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RESEARCH ARTICLE

# A Stochastic Spectrum Trading and Resource Allocation Framework for Opportunistic Dynamic Spectrum Access Networks

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**ABSTRACT** In this article, the spectrum trading problem between primary users and secondary networks is investigated. The secondary network requests multiple channels with the targeted availability to satisfy its users' demands. Due to the uncertainty about the channels availability, stochastic optimization techniques are adopted to find the optimal set of channels for each secondary network for the lowest cost. Two different constraints on the secondary demand are defined. The first one is when the throughput has to be fully satisfied for a certain percentage of time, and the second one is when the expected value of the throughput has to exceed a certain percentage of the requested one. Also, the possibility for channel subleasing among the secondary networks is investigated to reduce the demand shortage. The results show that demanding simultaneous channels increases the cost as it reaches up to 20% higher than if the same resources were requested individually. Also, channels subleasing reduces the demand shortage probability and increases the achieved throughput, especially at low value of requested demand. In this case, the demand satisfaction probability increases by around 30% while the achieved throughput increases up to 40% compared to the scenario where channels subleasing is not allowed.

**INDEX TERMS** Dynamic spectrum access, cognitive radio, spectrum trading, stochastic optimization.

## I. INTRODUCTION

Dynamic Spectrum Access (DSA) has been proposed as a promising solution to overcome the spectrum scarcity problem. In DSA systems, unused spectrum (time slots/frequency bands) of the incumbent user (Primary User (PU)) may be utilized by another unlicensed user (Secondary User (SU)) using an access mechanism that does not cause any service degradation for the PU. Cognitive Radio (CR) is the enabling technology behind DSA systems. A radio transceiver equipped with CR technology continuously senses the available channels and switches among them to find the best one to use without interfering with the PU's transmission. There are many challenges facing the CR realization. Some of these challenges require modifying conventional wireless technologies like physical layer [1], MAC layer [2], and higher layers like routing [3] and security [4]–[6] to cope with the DSA network characteristics. Other challenges rise due to the probabilistic nature of the DSA networks. Two of these challenges are the resource allocation (spectrum sharing between PUs and SUs), and the secondary network channel access mechanism.

In our previous work [7], we investigated the joint problem of price-based spectrum trading and channel access in opportunistic DSA networks where the secondary system consists of a single Secondary Network (SN)[1] and a number of PUs who wish to trade their free spectrum time. The objective is to achieve an optimal spectrum trade and resource allocation agreement between the SN and the licensed PUs such that the SN pays the lowest cost for the minimum amount of resources that satisfy its SUs' demand. To facilitate the SUs

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[1] SN refers to an infrastructure based network which serves a number of SUs and control their access to the PUs' channel.

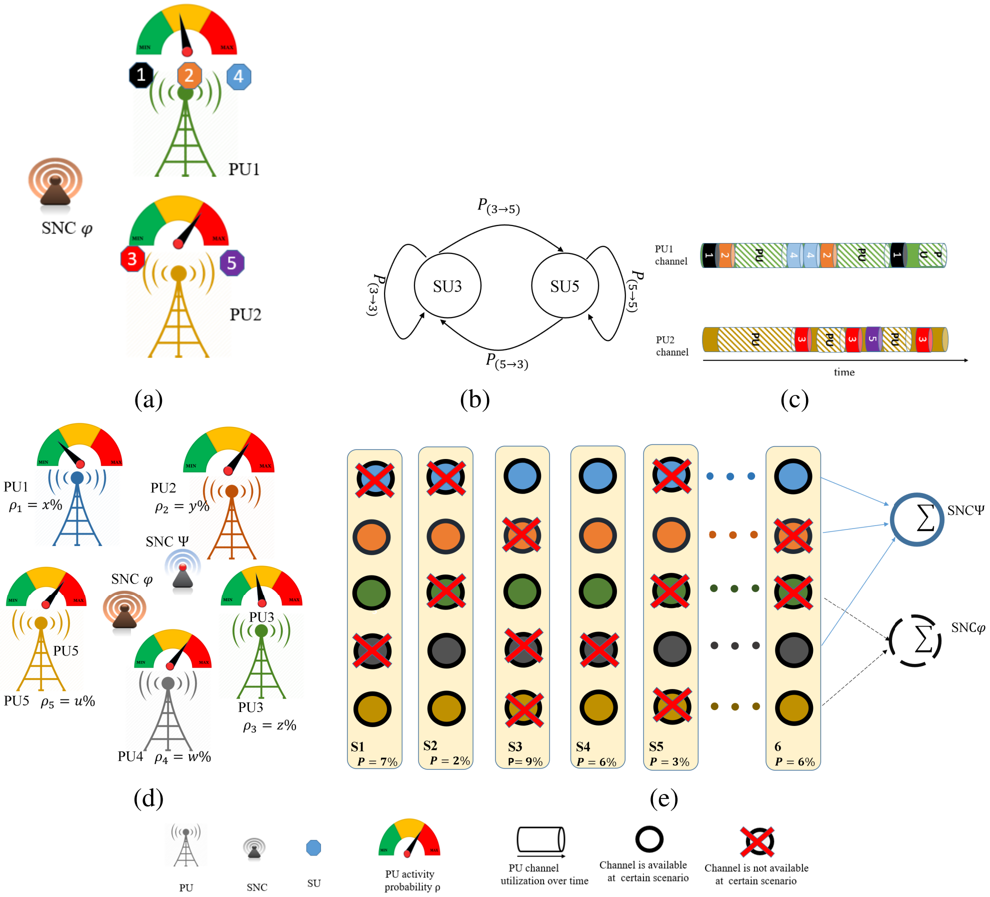

**FIGURE 1.** (a) SN $\phi$ and its SUs operating over two PU channels (b) The Markov Chain depicts the access mechanism of SU 3 and SU 5 to PU 5's channel (c) PU 3 and PU 5 channels utilization over time (d) Overall network model (e) PUs' channel availability at different scenarios.

access to the shared channels, a novel probabilistic channel access mechanism has been designed which accounts for the possibility of a PU interrupting the ongoing transmission. The main contribution of this work is the probabilistic access mechanism used by the SN which allows the PUs to act freely over their channels without the need to change their transmission behavior to adapt for the SUs transmissions. In this work, the uncertainty problem domain is limited to a single channel where the PU access is not predictable. This problem was solved by applying the proposed probabilistic secondary access mechanism.

In this paper, we extend our work such that the price-based spectrum trading problem is investigated from a macroscopic point of view. Instead of limiting the problem scope to one SN and directly satisfying its SUs demand (which is considered a microscopic point of view for the problem), this work considers the scenario in which there are more than one SN, each tries to construct its own operating frequency bands by selecting a *group* of PUs channels to achieve a certain overall availability probability to satisfy its SUs overall demands. However, as each PU channel has a probabilistic availability pattern which is different from one to the other, deciding the overall availability probability of the constructed spectrum band, which is formed from multiple PUs' channels, is not a straight forward function. This creates a complex resource allocation problem with uncertainty domain that spans multiple channels and affects the value of the achieved demand. For that, the investigated problem is considered a joint spectrum trading and stochastic resource allocation one. Fig. 1 explains the difference between the work presented in [7] and this paper. As shown in Fig. 1 (a), the previous work deals with one secondary network where the Secondary Network controller (SNC) has to find the optimal channel allocation for its SUs. The SNC has to deal with the uncertainty of each PU's availability alone as no SU is able to use multiple PU channels simultaneously. The SNCs have to know the channel utilization of every PU and based on the free channel time, they reallocate the SUs over the available channel and distribute the resources (channels; free time slots) according to the SUs demands. As a result, linear programming formulation was used to find the optimal allocation of resources. The uncertainty problem appears when the SNC has to coordinate the SUs access to a single PU's channel taking into consideration the uncertainty about the PU's activity and the possibility of its interruption to the ongoing SU's transmissions. This problem was solved by adopting a probabilistic channel access mechanism based on Markov chain model for SUs access to the shared channel that captures the PU's activities and the probability of the PU's interruption. This probabilistic model assigns a set of channel access probabilities to each SU as shown in Fig. 1(b) based on their demand and PU's activity. By adopting this access probabilities, the SUs can access the PU channel and utilize its available free time slots as shown in Fig. 1(c).

