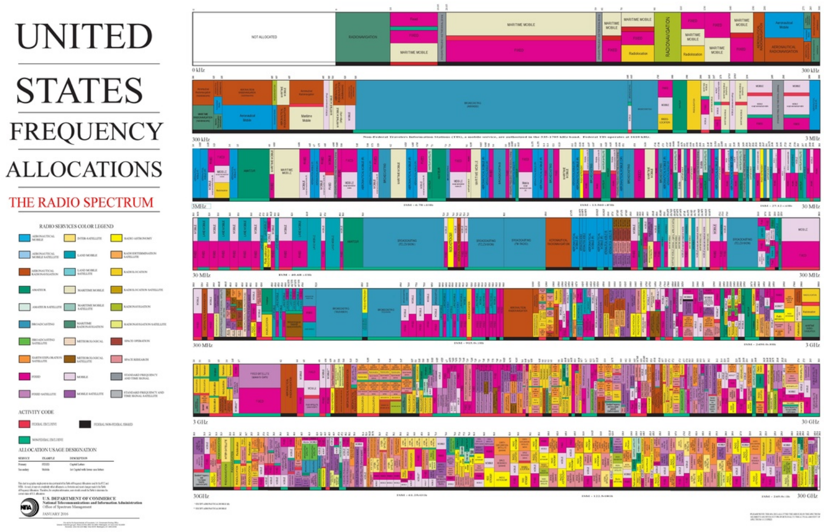

Figure 1-1: Frequency allocation chart for United State [36]

are unused portions of the spectrum that could be effectively utilized for future wireless services. As shown in Figure 1-1, the frequency allocation chart for the United States [36, 38] illustrates that, in some locations or at certain times of day, up to 70% of the allocated spectrum remains idle. On the other hand, the limited size of spectrum bands allocated for unlicensed users results in overcrowding, contributing to spectrum scarcity. This indicates the need for a flexible spectrum allocation strategy to address this observed disparity between spectrum allocation and spectrum utilization. Dynamic spectrum access (DSA), introduced as a solution to radio spectrum scarcity and the limitations of fixed spectrum allocation policies [8, 129], allows unlicensed users to dynamically access licensed bands from legacy spectrum holders either on a negotiated or an opportunistic basis without causing harmful interference to licensed users. Cognitive radio (CR), enabled by Software Defined Radio (SDR) technology [84], plays a crucial role in implementing DSA.

1.1 Cognitive Radio

The term Cognitive Radio (CR) was coined by Joseph Mitola-III [84] in late 1990s. CR is a context-aware intelligent radio, which can learn from the surrounding communication environment and can adapt/change its operative parameters as per requirements. The two primary characteristics of CR which makes it a key technology for DSA are: cognitive capability and reconfigurability [49], [7], [84]. Cognitive capability refers to the capacity of a device (or a node) empowered

