The Korean Institute of
Communications and
Information Sciences

Available online at www.sciencedirect.com

ScienceDirect

ICT Express xxx (xxxx) xxx

www.elsevier.com/locate/icte

Price- and rate-aware multi-channel spectrum access for profit enhancement in opportunistic networks with QoS guarantees

Haythem Bany Salameh[a,b,c,*], Ghaleb El Refae[d]

[a] College of Engineering, Al Ain University, United Arab Emirates
[b] Telecommunications Engineering Department, Yarmouk University, Jordan
[c] Artificial Intelligence Research Center, Al Ain University, United Arab Emirates
[d] College of Business, Al Ain University, Al Ain, United Arab Emirates

Received 6 November 2020; received in revised form 14 March 2021; accepted 10 June 2021
Available online xxxx

Abstract

Cognitive radio (CR) is a key technology that can enable opportunistic spectrum access, which enables secondary users (SUs) to dynamically exploit the under-utilized channels in the licensed spectrum, owned by primary radio networks (PRNs), referred to as *dominant firms*. Such sharing is subject to interference, SU QoS and cost constraints, in which SUs should not introduce harmful interference to PR users, achieve QoS rate demand and pay a price for using the licensed PR spectrum. The price of accessing idle PR channels depends on the level of channel utilization and price paid by PRs to access the channels, while the amount of needed spectrum to serve the rate demand of each SU heavily depends on the link-quality of the various channels. In this paper, the spectrum assignment problem in a CR network (CRN), referred to as *follower firm*, is investigated with the target of serving the largest possible number of SUs with the least possible total price paid to the PRNs (highest CRN profit) while being aware of the time-varying achieved transmission rate and level of utilization of the various PR channels. The problem is mathematically expressed as an optimization problem with the goal of maximizing the number of served SUs and the profit made by the CRN, which has been shown to be a binary linear programming (BLP) problem. Due to the high complexity of solving such optimization, we use the well-known sequential-fixing optimization method to obtain sub-optimal solutions. Simulation results indicate that our channel-assignment optimization significantly increases the CRN profit by reducing the price paid to the PRNs while achieving comparable performance offered by previous price-unaware protocols.

Keywords: Licensed incentive; CR revenues; Dynamic spectrum allocation; Utilization-dependent Spectrum Price

1. Introduction

Cognitive radio (CR) networking is considered a revolutionary paradigm that can tackle the spectrum scarcity problem by allowing dynamic and opportunistic access to the vastly under-utilized licensed spectrum. Such opportunistic access allows the CR technology to support high-speed wireless transmission services and applications in next generation wireless networks (e.g., 5G) and enables large-scale deployment of massive number of wireless IoT-based devices [1,2]. Utilizing licensed spectrum owned by primary radio networks (PRNs) requires the SU to pay a price to the PRNs and provides guarantees on PRN's performance [3]. According to the FCC spectrum measurement reports, the temporal and geographical utilization of the PR licensed spectrum ranges from 15% to 85%. The underutilized spectrum can be opportunistically exploited by secondary users (SUs) in a CR network (CRN), referred to as *follower firm*, subject to price paid to the *dominant-firm* PRNs and interference regulations [4,5]. The price is utilization-dependent, by which higher price will be required when the PR utilization is higher. This is because the PRNs need to be highly incentivized to share their spectrum when PR user activities are high, where the PR users are utilizing their channels and are already paying for the received services [6,7]. In a wireless environment where a number of licensed PRNs are operating, the channel-quality gain (achieved data rate) over the various channels is time-varying due to fading.

---

* Corresponding author at: College of Engineering, Al Ain University, United Arab Emirates.
E-mail address: haythem.banysalameh@aau.ac.ae (H. Bany Salameh).

Peer review under responsibility of The Korean Institute of Communications and Information Sciences (KICS).

https://doi.org/10.1016/j.icte.2021.06.003

Please cite this article as: H. Bany Salameh and G. El Refae, Price- and rate-aware multi-channel spectrum access for profit enhancement in opportunistic networks with QoS guarantees, ICT Express (2021), https://doi.org/10.1016/j.icte.2021.06.003.