On the other side, this paper adopts the model in which there are multiple secondary networks trying to find the optimal (lowest cost) combination of the PUs channels that meets their SUs demand as shown in Fig. 1(d). The uncertainty problem arises as the SNC, whose duty is to satisfy its SUs demand and regulate their access to the shared channels, has to collect more than one PUs' channel to construct its spectrum band with certain availability threshold. However, as their PU's activities are in general independent, the SNCs have to consider different realization scenarios and their probabilities to find the net availability that satisfies its SUs demands as shown in Fig. 1(e). Hence, the resource allocation problem will be faced by uncertainty of the simultaneous availability of resources.[2] To solve the channel allocation problem under the previously mentioned challenge, the deterministic optimization approaches like those used in [7], are not usable due to the uncertainty of the problem's feasibility region. To overcome this problem, stochastic optimization techniques such as those described in [9]–[11] are adopted to deal with the uncertainty in resource availability.

### A. OUR CONTRIBUTION

This paper proposes a framework based on stochastic optimization techniques to solve the joint price-based spectrum trading and resource allocation problem under two different demand constraints:

- **`Minimum Demand Availability Threshold Problem (MinDAT)`** In the `MinDAT` problem, the SNs objective is to achieve a minimum throughput demand (which may be translated to a number of usable channels with minimum overall availability) with a probability higher than a certain threshold ($\alpha$) at all scenarios. In other words, the requested demand has to be fully satisfied $\alpha\%$ of the time. The problem is formulated as a chance constraints one in its probabilistic form, then its deterministic counterpart is formulated and solved. The analysis is then extended to include a second stage problem which enables channel sharing among SNs after the optimal resources are assigned to each secondary network and hence named `MinDAT_CSh`. In this stage, at a certain scenario, an SN with over-satisfied demand, may sublease[3] some of the assigned channels to another SN with under satisfied demand given that the donor SN will not be come under-satisfied. The goal of this stage is to lower the dissatisfaction rate of all the SNs.
- **`Minimum Expected Demand Problem (MinExD)`** In the `MinDAT` problem, the targeted demand has to be fully satisfied $\alpha\%$ of the time which requires a high number of resources, especially at higher values of $\alpha\%$. The SN may relax its objective such that its *expected* achieved throughput that is higher than a certain level ($\beta\%$) of the requested one regardless of the exact achieved throughput at any given scenario.

Each of the two formulations `MinDAT` and `MinExD` is useful in certain network models and has some limitations. The `MinDAT` formulation is more suitable to be used for an SN which requires a high Quality of Service (QoS). For example, when the requested channels must have a simultaneous availability to satisfy a high throughput demand. On the other hand, The `MinDAT` may not be useful in case of limited resources. The `MinExD` formulation is useful in scenarios where the different SUs have low throughput demand, i.e., where the SN is able to distribute any small blocks of available resources among the SUs regardless of their availability schedule, to satisfy the SUs needs.

### B. PAPER ORGANIZATION

The rest of the paper is organized as follows: The related work is presented in Section II. The network model is described in Section III. The mathematical formulations of the problems are presented in Section IV. Detailed performance evaluation is provided in Section V. Finally, the paper is concluded in Section VI.

## II. RELATED WORK

In this section we discuss the different models of channel sharing and the related work in this area. In the DSA systems, there are Two channel sharing concepts. The first one is the Dynamic Spectrum Leasing (DSL) [12], in which the SUs gain an opportunistic access to the PUs channels when these channels are not utilized. In this way, the SUs do not guarantee any protection against the PUs' interruption. The other concept is the Licensed Shared Access (LSA) [13], [14] which gives the SUs an authorized access to the spectrum according to a set of rules both the SUs and PUs have agreed on. By this way, the SUs transmission is protected from being interrupted by that of the PU. In this paper we focus on the DSL type of channel sharing.

The dynamic spectrum trading and the resource allocation problems in DSA have a probabilistic nature due to the uncertainty about the channels availability over time. Therefore, there is uncertainty about the exact throughput value achieved over these channels. The channel access mechanism in DSA has to take into account the possibility of the PU's interruptions to the ongoing SUs' transmissions. Also, the mechanism has to control the way the SUs access the shared resources and satisfy their demand. A spectrum management framework [15] is required to facilitate the operation of DSA systems and to overcome these challenges. The Spectrum

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[2] Here, it is assumed that there is a spectrum manager who is able to sell the PUs channels to the SNCs and coordinate between them [8].

[3] In this manuscript, the term "sublease" refers to the process in which the SN frees some of its assigned resources (channels) and gives them to another SN for a limited time.

management framework consists of a number of functions: namely, spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. In dynamic spectrum trading framework, incentive rewards are offered to the PUs in return for using their channels in a dynamic way [16]. In this case, trading may take one of two forms. The first one is the resource exchange model. In this model, the SU sacrifices part of its energy to enhance the PU transmission characteristics by acting as an intermediate relay for the PU. In return, the PU allows the SU to access its channel based on a mutual agreement [17], [18]. To realize this model, different approaches have been used to facilitate the trading agreement between the PU and the SU which include contract theory [19], [20], Stackelberg game [21], [22], matching theory [23], and bargaining theory [24].

The other approach in spectrum trading is the price-based one. In this approach, a monetary reward is given from the SU to the PU as payment for the leased spectrum. To find the fair price for the leased resources, different techniques have been used including auction theory [25]–[29], market equilibrium pricing mechanism [30]–[34], Bertrand game model [35], matching theory [36], bargaining theory [37], contract theory [38], bilateral negotiation [39], and optimization techniques [40], [41].

The previously mentioned research work focused on achieving an acceptable agreement between the spectrum owner and the unlicensed user using game theory models or optimization techniques. However, they did not investigate how this deal will be facilitated, especially for an opportunistic SU who is characterized by its random access to the spectrum and its transmission being prone to PUs interruption. Also, they do not investigate the case where there is an uncertainty regarding the availability of the simultaneously available resources (PU channels).

## III. NETWORK MODELS

The proposed network model consists of multiple SNs $n \in \mathcal{N} = \{1, 2, \ldots, N_s\}$. The SNs operate in a geographical area covered by a number of PU channels $C \in \mathcal{C} = \{1, 2, \ldots, N_c\}$ each with a PU activity probability equals to $\rho_c$. Each PU offers its channels to the SUs for a utilization cost $\sigma_c$ which is set to be proportional to its channel availability probability$(1-\rho_c)$. Each secondary network SUs operate under a common administration of a SNC. Each SN $n$ has a certain demand $d_n$ it tries to satisfy by choosing the appropriate set of PU channels for the lowest cost.[4]

In this paper, the secondary network demands are assumed to be in one of the following two forms:

- (`MinDAT` Problem): In this form, the SNC requests a number of PU channels (or a certain throughput demand) to be fully available satisfied) at least $\alpha\%$ of the time.
- (`MinExD` Problem): In this form, the SNC relaxes its demand compared to `MinDAT`, where the SNC tries to achieve an expected throughput value which is, at least, $\beta\%$ of the requested throughput regardless of the exact channels availability at each scenario.

**TABLE 1.** Mathematical Notations.

| Symbol | Description |
|---|---|
| $\mathcal{C}$ | The set of all PUs channels |
| $\mathcal{N}$ | The set of SNs |
| $\mathcal{A}$ | The set of different scenarios |
| $\mathcal{D}$ | The set of SNs requested demand in Mbps |
| $N_s$ | Total number of SNs |
| $N_c$ | Total number of PUs channels |
| $L_s$ | Total number of achievable scenarios |
| $\rho_c$ | PU $c$ availability probability |
| $\alpha_n$ | The demand availability threshold of SN $n$ |
| $\beta_n$ | The realized throughput threshold of SN $n$ |
| $d_n$ | Throughput demand of SN $n$ (Mbps) |
| $R_{nc}$ | Data rate of SN $n$ over channel $c$ (Mbps) |
| $\sigma_c$ | The cost of channel $c$ |
| $P^{(s)}$ | The probability of scenario $s$ |
| $C_{opt}$ | Optimal (lowest) achieved cost by the secondary network |
| $T_n$ | The realized throughput of SN $n$ (Mbps) |
| $\tilde{\zeta}_c$ | Random variable represents channel $c$ availability |
| $x_{cn}$ | Decision variable describes if channel $c$ is leased to SN $n$ |
| $u_n^{(s)}$ | Decision variable describes if the SN $n$ demand is satisfied at scenario $s$ |
| $z_c^{(s)}$ | Decision variable describes if the channel $c$ is available at scenario $s$ |

Table 1 lists the different mathematical symbols used in the paper.