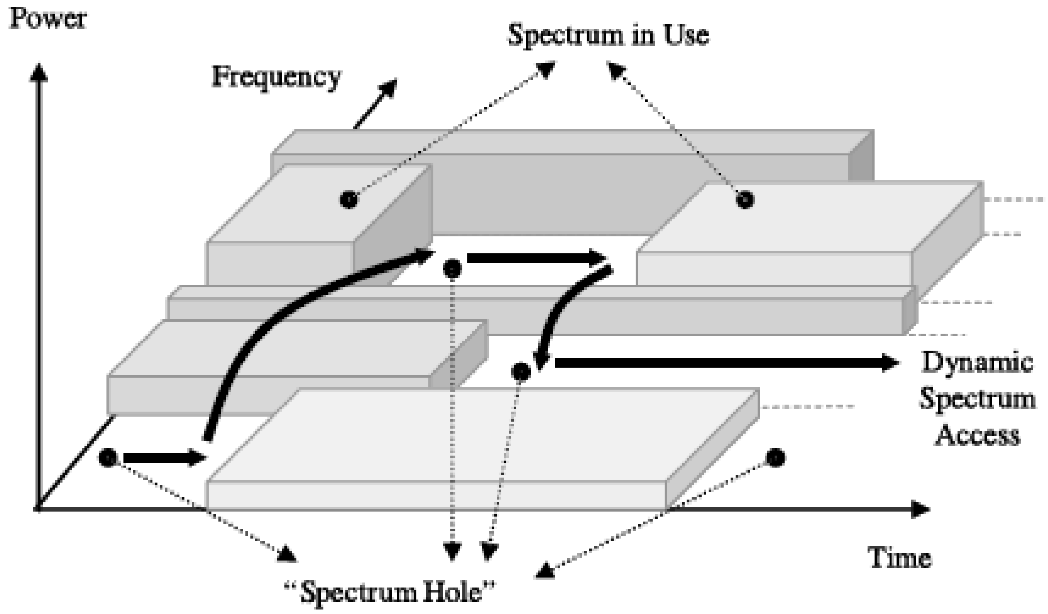

Figure 1-2: Opportunistic Use of Spectrum Holes [7]

with cognitive radio technology to effectively sense and acquire information from its immediate radio environment. Reconfigurability refers to the transceiver's capacity to dynamically adjust the parameters of the transmitter according to changes in the surrounding radio environment. Thus, a CR enabled node makes a flexible use of radio spectrum by sensing the network environment and dynamically adapt/reconfigure network parameters. Figure 1-2 illustrates the opportunistic use of spectrum holes by dynamically reconfiguring the parameters.

1.1.1 Cognitive Radio Network Architecture

Cognitive radio networks (CRNs) comprise two user types: primary users (PUs) and secondary users (SUs), each with distinct usage rights. PUs hold licenses granting exclusive access to fixed spectrum bands, while SUs opportunistically utilize unoccupied spectrum or negotiate with PUs for transmission rights. The field of CRN research focuses on addressing spectrum allocation and sharing challenges. Numerous spectrum sharing models have been proposed, emphasizing collaboration between PUs and SUs. This thesis specifically investigates the relay-based collaboration model within CRNs. As shown in the Figure 1-3 [8], the major components of a cognitive radio network (CRN) can be categorised into two parts, namely primary network and secondary network.

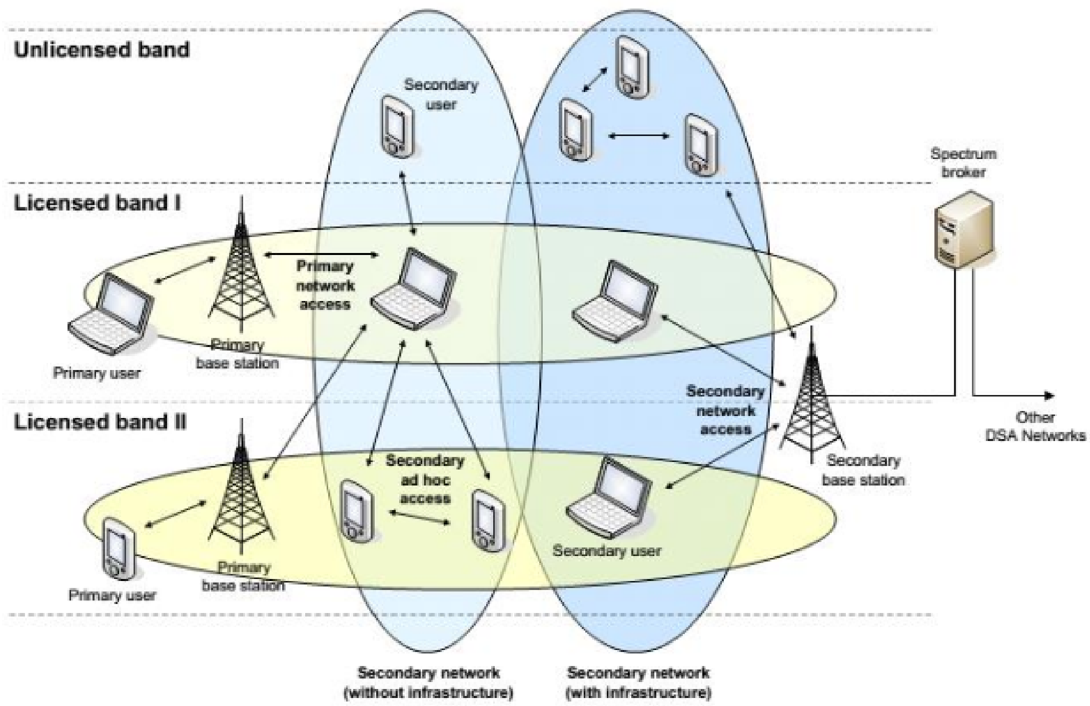

Figure 1-3: Cognitive Radio Network Architecture [8], [84]

- Primary network: It refers to an existing infrastructure network in which only primary or licensed users have access to a particular frequency band. The primary base station exercises control over the activities conducted by primary users (PUs). Primary networks encompass various types of communication systems, such as GSM cellphone networks, military networks and TV broadcast networks etc.

