Chapter 5

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

5.1 Introduction

To address the challenge of limited spectrum availability and optimize overall spectrum utilization, implementing cooperative spectrum sharing (CSS) between primary users (PUs) and secondary users (SUs) is a promising approach. In the previous chapter, inspired by matching theory, we consider open matching market scenario for the set of PUs and SUs and formulated the CSS problem as a one-to-one matching scheme between PUs and SUs within a cognitive radio network (CRN). In such open matching market, most of the network information like (i) the configuration and capability of PUs and SUs, (ii) their individual resource constraints, and (iii) the preference lists of each user, are broadcast over the network. In this context, modeling SU's optimal matching in terms of maximizing secondary network utility is found to be challenging, as each SU competes with one another for the same utility. Moreover, in the overlay access paradigm, PUs have exclusive rights over the licensed bands, and thus the resource optimization is done from the PU's perspective by optimizing the gain of the primary network. Previous studies (e.g., [40], [85], and [44]) established one-to-one matching among the cooperative PU-SU pairs and obtained optimal utility for the set of PUs, but obtained non-negative utility for SUs, which satisfied only the targeted transmission objective of SUs. This results in significant gains for the primary network but comparatively less benefit for the secondary network. There are few more works [96] and [113], based on one-to-many and many-to-one matching concept, where each PU collaborates with multiple SUs during CSS. However, in both of these works, the matching between PUs and SUs were designed from the perspective of PUs rather than SUs, aiming to enhance the performance of the primary network. Furthermore, in realistic CRN scenarios, the number of PUs is always smaller than the number of SUs, making it challenging to accommodate all feasible SUs with suitable PUs during CSS, thereby preventing many SUs from achieving their intended transmissions [44]. To maximize the participation of all feasible SUs during CSS and to enhance the efficacy of the secondary network, it is crucial to implement a cooperative strategy for the SUs. This strategy helps to optimize and share resources among cooperative partners effectively from the SU's standpoint.

In this chapter, we present a novel utility aware cooperation strategy among SUs is proposed, where favorable SUs jointly map to their most preferable PU, establishing a many-to-one matching during CSS. The proposed scheme aims to maximize the utility of each involved SU, gross utility of cooperative SUs and overall utility of secondary network. We focus predominantly on the selection of cooperative partners, represented as tuples comprising cooperative SUs and a preferred PU, allocate optimal fractions of access time (α^*, β^* as discussed in the previous chapter) among the chosen partners to facilitate cooperative communication and secondary transmission. At the outset, PUs and SUs declare the limitations on resources as well as the corresponding proposals for resource exchange that are integral to the negotiation process. Based on the shared resource information, every SU prepares a preference list for PU and shares the list among other SUs. Rather than engaging in individual competition, SUs with similar PU preferences are grouped into suitable tuples. Together, they approach the most favored PU for cooperative communication and offer to relay PU services by accessing the rewards provided by the PU in a sequential manner. This collaborative strategy among SUs serves to prevent multiple rejections by PUs in their quest for maximizing PU utility. However, by ensuring a guaranteed utility for each PU, this scheme effectively enhances several aspects: (i) individual utility of each SU, (ii) gross utility of cooperative SUs, (iii) overall utility of secondary networks, (iv) percentage of participation of SUs during CSS, and (v) satisfaction level of SUs when paired with PUs.

The rest of this chapter is organized as follows: Section 5.2 defines the problem, assumptions, and symbols and notations used. Section 5.3 discusses the system model. Section 5.4 presents the proposed scheme. Section 5.5 covers the simulation experiments and performance analysis. Finally, Section 5.6 concludes the chapter.

5.2 Problem Statement

The problem is to develop a many-to-one matching scheme among SUs and preferred PUs for cooperative spectrum sharing (CSS) and communication in a multi-PUs multi-SUs overlay CRN scenario. The scheme aims to allocate fractions of PU access time among cooperative partners from SU's perspective, considering penalties imposed by PUs. By integrating a cooperative strategy among SUs, the proposed scheme forms suitable groups (or tuples) of SUs that work together and match with the most preferred PUs. Using the concept of group stable matching of matching theory, the scheme achieves optimal matching equilibrium for SUs and stable matching equilibrium for PUs during the cooperative communication process.

5.2.1 Assumptions

- SUs adopt time division sharing model based on TDMA for CSS over PU band.
- PUs and SUs are equipped with a single antenna and work in half-duplex mode.
- In the context of matching theory, an open matching market model is assumed where the transmission power of PUs and SUs, the distance between them, the target transmission constraints of PUs, and the reward constraints of SUs are known.
- The locations of SUs and PUs are fixed in the network; that is, SUs and PUs are stationary during the partner assignment phase.
- All SUs willingly adopt a cooperation strategy to increase both individual and collective profit.
- All SUs in the network are non-malicious, and the resource information they provide is trustworthy.

- The noise environment is assumed to be zero-mean Additive White Gaussian Noise (AWGN), and the channel gain between two nodes depends solely on distance and path loss components [100], [97].
- Necessary control information exchange between PU and SU takes place through a dedicated common control channel [80] These control information focuses on the operational aspects of communication to ensure efficient channel usage.

5.2.2 Notations and Symbols Used

To remind the symbols and notations used particularly in this chapter, the same are summarized in Table 5.1.

Symbols/Notations	**Comments**
$\mathcal{M}$	Set of PUs
$\mathcal{N}$	Set of SUs
M	Number of PUs
N	Number of SUs
F	Number of frames in a PU band
P_{PT}	Transmission power of PU
P_{ST}	Transmission power of SU
U_{PU}	Utility achieved by PU
U_{SU}	Utility achieved by SU
C_{PT}^{coop}	Cooperative gain achieved by PU during cooperation with ST
EN_{ST}	Energy consumption of SU
ER_{ST}	Expensive rate of SU
c_1^{target}	Reward constraint of SU for relaying PU service
C_{ST}	Total capacity achieved by SU during secondary communication
$d_{PT,PR}$	Euclidean Distance between PT and PR (in m)
$d_{ST,SR}$	Euclidean Distance between ST and SR (in m)
μ	Matching
GU_{SU}	Gross Utility of SUs
OU_{SN}	Overall utility of secondary networks
t_{PT}	Tuple of cooperative SUs that prefer PT
PA_{list}	Priority access list

SAT_{ST}	Average satisfaction of SUs
$\%P_{ST}$	Percentage of SUs participated in coop. communication
Th_{ST}^{FI}	Throughput fairness index of SUs

Table 5.1: Notations and Symbols used

5.3 System Model

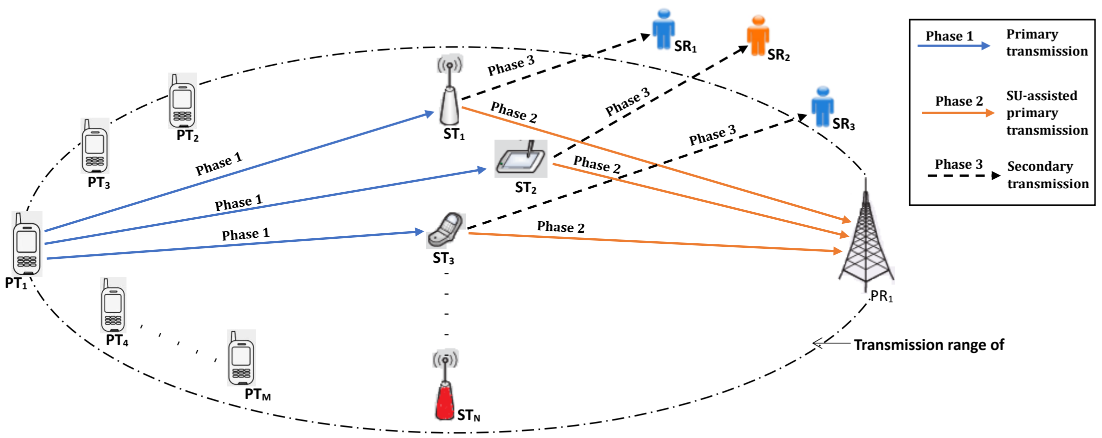

Figure 5-1: Proposed cooperative communication scheme among PUs and SUs for considered CRN scenario

In line with the discussion in the preceding chapter (Chapter 4), we examine a Cognitive Radio Network (CRN) framework with a set of M PU transceiver pairs denoted as $\mathcal{M} = \{(PT_1, PR_1),.., (PT_i, PR_i),.., (PT_M, PR_M)\}$ and a set of N SU transceiver pairs denoted as $\mathcal{N} = \{(ST_1, SR_1),.., (ST_j, SR_j),.., (ST_N, SR_N)\}$. We have assumed overlay spectrum access involving PUs and SUs, wherein PUs maintain exclusive control over their licensed bands and allow spectrum access by SUs in exchange of relaying service rendered by SUs in PU's data transmission. PUs enlist the assistance of SUs for relaying services to transmit primary data to specified receivers. In exchange, PUs provide access opportunities to the SUs for secondary transmission by leasing some portion of access time over their licensed bands, but only if the cooperative capacity enhanced by SUs results in improved performance compared to direct transmission by PUs. Likewise, SUs will agree to PU's offers only if they stand to benefit from enhanced secondary transmission rates. The comprehensive CSS and communication scheme involving cooperative SUs and preferred PU is illustrated in Fig. 5-1. Interference between the primary and secondary systems is mitigated through collaboration. By exchanging transmitted information, mutual collisions can be eliminated, thereby preventing interference [25]. The entire PU band structure is depicted in Fig. 5-2. Each PU