Hence, to achieve a required QoS rate demand for a given SU, a channel or a set of channels needs to be utilized such that the SU is served. Specifically, SUs dynamically utilize the idle portion of the licensed spectrum and adapt their transmission parameters (e.g., waveform, number of assigned channels, carrier frequency, etc.) based on the operating RF environment, required price to utilize a given PR channel, the supported rate over the different channels and required QoS requirements. Hence, the network of SUs that co-exists with the PR users should exploit the underutilized licensed channels in an efficient cost-effective manner such that the QoS demands are satisfied. In such hybrid network, the main challenge is how the SUs can share the licensed channels with the PRNs such that the number of served SUs is maximized with highest possible CRN profit (least amount of paid cost to PRNs) subject to SU QoS requirements, utilization-dependent PR price regulations and time-varying channel-quality conditions due to fading. Most of the previous works that dealt with spectrum pricing in CRNs (e.g., [8–14]) aimed to provide optimal pricing strategies for using the spectrum without dealing with the channel assignment problem (they assume that upon the arrival of SU packet, the SU randomly chooses one of the idle PR channels). On the other hand, most of previously proposed channel assignment schemes for CRNs were designed to optimize network performance (e.g., network sum-rate, spectrum utilization, energy consumption, etc.) without considering the economical aspect of accessing the PR channels [15,16]. Unlike the previous literature, in this paper, we advocate a profit-maximization channel assignment scheme that allows cost-efficient opportunistic SU transmissions while satisfying SU QoS requirements, hardware constraints and price requirements for PRNs. Our key performance measure is the net profit made by the CRN, defined in [13,14] as the CR revenue (total price paid by SUs to the CRN) minus the total cost by the CRN to the dominant PRN firms (i.e., spectrum owners) to utilize their channels. Specifically, the channel assignment is expressed as a binary linear programming (BLP) optimization with the objective of serving the largest number of SUs with highest possible CRN profit (least cost paid to PRNs), which is an NP-hard problem. Thus, a polynomial-time sequential-fixing optimization method is used to obtain sub-optimal solutions to the BLP problem. Compared to previous CRN channel assignment mechanisms that attempt to serve the largest possible number of SUs with least number of channels, simulation results indicate that our algorithm serves a comparable number of SUs while achieving significant improvement in CRN profit by jointly considering the impact of the time-varying achieved data rates over the various channels and the utilization-dependent price that is to be paid by SUs for exploiting the PR channels. Note that when employing channel assignment schemes that minimize the amount of used spectrum (e.g., [15]) or maximize the achieved network sum-rate (e.g., [16]), the SUs may be served using channels with high cost resulting in reduced CRN profit.

The remainder of this paper is organized as follows. Section 2 overviews the related work on spectrum pricing in CRNs. In Section 3, we describe our network model. The problem statement, formulation and solution are given in Section 4. Section 5 presents the simulation results and discussion. Section 6 provides concluding remarks.

2. Related work on pricing models in CRNs

Various queueing systems were used to derive system performance measures for the purpose of obtaining optimal pricing and performing resource allocation [8–14,17]. The authors in [9] developed two novel dynamic-spectrum leasing strategies and introduced a dynamic pricing mechanism to improve the QoS performance of SUs. The works in [12,17] investigated the optimal pricing strategies in CRNs by using the approach of queueing Economics. The authors have focused on optimal pricing policies from the viewpoint of service profit/social welfare maximization, by which revenue-optimal pricing and socially-optimal pricing were derived [12, 17]. The paper [13] derived the appropriate admission fee to SU transmission with a pricing policy with the objective of maximizing the social Mobile companies profit. The work in [10] investigated the pricing problem in CRNs with multiple PR users through Bertrand competition and market equilibrium. In [11], an optimal pricing strategy for duopoly in CRNs was demonstrated based on a single-server queue with breakdowns. In [13,14], the CRN profit was defined and used as objective to derive optimal pricing policies and CR/PR contracts, but not to optimize the channel assignment for SUs to maximize the overall CRN net profit. In summary, most of previous pricing-based mechanisms in CRNs focused on providing optimal pricing strategies for using the spectrum without dealing with the spectrum allocation problem. Up to the author's knowledge, this is the first paper that formulates the CRN profit maximization problem as a channel assignment optimization problem with the objective of serving the largest number of contending SUs with highest possible CRN profit (payoff) while being aware of the aforementioned factors.

