Joint Optimal Rate, Power, and Spectrum Allocation in Multi-hop Cognitive Radio Networks

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***Abstract*—Interference due to the sharing of common spectrum band among links and congestion due to the contention among flows sharing the same link have become obstacles to good performance in wireless networks, especially in multi-hop cognitive radio networks (MHCRNs). Consequently, the high end-to-end throughput for MHCRNs calls for a framework of cross-layer optimization design. In this paper, by taking into account the problem of joint optimal rate, power, and spectrum allocation (JORPS), we propose a new cross-layer optimization framework for MHCRNs under spectrum underlay manner using orthogonal frequency division multiple access (OFDMA). The formulation is shown to be a mix-integer non-linear non-convex optimization problem, which is $\mathcal{NP}$-hard in general. To tackle this cumbersome, we firstly applied a partially distributed solution. Then, we showed that this approach fast converges to the global optimum at a cost of computational complexity.**

***Index Terms*—cross-layer optimization, congestion and power control, spectrum allocation, multi-hop cognitive radio networks.**

I. Introduction

Cognitive radio (CR), a new communication paradigm addressing the radio spectrum scarcity, has been considered as a promising technology for realizing dynamic spectrum access (DSA) [1]. Many standardization activities such as IEEE 802.22, ECMA 392, IEEE SCC41, and IEEE 802.11af have been released for potential CR applications. In CR networks, secondary users (SUs) enable flexible and agile access to the licensed spectrum without any explicit approval from the licensees, either in *interweave* or *underlay* mode known as shared-use model [2]. In interweave mode, SUs employ sophisticated sensing mechanisms to discover and utilize the white space spectrum. While in underlay mode, SUs implement a concurrent spectrum sharing with primary users (PUs) as long as the quality-of-service (QoS) degradation of the PU transmission due to the SU interference is tolerable.

In the literature, there are several studies on resource allocation design under interweave paradigm in which spectrum sensing needs performing at each SU before channel access in order to avoid possible collisions with PUs (e.g., [3]–[5]). Thereby, spectrum sensing plays an essential role in all SUs. If the detection is highly unreliable, the collisions between the SUs and PUs may happen more frequently. As a result, the overall spectral efficiency can not be improved. Some recent studies [6]–[9] proposed different solutions to optimally allocate power for SUs in spectrum underlay fashion. In [6], Hasan *et al.* proposed the power allocation algorithms using the risk return model to consider the reliability and availability of licensed channels. The authors in [8] maximized the total rate subject to the power constraints. An spectrum utilization solution has been proposed in [7] by a traditional interference constraint to protect primary transmissions under the SUs' power budget. However, most of the above works focus on CR networks where the secondary transmission only occurs in the single hop between the SUs and CR base station. This approach can not be extended to multi-hop scenarios because the mutual interference among SUs has not been taken into consideration yet.

In this paper, we investigate an efficient spectrum and power allocation strategy coupled with congestion control mechanism that the diversity of orthogonal licensed channels is taken into account for CR links under *two-hop* interference model (e.g., Bluetooth and FH-CDMA networks [10]). More specifically, we focus on underlay mode in OFDMA-based MHCRNs, where PU outage constraint [7], [9], [11] is taken into consideration as a target constraint to protect the primary transmission. Thereby, it is not necessary to perform the proposed algorithm again when the primary-related fading channel changes state.

II. System Model and Problem Formulation

The OFDMA-based MHCRN is modeled by a directed graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of secondary users, $\mathcal{L}$ is the set of logical links, and N, L are their corresponding cardinalities. We assume that the whole spectrum is divided into a set of orthogonal frequency bands $\mathcal{M}$, each of which with bandwidth W is correspondingly licensed to one pair of PUs. We assume that each secondary node is equipped with multiple reconfigurable transceivers for data communication and one transceiver for signalling. Each CR link can simultaneously switch to different licensed bands during transmission. We further assume that the network is shared by a set of sources $\mathcal{S} = \{1, ..., S\}$ indexed by s. Each source $s \in \mathcal{S}$ traverses multiple hops to get its destination through the set of links, $\mathcal{L}_s \subseteq \mathcal{L}$, which is called the path of source s.

