Chapter 2

Literature Survey

To gain a comprehensive understanding of the research challenges and the proposed solutions, we delve into key background topics including spectrum sharing, cooperative spectrum sharing, matching theory in cooperative spectrum sharing, and energy harvesting in Cognitive Radio Networks (CRNs) utilizing SWIPT (Simultaneous Wireless Information and Power Transfer) technology. This chapter aims to furnish sufficient context for elucidating the contributions made in this thesis.

2.1 Introduction

Cognitive Radio (CR) is acknowledged as a crucial technology facilitating the implementation of dynamic spectrum access (DSA) in radio communication, offering a solution to the challenge of spectrum scarcity [129]. DSA enables unlicensed users (SUs) to dynamically access the unused segments of licensed bands from legacy spectrum holders, either through negotiation or opportunistically, without causing harmful interference to licensed users (PUs) [130]. Inspired by the principles of DSA, spectrum sharing works towards efficiently distributing available licensed spectrum bands among coexisting SUs, with the goal of maximizing overall spectrum utilization [128]. This thesis contributes to the spectrum sharing domain by introducing various cooperative spectrum sharing schemes among PUs and SUs, aiming to improve both spectral and energy efficiency [81]. In this context, this chapter provides background information on spectrum sharing and cooperative spectrum sharing (CSS) in Cognitive Radio Networks (CRNs), along with a comprehensive survey of various works conducted in these areas. The rest of this chapter is organized as follows.

In Section 2.2, we discuss the various classifications of spectrum sharing commonly used by researchers worldwide. Section 2.3 details cooperative spectrum sensing (CSS), including relay-based CSS, its types, cooperation models, and a comprehensive survey of related works in CRNs. Section 2.4 provides a background on energy efficiency in CSS, covering energy harvesting and surveying various studies on energy-efficient CSS. Finally, Section 2.5 concludes this chapter.

2.2 Spectrum Sharing in CRN

Cognitive radio stands out as an intelligent wireless communication technology designed to leverage unused spectrum bands to meet the escalating spectrum requirements of unlicensed users [7]. This demand is particularly significant with the continuous increase in the wireless user population. In order to optimize network performance by making use of these available spectrum bands, spectrum sharing plays a crucial role by efficiently distributing or sharing spectrum resources among coexisting users [98]. Current solutions for spectrum sharing in CRNs can be broadly categorized based on three key factors [90, 120]: network architecture, user's interacting behavior, and user's spectrum access paradigm, as shown in Figure 2-1. The first classification for spectrum sharing techniques in CRNs based on the **network architecture** is described as follows [8]:

- *Centralized approach:* In this approach, a centralized entity manages the distribution of spectrum bands by collecting spectrum opportunities from various SUs and subsequently coordinating the allocation of spectrum bands among these SUs.
- *Distributed approach:* In this approach, there is no central entity tasked with overseeing spectrum sharing. Instead, each SU, whether individually or in collaboration with other SUs, determines the allocation strategy by assessing the local spectrum availability.

The second classification for spectrum sharing techniques in CRN is based on the **user's interactions** while accessing spectrum bands is described as follows [7, 8]:

- *Non-cooperative approach:* In this approach, SUs engage in competition, exhibiting selfish behavior as they strive to secure access rights to the spectrum