## IV. PROBLEM FORMULATION

In this section, the mathematical formulations of the proposed technique are introduced. First, the stochastic optimization problems different formulations and their solutions techniques are introduced. Then, the `MinDAT` problem, in its probabilistic and deterministic forms, is introduced and

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[4] In this paper, the SNs demand a certain throughput limit. However, the overall demand is expressed by the required number of channels needed with a certain availability assuming that SUs are able to transmit over all channels using the same rate and the only difference between channels is the channel utilization level.

solved. After that, the second stage channel sharing problem `MinDAT_CSh` is presented. Finally, the `MinExD` problem is formulated and solved.

### A. RESOURCE ALLOCATION PROBLEM WITH RANDOM CHANNEL AVAILABILITY

In the resource allocation problem in DSA networks, the channel availability is not deterministic and its availability can be represented by a random variable $\tilde{\zeta}$. Such that the general resource allocation optimization problem can be formulated as:

$$min\{f(x)|g(x,\tilde{\zeta}) \geq \lambda\}, \tag{1}$$

where $x$ is the decision variable, $\tilde{\zeta}$ is the random variable, $f(x)$ is the objective function, $g(x,\zeta)$ is the constraint mapping function and $\lambda$ is the minimum threshold to satisfy. The stochastic optimization problem described in (1) may be solved by three ways according to the format of the constraints which contain the random variable $\tilde{\zeta}$. The three methods are [42]:

- **Chance constraints:** In this case, the problem takes the following general form

  $$min\{f(x)|\mathbb{P}\{g(x,\tilde{\zeta}) \geq d\} \geq \alpha\}. \tag{2}$$

  The chance constraints formulation provides a robust solution where the availability constraint is satisfied with a certain probability. However, it comes with a higher cost compared to the expectation constraints and may not exist at higher probability values.

- **Expectation constraints:** In this case, the problem takes the following form

  $$min\{f(x)|g(x,\mathbb{E}\{\tilde{\zeta}\}) \geq \beta\}. \tag{3}$$

  In this problem, the constraint on the expected value of the random variable provides a relaxed solution for a lower cost compared to the chance constraints case.

- **Worst-case constraints:** In this formulation, the problem takes the following form:

  $$min\{f(x)|g(x,\tilde{\zeta}) \geq \beta\} \quad \forall\tilde{\zeta}. \tag{4}$$

  This formulation requires that the constraint is satisfied at all scenarios. Generally, the problem in this form does not have a solution or can be achieved for a very high cost.

In this paper, the chance constraints formulation is adopted to solve the `MinDAT` problem where the demand has to be fully satisfied with a certain probability. While the expectation constraint formula will be used for the more relaxed problem `MinExD`, where the expected SN throughput demand has to exceed a certain threshold level. In both cases, the problems formulation is converted from the probabilistic form, which contains the random variable, to the deterministic equivalent form, where there is no random variables in it. The deterministic forms are considered a Linear Integer programming (LIP) problems which are solved using Branch and Bound algorithm implemented using IBM CPLEX solver [43].

### B. MINIMUM DEMAND AVAILABILITY PROBLEM (`MinDAT`)

To describe the PU channel uncertainty, a random variable $\tilde{\zeta}_c$ is defined to describe the channel $c$ availability from the SU's point of view. If $\rho_c$ represents the PU's utilization probability of channel $c$, then $\tilde{\zeta}_c$ equals 0 with a probability of $\rho_c$ and 1 with probability of $(1-\rho_c)$. To formulate the resources (channels) allocation problem, a binary decision variable named $x_{cn}$ is defined as follows:

$$x_{cn} = \begin{cases} 1, & \text{if channel } c \text{ is allocated to SN } n \\ 0, & \text{otherwise} \end{cases}$$

In this formulation, the objective is to minimize the total cost of constructing the SNs spectrum band from the PUs channels and at the same time, to satisfy their demand. Hence the chance constrains problem is defined as follows:

**`MinDAT` (Probabilistic form):**

$$\min_{\substack{x_{cn} \\ \{\forall n\in\mathcal{N},c\in\mathcal{C}\}}} \left\{\sum_{c=1}^{C} \sigma_c \cdot x_{cn}\right\} \tag{5}$$

subject to:

$$\sum_{n=1}^{Ns} x_{cn} \leq 1, \quad \forall c \in \mathcal{C} \tag{6}$$

$$Pr\left\{\left(\sum_{c=1}^{N_c} R_{nc} \cdot x_{cn} \cdot \tilde{\zeta}_c\right) \geq d_n\right\} \geq \alpha_n$$

$$\forall n \in \mathcal{N} \tag{7}$$

$$x_{cn} \in \{0,1\}, \quad \forall c \in \mathcal{C} \;\&\; \forall n \in \mathcal{N}. \tag{8}$$

Constraint (6) is used to ensure that each PU channel is assigned initially to at most one SN. The chance constraint (7) enforces that the demand is satisfied with a probability for time higher than the minimum threshold. The term $R_{nc}$ refers to the data rate achieved by the SUs of SN $n$ over channel $c$. However, we assume that the different SUs are able to transmit/receive over all PUs' channels with the same data rate and so, the only factor controlling the achieved throughput is the channel availability. For that, while keeping it in the formulations, the value of $R_{nc}$ is set to 1Mbps $\forall n \in \mathcal{N}$ and $\forall c \in \mathcal{C}$ when evaluating the different formulations performance. Because of the random variable $\tilde{\zeta}_c$ found in the chance constraint (7), it cannot be solved directly by deterministic programming methods. To overcome this problem, the deterministic equivalent problem is derived for the stochastic one where the random variables are omitted. To solve this problem, the various channel availability scenarios are listed and the probability of each one is determined. Then, a group of channels are selected for every SN such that, in different realization scenarios, the SN's demand is satisfied with a probability higher than a certain threshold $\alpha$.

To convert the problem to its deterministic equivalent form, the set of all possible PU channels' availability scenarios $\mathcal{A} = \{1, 2, 3, \ldots, s, \ldots Ls\}$ are defined where each scenario $s$ has a realization probability $P^{(s)}$. Each scenario represents one possible combination where some of the channels are available and others are not. A new binary variable $u_n^{(s)}$ for SN $n$ and scenario $s$ is introduced such that:

$$u_n^{(s)} = \begin{cases} 1, & \text{if SN } n \text{ demand is satisfied in scenario } s \\ 0, & \text{otherwise} \end{cases}$$

and a binary variable $z_c^{(s)}$ that represents the channel $c$ availability at scenario $s$ as follows:

$$z_c^{(s)} = \begin{cases} 1, & \text{if channel } c \text{ is available in scenario } s \\ 0, & \text{otherwise} \end{cases}$$

The equivalent deterministic problem will be in the following form:

**`MinDAT` (Deterministic form):**

$$\min_{\left\{\substack{x_{cn}, u_n^{(s)} \\ \forall n \in \mathcal{N}, c \in \mathcal{C}, s \in \mathcal{S}}\right\}} \left\{ \sum_{c=1}^{N_c} \sigma_c \cdot x_{cn} \right\} \tag{9}$$

subject to:

$$\sum_{c=1}^{C} R_{nc} \cdot x_{cn} \cdot z_c^{(s)} \geq d_n \cdot u_n^{(s)}$$

$$\forall n \in \mathcal{N} \text{and } \forall s \in \mathcal{S} \tag{10}$$

$$\sum_{s=1}^{S} P^{(s)} \cdot u_n^{(s)} \geq \alpha_n, \quad \forall n \in \mathcal{N}_S \tag{11}$$

$$x_{cn} \in \{0, 1\}, \quad \forall c \in \mathcal{C} \;\&\; \forall n \in \mathcal{N}, \tag{12}$$

$$u_n^{(s)} \in \{0, 1\}, \quad \forall n \in \mathcal{N} \;\&\; \forall s \in \mathcal{S}, \tag{13}$$

$$z_c^{(s)} \in \{0, 1\}, \quad \forall c \in \mathcal{C} \;\&\; \forall s \in \mathcal{S}, \tag{14}$$

$$\text{and (6).}$$

In the deterministic equivalent formulation, constraints (10), and (11) replaced constrained (7) in the original problem. In (10) for SN $n$ at scenario $s$, if the achieved throughput is higher than the requested one, the constraint is satisfied and the decision variable can be 0 or 1. However, it will be set to 1 by constraint (11). On the other hand, if the throughput is lower than the requested demand, the constraint forces the decision variable to be equal to 0. Constraint (11) ensures that the SU ($n$) demand is satisfied with a probability higher than or equal to the minimum availability threshold $\alpha_n$. In other words, these two constraints ensure that every SN $n$ gets access to PUs' channels in a sufficient number of scenarios such that its demand is satisfied with availability probability higher than $\alpha_n$.