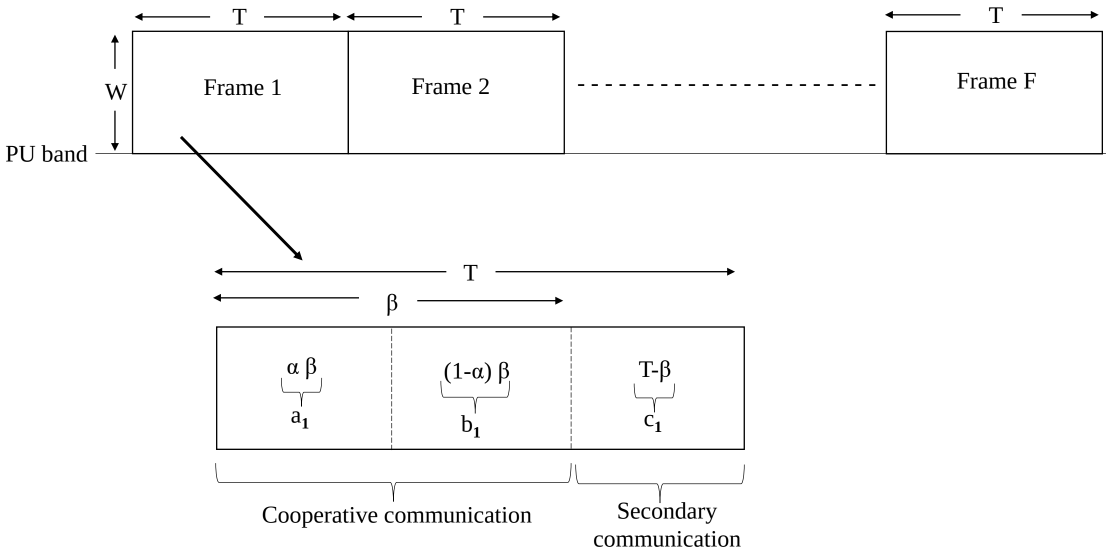

Figure 5-2: Frame wise time-slot division structure of PU band

owns a licensed band with F transmission frames, each lasting a duration of T time units and having a bandwidth of W MHz. PUs use time division multiple access (TDMA). The entire time duration T of each PU frame is divided into three sub-slots of durations a_1, b_1 and c_1, based on two decision variables namely α $(0 < \alpha \leq 0.5)$ and β $(0 < \beta < T)$. The SU-assisted cooperative communication occurs over the duration $\beta{=}a_1{+}b_1$. During a_1 (Phase 1), the PT transmits its data to the selected relay node (or ST). During b_1 (Phase 2), the ST forwards the received primary data to the corresponding PU receiver (or PR). The remaining time c_1 (Phase 3), where $c_1 = T - \beta$, is allocated to the ST for secondary transmission as compensation for relaying the primary service.

In this context, each ST employs the amplify-and-forward (AF) relaying technique to transmit primary data towards PR. The optimization problem for the optimal allocation of frame duration T, based on decision variables α and β, remains consistent with the formulation in Chapter 4. The near-optimal results α^* and β^* obtained from Algorithm 1 in Chapter 4 are applied here during the cooperative communication between PUs and SUs. Additionally, it is assumed that PUs and SUs can adjust their transmission power levels (P_{PT} and P_{ST}) while transmitting data. The utility of each PU (in Mb/Joule), denoted as U_{PU}, achieved in each frame for relay-assisted transmission, can be formulated in terms of maximizing cooperative capacity, C_{PT}^{coop}, with minimal energy consumption, as expressed in Eq.(5.1).

$$U_{PU} = \frac{C_{PT}^{coop} - C_{PT}^{direct}}{P_{PT} \times a_1} \tag{5.1}$$

Here, C_{PT}^{coop} is achieved by the PU assisting with suitable relay node due to AF relaying method (detail formulation of C_{PT}^{coop} is already provided in Chapter 4) and C_{PT}^{coop} is the capacity achieved through direct transmission by the PT itself. Similarly, the utility of ST (in Mb/Joule), denoted as U_{SU}, can be formulated in terms of maximizing C_{ST} under the reasonable cost values incurred as expressed in Eq.(5.2).

$$U_{SU} = \frac{C_{ST}}{EN_{ST} + ER_{ST}} \tag{5.2}$$

Here, C_{ST} is the capacity achieved by ST during secondary transmission phase, EN_{ST} is the total energy consumption by ST during relay based transmission and secondary transmission phase and ER_{ST} is the expensive rate of ST obtained during optimization phase. Detail formulations of C_{ST}, EN_{ST} and ER_{ST} are already provided in Section 4.3 of Chapter 4.

5.4 Proposed Cooperative Communication Framework

This chapter focuses on enhancing the secondary network's performance by establishing many-to-one ($M2O$) matching among cooperative SUs and preferred PUs during CSS. Figure 5-3 illustrates the entire cooperative communication process involving PUs and SUs, based on $M2O$ matching. Before detailing the proposed $M2O$ matching, we explain why $M2O$ matching is preferred over one-to-one ($O2O$) matching. In $O2O$ matching, a single PU is paired with only one SU, and vice versa, for resource sharing and cooperative communication. Let's analyze $O2O$ matching from both the PU and SU perspectives. In overlay CRNs, PUs have exclusive rights over their licensed bands and can select the most beneficial SUs as cooperative partners. Each SU aims to pair with a PU that enhances its secondary transmission capabilities. Consequently, SUs compete by independently sending request messages to their preferred PUs. This approach benefits PUs by

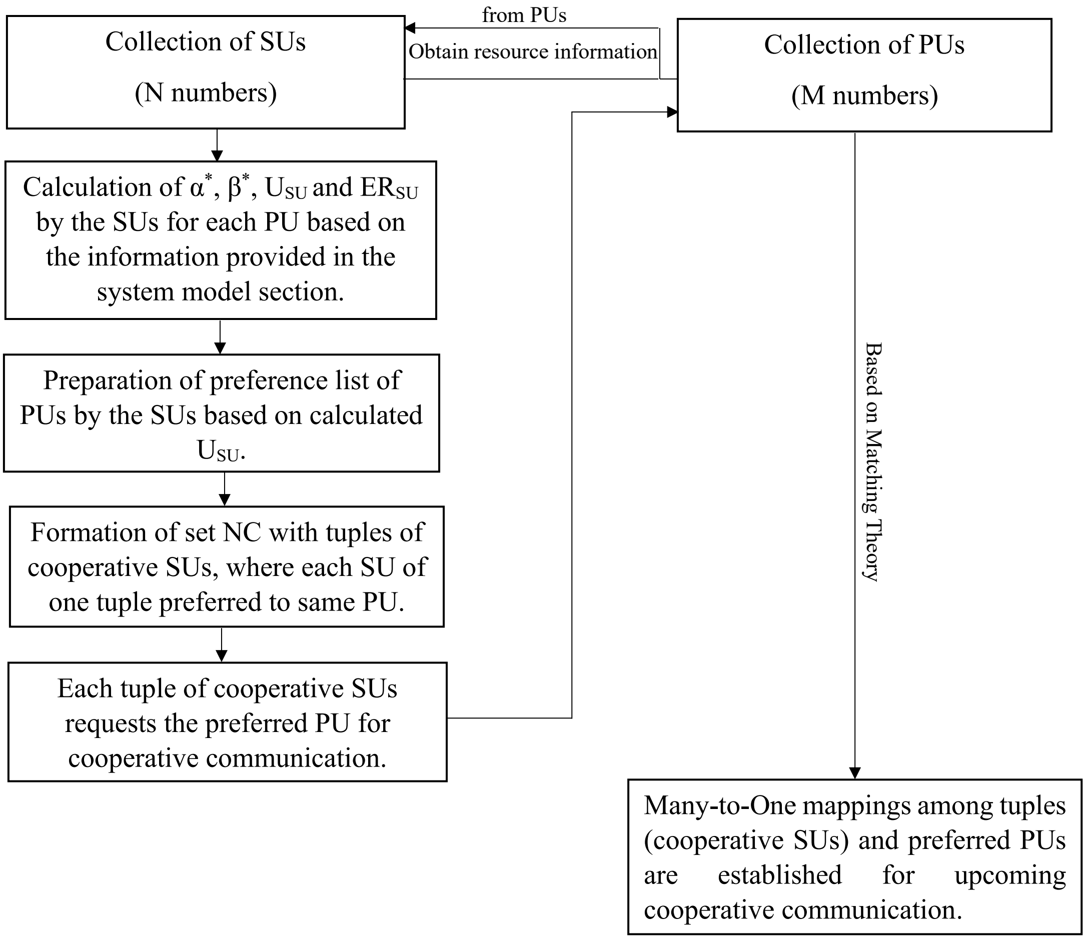

Figure 5-3: Block diagram for many-to-one matching based cooperative communication framework

allowing them to choose the most suitable SUs, leading to optimal matches for the PUs. However, in the worst-case scenario, SUs may end up paired with their least preferred PUs or remain unmatched. This situation directly affects the SU's transmission opportunities and the overall performance of the secondary network.