3. Network model

We consider a centralized multi-channel CRN with N SUs and a serving CR base-station. The SU network coexists geographically with M different licensed legacy PRNs. Each PRN m is licensed to operate over a predefined portion of spectrum that is sub-divided into C_m orthogonal frequency channels, where $\mathcal{C}_m$ is the list of all channels licensed to PRN m. Let $\mathcal{C} = \{\mathcal{C}_1, \mathcal{C}_2, \ldots \mathcal{C}_M\}$ denote the list of all PR channels that can be adaptively and opportunistically exploited by the SUs and. We consider an alternating two-state IDLE/BUSY Markov process to model the status of channel i, $\forall i \in \mathcal{C}$ [18,19]. A channel is considered idle when PR users do not use it and the SNR over this channel for the SU exceeds a given SNR threshold. The utilization of channel i is quantified by the busy probability metric. The busy probability can be determined as $P_{Busy}^{(i)} = \frac{\overline{T}_B^{(i)}}{\overline{T}_B^{(i)}+\overline{T}_I^{(i)}}$, where $T_B^{(i)}$ and $T_I^{(i)}$ are exponentially distributed IDLE and BUSY states with rates $1/\overline{T}_I^{(i)}$ and $1/\overline{T}_B^{(i)}$, respectively. If the ith channel is available at a given time t, a SU can utilize it and has to pay a unit price of

$f_i(t)$ to the PRN operators. The unit price $f_i(t)$, is determined by the PRNs based on the PR activity level (channel utilization over channel i). Higher PR utilization results in higher price $f_i(t)$. We note that $f_i(t)$ should be greater than or equal to the price paid by PR users, denoted by β_i ($f^{(i)} \geq \beta^{(i)}, \forall i \in \mathcal{C}$). This constraint will give more price-privilege to licensed PR users. The total price that is to be charged to the CRN operator by the PRNs to serve each SU j by utilizing multiple channels is limited to γ_j. The price heavily depends on the subscription fee (Z_j) that SU j pays for the CRN operator to get serviced.

4. The price-based channel assignment problem

4.1. Problem statement and design constraints

The CRN profit-maximization problem statement is stated as: "Given a number of contending opportunistic SUs ($|\mathcal{N}|$) with a predefined $R_{D,j}$ transmission rate requirement for each SU j, $\forall j \in \mathcal{N}$, a set of available licensed channels at time t ($\mathcal{M}_{idle}$) with the time-varying achieved rate for each user over each channel ($r_j^{(i)}, \forall j \in \mathcal{N}$ and $i \in \mathcal{M}_{idle}$), the unit price f_i at time t, the maximum price that the CRN operator is willing to pay to PRNs to provide service to each SU j γ_j, the subscription fee Z_j, and the minimum acceptable SNR over each channel for each SU (SNR$_{th}$), our objective is to maximize the profit made by the CRN (equivalently, minimize the price to be charged to the CRN) while simultaneously serving the largest number of SUs with achieved rate demands subject to the below QoS and cost constraints:

C1. Transmission rate constraint: Each SU needs a rate demand R_{D_j} that is determined based on the user's requested service and application. The SU is denied service if there is no assignment that can satisfy the rate demand requirement.

C2. Hardware constraint: The number of selected channels for each SU is limited to the number of transceivers per SU, denoted by n_x.

C3. Exclusive spectrum sharing: A PR channel cannot be simultaneously allocated to more than one SU transmission.

C4. Total Price constraint: The total paid charge for PRNs to serve SU j should be less than or equal to a predefined price γ_j. The jth SU cannot be served if the charges exceed the amount the CRN is willing to pay.

C5. SNR constraint: The SNR at the receiver over an assigned channel must be greater than SNR$_{th}$.