- Secondary network: A secondary network is characterized by the presence of unlicensed or secondary users (SUs) that operate inside a communication framework that can be either infrastructure-based or infrastructure-less. However, it is important to note that these users do not possess the necessary license to operate within a specific permitted frequency band. In order to effectively utilize the licensed frequency band with primary networks, SUs must be CR-enabled. A secondary network that relies on infrastructure is characterized by the presence of a central entity, such as a cognitive radio (CR) base station. In contrast, an infrastructure-less network refers to the establishment of an ad-hoc network in which a secondary user (SU) is able to engage in communication with other SUs via an ad-hoc connection that operates on both licensed and unlicensed spectrum bands.

1.1.2 Cognitive Radio Functionalities

In order to effectively identify and strategically utilize the idle licensed spectrum bands without causing harmful interference to PUs, CR enabled nodes are equipped with four primary functionalities: spectrum sensing, spectrum decision, spectrum sharing, and mobility [8], [6].

- Spectrum sensing: During sensing, SUs have the capability to identify and detect the unused portion of the licensed spectrum and continuously monitor the presence of PU within that portion of spectrum.
- Spectrum decision: During spectrum decision, SUs select the best available spectrum to meet user communication requirements.
- Spectrum sharing: During spectrum sharing, spectrum bands are managed and distributed amongst SUs with an aim to enhance spectrum utilization and ensure fair access to spectrum resources among SUs.
- Spectrum mobility: During spectrum mobility, SUs maintain seamless communication requirement and vacate the currently utilized channel in the event that a PU is spotted operating on said channel.

In summary, cognitive radio (CR) technology revolutionizes spectrum management, optimizing its utilization. Within CR networks, fair distribution of spectrum resources among coexisting secondary users (SUs) is ensured, addressing the challenge of spectrum sharing effectively. For instance, in IEEE 802.22 Wireless Regional Area Networks (WRANs), CR facilitates wireless internet access by coordinating between television users and CR users [29, 107]. Similarly, CR technology extends to critical services such as e-health [92], intelligent transportation systems like Vehicular Ad-hoc Networks (VANET)[104] , emergency services [91], and military applications [109].

1.1.3 Cognitive Radio Access Paradigm

In spectrum sharing, three main access paradigms are employed in cognitive radio networks (CRNs): interweave, underlay, and overlay [18, 46].

- Interweave: This paradigm enables secondary users (SUs) to sense licensed spectrum and opportunistically utilize spectrum holes for their communication without disrupting primary users' (PUs) transmissions.

- Underlay: In the underlay paradigm, SUs can operate simultaneously on a specific spectrum band with PUs, as long as the interference caused by SUs to PUs remains below a predefined threshold [69].
- Overlay: The overlay paradigm allows SUs to share a particular licensed spectrum concurrently with PUs. SUs in this paradigm assist PUs' transmissions through cooperative communication techniques like advanced coding [69] or cooperative relaying [70], resulting in mutual benefits for both PUs and SUs. This thesis focuses on investigating this paradigm.

In the interweave paradigm, primary users (PUs) are unaware of the presence of secondary users (SUs). SUs can access the PU spectrum only if their secondary transmissions do not disrupt PU operations, a condition typically achieved through spectrum sensing. Consequently, SUs operate transparently to PUs, and their performance is heavily influenced by both spectrum sensing errors and PU traffic patterns. In contrast, PUs are aware of the presence of SUs in both the underlay and overlay paradigms. In these paradigms, SUs utilize the frequency bands allocated to PUs without considering PU traffic patterns. However, the underlay paradigm poses a notable concern regarding potential performance degradation for SUs due to power constraints, especially when SU transmitters are close to PU receivers [123]. Conversely, the overlay paradigm imposes less stringent power constraints on SUs to minimize interference with PUs [46]. While PUs have priority access to the licensed band and can improve their performance by charging SUs for spectrum use, they do not interfere with SUs during secondary transmission in the overlay paradigm.