To improve the performance of the secondary network in an overlay CRN, the need for collaboration among SUs has arisen and accordingly a cooperation strategy for SUs is devised. In this approach, SUs share preference lists and form groups of cooperative SUs that share a common preference for a particular PU. Unlike the individual request messages used in *O2O* matching, we employ the concept of *M2O* matching, where a group of collaborative SUs (also termed as tuple of cooperative SUs and denoted as t_{PT}) collectively sends a single request message to their preferred PU (say PT). It is worth mentioning that the expression t_{PT_i} signifies that a specific tuple is mapped to the primary user PT_i. Unlike *O2O* matching, this strategy counteracts the profit-maximizing tendencies of PUs by preventing them from selecting the most lucrative SU request and declining all other requests from SUs. Conversely, each t_{PT} has the opportunity to be paired with its preferred PT, thereby enhancing individual utility (U_{SU}) of each ST as well as the gross utility (GU_{SU}) of each t_{PT}, ultimately enhancing the overall utility of secondary network (OU_{SN}). The cooperative strategy, employing $M2O$ matching between SUs and PUs, is formulated as follows.

$$\begin{aligned} OU_{SN} &= \arg\max_{Q\subset Q'} \left(\sum_{q=1}^{|Q|} GU_{SU_{t_{PT_q}}} \right) \\ &= \arg\max_{Q\subset Q'} \left(\sum_{q=1}^{|Q|} \left(\sum_{k=1}^{|F|} U_{SU_{q,k}} \right) \right) \end{aligned} \tag{5.3}$$

$$OU_{SN} = \max_{Q\subset Q'} \left(\sum_{q=1}^{|Q|} \left(\sum_{k=1}^{|X|} U_{SU_{q,k}} \right) \right) \tag{5.4}$$

In this context, Q' represents all possible combinations of tuples comprising cooperative SUs, while Q denotes the total tuples formed through the proposed cooperation strategy. The variable F represents the available transmission frames of each PT corresponding to a specific tuple, denoted as t_{PT_q}. The cooperation technique, grounded in matching theory, is employed among the set of SUs to create Q suitable tuples. Each tuple of cooperative SUs is then paired with a preferred PU, accessing each of its frames for cooperative resource sharing and communication, thereby establishing a $M2O$ matching framework between the SUs and PUs. The establishment of the proposed $M2O$ matching model, comprising the formation of Q number of suitable tuples, and their mapping with preferred PUs for cooperative communication is illustrated as shown in Figure 5-4.

5.4.1 Analysis of matching theory for the proposed cooperative scheme

Due to the involvement of heterogeneous users with dynamic characteristics, optimal allocation of scarce resources among the users is more challenging in CRN. While optimizing, resources must be managed and allocated in a distributed manner so that the overall resource utilization gets be maximized and the users can jointly benefited. Matching theory is proven to be an efficient framework that analyzes mutually beneficial relationships between the users of two disjoint sets

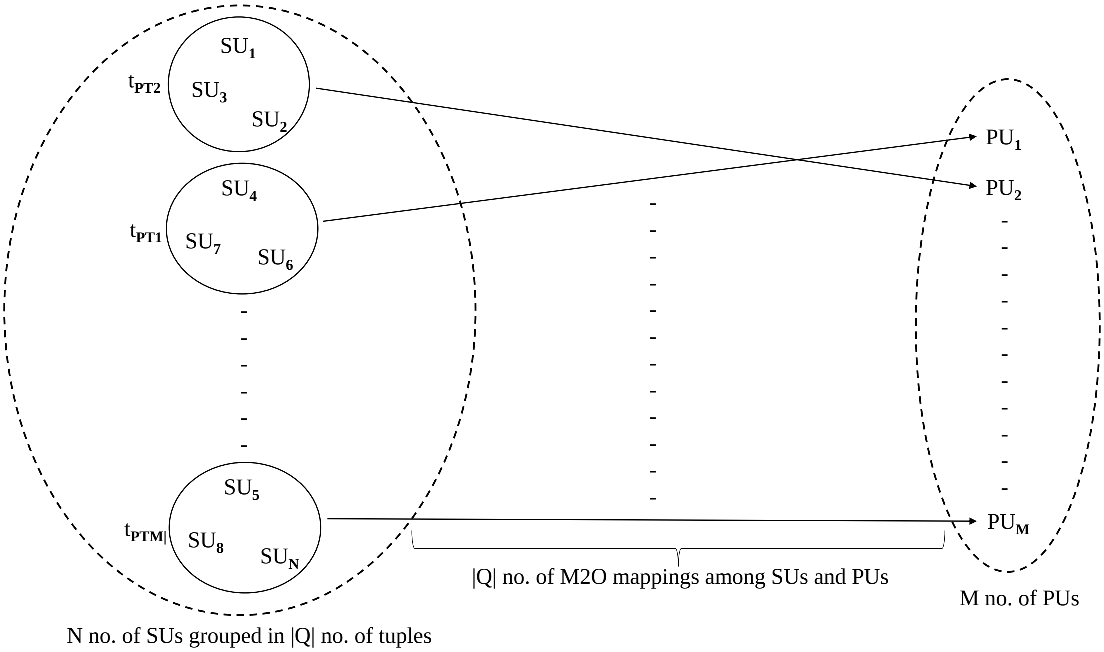

Figure 5-4: Proposed M20 matching based cooperative communication framework

and establishes win-win situations among them. The term "matching" is generally defined as two users suitably paired together to reach a stable or optimal state, where both are fully benefited from the each-other. In case of CRN, while dealing the sets of PU,s and SU's (or PU and SU market scenarios) for cooperative partner selection, the term *market equilibrium* offers a balanced (fair) solution through the formation of stable or optimal matching among the selected PU-SU partners. However, such equilibrium or matching are highly influenced by the nature of the market scenarios considered for resource sharing. Different types of matching under various market scenarios influence equilibrium. Before discussing these, relevant definitions of matching models are provided [44, 47, 55, 66] as follows.

Matching models

- ***O*ne-to-One ($O2O$) 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.,* $\mu(j) = i$*) Further,* $\mu(i) = i$ *and* $\mu(j) = j$ *indicates* i *and* j *stay single.*

- ***M*any-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 mapped 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 mapped 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.*

Matching market vs. matching types The types of matching differ depending on the network information known to the users. Here's a brief description of some matching market scenarios and the associated matching types for each scenario [22, 44, 66] are provided as below:

- **Open Market Scenario:** Here, each user of both the set PU and SU gains complete network information, like each others characteristic, configuration, 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 PU ($\mathcal{M}$) or for the set SU ($\mathcal{N}$).

  - *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 [44].

    However, in many-to-one matching model, an optimal matching between the group of cooperative users of set $\mathcal{N}$ (say $Coop_j$) and each user $i \in \mathcal{M}$ is the one that maximizes the individual utility of each cooperative user, thereby maximizing the gross utility of the cooperative group mapped to $i \in \mathcal{M}$ [40]. Alternatively, there exists an optimal matching for each $i \in \mathcal{M}$, ensuring that each i achieves the highest possible utility when paired with the cooperative user group in set $\mathcal{N}$.

    Consequently, to achieve SU-optimal matching in the proposed model, each $SU \in t_{PT_i}$ of set $\mathcal{N}$ should attain maximum U_{SU} when paired with preferred $PT_i \in \mathcal{M}$; so that the GU_{SU} belonging to t_{PT_i} increases and accordingly OU_{SN} of set $\mathcal{N}$ gets maximized. That is, in the proposed

M2O matching $\mu(t_{PT_i}) = PT_i$ is said to be optimal matching for set $\mathcal{N}$, if:

- Each ST $\in t_{PT_i}$ provides maximum U_{SU}.
- Each $\mu(t_{PT_i}) = PT_i$ provides maximum GU_{SU}.
- OU_{SN} of set N maximizes.

- **Partially Open Market Scenario:** Here, either the users of set PU or set SU or both are restricted from knowing the entire market information and they are allowed to know only few of the local information. This restricts the users from selecting most suitable partner for cooperative communication; as well as turns difficult to achieve optimal matching. In the proposed model, due to cooperative strategy adopted by SUs, PUs are confined from receiving multiple request messages from SUs. This turns the message exchange mechanism among PUs and SUs is partially opened for the set of PUs. In this context, new terminology called *Stable matching* is found more suitable for PUs as defined below.

  - *Stable matching*:

    In one-to-one matching, a pairing between user $i \in \mathcal{M}$ with the user $j \in \mathcal{N}$ is considered to be *stable*, if each of the resultant $i - j$ pair has no incentive to deviate from current partnership and both the partners achieve maximum possible benefit from each other. Such pairs are termed as **Unblocked pair** and a one-to-one matching having unblocked pairs of users is termed as *Stable 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 $\mu^{total} = \sum_{q=1}^{|Q|} \mu_q$ is a grand *M2O* matching with $|Q|$ number of individual *M2O* matching in it. A grand *M2O* matching $\mu^{total}()$, is said to be blocked by an individual *M2O* matching $\mu(t_{PT_i}) = PT_i$, if there exist another *M2O* matching $\mu^{/}()$ such that either t_{PT_i} or PT_i prefers $\mu^{/}()$ over $\mu()$. i.e.

    - $\mu^{/}(t_{PT_i}) \succ_{t_{PT_i}} \mu(t_{PT_i})$
    - $\mu^{/}(PT_i) \succ_{PT_i} \mu(PT_i)$

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. Similarly, in our proposed model, if any one of the $ST \in t_{PT_i}$ prefers $\mu^{/}(PT_i)$ over $\mu(PT_i)$ and yields more benefit from $\mu^{/}(PT_i)$, then the matching $\mu(t_{PT_i}) = PT_i$ becomes a **blocked** matching and accordingly the grand $M2O$ matching μ^{total} is termed as ***Group Unstable***.