4.2. Problem formulation

The main idea behind our proposed formulation is to maximize the CRN profit by minimizing the total cost paid to the dominant PRN firms while serving the maximum number of SUs in a given time subject to the aforementioned design and cost constraints. For a given SU transmitter $j \in \mathcal{N}$, we introduce a decision 0/1-variable ($\alpha_j^{(i)}$) as:

$$\alpha_j^{(i)} = \begin{cases} 1, & \text{if channel } i \text{ is allocated to SU transmission } j \\ 0, & \text{if the } i\text{th channel is not assigned to } j \text{ or busy.} \end{cases}$$

The CRN profit ($\mathbf{\Pi}_{\text{CR}}$) can be written in terms of $\alpha_j^{(i)}$ as:

$$\mathbf{\Pi}_{\text{CR}} = TR - TC = \sum_{j \in \mathcal{N}} Z_j \mathbf{1}[\sum_{i \in \mathcal{C}} \alpha_j^{(i)}] - \sum_{j \in \mathcal{N}} \sum_{i \in \mathcal{C}} f_i \alpha_j^{(i)} \qquad (1)$$

where $\mathbf{1}[.]$ represents the indicator function, TR and TC are the total revenue made by the CRN and the total cost paid to the PRNs, respectively [13]. The SNR constraint can be assured by setting the associated $\alpha_j^{(i)}$ to 0 for any channel i of SU transmission j with SNR<SNR$_{th}$. Accordingly, our problem can be mathematically expressed using the objective in (1) as:

$$\begin{aligned} &\max \sum_{j \in \mathcal{N}} Z_j \mathbf{1}[\sum_{i \in \mathcal{C}} \alpha_j^{(i)}] - \sum_{j \in \mathcal{N}} \sum_{i \in \mathcal{C}} f_i \alpha_j^{(i)} \\ &\text{subject to} \\ &\sum_{i \in \mathcal{C}} r_j^{(i)} \alpha_j^{(i)} \geq R_{D_j} \text{ or } \sum_{i \in \mathcal{C}} R_j^{(i)} \alpha_j^{(i)} = 0, \forall j \in \mathcal{N} \\ &\sum_{i \in M} f_j^{(i)} \alpha_j^{(i)} \leq \gamma_j, \forall j \in \mathcal{N} \\ &\sum_{i \in \mathcal{C}} \alpha_j^{(i)} \leq L_{x_j}, \forall j \in \mathcal{N} \\ &\sum_{j \in \mathcal{N}} \alpha_j^{(i)} \leq 1, \forall i \in \mathcal{C} \end{aligned} \qquad (2)$$

The indicator function $\mathbf{1}[\sum_{i \in \mathcal{C}} f_i \alpha_j^{(i)}]$ can be rewritten in a linear form by defining a binary decision variable $X_j = \mathbf{1}[\sum_{i \in \mathcal{C}} \alpha_j^{(i)}]$ ($X_j = 1$ indicates that SU j is assigned channels and will be served) and adding the following 2 linear constraints as:

$$X_j \leq \sum_{i \in \mathcal{C}} \alpha_j^{(i)} \text{ and } X_j \geq \frac{\sum_{i \in \mathcal{C}} \alpha_j^{(i)}}{C}, \forall j \in \mathcal{N} \qquad (3)$$

Note that the two added constraints ensure that $X_j = 1$ if-and-only-if at least one $\alpha_j^{(i)} = 1$, which means that SU j is served. The either/or rate-demand constraint can be rewritten in a linear form by introducing two binary-auxiliary variables associated with each SU j (z_j^1 and z_j^2) as:

$$\begin{aligned} &\sum_{i \in \mathcal{C}} r_j^{(i)} \alpha_j^{(i)} \leq \Gamma z_j^1 \\ &-\sum_{i \in \mathcal{C}} R_j^{(i)} \alpha_j^{(i)} \leq -R_{D_j} + \Gamma z_j^2, \\ &z_j^1 + z_j^2 = 1, \ \forall j \in \mathcal{N} \end{aligned} \qquad (4)$$

Thus, the CRN profit maximization problem is formulated as:

$$\begin{aligned} &\max_{\{X_j, \alpha_j^{(i)}, z_j^1, z_j^2\}} \sum_{j \in \mathcal{N}} Z_j X_j - \sum_{j \in \mathcal{N}} \sum_{i \in \mathcal{C}} f_i \alpha_j^{(i)} \\ &\text{s.t.} \\ &\sum_{i \in \mathcal{C}} r_j^{(i)} \alpha_j^{(i)} \leq \Gamma z_j^1, \forall j \in \mathcal{N} \\ &-\sum_{i \in \mathcal{C}} R_j^{(i)} \alpha_j^{(i)} \leq -R_{D_j} + \Gamma z_j^2, \forall j \in \mathcal{N} \\ &z_j^1 + z_j^2 = 1, \forall j \in \mathcal{N} \\ &X_j - \sum_{i \in \mathcal{C}} \alpha_j^{(i)} \leq 0, \forall j \in \mathcal{N} \\ &-X_j + \frac{\sum_{i \in \mathcal{C}} \alpha_j^{(i)}}{C} \leq 0, \forall j \in \mathcal{N} \end{aligned}$$