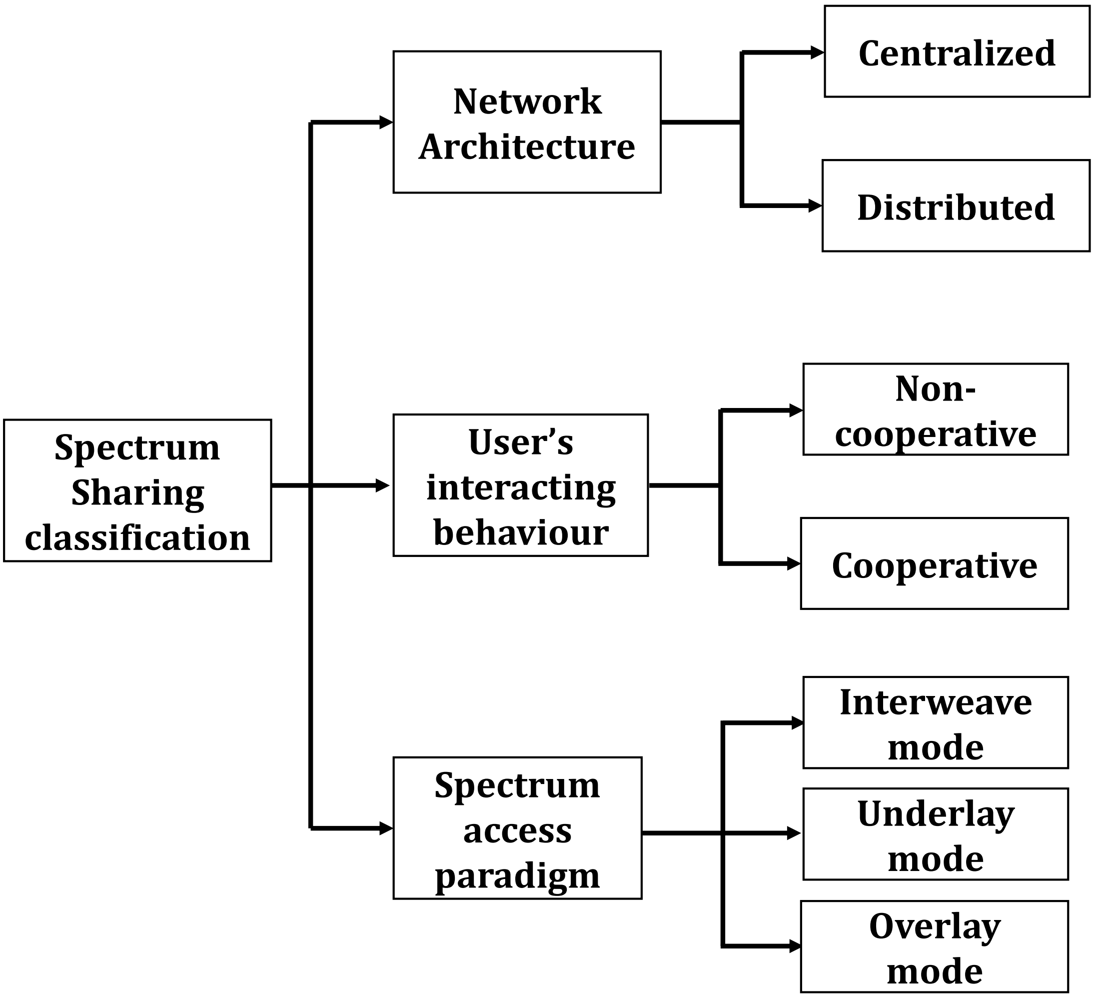


Figure 2-1: Classification of spectrum sharing techniques

band with the goal of maximizing their individual benefits.

- *Cooperative approach:* In this approach, through a cooperative strategy, users work together by sharing spectrum opportunities. This collaboration helps determine the optimal policy to achieve a common goal.

Finally, the third classification for spectrum sharing in CRN is based on the **spectrum access technology** employed by the users is described as follows [8, 46]:

- *Interweave mode:* This approach deals with opportunistic spectrum sharing, where SUs detect unused spectrum bands and opportunistically access them without interfering PU's transmission.
- *Underlay mode:* This approach deals with cooperative spectrum sharing, where SUs and PUs transmit together. Here, SUs are enabled to transmit

over licensed bands along with PU, such that interference from SUs to the PU is within some threshold power limit, and PU can transmit its data successfully.

- *Overlay mode:* This approach also deals with cooperative spectrum sharing, where SUs and PUs transmit over the same spectrum band by aiding each other and offering transmission opportunities for mutual benefit.

In a heterogeneous CRN where the number of PUs and SUs varies and is subject to frequent change, devising effective spectrum sharing schemes presents a significant challenge [6]. Moreover, in CRNs, PUs hold exclusive rights over their licensed bands, making it even more challenging to model spectrum sharing schemes, especially in scenarios where the number of SUs is considerably larger than the number of PUs. In recent times, cooperative DSA, often referred to as cooperative spectrum sharing (CSS), has garnered considerable research interest [83, 117]. In CSS, PUs and SUs collaborate, sharing scarce spectrum resources for cooperative communication, with the aim of achieving mutual benefits. The overlay spectrum access mode is widely utilized in CSS [75], where PUs enlist the help of SUs as relay node during primary transmission and, in return, grant transmission opportunities to SUs over their bands as compensation. SUs accept the PU's offer only if the compensation provided by PUs fulfills their transmission requirements. Therefore, relay-based CSS creates a mutually beneficial situation for both PUs and SUs, leading to enhanced performance in both the primary and secondary networks [57].

2.3 Relay-aided cooperative spectrum sharing in CRN

Spatial diversity, achieved by using multiple transceiver antennas, has proven highly effective in mitigating fading in wireless channels [70]. However, outfitting a wireless node with multiple antennas may not always be feasible due to space and cost constraints. To address such challenge and achieve spatial diversity without the need for multiple transceiver antennas on the same node, the concept of cooperative communications (CC) has emerged. Cooperative communication [57, 125] leverages the inherent broadcast nature of wireless communications, where one node (the relay) forwards the transmission to another node (the source) towards the intended destination, to achieve similar benefits as those provided by Multiple-

Input Multiple-Output (MIMO) systems. Consequently, a wireless network with many source-destination pairs, relay-aided cooperative communication (or cooperative relaying) has the potential to enhance communication capacity, transmission reliability, power efficiency and diversity gains [87, 102].