### C. MINIMUM DEMAND AVAILABILITY THRESHOLD WITH CHANNEL SHARING PROBLEM (`MinDAT_CSh`)

The previous formulations try to satisfy each SN demand by accounting for the channels availability at different scenarios. However, this formulation may result in a situation where, in some scenarios, one (or more) SN does not satisfy its demand (the number of available channels at this specific scenario assigned to it is below the required minimum) while others have extra channels which are not necessary at this scenario and not utilized by the SNs. While the availability demand over all scenarios are satisfied, the performance of the network can be enhanced and the throughput satisfaction rate of the SNs is raised by allowing channel sharing between the SNs where SNs with extra not utilized channels are able to sub-lease them to the SNs which are not able to satisfy their demand at this specific scenario. To overcome this point, channel sharing between more than one SN is allowed. This process is carried out by a central entity like the spectrum manager or network operator. The new formulation consists of two stages. The first is identical to the previous problem, in which the channels are optimally allocated to SNs for the given demand. In the second stage, based on the optimal allocation, the channels are allowed to be released from their assigned SNs to those SNs who cannot satisfy their minimum demand at a specific scenario. This is only allowed if the donor SNs will not suffer from demand dissatisfaction at this specific scenario.

A binary sharing decision variable $y_{cm}^{(s)}$ is defined such that:

$$y_{cm}^{(s)} = \begin{cases} 1, & \text{if channel } c \text{ is released to SN m at scenario } s \\ 0, & \text{otherwise} \end{cases}$$

Here, the objective is to maximize the SNs total achieved throughput using the `MinDAT_CSh` initial allocation. This can be translated to maximizing the number of leased channels and the problem may be formulated as follows:

**`MinDAT_CSh`:**

$$\max_{\{y_{cm}^{(s)}\}} \left\{ \sum_{c=1}^{N_c} \sum_{n=1}^{N_s} (R_{nc} \left( x_{cn} + \sum_{\substack{m \in \mathcal{N} \\ n \neq m}} y_{cm}^{(s)} \right)) \right\}$$

$$\forall s \in \mathcal{S} \tag{15}$$

which may be reduced to

$$\max_{\{y_{cm}^{(s)}\}} \left\{ \sum_{c=1}^{N_c} \sum_{m=1}^{N_s} \sum_{s=1}^{L_s} y_{cm}^{(s)} \right\} \tag{16}$$

subject to:

$$y_{cm}^{(s)} \leq x_{cn}, \quad \forall c \in \mathcal{C}, m, n \in \mathcal{N}, \text{and } s \in \mathcal{S} \tag{17}$$

$$\left( \sum_{c=1}^{C} R_{nc} \cdot x_{cn} - \left( \sum_{\substack{m \in \mathcal{N} \\ n \neq m}} R_{mc} \cdot y_{cm}^{(s)} \right) \right) \cdot z_c^{(s)} \geq d_n \cdot u_n^{(s)}$$

$$\forall n \in \mathcal{N} \text{ and } \forall s \in \mathcal{S} \tag{18}$$

$$\sum_{c=1}^{C} (R_{nc} \cdot x_{cm} + R_{mc} \cdot y_{cm}^{(s)}) \cdot z_c^{(s)} \geq d_m$$

$$\forall m \in \mathcal{N} \text{ and } s \in \mathcal{S} \tag{19}$$

$$\left( \sum_{h=1}^{C} R_{hc} \cdot x_{hm} \cdot z_h^{(s)} \right) \cdot y_{cm}^{(s)} \leq d_m$$

$$\forall m \in \mathcal{N}, \quad \forall c \in \mathcal{C} \text{ and } \forall s \in \mathcal{S} \tag{20}$$

$$\sum_{m=1}^{N_s} y_{cm}^{(s)} \leq \sum_{n=1}^{Ns} x_{cn}, \quad \forall c \in \mathcal{C}, s \in \mathcal{S} \tag{21}$$

$$y_{cm}^{(s)} \in \{0, 1\}, \quad \forall c \in \mathcal{C} \; \& \; \forall m \in \mathcal{N}, \text{ and } s \in \mathcal{S}. \tag{22}$$

The first stage formulation is used to calculate the value of $x_{cn}$. For proper formulation of the second stage sharing technique, the following constraints are added:

1) To keep the same optimal cost, the channel may be released to another SN only if it is already assigned to one SN in the first stage. This is ensured using constraint (17).
2) At a specific scenario $s$, the channel $c$ is released from SN $n$ if it will not reduce its demand satisfaction below the threshold. This condition is satisfied using constraint (18).
3) At a specific scenario $s$, the channel $c$ is released to SN $m$ if it increases its demand satisfaction above its minimum level which was not satisfied before at this scenario. Constraint (19) and (20) satisfy this condition. In constraint (19), if the decision variable $y_{cm}^{(s)} = 1$, the constraint will be satisfied only if the SN $m$ has an under-satisfied demand in this specific scenario.
4) At a specific scenario $s$, the channel $c$ can be released to one SN only. This is ensured using constraint (21).[5]

### D. MINIMUM EXPECTED THROUGHPUT PROBLEM (`MinExD`)

In the previous formulations, the objectives were to satisfy 100% of the SNs demand (throughput or channels availability) with a certain availability percentage $\alpha$. This means, in some scenarios, there are some free channels to use, however they are not sufficient to satisfy the SN total demand and hence ignored in the calculation. Alternatively, the coordinator may want to satisfy an expected throughput value which is not less than $\beta\%$ of the requested throughput regardless of the achievement time of this demand. For that, the resource allocation problem is formulated as an expectation constraint one as follows:

**`MinExD:`**

$$\min_{\left\{\substack{x_{cn}, u_n^{(s)} \\ \forall n \in \mathcal{N}, c \in \mathcal{C}, s \in \mathcal{S}}\right\}} \left\{ \sum_{c=1}^{N_c} \sigma_c \cdot x_{cn} \right\} \tag{23}$$

subject to:

$$\sum_{n=1}^{Ns} x_{cn} = 1, \quad \forall c \in \mathcal{C} \tag{24}$$

$$\mathbb{E}\{T(n)\} \geq \beta_n \cdot d_n, \quad \forall n \in \mathcal{N} \tag{25}$$

$$x_{cn} \in \{0, 1\}, \quad \forall c \in \mathcal{C} \; \& \; \forall n \in \mathcal{N} \tag{26}$$

where $\mathbb{E}\{T(n)\}$ represents the expected value of SN $n$ realized throughput which can be written as:

$$\mathbb{E}\{T(n)\} = \mathbb{E}\{\sum_{c=1}^{C} R_{nc} \cdot x_{cn} \cdot \tilde{\zeta}_c\}. \tag{27}$$

The above equation contains the random variable $\tilde{\zeta}_c$ which can be converted to its deterministic equivalent form by replacing the random variable $\tilde{\zeta}_c$ by the probability of each scenario $P^{(s)}$ and summing over all possible scenarios.

$$\mathbb{E}\{T(n)\} = \sum_{s=1}^{S} P^{(s)} \cdot \sum_{c=1}^{C} R_{nc} \cdot x_{cn} \cdot z_c^{(s)}. \tag{28}$$

In this way, the deterministic equivalent of the `MinExD` is obtained by replacing constraint (25) by its deterministic equivalent (28).

## V. PERFORMANCE EVALUATION

This section investigates the performance of the proposed formulas. It starts by a simple illustrative example where the mechanism of the proposed solution is illustrated. Then, the proposed system is evaluated for different network parameters.