5.4.2 Proposed cooperative strategy among SUs based on Matching Theory

We introduce a cooperation scheme designed for the set of SUs with the objective of enhancing secondary performance, focusing on maximizing SU utility, satisfaction, participation, and overall secondary network utility. The core concept behind this cooperation strategy is to group the most compatible SUs with similar PU preferences, aiming to pair them with the most preferred PU for CSS. Based on the concept of matching theory, the proposed cooperative scheme adopted by SUs is divided in two phases: (i) First phase: Formation of Non-Colloidal (NC) tuples of cooperative SUs and (ii) Second phase: Cooperative communication among the NC tuples and preferred PUs. The specifics of both phases of the proposed cooperative scheme are outlined in Algorithms 6 and 7. Prior to the commencement of the cooperative scheme, each SU constructs a Preference List (PL) based on the achieved U_{SU} values for respective α^* and β^* values (obtained from Algorithm 4 of Chapter 4). Subsequently, these PLs are exchanged among the SUs to share insights into each other's PU preferences. A colloidal (C) set is then formed, comprising SUs with identical PU preferences across consecutive PL locations, while SUs with non-colloidal PU preferences are segregated into another set termed as NC. The procedure for forming such NC set from set C is elaborated below. It should be noted, however, that all SUs are presumed to be trustworthy and dependable throughout the partner assignment and cooperative communication process.

First phase: In the beginning of this phase, the STs of set C having same PU preferences are shifted to set NC by grouping them in suitable tuple. Let consider a tuple $t_{PT_i} = \{ST_a, ST_b, ST_c\}$ is formed, where ST_a, ST_b and ST_c are cooperative SUs of tuple t_{PT_i}. All of these SUs in t_{PT_i} have PT_i as their top preference for cooperative communication, and consequently, t_{PT_i} collectively sends a single request to PT_i. In this way, each PT receives single request from corresponding t_{PT}. This constraint hinders the profit maximization inclination of PT, as it prohibits the PT from selecting the most lucrative ST by declining all requests received from other STs. The steps outlining the process of forming appropriate tuples of cooperative SUs are succinctly outlined in Algorithm 6.

Algorithm 6: Formation of Set NC with tuples of cooperative SUs

Input : α^*, β^* computed by each SU (in Algorithm 4).
Output: Suitable tuples t_{PT} of cooperative SUs in set NC.

Initialize: $C = \phi$, $NC = \phi$.
Preference List (PL) creation by SUs:
Based on (α^*, β^*), each SU computes U_{SU}.
Each SU prepares PL of PUs with decreasing order of U_{SU}, where size of $PL = [1 \times M]$.
Share the PLs of SUs among each other and keep the SUs with colloidal PU preferences in set C.
Keep each SU with non-colloidal PU preferences in set NC by adding them in individual tuple t_{PT} and mapped each t_{PT} to respective PU.
Update set C, where C = [no. of SUs with colloidal PU preference $\times$ no. of PU preferences]
Update set NC, where NC = [no. of t_{PT} of SUs having non-colloidal PU preference $\times$ 1].
while *(rows of $C \neq \phi$)* **do**
  for *i=1 to |columns| of set C* **do**
    for *j=1 to |rows| of set C* **do**
      for *k=1 to |rows| of set NC* **do**
        if *($Pref_i(SU_j)$==$Pref_i(SU_k)$ of $t_{PT_{SU_k}}$)* **then**
          Calculate remaining no. of frames of $Pref_i(SU_k)$ as: $frame_{rem,k}$ == ($frame_{total,k}$ - $frame_{allotted,k}$)
          if *($frame_{rem,k} > 0$)* **then**
            SU_j is added to the tuple $t_{PT_{SU_k}}$ followed by SU_k in set NC and all the further preferences of SU_j get removed from set C.
            Update $t_{PT_{SU_k}}$, C and NC accordingly.
          else
            SU_j waits for its next preferred PU.
          end
        else
          Compare ER_{ST} of all the SUs having same $Pref_i$ in set C and select SU_j with least ER_{ST}.
          Form a tuple $t_{PT_{SU_j}}$ in set NC and add SU_j to it.
          Remove SU_j along with its further preferences from set C.
          Update C and NC accordingly.
        end
      end
    end
  end
end
Extract all the tuples formed in set NC.

Time complexity of Algorithm 6: To analyse the overall time complexity of Algorithm 6, we need to investigate the running time of each **For** loop (steps 10, 11, 12) separately. The **For** loop (step 10) runs for maximum M times, as number of columns of set C depends on the length of SU's PL. Next, **For** loop (step 11) runs $\leq N$ number of times, as few of the SUs became the part of set NC. Finally, the third **For** loop (step 12) depends on the number of matching among the tuples and the preferred PUs in set NC. Let analyse the worst case scenario, where all the N SUs prefer PT_i as their first preference, PT_{i+1} as second preference and so on. In such condition, tuple t_{PT_i} is formed considering the SUs equal to the number of available frames of PT_i. Similarly, tuple $t_{PT_{i+1}}$ is formed from the rest of the SUs and this process continues until all N SUs could include in suitable t_{PT}. Since there are M PUs, so at most M number of t_{PT} could be formed preferring M PUs separately. This implies the number of matching among t_{PT} and preferred PU is at most M. Therefore, the worst case running time of all the three **For** loops is $= O(M \times N \times M) = O(NM^2)$, which is a **polynomial time** complexity.

Second phase: In this phase, each PT_i receives request from corresponding t_{PT_i} and established a $M2O$ matching among t_{PT_i} and PT_i i.e. $\mu(t_{PT_i}) = PT_i$. It is important to note that PT_i accepts the request of t_{PT_i} only if the number of cooperative SUs in t_{PT_i} is less than or equal to its available frames. Now, let analyse how cooperative SUs belonging to t_{PT_i} participate in cooperative communication with PT_i and transmit both primary and secondary data to intended receivers. As outlined in section 5.3, we have adopted frame-based data transmission for cooperative communication between PUs and SUs, where each PU frame is further divided into three phases for cooperative and secondary communications. In this context, to engage in cooperative communication with the matched PU, each ST $\in t_{PT_i}$ cooperatively takes turns to serve PT_i on a per-frame basis. Additionally, to determine the sequence among the SUs, a *Turn Unit* is established for each ST over R rounds. It's important to note that the value of R depends on the PU's service requirements and is defined by the PU itself.

Initially, PT_i provides turn to the least expensive ST of t_{PT_i} for transmission; then prefer second least expensive ST and so on. For example, in case of $t_{PT_i} = \{ST_a, ST_b, ST_c\}$, if ST_b is the least and ST_c is the most expensive users, then PT_i provides initial transmission access to ST_b followed by ST_a and ST_c in its adjacent frames according to a priority access list (PA_{list}). The PA_{list} for STs in subsequent rounds is formulated using the same method and the process continues until the total number of rounds is completed. The PA_{list} for the aforementioned,

t_{PT_i} for $F = 4$ frames and $R = 2$ rounds is constructed as follows:

	1	2	3	4
$PA_{list,1}$ =	ST_b	ST_a	ST_c	ST_b

	1	2	3	4
$PA_{list,2}$ =	ST_a	ST_c	ST_b	ST_a

According to $PA_{list,1}$ and $PA_{list,2}$ each $ST \in t_{PT_i}$ gets equal turn (or opportunity) for transmission, except ST_c at the end of round 2. Hence, we conclude that after R rounds each ST of tuple t_{PT_i} gets chance to access each PT frame equally, except the top expensive STs arranged in descending order, if t_{PT} consist odd number of STs and matches the PT with even number of frames as well as rounds or vice versa. The details of second phase are summarized in Algorithm 7.

Time Complexity of Algorithm 7: To analyse the overall time complexity of Algorithm 7, we need to investigate the running time of outer **For** loops (steps 3 and 4) as well as the nested **For** loop (step 15) separately. The outer **For** loop (Step 3) runs maximum M times as number of tuples in set NC are not more than total number of PUs i.e. M. Next **For** loop (Step 4) runs maximum M times, where each iteration j again depends on the nested **For** loop (step 15), which is based on the number of transmission frames available at each PU. Let's consider that PT_1 has 1 frames, so the nested **For** loop k runs 1 time. Similarly, PT_2 has 2 frames and thus k runs 2 times. Lets assume the worst-case scenario, where PT_M has a maximum F number of frames for which k runs F times. So, in worst case, the nested **For** loop runs $= 1 + 2 + 3 + ... + F = \frac{F(F+1)}{2} = F^2$ times, and thus the running time complexity of both the **For** loops (step 4 and 15) is $= O(M \times F^2) = O(MF^2)$. Therefore, the worst-case running time complexity of all the **For** loops (step 3, 4 and 15) are $= O(M \times M \times F^2) = O(M^2F^2)$, which is a polynomial time complexity. However, the value F depends on each PU's service requirements and it will not be a very large number.

5.4.2.1 Stability analysis of the proposed matching game model

Theorem 1: Algorithms 6 and Algorithm 7 converge pairwise stable for each $\mu(t_{PT_i}) = PT_i$, which further converges the resultant $\mu^{total}()$ as Group Stable for the set of PUs.

Proof: The set NC in Algorithm 6 is designed to facilitate the formation of tuple t_{PT_i} by the SUs that have the highest preference for PT_i. This allows them to engage in cooperative communication with PT_i in a sequential manner,

Algorithm 7: $M2O$ matching among cooperative SUs and preferred PUs.