When a relay (r) or a group of relays are physically located between the source (s) and the destination (d), the relays may facilitate transmission from s to d using the following two modes of cooperative relaying [73, 100, 124]:

- *Amplify and Forward (AF):* In this mode of cooperative relaying, the relay r receives signal from source s in the first time slot, and then simply amplifies and re-transmits the received signal towards the intended receiver r in the second time slot. If $SNR_{s,d}$, $SNR_{s,r}$ and $SNR_{r,d}$ refer to the SNRs received at d from s, at r from s and at d from r respectively, then the achievable data rate for AF relaying mode under the two time-slot structure is written as:

$$C_{AF}(s,r,d) = \left(\frac{1}{2}W log\left(1 + SNR_{s,d} + \frac{SNR_{s,r}SNR_{r,d}}{SNR_{s,r} + SNR_{r,d} + 1}\right)\right) \tag{2.1}$$

  Here, W is the available bandwidth of the link and $\frac{1}{2}$ states that two phases of time are used for transmission from s to d.

- *Decode and Forward (DF):* In this mode of cooperative relaying, the relay r fully decodes and estimates the received signal from source s in the first time slot, and then transmits the estimated data to destination d in the second time slot. Therefore, the achievable data rate for DF relaying mode under the two time-slot structure is written as:

$$C_{DF}(s,r,d) = \left(\frac{1}{2}W \min\left(log(1 + SNR_{s,r}), log(1 + SNR_{s,d} + SNR_{r,d})\right)\right) \tag{2.2}$$

  The first term in Eq. (2.2) signifies the highest achievable rate at which the relay can accurately decode the source message. Meanwhile, the subsequent term in Eq. (2.2) denotes the maximum rate at which the destination can correctly decode the source message, assuming repeated transmissions from both the source and destination. Mandating error-free decoding of the entire codeword by both the relay and destination results in the minimum of the two mutual information values in Eq. (2.2).

Cooperative communications play a key role in the advancement of CR networks. A cooperative communication-aided CR system has the ability to significantly enhance the capacity of both primary and secondary networks, increase spectrum access opportunities for SUs and promote power savings for both PUs and SUs. It can be categorized into the following two types [75, 102]:

- *Cooperation among the SUs:* In this approach, a SU may act as a relay node for other SUs that may have access to different available spectrum bands. The spectrum availability and traffic requirements of SUs vary due to differences in their locations, the dynamic nature of PU traffic, and the opportunistic spectrum access behavior of SUs. To address these challenges, SUs with low traffic demands can assist (or serve as relay nodes) for other SUs to meet heterogeneous traffic demands, thereby enhancing the performance of the secondary network. Thus, cooperative communication among SUs can greatly improve the spectrum access opportunity as well as sharing efficiency for SUs with the help of cooperative SUs (or relay nodes).
- *Cooperation between PUs and SUs:* PUs hold exclusive rights to their licensed bands and can utilize them based on their traffic requirements and quality-of-service criteria. To bolster the capacity of the primary network and reduce transmission power usage, primary transmitters may willingly allow channel access to SUs for a portion of the temporal or spectral resource in exchange for relaying primary traffic towards primary receivers [108]. Conversely, SUs also accept offers from PUs to enhance secondary transmissions. Therefore, in this approach, PUs and SUs collaboratively access the shared spectrum band based on the overlay access mode of spectrum sharing, resulting in benefits for both primary and secondary networks while also enhancing overall spectrum utilization.

When fostering collaboration between PUs and SUs, a significant obstacle arises in identifying appropriate PU-SU pairs for cooperative communication while ensuring their transmission requirements are met. Depending on the number of PUs and SUs involved in the collaboration, CSS in overlay mode unfolds in two network scenarios, elaborated as follows:

2.3.1 Relay-aided CSS in single-PU multi-SUs CRNs

In a single-PU multi-SUs CRN, there is only one PU channel available, and multiple SUs compete for access opportunities on this single channel. In this situation, the PU maximizes its benefit by selecting the most advantageous SU (or SUs) as its relay node for transmitting primary data, aiming for the highest cooperative gain possible. However, because there are no additional PU channels in the network, the chosen SUs cannot negotiate further with the PU apart from accepting the offer for cooperative communication. Nevertheless, the SUs do not compromise their transmission constraints when paired with the PU. This mapping of PU and SU typically favors the effectiveness of the primary network, but researchers are striving to optimize the performance of both the secondary and primary networks simultaneously.