### A. ILLUSTRATIVE EXAMPLE

In this example, the mechanism of the proposed analytical framework is illustrated. The example model consists of two SNs (1, 2) and 5 PU channels with different availability probabilities and costs where the cost is set to be proportional to each channel availability. The `MinDAT` problem is formulated for the example network where the SNs request a throughput demand $\mathcal{D} = \{2, 2\}$[6] that will be satisfied by leasing two PUs channels simultaneously for each SN. Recall that $R_{nc} = 1$ $Mbps$ $\forall n \in \mathcal{N}$ and $\forall\, c \in \mathcal{C}$. This demand must be achieved with availability thresholds $\alpha = \{0.4, 0.7\}$ for SN 1, and SN 2 respectively. As one or more SNs request more than one channel to utilize, conventional resource allocation will not be feasible to use and the different channels availability scenarios should be taken into consideration. Fig. 2 (a) and Fig. 2 (b) show the different channel availability scenarios and their probabilities, respectively, for each of the scenarios that were simulated. Fig. 2(c) shows the scenarios where each SN satisfies its demand which is corresponding to the value of the decision variable $u_n^{(s)}$. Fig. 2 (d) shows the channels allocation among the two SNs. The vertical axis represents the decision variable $x_{cn}$. As can be inferred from the figure, 3 channels are assigned to SN 2 as it requires at least two channels for 70% of the time while SN 1 receives only two channels as its availability threshold equals 40%. Fig. 2 (e) shows the difference between the SNs requested and achieved demand. As can be clearly noticed from the figure, both SNs achieved demands higher than the requested ones. On the other hand, if the problem is re-formulated as

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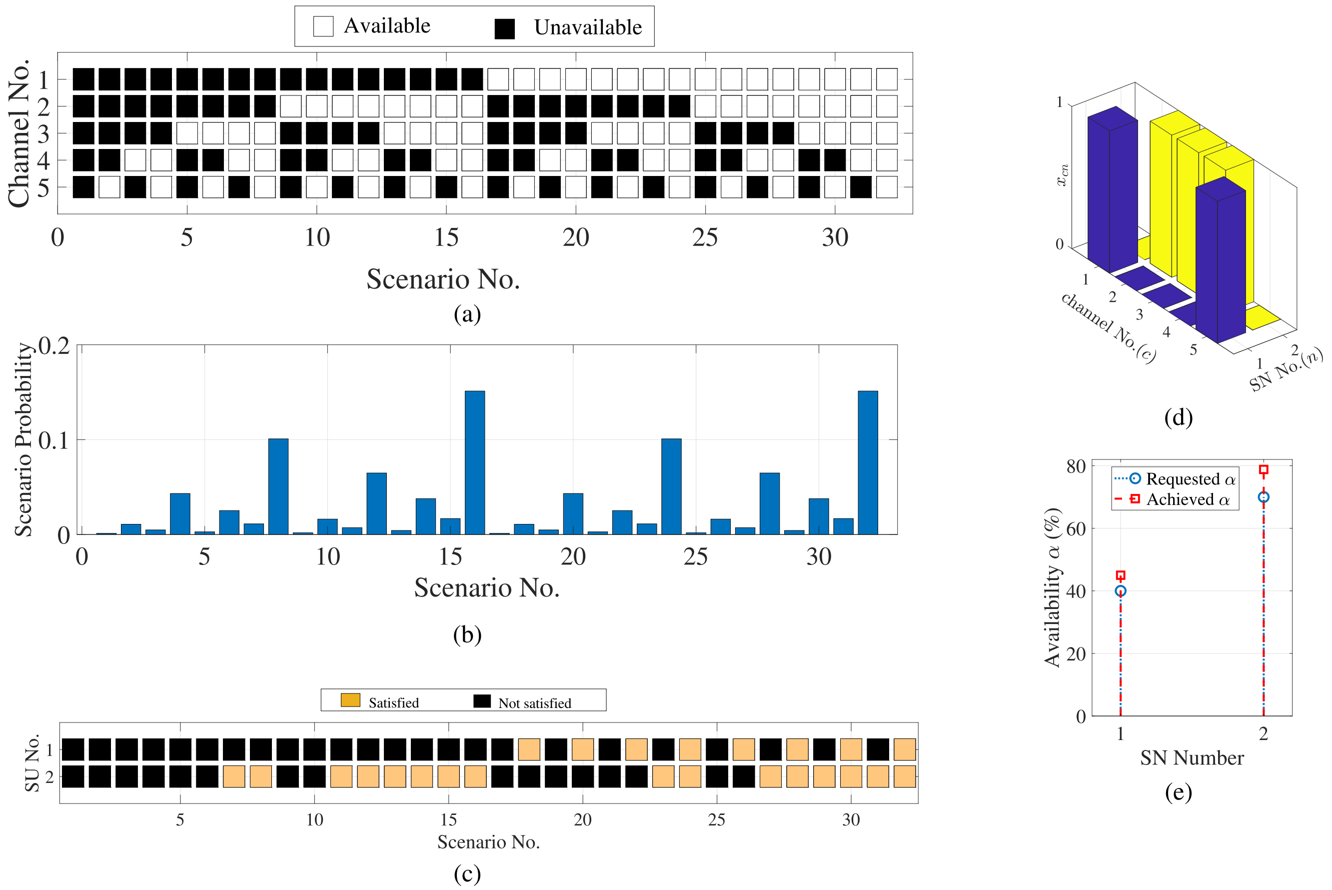
[5] The term $\sum_{n=1}^{Ns} x_{cn}$ is always $\leq 1$ according to constraint (6).

[6] $\mathcal{D} = \{d_1, d_2, \ldots, d_n\}$ is the set of requested demand in Mbps for $SN1, SN2, \ldots, SN\ n$.



(a) (b) (c) (d) (e)

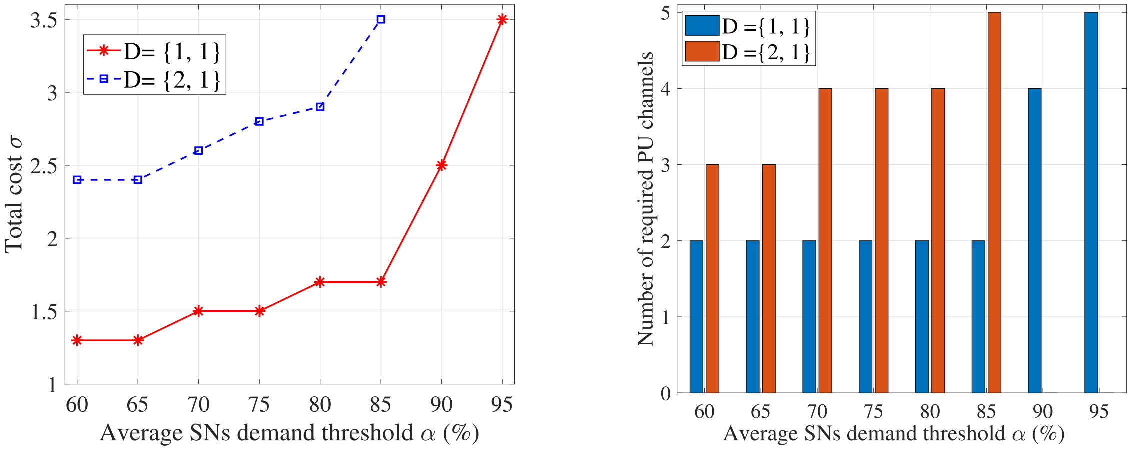
**FIGURE 2. Illustrative example of two SNs which operate within the coverage of 5 PU channels where the channel availability probability $(1-\rho) = \{0.5, 0.6, 0.7, 0.8, 0.9\}$ and cost $\sigma_c = (1-\rho_c)$, (a) Channels availability at different scenarios, (b) Scenarios probabilities, (c) SNs demand satisfaction at different scenarios, (d) Channels distribution among SNs, and (e) Spectrum availability for each SN.**

an expectation constraint one like `MinExD` and for $\beta = \{0.4, 0.7\}$, the number of resources needed is lower than the case of `MinDAT`. Here, only 3 channels are needed where channel 4 with availability probability $(1-\rho) = 80\%$ is assigned to SN 1 and channels number 1 and 5 are assigned to SN no. 2. For example, SN 1 requests to achieve 40% of its 2 *Mbps* demand which can be satisfied by using only channel 4 with availability equals 80%.