Input : All tuples of cooperative SUs formed in set NC.
Output: Utility of PUs, Gross Utility of each t_{PT} and Overall Utility of set N.

Initialize: Matching among (t_{PT}, PT) is null, i.e. $\mu(t_{PT}) = PT = \phi$, $\mu^{total}() = \phi$, $OU_{SN} = 0$.
while *(Till the STs of each t_{PT} is matched with preferred PT.)* **do**
  for *each t_{PT} $i = 1$ to $|NC|$.* **do**
    for *each PT $j = 1$ to $|M|$.* **do**
      if *($Pref(t_{PT,i}) == PT_j$)* **then**
        Establish $\mu(t_{PT_i}) = PT_j$.
        Calculate $frame_{total}$ of PT_j.
        Extract individual resource information of each ST $\in t_{PT,i}$.
        Ranked the STs based on their ER_{ST}.
        Construct $PA_{list,j}$ based on the ranking.
        Set $flag == 0$ for all STs of $PA_{list,j}$.
        Initialize $U_{PU,j}^{|frame_{total}|} = 0$.
        Initialize $GU_{SU,i} = 0$.
        while *($flag == 1$ for all STs of $PA_{list,j}$)* **do**
          for *each frame $k = 1$ to $|frame_{total}|$* **do**
            Allocates $frame_k$ to the ST present at location $PA_{list,j}[k]$.
            Extracts α^* and β^* of the ST allocate to $frame_k$.
            Calculate $U_{PU,j}^{frame_k}$ based on α^* and β^* provided by ST^{frame_k} and releases $(T - \beta^*)$ to the same.
            Calculate $U_{PU,j}^{|frame_{total}|} = U_{PU,j}^{|frame_{total}|} + U_{PU,j}^{frame_k}$.
            Based on released $(T - \beta^*)$, ST^{frame_k} calculates $U_{SU}^{frame_k}$.
            $GU_{SU,i} = GU_{SU,i} + U_{SU}^{frame_k}$.
            Set $flag == 1$ for the ST present at location $PA_{list,j}[k]$.
          end
        end
        Extract $U_{PU,j}^{|frame_{total}|}$ of PT_j and termed it as $U_{PU,j}$.
        Extract $GU_{SU,i}$ for corresponding $t_{PT,i}$.
        Add $\mu(t_{PT_i}) = PT_j$ to $\mu^{total}()$ and update it.
      end
    end
    $OU_{SN} = OU_{SN} + GU_{SU,i}$
  end
  Extract OU_{SN} of set NC and $\mu^{total}()$.
end

resulting in the highest possible U_{SU} of each SU. This guarantees that every SU of tuple t_{PT_i} is inclined to sustain the relationship with PT_i and has no intention to deviate from the existing partnership. In contrast, when transmitting the request message to the PUs, the STs adhere to a cooperative method in which each PT_i can only receive a single request message from the corresponding t_{PT_i}. Hence, PT_i has no additional alternatives to consider except accepting the request transmitted by t_{PT_i}. Therefore, PT_i readily agrees to the request and permits cooperative communication in a turn-based manner with each ST of t_{PT_i}. This results in every (t_{PT_i}, PT_i) as the unblocked pair and every matching $\mu(t_{PT_i}) = PT_i$ as pairwise stable. Hence, proved that the resultant $\mu^{total} = \sum_{q=1}^{|Q|} \mu_q$ is Group stable.

Theorem 2: Algorithm 6 and Algorithm 7 converge to optimal equilibrium for the set of SUs.

Proof: Algorithm 6 generates tuples of cooperative SUs by taking into account the maximum number of SUs that have the highest preference for PT_i are grouped together to form tuple t_{PT_i}. This formation allows each $ST \in t_{PT_i}$ to engage in cooperative communication with its preferred PT_i. Thus, the proposed technique offers an opportunity for each ST to engage in cooperative communication by forming pairs with their preferred PT.

Moreover, in Algorithm 7, PT_i grants access to all ST within t_{PT_i} over its dedicated frames, as outlined by the priority access list. This enables each $ST \in t_{PT_i}$ to achieve its desired transmission rate and maximize its U_{SU} (as calculated in Algorithm 6). As a result, the GU_{SU} of each t_{PT} and, correspondingly, the OU_{SN} of set $\mathcal{N}$ are maximized. This substantiates that the set of SUs attains an optimal equilibrium.

Summary: The proposed many-to-one matching scheme effectively maps the maximum feasible SUs with their preferred PUs for cooperative spectrum sharing. However, it's essential to note that in a worst-case scenario, where a large number of SUs primarily prefer the same PU, two situations may emerge: (i) the most expensive SUs might not be included in the desired tuple and therefore refrain from being matched with their top-choice PU, and (ii) the less preferred PUs may remain unmatched or unpaired with any SUs within the CSS framework. In situation (i), this results in a stable match for the most expensive SUs rather than an optimal match. Furthermore, we can address situation (ii) more effectively by delving into the concept of many-to-many mapping between the sets of PUs and SUs. However, it is worth noting that this area requires further investigation and development to fully resolve such concerns.

5.5 Simulations Results and Discussion

We carried out a simulation-based experiment in MATLAB [4] to study and evaluate the performance of the proposed many-to-one matching based cooperative communication scheme among PUs and SUs. A cognitive radio network (CRN) comprising M primary users (PUs) and N secondary users (SUs) is considered, where M is less than N ($M < N$). The PUs and SUs are randomly distributed within a square area measuring 1000×1000 m^2. We adopt channel gain formulas and path loss exponents as specified in [100]. Other simulation parameters and their values used to perform simulation are given in TABLE 5.2. These meticulously chosen parameters and settings form the foundation for our comprehensive evaluation of the proposed solutions within the context of the CR network under investigation.

Parameters	Values
M	5 to 15
N	5 to 30
F	2 to 4 (variable)
T	10 sec.
W	1 MHz.
P_{PT}, P_{ST}	[0.02 to 0.05] Watt
$d_{PT,PR}$	600 to 800 m (variable)
$d_{ST,SR}$	300 to 500 m (variable)

Table 5.2: Simulation parameters and their values

To evaluate the performance of proposed many-to-one based matching scheme (also termed as $M2O-P$) an existing work [113] based on one-to-many matching (termed as $M2O-E$) was proposed, where each PU collaborates with multiple SUs during cooperative spectrum sharing (CSS) process with an aim to maximize their utility. It is noted that in both the $M2O-P$ and $M2O-E$ schemes, the utility functions' units are maintained by restructuring the utility of PUs and SUs in terms of data transmitted per unit of energy consumed. Further, inspired by [96], a many-to-one 'nearest-SU' matching scheme (termed as $M2O-N$) based on greedy method is also considered for performance evaluation purposes, where each PU gets paired with its two closest SUs that haven't been matched with any other PU. Finally, the $O2O$ scheme detailed in the preceding chapter (Chapter 4), which grounded in a non-cooperative approach among SUs is also considered for performance evaluation purposes, where each PU being paired with the most suitable SU and establish stable PU-SU pairs for cooperative communication. To conduct the comparative analysis across varying numbers of PUs and SUs in the network, we have considered two CRN scenarios: (a) with $N = 5$ to 30 SUs and $M = 5$ PUs and, (b) with $N = 5$ to 30 SUs and $M = 10$ PUs.

5.5.1 Performance Metrics

Following metrics have been used for simulation based performance analysis.

- Average utility of PUs (avg. U_{PU}): Utility achieved by M number of PUs that calculated based on Eq. (5.1).
- Average utility of SUs (avg. U_{SU}): Utility achieved by N number of SUs that calculated based on Eq. (5.2).
- Average satisfaction of SUs (avg. SAT_{ST}): Satisfaction achieved by N number of SUs (in %) during cooperative communication with preferred PU that calculated based on Eq. (5.7).
- Percentage of participation of SUs ($\%P_{ST}$): Out of total N number of SUs, how many of them can able to participated in the cooperative communication and calculated based on Eq. (5.10).
- Throughput fairness index of SUs (Th_{ST}^{FI}): It measures (between 0 to 1) how fairly the PU resources are allocated among SUs to obtain corresponding SU throughput or utility and calculated based on Eq. (5.11).

5.5.2 PU utility analysis for proposed scheme vs. existing schemes

Figure 5-5 depicts the avg. utility of PUs (U_{PU}) achieved in both (a) and (b) scenarios from the considered schemes. In *O2O* scheme, as the number of SUs increases, PUs have more options to choose the best SU request by rejecting the prior one. This consequently improves the avg. U_{PU} in both (a) and (b) scenarios as shown in the figure (blue lines). Moreover, scenario (b) involves a greater number of PUs than scenario (a), which increases the number of *O2O* mappings between PUs and SUs in the network, thereby enhancing the value of avg. U_{PU}.