In this direction, Simeone *et al.* in [101], a cooperative relaying technique among a single PU and multiple SUs was addressed. Here SUs acted transparent relay to forward primary user data packets that have not been successfully received by an intended destination and in return utilize spectrum holes obtained over the primary communication link and able to achieve stable throughput of the secondary link. Chen *et al.* expanded upon the previously mentioned scheme in [27] to encompass a PU channel accommodating delay-sensitive services. Both PU and SU utilized rateless codes, where the SU receiver's concern was solely the count of received coded packets, rather than specific packet identities. Consequently, when relaying unsuccessful PU packets, SUs incorporated and transmitted their own data using dirty-paper coding techniques. In [108], a collaborative protocol involving active cooperation between pairs of PUs and SUs was examined by Weifeng *et al.*. In this protocol, SUs aided in relaying PU's signals, receiving some spectrum resource released from the PU in return, and gaining permission for continuous secondary transmission within the networks. The suggested protocol is designed to optimize both the PU's energy conservation and the SU's data transmission rate. Another study, outlined in [74] by Liang *et al.*, explored cooperative communication between a PU and an SU. In this scenario, the SU relayed the PU's message to another PU, and in exchange, the PU allocated a substantial portion of its bandwidth for the SU's use. A cooperative relaying scheme employing adaptive turbo trellis coded modulation (ATTCM) was introduced to enhance the utilization of the bandwidth made available by the PUs. This enhancement notably boosted the transmission rates for both the PU and the SU under a given signal-to-noise ratio (SNR). In [35], Elmahdy *et al.* addressed the challenge of ensuring the desired quality of service (QoS) for the PUs while optimizing the performance of a relay SU within an overlay cooperative CRN. While relaying the primary data, the admission of PU packets into the SU relaying queue was probabilistically managed. Two types of queues were established, one with a work-conserving policy and the other with a non-work-conserving policy, each with the objective of optimizing SU and PU throughput or minimizing transmission delay, respectively. In [127], Xiaokai *et al.* investigated the Vickery auction-based secondary relay selection for cooperative overlay spectrum sharing in hybrid satellite–terrestrial sensor networks (HSTSNs) comprises a single PU and a set of secondary relays. Given that both primary and secondary networks are rational and honest but possess incomplete network information, they aim to maximize their potential payoffs through cooperation between the two networks and competition within the secondary networks. Simulation results demonstrate the effectiveness of the Vickery auction mechanism for relay node selection and for enhancing the performance of the secondary network. Alvi *et al.* in [10], introduced a buffer-supported cooperative relaying system within a single-PU, multi-SUs CRN. Here, the PU selected the most suitable relay based on the specific QoS profile to meet the application's requirements. A multi-objective optimization strategy was employed, aiming to maximize throughput and available buffer space while minimizing delay and battery power consumption. This optimization utilized weighted sum and rank sum approaches to derive optimal solutions. In the context of cellular network, Huang *et al.* introduced a cooperative overlay cognitive radio network in [54], featuring a single PU and multiple SUs in a scenario characterized by imperfect successive interference cancellation (SIC) and imperfect channel state information (CSI). The approach involves selecting the best cell-center cognitive SU with the highest signal-to-noise ratio (SNR) from the received signals between the primary transmitter and multiple SUs. This selected SU then transmits both the PU's signals and its own signal to cell-edge users using the non-orthogonal multiple access (NOMA) principle. The system's performance was assessed by evaluating the end-to-end outage probability and capacity for both the primary and secondary networks, accounting for the imperfections in SIC and CSI.

2.3.2 Relay-aided CSS in multi-PUs multi-SUs CRNs

In a multi-PUs multi-SUs CRN, the presence of multiple PU channels alongside multiple SUs adds complexity, particularly regarding the mapping of multiple SUs onto desired PU channels to enable CSS. Within this context, two key trade-offs emerge during CSS: the selection (or assignment) of cooperative PU-SU partners and the optimal distribution of PU spectrum resources among these chosen partners. The first trade-off involves determining the most suitable PU-SU pairs for CSS, ensuring mutual preference between the PU and SU. Meanwhile, the latter trade-off pertains to the optimal allocation of PU spectrum resources among the selected partners to maximize the individual utility (or profit) for both the involved partners. However, suitable partner selection and resource allocation for CSS become challenging problems due to the heterogeneous characteristics and conflicts of interest associated with PUs and SUs. While optimizing, resources must be managed and allocated in a distributed manner so that the overall resource utilization gets maximized and the users can jointly be benefited. To analyse and handle such interactions among two disjoint sets of users with cooperative or competitive behaviours, ***matching theory*** [22, 43, 47, 71] is proven to be an efficient framework that analyzes mutually beneficial relationships between the users of two disjoint sets and establishes win-win situations among them. The term *two-sided matching market* is employed within matching theory to explore the dynamics between two separate sets of players. In such matching markets, matching theory systematically captures not only cooperative interactions between users from different sides but also competitive interactions among users within the same side. The foundational models, properties, and formulations of a *two-sided matching market* utilized in the context of CSS are defined as follows [44, 47, 55, 66]:

2.3.2.1 Matching models

- *One-to-one matching:* A one-to-one matching between two disjoint sets $\mathcal{M}$ and $\mathcal{N}$ can be represented by a one-to-one correspondence $\mu(.)$, where $i \in \mathcal{M}$ is mapped to $j \in \mathcal{N}$ (i.e., $\mu(i) = j$) if and only if j is also mapped to i (i.e., $\mu(j) = i$).
- *Many-to-One (M2O) matching: A many-to-one matching between set $\mathcal{M}$ and $\mathcal{N}$ is defined such that (a) more than one user of set $\mathcal{M}$ say i_1, i_2 are allowed to map with the same user j_1 of set $\mathcal{N}$, i.e. $\mu(i_1, i_2) = j_1$, where $\mu(i_1) = j_1$ and $\mu(i_2) = j_1$ only or (ii) more than one user of set $\mathcal{N}$ say j_1, j_2 are allowed to map with the same user i_1 of set $\mathcal{M}$, i.e. $\mu(j_1, j_2) = i_1$, where $\mu(j_1) = i_1$ and $\mu(j_2) = i_1$ only.*
- *One-to-Many (O2M) matching: A one-to-many matching between set $\mathcal{M}$ and $\mathcal{N}$ is defined such that (a) one user of set $\mathcal{M}$ say i_1 is allowed to map with more than one user say j_1, j_2 of set $\mathcal{N}$, i.e. $\mu(i_1) = (j_1, j_2)$, where $\mu(i_1) = j_1$ and $\mu(i_1) = j_2$ only or (ii) one user of set $\mathcal{N}$ say j_1 is allowed to map with more than one user say i_1, i_2 of set $\mathcal{M}$, i.e. $\mu(j_1) = (i_1, i_2)$, where $\mu(i_1) = j_1$ and $\mu(i_1) = j_2$ only.*

The *M2O* and *O2M* matching can be used interchangeably as and when required.

2.3.2.2 Matching types

The types of matching differ depending on the network information known to the users. A brief description of some matching market scenarios and the associated matching types for each scenario [22, 44, 66] is provided as below:

- **Open market scenario:** Here, each user of both the sets $\mathcal{M}$ and $\mathcal{N}$ gains complete network information, like each other's characteristics, configurations, connectivity, resource constraints, and preferences. This drives easy access during the resource sharing process among the users and can establish ***optimal matching*** either for the set $\mathcal{M}$ or for the set $\mathcal{N}$.
    - ***Optimal Matching:*** In a one-to-one matching model, there exists an optimal matching for each $i \in \mathcal{M}$, where every i achieves the maximum possible utility (or matching benefit) with its matching partner $j \in \mathcal{N}$. Similarly, there exists an optimal matching for each $j \in \mathcal{N}$, where every j achieves the maximum possible utility (or matching benefit) with its matching partner $i \in \mathcal{M}$. But the point to be noted is that a matching or an equilibrium that is optimal for the users of one set will not be optimal for the users of opposite set, but of course it should satisfy the Individual Rationality (IR) constraint for the users of non-optimal set, so that they can accept the matching [55, 59].

      However, in many-to-one matching model, an optimal matching between the group of cooperative users in set $\mathcal{M}$ (say $Coop_i$) and each user $j \in \mathcal{N}$ is the one that maximizes the individual utility of each cooperative user, thereby maximizing the gross utility of the cooperation model mapped to $j \in \mathcal{N}$. Alternatively, there exists an optimal matching for each $j \in \mathcal{N}$, ensuring that each j achieves the highest possible utility when paired with the cooperative user group in set $\mathcal{M}$.

- **Partially open market scenario:** Here, either the users in set $\mathcal{M}$, set $\mathcal{N}$, or both have limited access to the entire market (network) information and are only privy to a subset of local information [44]. This limitation hinders users from selecting the most suitable partner for cooperative communication and makes it challenging to achieve optimal matching. In this context, a new term, *stable matching*, is deemed more appropriate for users in each set, as described below.