### B. THE EFFECT OF THE DEMAND AVAILABILITY THRESHOLD $\alpha$

In this subsection, the effect of the availability threshold on the performance of the SNs is investigated. The same setup used in the illustrative example for two SNs for two different demands of values $\mathcal{D} = \{1, 1\}$ and $\{1, 2\}$ is adopted in this experiment. As can be inferred from Fig. 3 (a), as the demand availability threshold of the SNs increases, the cost of forming the SN spectrum band increases. Also, it is clear that the cost increases exponentially as the threshold increases. For example, when the availability threshold increases by just 0.1 from 85% to 95% the cost is doubled. Also, a threshold above 95% cannot be satisfied for SN 1 when $\mathcal{D} = \{1, 1\}$. Fig. 3 (b) shows the number of channels needed to satisfy the SNs availability demand. It is noticeable that at the two demand values the number of channels stays constant for some consecutive values of $\alpha$ but with different costs as indicated by Fig. 3 (b). That is because the leased channels are not the same at every value. For example, for $\mathcal{D} = \{1, 1\}$ the SN 1 (blue bars) requires two channels for values of $\alpha$ between 60% to 85%, but, at each of these values, the leased channels may be changed to minimize the cost and satisfy the availability demand of the SNs.

Fig. 4 shows the effect of the demand availability threshold at much higher available resources (PU channels) to investigate the highest availability that can be achieved. As can be inferred from the graph, at higher demand i.e $\mathcal{D} = \{3, 3\}$ the demand is satisfied only at lower values of the availability threshold $\alpha$ and for the maximum possible number of channels. On the other hand, at lower value of demand i.e $\mathcal{D} = \{1, 1\}$ the demand is satisfied up to higher values like 98%, however it cannot exceed this value despite of availability of unused resources (channels) as any additional channel with availability less than 100% will not result in enhancement in



(a) (b)

**FIGURE 3.** The effect of SN demand availability threshold on (a) the total cost and, (b) the number of required PU channels.

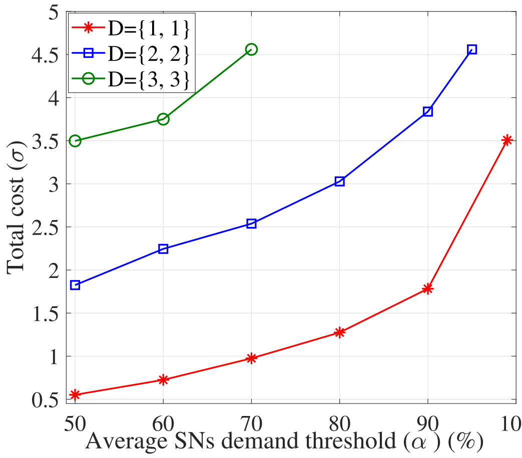


**FIGURE 4.** The effect of SN demand availability threshold on the total cost at $(1-\rho_c) = [0.5 : 0.05 : 0.9]$ for $N_c = 9$.

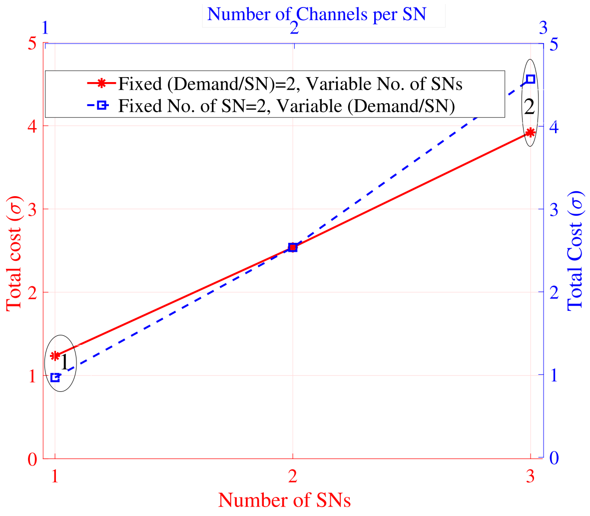


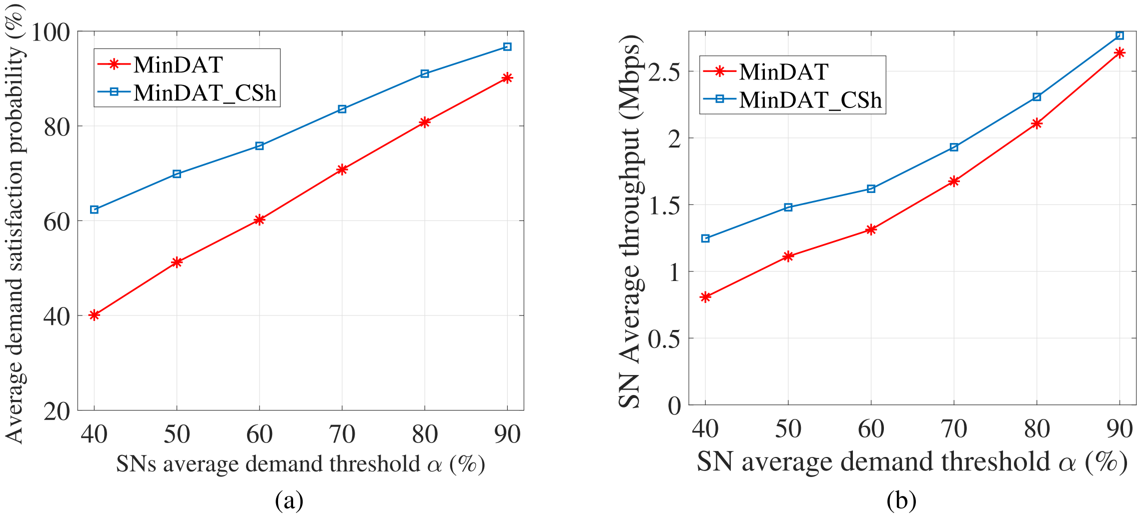
**FIGURE 5.** The effect of number of SN and number of required channels for $\alpha = 70\%$.

the overall demand availability of the SN. The last example shows the significance of the requesting demand with certain availability less than unity in scenarios where the channel availability is not guaranteed all the time. Also, the SN may tend to lower the requested availability in favor of reducing the cost significantly as can be noticed in the $\mathcal{D} = \{1, 1\}$ curve. In this case, the SN may want to reduce the availability threshold to 90% and, at the same time, to nearly halve the cost at maximum availability of 98%.

Fig. 5 emphasizes the effect of requesting simultaneous resources availability on the cost. In the first graph (in RED), the number of demanded channels per SN is fixed to two and the number of SNs is changed. In the second graph (in BLUE), the number of SNs are fixed to two while the number of demanded channels is variable. At point no.1, the total requested channels in both cases are 2, but when one SN asks for two channels, it pays a higher cost than when two SNs each demand one channel with the same availability. The same can be noticed at point no.2 when a total of 6 channels are needed in the two cases. The first one is when two SNs each asks for two channels and when three SNs each asks for two channels for the same availability threshold. This is due to the uncertainty nature of the PU channels. Here, the same number of usable channels cost more if they are requested to be available simultaneously compared to the case when requested individually.

### C. EFFECT OF CHANNEL SHARING CAPABILITY (`MinDAT` VS `MinDAT_CSh`)

In this subsection, the performance enhancement of the (`MinDAT_CSh`) formulation is quantified and compared to that of `MinDAT`. In this formulation, SNs start with the same optimal initial channel allocation obtained from `MinDAT`. But due to the minimum availability threshold, each SN may be assigned a higher number of PU channels than that



(a) (b)

**FIGURE 6.** **Comparison between `MinDAT` and `MinDAT_CSh` in terms of (a) achieved demand availability and (b) average achieved throughput, for $N_c = 9$, $(1 - \rho) = [0.5 : 0.05 : 0.9]$.**

actually needed at any specific scenario to ensure the minimum channels availability needed at all scenarios. So, at a given scenario, the SN with over satisfied demand (excess channels) can sub-lease one of its channels to another SN (with unsatisfied demand) to enhance its demand availability satisfaction. Fig. 6 (a) shows the average demand satisfaction probability for problem `MinDAT` and `MinDAT_CSh`. As shown in the figure, in `MinDAT_CSh` problem, the SNs achieve a higher demand satisfaction compared to that in `MinDAT`, which achieves slightly higher availability than the minimum threshold, due to the ability of the system to supply the under satisfied SNs with channels from over satisfied ones. Fig. 6 (b) shows the average achieved throughput of the SNs in the two formulations. The figure shows a significant enhancement in the throughput performance when `MinDAT_CSh` is applied. From Fig. 6 (a) and (b), it can be inferred that the performance gap between `MinDAT` and `MinDAT_CSh` increases as the threshold decreases. Fig. 7 justifies the last observation as it shows the number of sub-leased channels at all scenarios at different values of $\alpha$. As shown in the figure, at low values of $\alpha$ the secondary system has more flexibility and SNs have extra resources which may not be needed in some scenarios and can be leased to other SNs. On the other hand, at higher values of $\alpha$ the number of leased channels is low as the SNs need almost all their channels at each scenario to keep higher availability demand.