$$\sum_{i\in\mathcal{C}} f_j^{(i)}\alpha_j^{(i)} \le \gamma_j, \forall j \in \mathcal{N}$$
$$\sum_{i\in\mathcal{C}} \alpha_j^{(i)} \le L_{x_j}, \forall j \in \mathcal{N}$$
$$\sum_{j\in\mathcal{N}} \alpha_j^{(i)} \le 1, \forall i \in \mathcal{C} \tag{5}$$

The optimization problem in (4) constitutes an NP-hard BLP. Hence, a sequential-fixing linear programming (SFLP) procedure can be used to solve this type of problems in polynomial-time. This method has been used in previous works to solve BLP optimization problems, in which sub-optimal solutions were demonstrated [20]. The SFLP is based on solving a series of polynomial-time linear programming (LP) problems to obtain a sub-optimal solution to the original NP-hard BLP problem. Specifically, the SFLP is executed as follows: It first relaxes the binary decision variables to take real values in the range [0, 1], in which the original NP-hard BLP problem is reformulated as relaxed LP (RLP) that can be solved in polynomial-time. Then, the SFLP sets the highest obtained $\alpha_j^{(i)}$ to 1, and then check the problem feasibility. If the problem is not feasible, the fixed decision variable is switched to 0. Then, the RLP problem is reformulated with the unfixed decision variables and solved using LP solvers. After that the decision variable with the highest value is set to 1, and the above process is repeated until $|\mathcal{N}|$ decision variables $\alpha_j^{(i)}$ are set to 1 (all users are assigned channels) or all the variables are fixed to either 1 or 0 with number of fixed decision variables with value 1 is less than $|\mathcal{N}|$.

Complexity Analysis: The SFLP method that is being used to solve our BLP problem has a polynomial-time complexity as it is based on solving a series of relaxed LP problems using standard polynomial-time LP solvers. Thus, for each optimization instance, a feasible sub-optimal channel assignment solution can be determined through solving at most $|\mathcal{N}| \times |\mathcal{C}|$ RLP problems with worse-case time-complexity of $O(|\mathcal{N}| \times |\mathcal{C}|)$ (i.e., the worst-case is to fix all the $|\mathcal{N}| \times |\mathcal{C}|$ variables α's to 0 or 1 by solving at most $|\mathcal{N}| \times |\mathcal{C}|$ LPs).

5. Performance evaluation

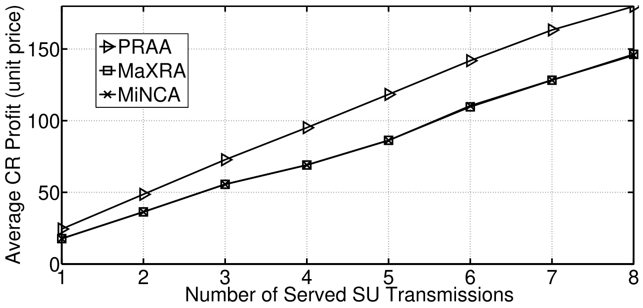
We conduct simulation experiments using MATLAB programs to investigate the effectiveness of our proposed price-rate-aware assignment, referred to as PRAA. We note that most of previously proposed channel assignment schemes for CRNs were designed to optimize network performance in terms of maximizing network sum-rate (e.g., [16]) or maximizing spectrum efficiency (e.g., [15]) without considering the economic aspect of accessing the PR channels. Thus, the performance of PRAA is compared to that of the maximum-rate channel assignment (MaXRA) [16] and minimum channel assignment (MinCA) [15]. MaXRA (MinCA) attempts to serve the largest number of SUs with the maximum possible achieved sum-rate (with least number of assigned channels). For a fair comparison, all simulated schemes attempt to serve the largest number of contending SUs. They differ in how to assign channels to those SUs. Our main performance metric is the total profit made by the CRN.