- ***Stable Matching:*** In one-to-one matching, pairing or mapping between user $i \in \mathcal{M}$ with user $j \in \mathcal{N}$ is considered to be *stable* or *unblocked*, if each of the resultant (i, j) pair or $\mu(i, j)$ satisfy the following two properties [55, 59]:
    - ∗ ***Property 1:*** Any i and j of matching μ is willing to maintain the current partnership rather than stay single.
    - ∗ ***Property 2:*** Neither i nor j of matching μ can increase their individual utility further, via unilateral deviation (choosing a new partner by betraying current partnership).

Otherwise, the (i, j) pair is called as blocking pair that results in an **unstable matching**.

Unlike in one-to-one matching, concentrating only on pairwise stability is not enough to prove stable matching in case of many-to-one matching. In this context, the concept of *Group Stability* [66], [61], [14] is used to establish stable matching for all the groups as a whole or for the entire set of cooperative users. Let consider a scenario, where $\mu^{total} = \sum_{i=1}^{|Q|} \mu_i$ is a grand $M2O$ matching with Q number of individual $M2O$ matching in it. A grand $M2O$ matching $\mu^{total}()$ is blocked by an individual $M2O$ matching say $\mu(Coop_i) = j$, if there exist another $M2O$ matching $\mu^{/}()$ such that either $Coop_i$ or j prefers $\mu^{/}()$ over $\mu()$. μ^{total} is ***Group Stable***, if it is not **blocked** by any one of its individual $M2O$ matching of any size. In the considered scenario, μ^{total} is not ***Group Stable*** due to the existence of **blocked** matching $\mu^{/}()$ in it.

In literature, authors have addressed most of the CSS works in terms of cooperative partners assignment and allocation of optimal resources using the concept of one-to-one matching rather than many-to-one or one-to-many matching. In [40], a relay based CSS among multiple PUs and multiple SUs was proposed by Xinxin *et al.*, where both the PUs and the SUs are competing for their own benefits using matching theory. Utility driven one-to-one matching models among PUs and SUs were constructed for different matching market scenarios. The proposed matching algorithms lead PUs to the unique pareto optimal equilibrium in the partially open matching market scenario, however in the incomplete information scenario, the proposed algorithms converged to stable equilibrium to

PUs as well as to SUs. Namvar *et al.* proposed an access time optimization and a utility maximization scheme for both PUs and SUs in [85]. Using the stable matching concept, one-to-one matching model was constructed for stable PU-SU pairs, which converged to an optimal match for the set of SUs and a stable match for the set of PUs. The study in [44] presented by Gao *et al.*, examined cooperative partner matching and resource sharing issues across various matching market scenarios. It explored different market equilibrium such as optimal, stable, and robust equilibrium, each tailored to specific scenarios. Additionally, the study formulated sufficient and necessary conditions for each equilibrium, along with the associated utility functions. In [75], Liang *et al.* explored a cooperative relaying technique within the overlay spectrum access scheme. Their goal was to facilitate PUs to transmit at reduced power levels with increased throughput while also enabling SUs to utilize the released bandwidth. Cooperative matching theory was employed, with PUs showing a preference for cooperation when selecting appropriate SUs. Using a round-robin scheduling approach, each PU could select the most suitable SU for cooperative relaying in each round. The proposed distributed solution tended to closely approximate the analytical benchmark method. A convex optimisation theory-based joint power and time allocation mechanism for SUs was proposed in [97] by Roumeliotis *et al.*, which aims to maximize the cooperative gain of PUs and satisfy the transmission objective of SUs. Here, the achieved outcome was found to be very close to the benchmark result. The problem of cooperative relays selection as well as resource allocation between multiple PUs and multiple SUs in a CRN was addressed in [23] by Chang *et al.*. Here, a distributed stable matching game-based power control algorithm was proposed to achieve stable matching between PUs and SUs and validated with the swap matching concept. The average capacities of PUs and SUs were found better in the solution based on swap matching than the stable and random matching approach. In [122], an energy-efficient resource allocation problem in orthogonal frequency division multiplexing (OFDM)-based CRN was proposed by Yan *et al.* to jointly optimize the relay selection, sub-carrier pairing, and optimal power allocation for primary secondary system. Using the fractional programming and the Lagrangian dual decomposition method, the optimization problem which is a mixed-integer nonlinear program (MINLP) can be efficiently solved to obtain an asymptotically optimal solution. In [94], a channel allocation model among SUs based on matching theory, was introduced by Rahim *et al.*. This model aimed to assign the appropriate channel to each SU, considering both the quality of PU channels and the QoS requirements of SUs. The effectiveness of the proposed schemes was assessed using the metric ”SU satisfaction,” indicating the extent to which an SU received the most suitable PU channel from the available pool.