In wireless networks, channel fading often leads to a significant decline in direct transmission quality between primary transmitters and receivers, consequently impairing the performance of primary users (PUs) in terms of data rate and outage probability. To mitigate this degradation, cooperative communication has emerged as a promising solution [24, 89]. By leveraging users with better channel conditions as cooperative relays, cooperative diversity can be exploited to enhance transmission rates and reduce outage probabilities [70]. In scenarios where PUs face unfavorable locations or high traffic loads, leaving them with limited idle time for data forwarding, selecting suitable secondary users (SUs) as cooperative relays becomes advantageous for improving primary transmission [72]. Augmenting the PU's transmission rate to accommodate primary traffic effectively shortens the transmission duration, allowing SUs to access the PU band and transfer additional data in the secondary system [26]. Through strategic collaboration, PUs and SUs can advance their respective objectives, leading to mutually beneficial outcomes. This collaborative approach, known as cooperative spectrum sharing (CSS), is the focus of this thesis, particularly exploring CSS mechanisms within the overlay paradigm and developing CSS models to address various challenges in CRNs.

1.2 Cooperative Spectrum Sharing in Cognitive Radio Networks

Cooperative spectrum sharing and communication among users has emerged as a powerful technique for the overlay paradigm of CRN, due to its ability to exploit user diversity and provide high reliability and capacity gain to PUs as well for SUs [26], [117]. This is achieved by the use of intermediate relay nodes, which are used to aid transmission between the source and destination nodes [57]. The source nodes or PUs hire suitable relays or SUs to forward primary signal towards intended destination in exchange of transmission opportunities for SUs over PU bands to fulfill secondary transmission. The two most common cooperation protocols in relay based CSS are Decode and Forward (DF) and Amplify and Forward (AF) [73], [124]. In DF technique, the relay node always decodes, re-encodes and transmits the received source signal towards the destination. Whereas, AF is a simple technique in which the relay node amplifies the received signal and forwards it to the destination. Compared to an AF relaying technique, the complexity of a DF one is significantly higher due to its full processing capability and it also requires a sophisticated media access control layer, which is unnecessary in the AF protocol [124].

On the other hand, in CSS the allowance of PU's spectrum resources to SUs is leased in exchange for different types of compensation, such as money or resource [40]. In the money compensation CSS, the PUs grant access opportunities to the SUs in exchange for monetary benefits. Price theory [82], including auction theory and bargain theory, together with market theory [62, 105, 115] are extensively utilized in the context of CSS. The strategy of money-compensation CSS has proven to be highly beneficial, particularly in situations where PUs possess temporarily unused (or ideal) resources. When considering the modeling of this particular type, it is important to note that the sharing can occur across varying durations, ranging from hours to days, and in some cases, even extending to months. Nevertheless, the money-compensation model requires a trustworthy billing system that enables both PUs and SUs to engage in spectrum trading according to their genuine individual requirements, and designing such a system poses practical challenges. Furthermore, in situations where the PU channels experience degradation, the PUs face significant challenges in having extra resources available for sale, since their own transmission demands are hard to be satisfied. In this particular scenario, the resource compensation model emerges as a more favorable option, in which PUs have the opportunity to enhance their performance aided by SUs in exchange for access to spectrum bands [40].

1.2.1 Resource Compensation based CSS

In resource compensation-based CSS, PUs and SUs work cooperatively and exchange relatively scarce spectrum resources during cooperative communication, thereby enhancing both cooperative and individual performances by mutually aiding each other [75]. Such a collaborative method involving PUs and SUs is commonly referred to as relay-based cooperative spectrum sharing in CRNs. In this setup, PUs strategically select appropriate SUs to serve as relay nodes for delivering primary services to designated recipients. This strategy effectively extends the coverage range and capacity of both primary and secondary connections by bolstering the signal strength of each link [102, 125]. Mainly two types of spectrum resources viz. channel bandwidth and channel access time are shared among the cooperative users as shown in following figure. In the context of bandwidth sharing (Figure 1-4(a)), SU relays PU's signal over a specific portion of available bandwidth for a predetermined duration, while simultaneously access the PU spectrum band to transmit its own signal by utilizing DF relaying technique. On the other hand, in time sharing (Figure 1-4(b)), PU divides the allotted time slot into multiple fractions and allocates certain portion for cooperative communication while the remaining portion is allocated for SU's transmission.