5.1. Simulation setup

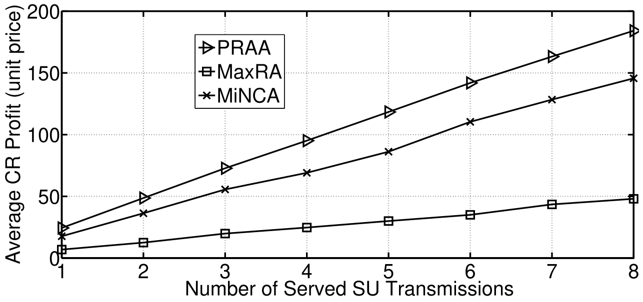
A network of 50 SUs that coexists with 4 PRNs is simulated in a field area of 200 × 200 m^2, each with 10 channels. The first 2 PRNs (i.e., PRNs $k = 1$ and 2) operate in the 900-MHz spectrum with 10 licensed non-overlapping 5-MHz channels. The PRNs $k = 3$ and 4 occupy 20 orthogonal 5-MHz channels in the 2.4 GHz band. The SU transmission power is set to 1 W and the SNR$_{th}$ = 2 dB. We set $n_x = 2$; i.e., a SU can be simultaneously assigned up to 2 data channels. The channel gain between any SU communicating pair is modeled as Rayleigh fading with path-loss exponent of 4 [20]. The price to be paid by each SU to access channel i (f_i) at a given time t depends on the average PR traffic load over that channel (spectrum utilization). The channel utilization level ζ_k, for each PRN k, where $k = 1, 2, 3, 4$, is uniformly varying in the range from 10% to 40%, 10% to 50%, 50% to 90%, and 40% to 90%, respectively. The number of idle channels per PRN is denoted by C_{PR_k}, which depends on the level of utilization ζ_k. The price f_i for channel i belonging to PRN k at time t with channel utilization ζ_k is given by $f_i = (1 + \zeta_k) \times 10$ unit of price. The subscription fee for each SU that to be paid to the CRN is set to $Z_j = 30$ unit of price. The maximum total price that the CRN is willing to pay for the PRNs for serving a SU is limited to $\gamma_j = 25$ unit of price. We note that f_i, γ_j and Z_j are provided in terms of unit cost (i.e., normalized costs). By substituting the unit price values of the used pricing policy in the formula, the actual price can be computed (e.g., in [12], CRN revenue-optimal and socially-optimal pricing models were derived [12,17]. The number of contending SU transmissions at a given time is $|\mathcal{N}|$, in which the communicating pairs are randomly selected from the 50 SUs. The rate demand for each SU j is set to $R_{D_j} = R_d$ Mbps, for all j. The presented results are averaged over 20 simulation experiments, each with 1000 optimization instances.

5.2. Simulation results

Fig. 1 plots the CRN profit versus the number of served SUs for various number of transceivers ($n_x = 1$ and 2) and $R_d = 10$ Mbps. This figure indicates that for the same number of served SUs, our PRAA scheme significantly outperforms the MaXRA and MiNCA algorithms, irrespective of n_x. This is because our proposed assignment jointly considers the interdependence between the spectrum utilization and the price of utilizing the PR channels while being aware of the achieved transmission rates over the various PR channels. Thus, PRAA selects the channel assignment that can serve the SU's demands with the least possible cost, irrespective of the number of used channels (i.e., PRAA favors selecting two low-price channels with aggregate data rate that can meet the SU demand over a single high-price high-data rate PR channel). Fig. 1(a) reveals that for $n_x = 1$, MiNCA and MaXRA provide comparable performance. For $n_x = 2$, Fig. 1(b) shows that MiNCA outperforms MaXRA. This is because MaXRA attempts to maximize the achieved sum-rate, and hence utilizing more PR channels, which incurs higher cost and reduced CRN profit. In