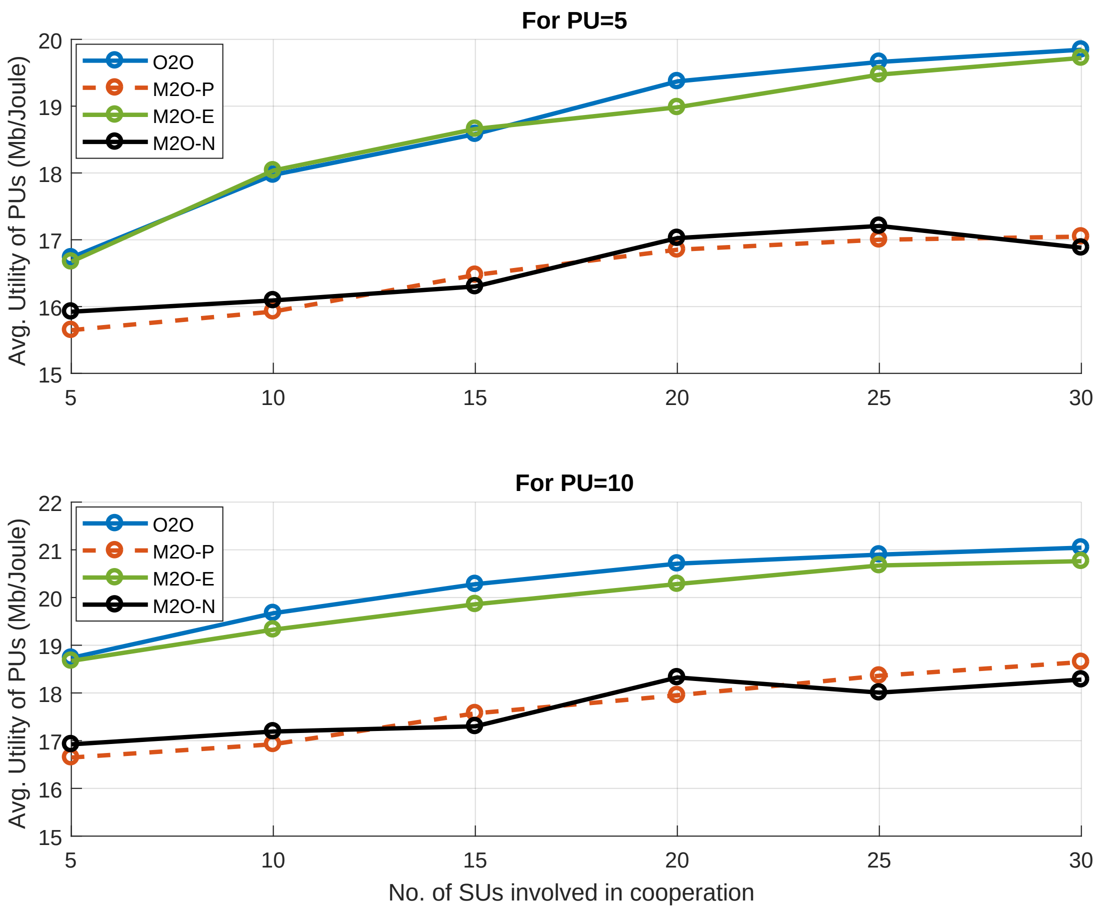

Figure 5-5: Avg. utility of PUs vs. varying no. of PUs and SUs in the network

Moreover, in the $M2O - E$ scheme, the matching process is primarily controlled by the PUs. Each PU generates its duplicate and independently sends requests to its most favored SUs for CSS. SUs accept the PU's offer if it promises greater profit than previous offers; otherwise, they decline it. Consequently, this strategy enhances the avg. utility value of PUs, as depicted in the graph (green lines), reaching a utility level comparable to that achieved in the $O2O$ process in both (a) and (b) scenarios. However, within the $M2O - N$ scheme, there is a possibility that in worst case a PU could either be paired with its least favored SUs or not be matched at all. Consequently, this results in minimal utility attainment for the PUs in such instances (black lines) despite the increased participation of both SUs and PUs in the cooperative communication process.

Finally in the proposed $M2O - P$ matching scheme, cooperative SUs collectively send the request message to their preferred PU by forming a suitable t_{PT} rather than sending individual requests. Now, as the number of SUs and PUs increases in the matching process, two possible outcomes may be observed: (i) the size of the existing t_{PT_i} may be increased by the addition of new SUs that prefer

PT_i, which affords the newly joined SUs the opportunity to perform cooperative communication with PT_i. And (ii) new tuples can be formed taking into account the newly added SUs, and they may favor either the newly added PUs or the PUs that have not yet been matched to any tuples. Thus, the entire procedure establishes matching between the tuples of cooperative SUs and preferred PUs. But unlike the $O2O$ and $M2O - E$ matching schemes, the $M2O - P$ matching scheme is modeled from SU's perspective, limiting each PU by receiving a single request from each tuple, which limits the rate of utility enhancement of PUs. Consequently, the graphs of avg. U_{PU} (dotted orange lines) in $M2O - P$ matching scheme show less growth, when compared to $O2O$ and $M2O - E$ matching schemes, despite the fact that more SUs and PUs participate in the cooperative communication process.

5.5.3 SU's utility analysis for proposed scheme vs. existing schemes

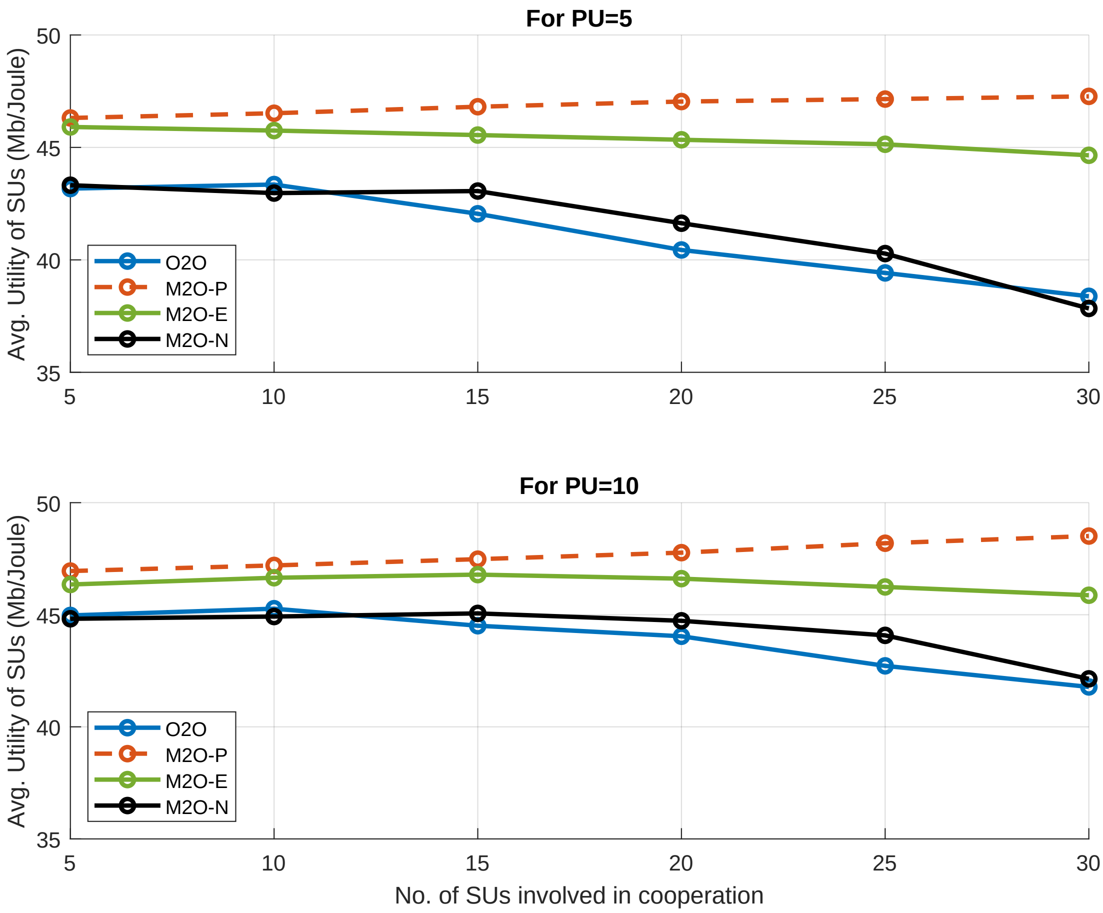

Figure 5-6: Avg. utility of SUs vs. varying no. of PUs and SUs in the network

Figure 5-6 shows the avg. utility of SUs (U_{SU}) obtained for $O2O$ matching and overall utility of set SUs achieved for the $M2O - E$, $M2O - N$ and $M2O$ matching schemes for both the scenarios (a) and (b). In $O2O$ approach, as the number of SUs increases, PUs might repeatedly reject the partnership with previously assigned SUs and are partnered with new SUs to maximize their U_{PU}. Therefore, some of the SUs may not be coupled with any of the PUs, or they may be paired with the least preferred PUs. This significantly degrades U_{SU}, as depicted in the graph (blue lines). However, due to involvement of more PUs in scenario (b), more SUs get opportunity to be paired with PUs, which limits the reduction of U_{SU} in (b) than in (a). Furthermore, in the case of the $M2O - E$ scheme, an SU has the option to either accept or decline PU's offer based on its utility gains, but it lacks the ability to negotiate for higher compensation in order to maximize its own utility. The authority for resource allocation remains solely with the PUs. Consequently, as more SUs participate in the cooperative process, PUs have a wider range of suitable SU options for CSS and can establish new pairings by breaking previous ones. This results in a decrease in SU utility, as depicted in the graph (green lines). However, with an increase in the number of PUs in scenario (b), SUs receive new proposals from PUs, thereby improving their utilities compared to scenario (a). However, $M2O-N$ matching scheme overlooks SU preferences when pairing with PUs, as PUs simply choose their two closest SUs for CSS without regard for SU preferences. Consequently, the likelihood of SUs being paired with suitable PUs is very low in this scheme, leading to a decrease in SU utility, as illustrated in the graph (black lines).