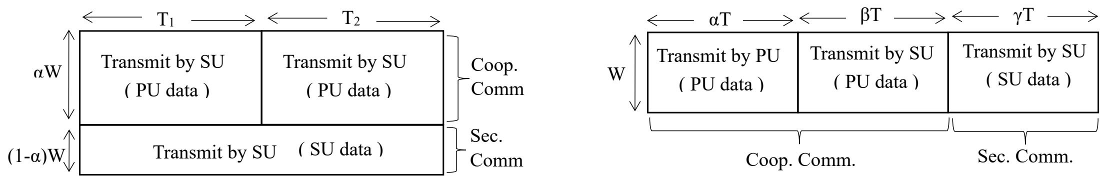

Figure 1-4: (a) Bandwidth Sharing (b) Time Sharing

In addition to bandwidth and access time, the operational efficiency of wireless devices is significantly dependent on the energy supply (battery) that accompanies them. Since, wireless devices are equipped with fixed energy supply that have limited operation time, it becomes imperative to harvest energy from an external source in order to extend the lifespan of wireless devices [46, 63]. A recent advancement in wireless technology has showcased the potential for concurrently extracting energy and conducting information processing from surrounding radio frequency signals. The technology of simultaneous wireless information and power transfer (SWIPT) has gained significant interest because to its ability to simultaneously utilize radio frequency (RF) signals for both information transmission and power transfer and thus potentially offers great convenience to mobile users [132]. Integrating the notion of CR with SWIPT technology offers an effective solution for energy harvesting in energy-constrained CRN.

1.2.2 Energy Harvesting in CSS using SWIPT technology

A SWIPT receiver can effectively decode information and harvest energy from the RF signal with the aid of suitable circuitry. The receiver design of SWIPT technology is modeled based on two commonly used techniques, namely time switching (TS) and power splitting (PS), which are derived from the notion of dynamic power splitting (DPS) [126, 132]. Upon the reception of RF signal, the TS technique allows the receiver in SWIPT systems to switch between information decoding and energy harvesting phases. However, in the PS approach, the received RF signal is divided into two separate power streams, each serving the dual purpose of energy harvesting and information decoding. With the aid of such SWIPT technology in each energy constraint SU, information decoding and energy harvesting is obtained at once from the received primary signal during cooperative communication with PU. Such integration of SWIPT technology with energy constraint SUs addresses the challenges of energy scarcity in CR nodes, hence extending their operational lifespan and provides energy efficient communication [67].

In the current era of 5G technology, relay-based CSS presents significant opportunities for expanding coverage in rural and remote areas where cellular signals frequently encounter challenges from distance and physical barriers [9, 51, 110]. By enabling SUs (such as mobile devices) to utilize unused spectrum allocated to PUs (such as TV broadcasters), relay-based CSS has the potential to amplify signals, substantially extending coverage, particularly in valleys, mountainous terrain, or thinly populated areas. Conversely, in a densely populated region, relay-based CSS helps to mitigate interference and improve signal quality, leading to better call quality, faster data speeds, reduced dropped calls, and ultimately enhanced quality of service.

Similarly, within contexts like industrial automation, smart cities, and sensor networks, relay-based CSS facilitates the direct exchange of content between adjacent, low-powered devices designed for short-range communication in D2D scenarios [95]. Additionally, energy-constrained IoT devices, such as wearables or smart home sensors, can harvest energy from their surroundings (e.g., radio waves, vibrations) while sharing spectrum with other devices. This enables them to transmit data without the need for constant battery charging, fostering more sustainable and scalable IoT networks [13, 64].

Literature study has revealed that although several approaches were proposed over the years for modeling relay-based cooperative spectrum sharing and energy harvesting in CRN, these models either have limitations or have ignored some key issues and challenges that are interesting and important to address.