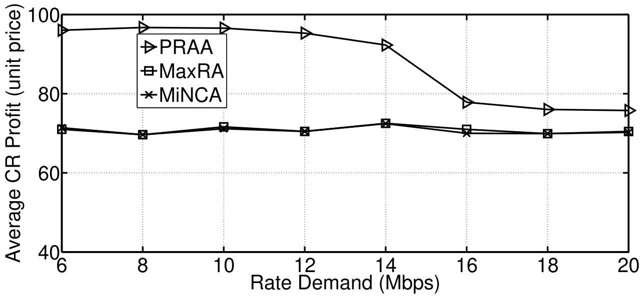


(a) $n_x = 1$

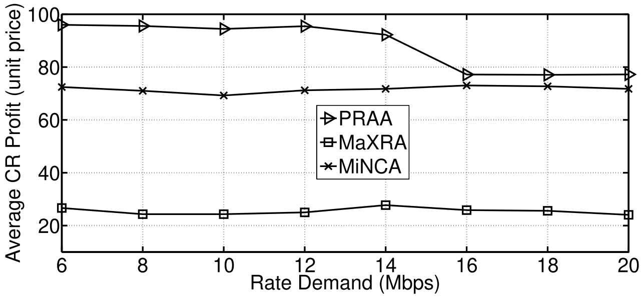


(b) $n_x = 2$,

Fig. 1. CRN profit vs. the number of served SUs for $n_x = 1$ and 2.



(a) $n_x = 1$



(b) $n_x = 2$

Fig. 2. CRN profit vs. the SU rate demand for $n_x = 1$ and 2.

Fig. 2, we investigate the CRN profit versus the rate demand for $n_x = 1$ and 2 with $|\mathcal{N}| = 4$. Fig. 2 shows that, for $R_D \leq 16$, PRAA respectively outperforms MiNCA and MaXRA by up to 35% for $n_x = 1$ and by up to 35% and 150% for $n_x = 2$, respectively. This is because PRAA jointly considers the spectrum utilization-based PR channel price and the achieved data rates over the various channels. For higher R_D, Fig. 2 show that as R_D increases the CRN profit decreases for the PRAA algorithm, and hence the improvement over MiNCA is reduced. This is because meeting higher demands requires utilizing more PR channels for $n_x = 2$ or forcing PRAA to select the channel that provides the required higher R_D for $n_x = 1$, irrespective of the paid price. In this case, higher cost will be paid to the PRNs, resulting in reduced CRN profit. We note that the performance of MiNCA does not change with increasing R_D as it selects the minimum number of channels that meet the rate demand, irrespective of the cost of utilizing the PR channels. Fig. 2 reveals that the performance of PRAA degrades to that of MiNCA under high demand rate. Fig. 2(b) reveals that for $n_x = 2$, the achieved CRN profit of MaXRA significantly decreases as more channels will be utilized to maximize the achieved sum rate, resulting in higher cost.

6. Conclusion

This paper investigated the channel assignment problem in CRNs with the target of serving the largest number of SUs at a lower price subject to predefined rate demand requirements while considering the time-varying nature of channel conditions and the spectrum-utilization-dependent cost of accessing PR channels. The channel assignment problem is mathematically expressed as BLP problem that maximizes the CRN profit by minimizing the CRN cost that is to be paid to the PRNs while serving the largest number of SUs. Our formulation considered the following constraints: the utilization-dependent required price by the PRNs, the total price to be paid by the served SUs, the link-quality conditions over the various channels and the number of transceivers per SU. Because the optimal solution of such BLP problem cannot be determined in polynomial-time, we adopted the well-known sequential-fixing algorithm that can provide polynomial-time sub-optimal solutions. Simulation results demonstrated that significant CR profit increase can be realized by considering the interdependence between the PR price and level of utilization while being-aware of the SU link-quality conditions.

CRediT authorship contribution statement

Haythem Bany Salameh: Conceptualization, Formal analysis, Methodology, Investigation, Software, Writing - original draft, Reviewing and editing. **Ghaleb El Refae:** Conceptualization, Investigation, Validation, Data curation, Visualization, Reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] S. Chowdhury, Matching theory for cognitive radio networks: An overview, ICT Express 5 (1) (2019) 12–15.

[2] Y. Shen, K.S. Kwak, Robust power control for cognitive radio networks with proportional rate fairness, ICT Express 1 (1) (2015) 22–25.