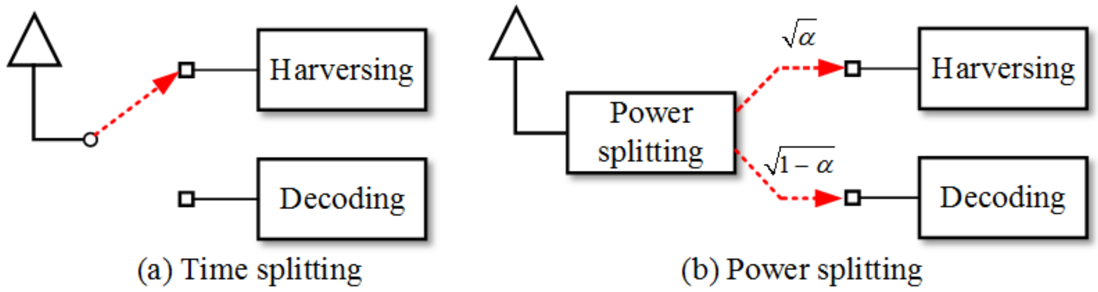
The proposed approach resulted in an optimal match for SUs, maximizing the throughput of the secondary network. Finally, Aziz *et al.* examined a two-sided stable matching model in [14], where uncertainty regarding the agents' preferences may arise due to limited information or communication. Three types of uncertainty models were explored: the lottery model, the compact indifference model, and the joint probability model. For each model, the objective was to compute the matching with the highest stability probability by minimizing the expected number of blocking pairs.

2.3.3 Summary

In the preceding sections, we have provided insights into cooperative spectrum sharing within both single-PU multi-SUs and multi-PUs multi-SUs CRNs. We have briefly outlined some common strategies, such as optimal matching, stable matching and swap matching, developed by various researchers to select optimal or stable PU-SU pairs and allocate resources efficiently among the selected pairs. In scenarios involving cooperative relaying, SUs must allocate adequate power for both cooperative and secondary transmissions. However, due to the inherent energy constraints of SUs, efficient distribution of these limited resources poses challenges, especially in achieving energy-efficient communication while boosting secondary throughput and meeting PU's rate requirements. To address these challenges, there is a need for a mechanism that integrates an energy harvesting model for SUs, maintaining a balanced trade-off between energy efficiency, throughput enhancement, and PU requirement fulfillment during cooperative communication. Energy harvesting by the SUs plays a crucial role in achieving this balance.

2.4 Energy harvesting for energy efficient communication during CSS

The rise of advanced wireless technologies has led to an exponential increase in the quantity of wireless devices. However, the performance of these devices hinges not only on available spectrum resources but also significantly effect on their associated energy sources [46]. Given the energy-constrained nature of these devices, researchers worldwide are grappling with substantial challenges concerning the energy-efficient communication of such devices [63]. Recent advancements in wireless technology show that it's now possible to both collect energy and pro-



(a) Time splitting (b) Power splitting

Figure 2-2: SWIPT architectures [2, 132]

cess information from ambient radio frequency signals using wireless methods for information and power transfer [132]. Traditionally, solar and wind power have been popular options for energy harvesting (EH). However, recent studies have uncovered the significant potential of radio-frequency (RF) signals for carrying both information and power simultaneously, leading to the development of simultaneous wireless information and power transfer (SWIPT) technology [132], [67]. Utilizing suitable circuitry, a SWIPT receiver can effectively decode information and harvest energy from the RF signal, thereby extending the network's lifetime. As cognitive radio presents a promising avenue for enhancing spectrum utilization, integrating cognitive radio networks with EH offers an effective solution to enhance energy efficiency for CR users (or SUs).

2.4.1 SWIPT technology in CRN

SWIPT technology is one of the most important applications of RF-EH which jointly uses the RF signal to transfer both energy and information [31, 68, 116]. It provides the possibility of balancing the information-rate and energy-harvesting tradeoffs. The receiver architecture of a node having SWIPT technology is able to harvest and process (or decode) signal information simultaneously from the same received signal. Mostly used receiver architecture in SWIPT technology are time-switching (TS) and power-splitting (PS) architecture [78, 132] as shown in Figure 2-2

In TS architecture (Figure 2-2(a)), the receiver utilizes a single antenna for both EH and information decoding (ID). Switching between the two operations is based on a switch that alternates the operation mode within specific time intervals. In PS architecture (Figure 2-2(b)), receiver divides the received signal power into two power streams based on the power splitting ratio, say $\sqrt{\rho} : \sqrt{1-\rho}$, where $\sqrt{\rho}$ power is used for EH and $\sqrt{1-\rho}$ power is used for ID.