1.3 Issues and Challenges in modelling Cooperative Spectrum Sharing

Some of the important issues and challenges identified for modeling cooperative spectrum sharing and energy efficient communication among PUs and SUs are listed below.

- In overlay CRN scenarios, optimal cooperative spectrum sharing requires effective collaboration between primary users (PUs) and secondary users (SUs). This involves dynamically selecting the most suitable SUs for cooperation. However, if the utility design does not consider cooperative gain, penalty, and energy overhead, the selection of SUs may not be optimal across different network setups and application requirements. Furthermore, in an overlay access paradigm, the utility design must account for the benefits of both PUs and SUs.

- Mapping the maximum number of feasible SUs to suitable PUs for cooperative communication in an overlay CRN scenario (where the number of PUs is less than the number of SUs) is challenging due to the higher priority or 'legacy rights' of PUs over their licensed band. This requires a cooperation strategy among SUs to achieve optimal utility of the secondary network. Cooperation among SUs allows all feasible SUs to participate in the cooperative communication process, maximizing spectrum utilization and enhancing secondary network performance.

- Prolonging network lifetime for efficient secondary transmissions with energy-constrained SUs is challenging, as SUs must invest significant energy during cooperative communication in overlay CRNs. This energy is needed both to relay primary information and to complete secondary transmissions.

- Limited attention has been given to jointly optimizing the TS factor and PS factor in majority of the energy harvesting models to maximize the energy harvesting rate at ST. Addressing multiple resource allocation elements within a single optimization problem is challenging due to the need of balancing trade-offs among the various components involved.

1.4 Motivation of the Research

Cooperative spectrum sharing (CSS) within overlay spectrum access mode has emerged as a promising approach to improving spectrum efficiency by fostering collaboration between PUs and SUs. However, such collaborative approaches pose intriguing challenges and opportunities. Two major hurdles involve establishing effective collaborations (or mappings) between suitable SUs and appropriate PUs for cooperative communication and addressing the energy constraints faced by energy-constrained SUs. To advance further in this domain, it is essential to integrate cooperation strategies among SUs and incorporate energy harvesting techniques during cooperative communication. By implementing cooperative strategies among SUs, we can optimize spectrum utilization and extend collaborative communication to all eligible SUs, thereby enhancing the performance of each SU as well as the overall secondary network. Moreover, emphasizing the simultaneous optimization of time-switching and power-splitting parameters during energy harvesting from the received primary signal enhances the energy harvesting rate for SUs, ensuring energy-efficient cooperative and secondary communication. These challenges and solutions motivate further research in the dynamic and promising field of cognitive radio networks.

1.5 Research Objective

The research reported in the thesis aims at identifying issues and challenges in cooperative spectrum sharing and propose effective solutions to make cognitive radio communication spectral efficient, energy-efficient and utility driven.

The broad objectives of this research work are to develop techniques for -

- Optimal allocation of PU spectrum resources among cooperative partners within the Cooperative Spectrum Sharing (CSS) framework in single-PU, multi-SUs overlay CRN scenario. This objective aims to enhance the effectiveness of the primary network in terms of utility enhancement and meet the Quality of Service (QoS) requirements of the secondary network.

- Optimal allocation of PU's transmission time among cooperative partners within the one-to-one Cooperative Spectrum Sharing and Communication framework in multi-PUs, multi-SUs overlay CRN scenario. This objective seeks to achieve optimal matching among PUs, stable matching among SUs and enhance the efficacy of each SU involved in the cooperative communication process.

- Allocation of optimal fractions of PU's transmission time during cooperative and secondary communication within the many-to-one Cooperative Spectrum Sharing and Communication framework in multi-PUs, multi-SUs overlay CRN scenario. The aim is to achieve stable matching among PUs, optimal matching among SUs and enhance the efficacy of each SU as well as the overall secondary network.

- Optimal allocation of PU's transmission time and power, and SU's harvested power within the energy harvesting CSS framework in multi-PUs, multi-SUs overlay CRN scenario. This objective is geared towards maximizing the rate of harvested energy at each SU and improving the efficacy of the overall secondary network.

Keeping the above objectives in mind, the research works done in this thesis are outlined in the next section (Thesis Contributions).