[3] C. Wu, R. Wang, P. Wang, Y. Cao, L. Liu, K. Zhu, B. Chen, On the profit maximization of spectrum investment under uncertainties in cognitive radio networks, in: 2018 IEEE International Conference on Communications (ICC), 2018, pp. 1–6, http://dx.doi.org/10.1109/ICC.2018.8422853.

[4] M. Hassan, G. Karmakar, J. Kamruzzaman, Reputation and user requirement based price modeling for dynamic spectrum access, IEEE Trans. Mob. Comput. 13 (9) (2014) 2128–2140, http://dx.doi.org/10.1109/TMC.2013.78.

[5] G. Sun, X. Tian, Y. Xu, X. Wang, Profit maximization for secondary users in dynamic spectrum auction of cognitive radio networks, Wirel. Commun. Mob. Comput. 15 (9) (2015) 1331–1341.

[6] M. Baye, J. Prince, Managerial Economics and Business Strategy, Mc Graeme Hill Education, USA, 2017.

[7] D. Besanko, D. Dranove, M. Shanley, S. Schaefer, Economics of Strategy, Wiley Custom, USA, 2017.

[8] C. Do, N. Tran, M. Nguyen, C. Hong, S. Lee, Social optimization strategy in unobserved queueing systems in cognitive radio networks, IEEE Commun. Lett. 16 (12) (2012) 1944–1947, http://dx.doi.org/10.1109/LCOMM.2012.111412.120830.

[9] I. M. Balapuwaduge, F.Y. Li, A. Rajanna, M. Kaveh, Channel occupancy-based dynamic spectrum leasing in multichannel CRNs: Strategies and performance evaluation, IEEE Trans. Commun. 64 (3) (2016) 1313–1328.

[10] M.S. A. Salem, Investigation of pricing issue using different game models in cognitive radio network, Wirel. Pers. Commun. 96 (2017) 4237–4249.

[11] C. Do, N.H. Tran, Z. Han, L.B. Le, S. Lee, C.S. Hong, Optimal pricing for duopoly in cognitive radio networks: Cooperate or not cooperate?, IEEE Trans. Wireless Commun. 13 (5) (2014) 2574–2587, http://dx.doi.org/10.1109/TWC.2014.031914.131363.

[12] S. Zhu, J. Wang, W.W. Li, Optimal pricing strategies in cognitive radio networks with multiple spectrums, IEEE Syst. J. (2020) 1–11, http://dx.doi.org/10.1109/JSYST.2020.3018662.

[13] Y. Zhang, L. Song, M. Pan, Z. Dawy, Z. Han, Non-cash auction for spectrum trading in cognitive radio networks: Contract theoretical model with joint adverse selection and moral hazard, IEEE J. Sel. Areas Commun. 35 (3) (2017) 643–653.

[14] L. Gao, X. Wang, Y. Xu, Q. Zhang, Spectrum trading in cognitive radio networks: A contract-theoretic modeling approach, IEEE J. Sel. Areas Commun. 29 (4) (2011) 843–855, http://dx.doi.org/10.1109/JSAC.2011.110415.

[15] H. Bany Salameh, S. Al-Masri, E. Benkhelifa, J. Lloret, Spectrum assignment in hardware-constrained cognitive radio IoT networks under varying channel-quality conditions, IEEE Access 7 (2019) 42816–42825.

[16] H. Zhang, J. Feng, Z. Shi, S. Ma, G. Yang, Rate maximization of wireless powered cognitive massive MIMO systems, IEEE Internet Things J. (2020) 1.

[17] Y. Zhang, J. Wang, W. Li, Optimal pricing strategies in cognitive radio networks with heterogeneous secondary users and retrials, IEEE Access 7 (2019) 30937–30950.

[18] K. Darabkh, et al., A–z overview of the in-band full-duplex cognitive radio networks, Comput. Commun. 145 (2019) 66–95.

[19] D. Roy, T. Mukherjee, M. Chatterjee, E. Pasiliao, Primary user activity prediction in DSA networks using recurrent structures, in: IEEE Symposium on Dynamic Spectrum Access Networks, 2019, pp. 1–10.

[20] H. Bany Salameh, H. Khasawneh, Routing in cognitive radio networks with full-duplex capability under dynamically varying spectrum availability, ICT Express (2020).