### D. MINIMUM EXPECTED DEMAND PROBLEM (`MinExD`) PERFORMANCE

In this subsection, the performance of the SNs when applying the second objective `MinExD` is investigated. In this formulation, the goal is to minimize the cost and satisfy a threshold on the expected value of the achieved throughput $\beta$ rather than to meet demand availability threshold as in the first objective. To show the performance of this formulation, we compare it with the `MinDAT` for the same values of the thresholds ($\alpha$ and $\beta$) for `MinDAT` and `MinExD`, respectively. Fig. 8 (a) shows the required cost in both formulations for the same value of threshold ($\alpha$ and $\beta$). As can be inferred from the figure, `MinExD` requires a lower cost for the same threshold compared to `MinDAT` due to its ability to utilize all the available resources at all scenarios which significantly reduces the cost. Also, when the number of SNs is increased to 4, the `MinExD` is able to satisfy the SN demand up to higher values of demand threshold compared to `MinDAT`. Fig. 8 (b) emphasizes the same observation by showing the number of required channels in both cases. It is clear that `MinExD` requires less resources compared to `MinDAT` for the same threshold.

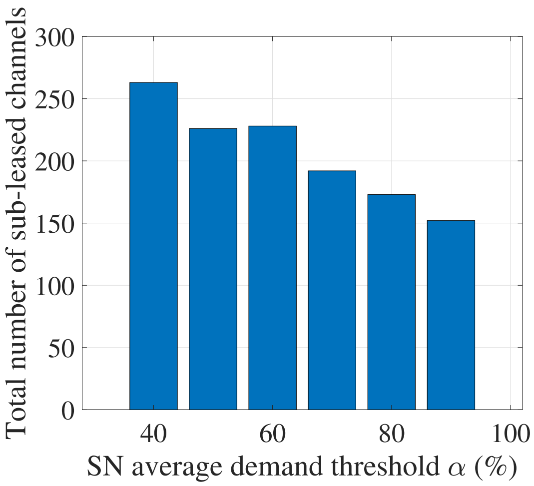
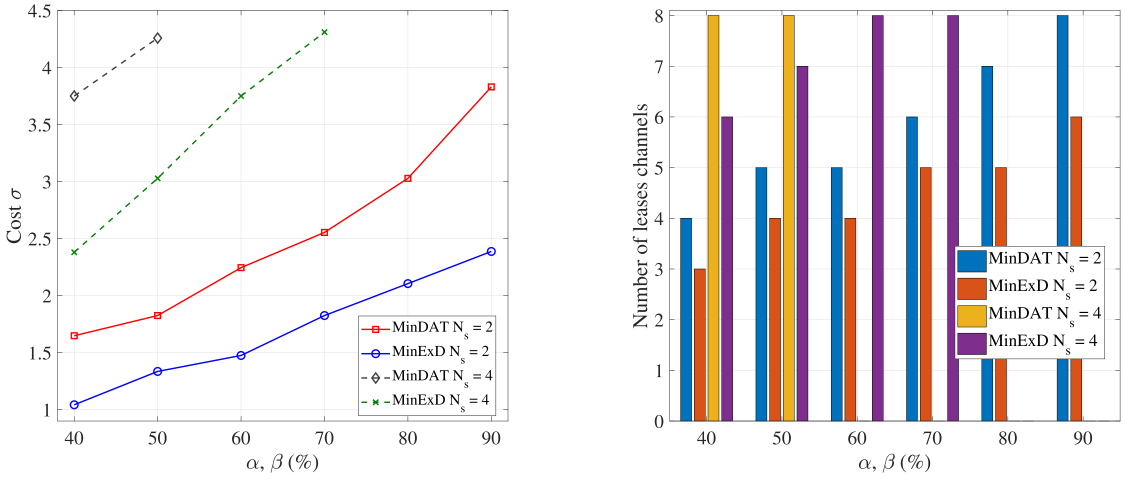


**FIGURE 7.** **Number of leased channels at all scenarios in `MinDAT_CSh` problem for two SNs at $\mathcal{D} = \{2, 2\}$.**



(a) (b)

**FIGURE 8.** **Comparison between `MinDAT` and `MinExD` in terms of (a) total cost (b) number of channels for $\mathcal{D} = \{2, 2\}$.**

## VI. CONCLUSION

This article presented a stochastic spectrum trading and resource allocation framework among multiple primary users and multiple secondary networks. The proposed framework aims to solve the uncertainty problem about the simultaneous availability of the selected channels by using stochastic optimization technique. Two different formulations are used to solve the problem according to the applied constraints on the demanded throughput. The first is the chance constraints formulation where the achieved throughput must not be lower than the requested one for at least $\alpha\%$ of the time. The other one is the expectation constraints formula where the constrain is relaxed such that the expected value of the achieved throughput should be higher than $\beta\%$ of the requested one. The results show that the secondary network can reduce the cost paid to the primary user if they accept a throughput availability threshold slightly lower than 100%. Also, if the expectation constraint is adopted, it will result in significant reduction on the needed resources and so, the cost compared to the chance constraints one. Finally, if the channel subleasing is allowed between secondary networks, the demand shortage of the secondary networks is reduced. In the future work, we will investigate the special cases where each SU has a different transmission rate over different channel. Additionally, a more complex problem will be investigated in which the same requested demand has to be satisfied over multiple secondary networks simultaneously.

## REFERENCES

[1] D. Cabric and R. W. Brodersen, "Physical layer design issues unique to cognitive radio systems," in *Proc. IEEE PIMRC*, vol. 2, Berlin, Germany, Sep. 2005, pp. 759–763.

[2] M. Zareei, A. K. M. M. Islam, S. Baharun, C. Vargas-Rosales, L. Azpilicueta, and N. Mansoor, "Medium access control protocols for cognitive radio ad hoc networks: A survey," *Sensors*, vol. 17, no. 9, p. 2136, 2017.

[3] R. A. Diab, N. Bastaki, and A. Abdrabou, "A survey on routing protocols for delay and energy-constrained cognitive radio networks," *IEEE Access*, vol. 8, pp. 198779–198800, 2020.

[4] A. Attar, H. Tang, A. V. Vasilakos, F. R. Yu, and V. C. M. Leung, "A survey of security challenges in cognitive radio networks: Solutions and future research directions," *Proc. IEEE*, vol. 100, no. 12, pp. 3172–3186, Dec. 2012.

[5] M. AbdelRaheem and M. M. Abdellatif, "Cooperative anti-jamming for secondary opportunistic networks: A colonel Blotto game model," in *Proc. IEEE 13th WiMob*, Oct. 2017, pp. 1–8.

[6] R. M. Al-Hashmy, M. AbdelRaheem, and U. S. Mohmed, "Anti-jamming cooperative technique for cognitive radio networks: A Stackelberg game approach," in *Proc. Int. Conf. Adv. Intell. Syst. Inform.* New York, NY, USA: Springer, 2019, pp. 750–759.

[7] M. AbdelRaheem and M. El-Nainay, "Demand-based spectrum trading for opportunistic secondary networks with probabilistic channel access mechanism," *IEEE Syst. J.*, vol. 13, no. 4, pp. 3803–3814, Dec. 2019.

[8] M. Rahman, S. H. Ahmed, and M. Yuksel, "Proof of sharing in inter-operator spectrum sharing markets," in *Proc. IEEE DySpan*, Oct. 2018, pp. 1–5.

[9] M. J. Abdel-Rahman, M. AbdelRaheem, A. MacKenzie, K. Cardoso, and M. Krunz, "On the orchestration of robust virtual LTE-U networks from hybrid half/full-duplex Wi-Fi APs," in *Proc. IEEE WCNC*, Apr. 2016, pp. 1–6.