Finally in the proposed $M2O - P$ matching scheme, each tuple of cooperative SUs requests the favored PU for cooperative communication. Unlike $O2O$ and $M2O - E$ matching scheme, this scheme prevents repeated rejection of SUs by the PUs and maximizes SU participation, with the majority of SUs having the opportunity to be partnered with the preferred PU. Moreover, the ability to allocate optimal time, represented by β, favors SUs significantly, leading to considerable increases in both U_{SU} and GU_{SU} of cooperative SUs. This subsequently maximizes the OU_{SN} of the SU network, as depicted in the graph (dotted orange lines). Involvement of more PUs in the network, as in scenario (b), provides more options for SUs to be mapped with their most preferred PU, which substantially improves their utility, as shown in Figure 5-6.

5.5.4 SU's satisfaction analysis for proposed scheme vs. existing schemes

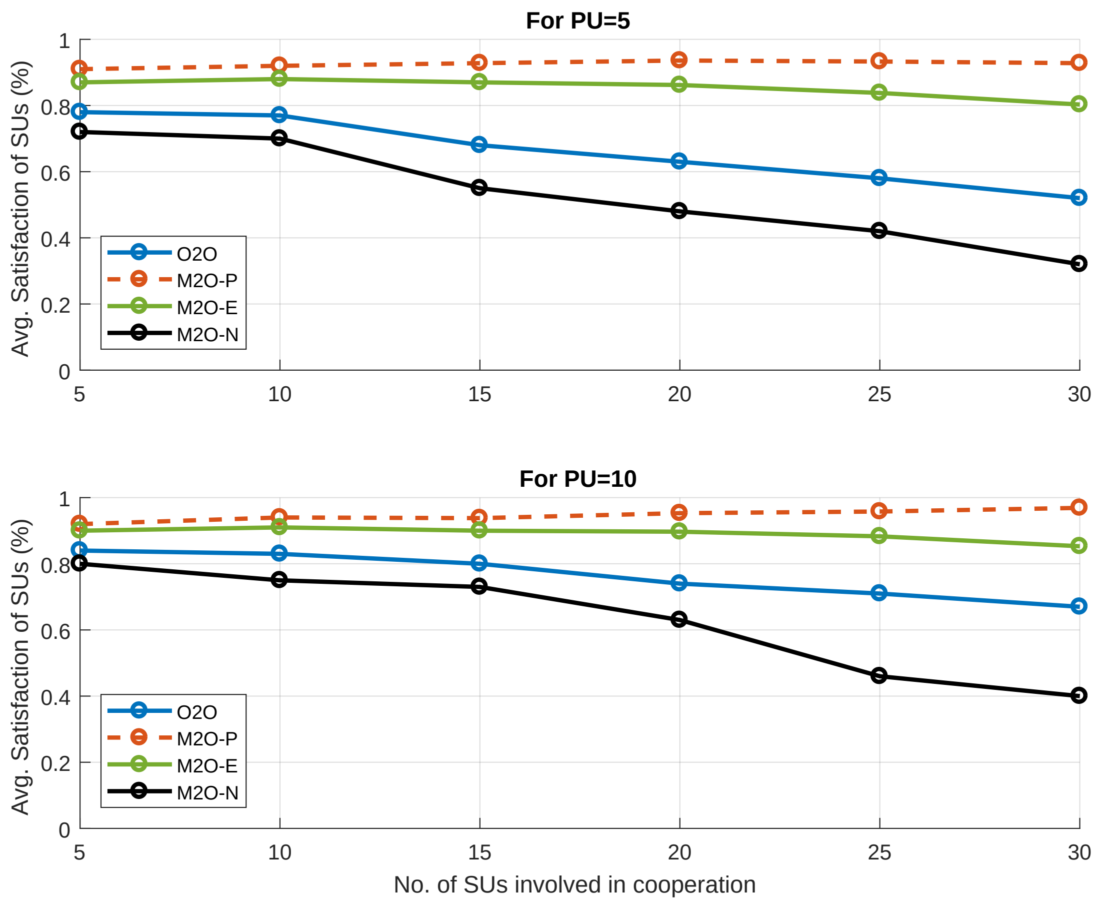

Figure 5-7: Avg. satisfaction of SUs vs. varying no. of PUs and SUs in the network

Figure 5-7 shows the avg. satisfaction level of SUs, with the increase of SUs and PUs participating in the proposed matching processes. Inspired by [94], satisfaction of each SU (SAT_{ST}) in a $O2O$ matching is determined based on the position of matched PU in the preference list of SU; and it is formulated as follows:

$$SAT_{ST}^{O2O} = \frac{(M+1)-p}{M} \tag{5.5}$$

Here, M is the total number of PUs and p is the position of PU in the preference list of SU. Similarly, the avg. satisfaction for N matched SUs with M PUs is given as follows:

$$SAT_{ST}^{avg} = \frac{\sum_{j=1}^{N}(M+1)-p_j}{M \times N} \tag{5.6}$$

The above formula is modified for the proposed $M2O$ matching approach for total N number of SUs and K number of (t_{pt}, PU) matching as follows:

$$SAT_{ST} = \frac{\sum_{j=1}^{N}\left(K_{(t_{pt},PU)} + 1\right) - p_j}{K_{(t_{pt},PU)} \times N} \tag{5.7}$$

In $O2O$ matching, each SU_j seeks to get pair with the most preferred PU of its PL_j. In this case, as the number of SUs increases, PUs have more opportunities to decline previously mapped SUs in favor of more profitable SUs. This causes some SUs to be paired with their least preferred PUs, substantially decreasing their satisfaction as shown in the graph (blue lines). As the number of participating PUs is greater in scenario (b), SUs have a greater chance of being paired with a more desirable PU, thereby preventing a decrease in their level of satisfaction compared to scenario (a). A comparable outcome is noted in the $M2O - E$ matching scheme, where the preferences of each PU regarding SUs are altered as the number of SUs increases. Unlike $O2O$ scheme, in this scenario, SUs have the opportunity to select the most favorable offer from PUs, resulting in an enhanced average utility for SUs (green lines) compared to the $O2O$ scheme. Conversely, the $M2O - N$ matching scheme is primarily driven by PU preferences, and SU's preferences regarding PUs are disregarded. Consequently, a significant decrease in SU satisfaction is evident in the $M2O - N$ matching scheme (black lines).

Finally, in the proposed $M2O - P$ matching scheme, each SU of tuple t_{PT_i} prefers PT_i the most and receives the opportunity to get paired with PT_i for cooperative communication. This assists all cooperative SUs of each t_{PT} in establishing optimal matching with the preferred PU, thereby increasing the average level of satisfaction among SUs, as depicted in the graph (dotted orange lines). Involving more PUs in the network, as in (b), increases the number of stable (t_{PT}, PT) pairs in the communication process, which enhances the satisfaction level of SUs more than in (a) as shown in Figure 5-7.

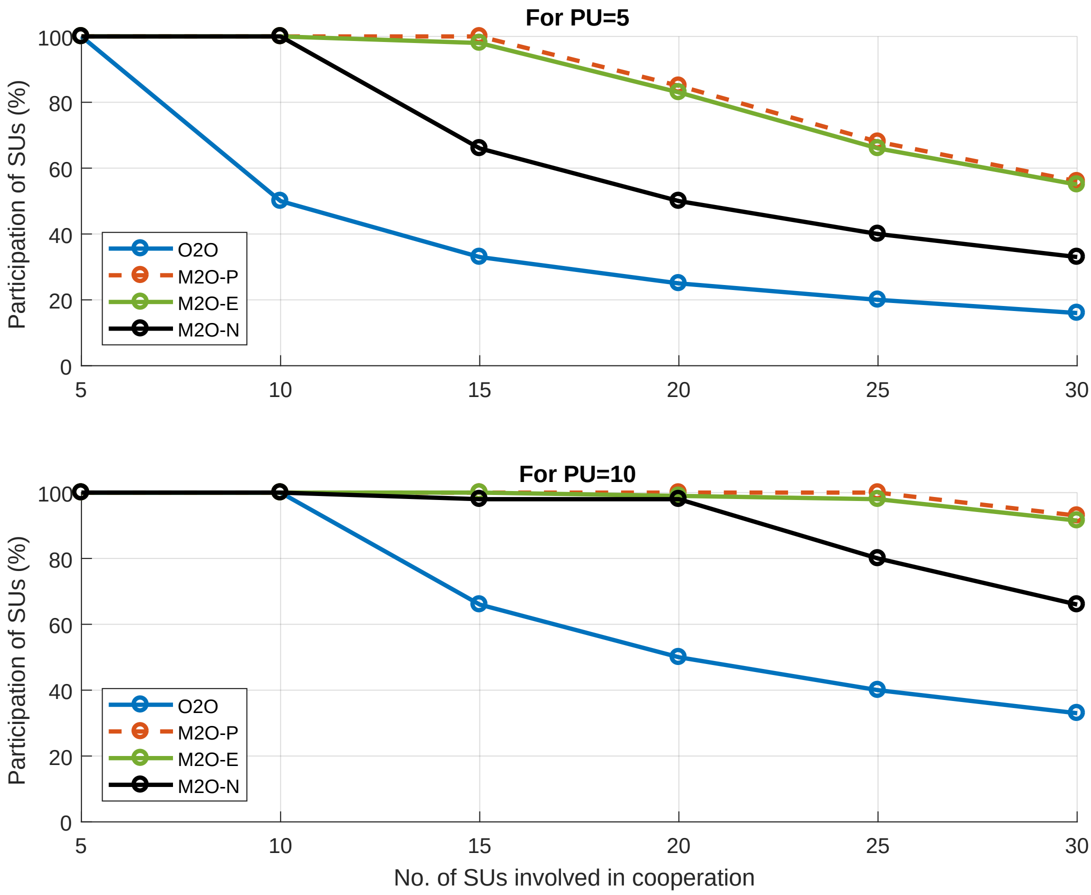

Figure 5-8: Participation of SUs vs. varying no. of PUs and SUs in the network

5.5.5 SU's participation analysis for proposed scheme vs. existing schemes

To further investigate the engagement of SUs in cooperative communication, we analyze the percentage of SUs participating in the proposed scheme (denoted as $\%P_{ST}$) and compare its performance with the SUs participating in the considered existing schemes as illustrated in Figure 5-8. In the case of *O2O* matching, the $\%P_{ST}$ is computed as follows:

$$\%P_{ST}^{O2O} = \frac{\text{Number of SUs involve in } O2O \text{ scheme}}{\text{Total number SUs}} \times 100\% \tag{5.8}$$