1.6 Thesis Contributions

Efficient cooperative spectrum sharing and energy harvesting models are highly desirable to facilitate better spectrum utilization while enhancing the attainable utility of secondary networks and providing energy efficient communication among the energy constraint SUs. This thesis addresses some of the challenges in CSS and energy harvesting in CRNs. The main contributions of the thesis can be divided into four parts. The following subsections briefly outline the major contributions of the thesis.

1.6.1 A utility driven bandwidth and time allocation CSS scheme for single-PU, multi-SUs overlay CRNs

The design objective of this approach is to efficiently allocate PU resources (either bandwidth or access time) for cooperative communication, enhancing the utility of PU while meeting the targeted transmission constraints of cooperative partner SU. We consider a CRN scenario comprising a single PU and N SUs, where the PU selects the most suitable SU as its partner for successful cooperative communication within its licensed band. Depending on the targeted service type and PU channel patterns, the PU adopts either bandwidth sharing with decode and forward relaying or time division sharing with amplify and forward relaying with the selected SU for cooperative communication. To demonstrate the effectiveness and applicability of each resource sharing scheme, we conduct a case study considering various PU service scenarios, confirming the validity of both the proposed schemes. The utility function of the PU is designed to strike a balance between the cooperative gain obtained during PU-SU cooperation and the energy consumption incurred by the PU, while also rewarding the SU with transmission opportunities for secondary transmission. Given the computational intractability of optimal resource allocation during cooperative communication due to its NP-Hard nature, we propose an iterative algorithm based on heuristic methods to achieve sub-optimal solutions for resource allocation. To assess the efficacy of both bandwidth and time sharing schemes, we compare their performances with the greedy method, random selection method, and non-cooperation method. Performance evaluation metrics include the obtained utility of the PU, energy consumption of the PU, and the rewards associated with partner SU. Experimental results demonstrate that both proposed schemes effectively allocate near-optimal resources during CSS among cooperative PU-SU pairs, outperforming all considered approaches in terms of providing maximum possible utility to the PU while satisfying the reward constraints and QoS requirement of partner SU.

1.6.2 A one-to-one mapping for multiple resource allocation CSS scheme in multi-PUs, multi-SUs overlay CRNs

The design goal of this CSS scheme is to allocate optimal fractions of PU transmission time for cooperative communication and secondary transmission to enhance the performance of both PUs and SUs in a multi-PUs multi-SUs CRN scenario. Each PU is paired with a suitable SU for resource sharing and cooperative communication. The problem of allocating optimal fractions of transmission time by the SU is formulated to maintain a balanced trade-offs amongst maximum throughput obtained by the SU, penalty incurred due to increased SU expense rate, and energy overhead due to cooperation. A proof is provided to illustrate the computational complexity of the problem, and a heuristic solution is proposed to solve the formulated optimization problem in polynomial time. The performance of the proposed solution is evaluated by comparing it with numerical (benchmark) and greedy methods in terms of the average utility of SUs and the optimal allocation of PU transmission time. The proposed solution achieves 96% accuracy compared to optimal utility and 97% accuracy compared to optimal allocation of PU transmission time. Additionally, the proposed scheme outperforms the greedy method in both aspects. To analyze the relationship between mapped PU-SU partners in the established one-to-one mapping, the concept of matching theory is applied. In the best case scenario, all mapped SUs are paired with preferred PUs and achieve optimal mapping with the set of PUs, while in the worst case, stable matching among the set of SUs is observed. However, PUs are always able to establish optimal matching during the entire cooperative communication phase.