[10] M. J. Abdel-Rahman, M. AbdelRaheem, and A. B. MacKenzie, "Stochastic resource allocation in opportunistic LTE-A networks with heterogeneous self-interference cancellation capabilities," in *Proc. IEEE DySPAN*, Sep. 2015, pp. 200–208.

[11] A. Nabil, M. J. Abdel-Rahman, A. B. MacKenzie, and F. Hassan, "A stochastic optimization framework for channel bonding in wireless LANs under demand uncertainty," *IEEE Trans. Wireless Commun.*, vol. 19, no. 11, pp. 7528–7542, Nov. 2020.

[12] M. A. Ramírez-Reyna, F. A. Cruz-Pérez, S. L. Castellanos-López, G. Hernandez-Valdez, and M. E. Rivero-Angeles, "Performance analysis of dynamic spectrum leasing strategies in coordinated cognitive radio networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2018, no. 1, pp. 1–22, Dec. 2018.

[13] I. A. M. Balapuwaduge, F. Y. Li, and V. Pla, "Dynamic spectrum reservation for CR networks in the presence of channel failures: Channel allocation and reliability analysis," *IEEE Trans. Wireless Commun.*, vol. 17, no. 2, pp. 882–898, Feb. 2018.

[14] A. U. Khan, G. Abbas, Z. H. Abbas, M. Tanveer, S. Ullah, and A. Naushad, "HBLP: A hybrid underlay-interweave mode CRN for the future 5G-based Internet of Things," *IEEE Access*, vol. 8, pp. 63403–63420, 2020.

[15] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A survey on spectrum management in cognitive radio networks," *IEEE Commun. Mag.*, vol. 46, no. 4, pp. 40–48, Apr. 2008.

[16] Q. Song, M. You, and T. Lv, "Incentives to spectrum trading," in *Proc. IEEE Int. Conf. Netw. Infrastruct. Digit. Content*, Nov. 2009, pp. 948–952.

[17] A. Papadopoulos, N. D. Chatzidiamantis, and L. Georgiadis, "Network coding techniques for primary-secondary user cooperation in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 19, no. 6, pp. 4195–4208, Jun. 2020.

[18] Z. Liu, S. Zhao, Y. Yuan, Y. Yang, and X. Guan, "Game-based approach of fair resource allocation in wireless powered cooperative cognitive radio networks," *AEU, Int. J. Electron. Commun.*, vol. 134, May 2021, Art. no. 153699.

[19] L. Duan, L. Gao, and J. Huang, "Cooperative spectrum sharing: A contract-based approach," *IEEE Trans. Mobile Comput.*, vol. 13, no. 1, pp. 174–187, Jan. 2014.

[20] A. V. Kordali and P. G. Cottis, "A contract-based spectrum trading scheme for cognitive radio networks enabling hybrid access," *IEEE Access*, vol. 3, pp. 1531–1540, 2015.

[21] O. Simeone, I. Stanojev, S. Savazzi, Y. Bar-Ness, U. Spagnolini, and R. Pickholtz, "Spectrum leasing to cooperating secondary ad hoc networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 1, pp. 203–213, Jan. 2008.

[22] X. Wang, K. Ma, Q. Han, Z. Liu, and X. Guan, "Pricing-based spectrum leasing in cognitive radio networks," *IET Netw.*, vol. 1, no. 3, pp. 116–125, Sep. 2012.

[23] X. Feng, G. Sun, X. Gan, F. Yang, X. Tian, X. Wang, and M. Guizani, "Cooperative spectrum sharing in cognitive radio networks: A distributed matching approach," *IEEE Trans. Commun.*, vol. 62, no. 8, pp. 2651–2664, Aug. 2014.

[24] M. Abdelraheem, M. J. Abdel-Rahman, M. El-Nainay, and S. F. Midkiff, "Spectrum-efficient resource allocation framework for cooperative opportunistic wireless networks," *IEEE Trans. Cogn. Commun. Netw.*, vol. 2, no. 3, pp. 249–262, Sep. 2016.

[25] G. S. Kasbekar and S. Sarkar, "Spectrum pricing games with spatial reuse in cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 1, pp. 153–164, Jan. 2012.

[26] H. B. Chang and K. C. Chen, "Auction-based spectrum management of cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 59, no. 4, pp. 1923–1935, May 2010.

[27] J. Jia, Q. Zhang, Q. Zhang, and M. Liu, "Revenue generation for truthful spectrum auction in dynamic spectrum access," in *Proc. ACM MobiHoc*, New Orleans, LA, USA, 2009, pp. 3–12.

[28] M. N. Tehrani and M. Uysal, "Auction based spectrum trading for cognitive radio networks," *IEEE Commun. Lett.*, vol. 17, no. 6, pp. 1168–1171, Jun. 2013.

[29] J. Wang, B. Zhang, B. Zhao, G. Ding, and D. Guo, "A game-theoretical learning approach for spectrum trading in cognitive satellite-terrestrial networks," *IEEE Commun. Lett.*, vol. 25, no. 9, pp. 3065–3069, Sep. 2021.

[30] D. Niyato and E. Hossain, "Market-equilibrium, competitive, and cooperative pricing for spectrum sharing in cognitive radio networks: Analysis and comparison," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4273–4283, Nov. 2008.

[31] I. Bajaj, Y.-H. Lee, and Y. Gong, "A spectrum trading scheme for licensed user incentives," *IEEE Trans. Commun.*, vol. 63, no. 11, pp. 4026–4036, Nov. 2015.

[32] N. Nie and C. Comaniciu, "Adaptive channel allocation spectrum etiquette for cognitive radio networks," in *Proc. 1st IEEE DySPAN.*, Nov. 2005, pp. 269–278.

[33] F. Li, K. Lam, L. Meng, H. Luo, and L. Wang, "Trading-based dynamic spectrum access and allocation in cognitive Internet of Things," *IEEE Access*, vol. 7, pp. 125952–125959, 2019.

[34] J. Wang, X. Zhang, Q. Zhang, M. Li, Y. Guo, Z. Feng, and M. Pan, "Data-driven spectrum trading with secondary users' differential privacy preservation," *IEEE Trans. Depend. Sec. Comput.*, vol. 18, no. 1, pp. 438–447, Jan./Feb. 2021.

[35] X. Jianli, G. Wenqian, L. Cuiran, and L. Anqi, "Cognitive spectrum sharing algorithm based on secondary users' services," in *Proc. IEEE ICSP*, Aug. 2018, pp. 103–107.

[36] C. Tsirakis, E. Lopez-Aguilera, P. Matzoros, G. Agapiou, and D. Varoutas, "Spectrum trading in virtualized multi-tenant 5G networks," in *Proc. 15th Int. Symp. Wireless Commun. Syst. (ISWCS)*, Aug. 2018, pp. 1–6.

[37] F. Li, K.-Y. Lam, N. Zhao, X. Liu, K. Zhao, and L. Wang, "Spectrum trading for satellite communication systems with dynamic bargaining," *IEEE Trans. Commun.*, vol. 66, no. 10, pp. 4680–4693, Oct. 2018.

[38] X. Huang, W. Zhang, J. Yang, L. Yang, and C. K. Yeo, "Two-tier trading strategy design for spectrum allocation in heterogeneous cognitive radio networks," *IET Commun.*, vol. 14, no. 16, pp. 2759–2768, Oct. 2020.

[39] A. Paul, D. Mukherjee, and M. Maitra, "Reinforcement learning-based negotiation for spectrum micro-trading framework," *IET Netw.*, vol. 7, no. 6, pp. 435–444, Nov. 2018.

[40] H. B. Salameh and G. El Refae, "Price- and rate-aware multi-channel spectrum access for profit enhancement in opportunistic networks with QoS guarantees," *ICT Exp.*, vol. 8, no. 1, pp. 77–82, Mar. 2022.

[41] W. Abbass, R. Hussain, J. Frnda, N. Abbas, M. A. Javed, and S. A. Malik, "Resource allocation in spectrum access system using multi-objective optimization methods," *Sensors*, vol. 22, no. 4, p. 1318, Feb. 2022.

[42] A. Shapiro, D. Dentcheva, and A. Ruszczynski, *Lectures on Stochastic Programming*. Philadelphia, PA, USA: Society for Industrial and Applied Mathematics, 2009.

[43] (Aug. 25, 2021). *CPLEX Optimization Studio*. [Online]. Available: http://www-01.ibm.com/software/commerce/optimization/cplex-optimizer/

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