Similarly, to compute the average participation of SUs involved in a *M2O* matching scheme, the Eq. (5.8) can be rewritten as:

$$\%P_{ST}^{avg} = \frac{\sum_{1}^{|PU|} (\text{Number of SUs mapped with each PU})}{\text{Total number SUs}} \times 100\% \tag{5.9}$$

Finally, Eq. (5.9) is modified for the proposed $M2O$ approach as follows:

$$\%P_{ST} = \frac{\sum_{1}^{|Q|} (\text{Number of SUs in each tuple})}{\text{Total number SUs}} \times 100\% \tag{5.10}$$

In Figure 5-8, it is evident that in $O2O$ matching scheme full participation of SUs is achieved for exactly 5 SUs involved in the cooperative communication process in case of scenario (a). A similar pattern is observed in scenario (b), where full participation of SUs is maintained only up to a total of 10 SUs in the network. Further, the graph of participation is found to gradually decline in both cases with the increase in the number of SUs (blue lines). Therefore, in $O2O$ matching, complete participation of SUs is achieved only up to the point where M is equal to N in the network. This limitation arises due to conventional concept of $O2O$ matching, wherein each SU can only collaborate with precisely one PU during cooperative communication. However, in the $M2O - N$ scheme, due to each PU selecting precisely two of its nearest SUs as cooperative partners, there's the potential for twice as many SUs as PUs to engage in the cooperative communication process. Consequently, with a further increase in the number of SUs surpassing twice the number of PUs, a notable decline in the graph illustrating the average participation of SUs has been observed (black lines).

Nevertheless, in the context of $M2O-E$ and $M2O-P$ matching schemes, complete SUs participation is maintained up to a certain point, even with an increased number of SUs involved in cooperative communication. However, as the number of SUs in the network continues to rise, a marginal decrease in SU's participation is observed for PU = 10, and a relatively larger reduction is noted for PU = 5 (green and dotted orange lines respectively). This decline is attributed to the constrained availability of PU frames in the network, preventing the accommodation of all available SUs.

5.5.6 SU's throughput fairness index analysis for proposed scheme vs. existing schemes

Finally, Figure 5-9 reveals the throughput fairness index (measure between 0 to 1) of all N SUs involved in the assignment process. Throughput fairness, is necessary to maintain equality among the users of CRN. This consideration stems from the need to fairly allocate resources among all SUs in a CRN scenario and determine the corresponding throughput (profit) achieved by each SU in the network.

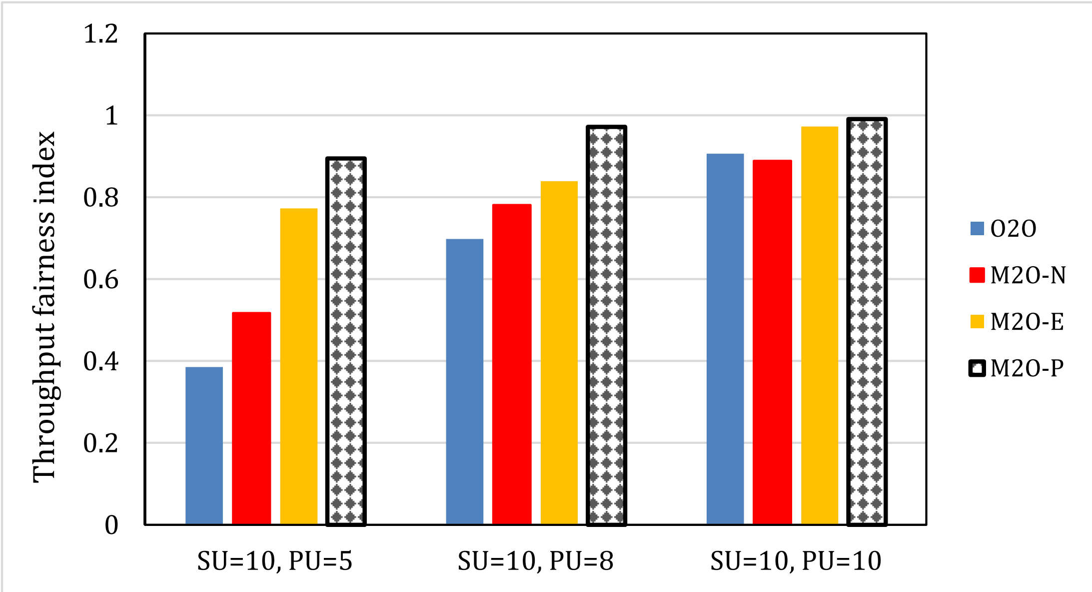

Figure 5-9: Fairness performance of the proposed approach vs. considered approaches

In case of $O2O$, $M2O-N$ and $M2O-P$ matching schemes, the throughput fairness for SUs is measured based on the parameter C_{ST} (given in Eq. (5.2)) obtained by each SU after accessing the compensation provided by the cooperative partner PU. However, in case of $M2O-E$ scheme, the throughput fairness for SUs is measured based on Eq.(9) given in the study [113]. Drawing inspiration from [56], [65], the avg. throughput fairness index (termed as Th_{ST}^{FI}) for N SUs is formulated as:

$$Th_{ST}^{FI} = \frac{\left(\sum_{SU\in\mathcal{N}} C_{ST}\right)^2}{\left(|N| \times \sum_{SU\in\mathcal{N}}(C_{ST})^2\right)} \tag{5.11}$$

To compare the fairness performances of SUs for each considered scheme, a CRN scenario with a constant number of SUs, denoted as $N = 10$ and three cases with increasing number of PUs, (i) $M = 5$, (ii) $M = 8$, and (iii) $M = 10$ are considered. In the $O2O$ matching scheme, each PU forms a partnership with the most profitable SU. As a result, only 5 SUs in case (i), 8 SUs in case (ii), and all 10 SUs in case (iii) get opportunities to engage in cooperative communication. However, in the $M2O-N$ scheme, each PU establishes partnerships with two of its nearest SUs, facilitating the potential engagement of all 10 SUs in the cooperative communication process. With the exception of case (iii), both cases (i) and (ii) have shown a better average throughput fairness index for SUs with the $M2O-N$ scheme compared to $O2O$, as more SUs receive transmission opportunities in the former scheme. Although SU's preferences over PUs are not considered in the $M2O-N$ scheme, a slight decrease in the average throughput fairness index is observed for case (iii) in $M2O-N$ (red bar graph) compared to the $O2O$ matching scheme (blue bar graph).

On the contrary, unlike the $M2O-E$ scheme, the proposed $M2O-P$ matching scheme is devised from the perspective of SUs, granting them the exclusive privilege to pair with their preferred PUs for cooperative communication. This results in increased capacity during secondary transmission, consequently enhancing the throughput fairness index of SUs in the $M2O-P$ matching scheme (patterned bar graph) compared to the $M2O-E$ matching scheme (yellow bar graph), as depicted in Figure 5-9.

5.6 Conclusion

In this chapter, we explored cooperative strategies used by secondary users (SUs) in cooperative spectrum sharing (CSS) to align with their preferred primary user (PU) for both cooperative and secondary communication. We implemented a many-to-one matching scheme using the concept of group stable matching. This allows each set of cooperative SUs to map with their most preferred PU. The proposed scheme achieves stable matching for PUs and optimal matching for SUs by maximizing the gross utility of cooperative SUs and the overall utility of the secondary network. The theoretical proofs for the stability and optimality of the matching game are provided. We conducted a simulation study of the many-to-one matching scheme in MATLAB and performed a comparative analysis to evaluate its performance against similar existing schemes and the one-to-one matching scheme. The comparison demonstrated the superior performance of our proposed scheme, enhancing overall secondary utility, SU satisfaction, participation, and throughput fairness. However, the proposed scheme may reduce PU utility, as each PU can only accept one joint-SU offer. Nonetheless, we theoretically established the stability of the proposed matching scheme for PUs and its optimality for SUs.

In addition to spectrum scarcity, energy constraints are a major concern for SUs in Cognitive Radio Networks (CRNs). Managing the allocation of limited energy during cooperative and secondary transmission is challenging. The next chapter addresses energy harvesting for SUs and explores efficient energy allocation during cooperative and secondary communication in a many-to-one mapping scenario between SUs and PUs.