1.6.3 A many-to-one mapping for multiple resource allocation CSS scheme in multi-PUs, multi-SUs overlay CRNs

The design goal of this approach is to address the limitations of the previous one-to-one mapping approach. This is achieved by modeling a many-to-one cooperative resource-sharing framework to involve the maximum feasible SUs in cooperative communication and enhance the performance of the secondary network. Considering a CRN with multi-PUs and multi-SUs, all SUs adopt a cooperative strategy to maximize both individual and collective utility. SUs form favorable groups, or tuples, where each tuple comprises SUs with the same PU preference. This ensures that each SU has the opportunity to engage in cooperative communication with its preferred PU, thereby increasing individual SU utility and the overall utility of cooperative SUs. To analyze the relationship among the SUs and PUs involved in cooperative communication, the concept of group stable matching is applied to propose a stable many-to-one matching solution. The effectiveness of this solution is evaluated for different equilibrium points of matching theory under various matching market scenarios. In an open matching market scenario, the proposed solution converges to optimal equilibrium for the cooperative SUs, allowing each SU to maximize its utility during cooperative communication. In a partial open market scenario, the proposed solution converges to stable equilibrium for the cooperative SUs, maximizing the gross utility of each tuple. Theoretical proofs are provided for the convergence of stability and optimality of the resultant equilibrium. To assess the effectiveness of the proposed cooperation scheme, a performance evaluation is conducted and results are compared with the previous one-to-one matching and similar existing approaches. Experimental results reveal that the proposed solution outperforms all the considered approaches in terms of average utility of SUs, average satisfaction, percentage of participation of SUs and throughput fairness index of SUs. However, the one-to-one matching approach outperforms the proposed solution in terms of average utility of PU.

1.6.4 A joint power-and-time allocation CSS scheme for energy harvesting multi-PUs, multi-SUs overlay CRNs

The design objective of this approach is to efficiently allocate optimal fractions of transmission time and power during CSS, aiming to maximize both the individual utility of each energy-constrained SU and the overall utility of the secondary network. In a multi-PUs and multi-SUs CRN scenario, each energy-constrained SU harvests energy from the received PU signal during cooperative communication and optimally allocates the harvested power for both cooperative and secondary communication. To achieve this, two optimization problems are formulated: one to maximize the harvested energy at the SU, and the other to maximize the SU's utility. These optimization problems balance various factors, including the harvested energy, the PU's decoding rate constraint, the utility from optimal allocation of transmission time and harvested power, and the energy overhead from cooperation. Due to the nonlinear and NP-Hard nature of these problems, iterative heuristic solutions based on greedy algorithms are proposed to achieve near-optimal results in polynomial time. The resultant solutions for harvested energy and maximum achievable utility of SU achieve high correctness rates of 97.7% and 98.5%, respectively, when compared with optimal results. Moreover, the proposed solution outperforms existing TS [132] and PS [93] schemes. To accommodate all feasible SUs during cooperative communication, we model a hedonic clustering game-based many-to-one cooperative framework. Favorable SUs form stable clusters and are mapped to preferred PUs for resource sharing and cooperative communication. Within each cluster, priority is assigned for accessing the mapped PU's resources. The mappings between PUs and SUs are established based on the stability criteria of the hedonic game. Simulations based experiments evaluate the proposed cooperation scheme's performance in terms of the average utility of the secondary network, the average utility of the primary network, the average satisfaction of the SUs, and the percentage of SU participation. Experimental results show that the proposed cooperation model outperforms the non-cooperation scheme across all evaluated parameters.

1.7 Thesis Organization

The rest of the thesis is organized as follows.

- Before going to discuss about the contributions, a literature review on spectrum sharing, cooperative spectrum sharing, matching theory in cooperative spectrum sharing, and energy harvesting in CRN using SWIPT technology is presented in **Chapter 2**. This chapter will provide adequate background for the thesis contributions.

- A utility driven bandwidth and time allocation CSS scheme for single-PU multi-SUs CRN scenario is presented in **Chapter 3**. Starting with the system model, we discuss problem formulation, proposed scheme, and simulation-based performance evaluation.

- **Chapter 4** is about the formation of stable one-to-one matching based CSS framework for cooperative PU-SU pair in a multi-PUs multi-SUs CRN scenario to enhance the utility of each SU involved in the cooperation process.

We present the system model, proposed scheme, and simulation-based performance evaluation.

- In **Chapter 5** of this thesis, we discuss the cooperative strategy adopted by the SUs to form a many-to-one matching based CSS framework to maximize the individual utility of SUs as well the gross utility of all cooperative SUs. We include the system model, proposed scheme, and simulation-based performance evaluation.
- In **Chapter 6**, a joint power and time allocation model for energy constrained SUs to yield energy efficient communication is developed in this thesis. We discuss system model, proposed scheme, and simulation-based performance evaluation.
- Finally, **Chapter 7** summarizes the overall contributions of this thesis and identifies some future research directions in this domain of research.