Many recent research endeavors have centered on achieving energy-efficient communication in CRNs, typically employing either TS-based or PS-based SWIPT technology at the receiver side of SUs. In the context of CSS, when a PU transmits its primary signal to a relay (or SU), the SU decodes the primary signal for relaying purposes while simultaneously harvesting energy from the received PU signal. In the work by Zhou *et al.* [132], both TS and PS techniques were applied individually to energy-constrained secondary users (SUs). The study analyzed the trade-offs between data rate and energy consumption when considering separate versus integrated information and energy receivers. Additionally, Xu *et al.* in [121] proposed both PS-based and TS-based relaying protocols, aiming to facilitate wireless information transfer and energy harvesting at battery-free relay nodes. They also formulated an optimization problem for determining the ideal allocation of power and time factors. Furthermore, the research delved into the end-to-end error performance and the resulting throughput during secondary transmission for both of these proposed protocols. In the study presented by Wang *et al.* in [119], explored an optimal power allocation problem using a PS-based approach within an energy-constrained cognitive relay network. This investigation encompassed several key aspects, including assessing outage probabilities for both primary users (PUs) and SUs, evaluating system energy efficiency, and examining the tradeoff between data rate and energy consumption. Furthermore, the research offered optimal power allocation strategies aimed at maximizing both primary and secondary transmission rates. In a different context, Derrick *et al.* employed a PS-based SWIPT technology in [86] within an Orthogonal Frequency Division Multiplexing (OFDM) system. This study explored two distinct scenarios, each considering varying power splitting capabilities of the receivers. In both scenarios, the research formulated non-convex optimization problems that carefully balanced the minimum data rate requirements and the minimum power constraints for services with specific delay requirements. In the study by Hsu *et al.* in [50], a PS-based SWIPT technology was implemented within a cooperative CRN. In this scenario, energy-constrained SUs harnessed energy not only from the primary transmitter's (PT) received signal but also from interfering sources. The research delved into the performance of two relay cooperation schemes, examining the tradeoff between the PU's and SU's performance, particularly concerning outage probabilities. Meanwhile, Tian *et al.* addressed an optimization problem in [111], involving transmitting time and transmission power of SU within an underlay RF energy-harvesting CRN. Their objective was to maximize the energy efficiency of the secondary network by enabling the SUs to reserve the residual energy after previous slots for upcoming transmissions. To achieve this, they proposed a rapid iterative algorithm based on Dinkelbach's method. A hybrid TS-PS model was established in [45] by

Ghose *et al.* for EH in a bidirectional relay-assisted communication and explored an end-to-end outage probability of the network. Primarily, this work solved an optimization problem of outage probability with respect to relay placement and time allocation factors. Furthermore, Hasan *et al.* explored techniques for simultaneous energy harvesting and information transfer within an EH-based CR network model in [48]. This approach combined both TS and PS receiver architectures. The research derived and analyzed optimal expressions for transmission power and energy harvesting power to attain maximum energy efficiency within the secondary network. In a study by Prathima *et al.* in [93], proposed a PS-based SWIPT architecture within a RF energy-harvesting-enabled CRN. Their research addressed two significant challenges: extending network lifetime and enhancing link reliability. Specifically, they tackled optimization problems related to reducing outage probabilities and maximizing system throughput in both the primary and secondary systems. Furthermore, in a different approach discussed in [34] by Du *et al.*, proposed a TS technique for EH at SUs. This technique utilized proximal policy optimization (PPO) to jointly control the EH time and transmission power of SUs while striking a balance between improving performance and ensuring successful transmission. Experimental results demonstrated that this algorithm exhibited remarkable stability in uncertain environments and achieved higher throughput and energy efficiency compared to greedy and random algorithms.

Most of the existing works discussed above focus on either TS or PS SWIPT technology separately during the optimization of harvested energy and primary information decoding rates at SU. To the best of our knowledge, there is limited research, such as [45] and [48], where integration of TS and PS techniques is used in the CRN framework to harvest energy from RF signal. However, these studies do not tackle the vital issue of optimizing the utility and operational duration of energy-constrained SUs. By simultaneously employing both of these techniques during the energy harvesting phase, SUs can accumulate a greater amount of energy compared to their separate uses, which in turn contributes to extending the lifespan of the secondary network. Additionally, the optimization of harvested power during cooperative and secondary communication has been relatively underexplored in the literature, despite its significant impact on enhancing the efficacy of the secondary network. Consequently, addressing multi-objective problems through the optimal allocation of values to multiple decision variables (ex. TS factor, PS factor, and harvested power allocation factors) poses a particular challenge that requires a delicate balance to achieve trade-offs among these decision variables.

2.5 Conclusion

In this chapter, we have presented a comprehensive survey on the background of spectrum sharing, cooperative spectrum sharing (CSS) and energy harvesting during CSS in CRN and the existing works related to the problems addressed in this thesis. With a detailed understanding of the state of the art, the research contributions are presented in the subsequent chapters.