A. Secondary Transmission

In an OFDMA-based MHCRN, links are separated by different bands in order to avoid co-channel interference. We define the band allocation variables $a_l^m \in \{0,1\}$, where 1 indicates that band m is assigned to link l and 0 otherwise. Then, we have

$$\sum_{m=1}^{M} a_l^m = 1, \; \forall l \tag{1}$$

in which each link l operates on at most one band at one time. Let η_l denote the additive white Gaussian noise (AWGN) power at link l on band m. Instantaneous channel gain-to-interference ratio (CIR) of link l on band m is expressed as $\gamma_l^m = \frac{G_{ll}^m F_{ll}^m}{\eta_l + G_{l0}^m F_{l0}^m P_0^m}$. We use the special index 0 to denote primary links (e.g., P_0^m is the transmit power of PU-Tx on band m). Generally, the channel gains G_{lh}^m and F_{lh}^m represent the large-scale fading and small-scale fading between the h-th link's transmitter and the l-th link's receiver on band m, respectively. We assume that F_{lk}^m is independent and identically distributed random variables (RVs) with unit mean and $G_{lk}^m = d_{lk}^{-n}$ only depends on the physical link distance d_{lk} with the path loss exponent n. The Shannon capacity at the link l is given by:

$$C_l(\mathbf{P}_l, \mathbf{a}_l) = \sum_{m=1}^{M} a_l^m \log\left(1 + \bar{\gamma}_l^m P_l^m\right) \tag{2}$$

where $\mathbf{P}_l = [P_l]$ and $\mathbf{a}_l = [a_l]$ are power and spectrum allocation vectors of link l, respectively. $\bar{\gamma}_l^m$ is the average CIR. We define $\mathcal{I}_l^m$ as the set of other links that interfere with the given link l on band m and assume that interference relationship is symmetric, then

$$\sum_{l \in \mathcal{I}_l^m} a_l^m = 1, \quad \forall m \tag{3}$$

which allows only one link $l \in \mathcal{I}_l^m$ to transmit on band m at any time instant. To avoid overwhelming link capacity, the offered load on each link should not exceed its capacity:

$$\sum_{s \in \mathcal{S}_l} x_s \le \sum_{m=1}^{M} a_l^m \log\left(1 + \bar{\gamma}_l^m P_l^m\right), \forall l \tag{4}$$

where $\mathcal{S}_l = \{s : l \in \mathcal{L}_s\}$ is the set of sources using link l.

B. Primary Protection

The instantaneous signal-to-interference ratio (SIR) at PU-Rx m:

$$\mathrm{SIR}_0^m(\mathbf{P}^m, \mathbf{a}^m) = \frac{G_{00}^m F_{00}^m P_0^m}{\eta_0 + \sum_l a_l^m G_{0l}^m F_{0l}^m P_l^m}, \forall m, \tag{5}$$

where $\mathbf{P}^m = [P_l^m], \forall l \in \mathcal{L}$ and $\mathbf{a}^m = [a_l^m], \forall l \in \mathcal{L}$. In order to maintain its quality of service (QoS), the PU-Rx m requires the fading-induced outage probability to stay below a certain threshold ζ_{th}^m, which indicates how much its SIR budget should decrease for secondary transmissions.

$$\Pr[\,\mathrm{SIR}_0^m(\mathbf{P}^m, \mathbf{a}^m) \le \gamma_{th}^m] \le \zeta_{th}^m, \forall m, \tag{6}$$

where γ_{th}^m is the SIR threshold at the PU-Rx m.

As can be observed from (5), $\mathrm{SIR}_0^m(\mathbf{P}^m, \mathbf{a}^m)$ has a complex distribution. We can adopt the closed-form of outage probability in [12] for PU-Rx m in the following.

$$\Pr[\,\mathrm{SIR}_0^m(\mathbf{P}^m, \mathbf{a}^m) \le \gamma_{th}^m] = 1 - (1 - \zeta_0^m) \prod_{l=1}^{L} \left(1 + \frac{a_l^m G_{0l}^m P_l^m \gamma_{th}^m}{P_0^m G_{00}^m}\right)^{-1}, \tag{7}$$

where $\zeta_0^m = 1 - \exp(\frac{-\eta_0 \gamma_{th}^m}{P_0^m G_{00}^m})$ is the outage probability of PU-Rx m in the absence of SUs.

By substituting (7) into (6), rewriting the resultant inequality as a lower bound on a posynomial function in $\mathbf{P}^m$, then taking logarithm on both sides, we have

$$\sum_{l=1}^{L} \log(1 + a_l^m \rho_l^m P_l^m) \le \log \mu^m, \tag{8}$$

where $\mu^m = (1 - \zeta_0^m)/(1 - \zeta_{th}^m)$ and $\rho_l^m = \frac{G_{0l}^m \gamma_{th}^m}{G_{00}^m P_0^m}$. We assume that the PU requirements including a tuple of $\{P_0^m, \zeta_0^m, \zeta_{th}^m\}$ must be declared *a priori* to all secondary nodes.

C. Problem Formulation

Our JORPS problem with the PU outage constraint for MHCRNs is formulated via the underlying NUM problem:

$$(\mathbf{P1}) \qquad \max_{\mathbf{x} \in \mathcal{X}, \mathbf{P} \in \mathcal{P}, \mathbf{a} \in \mathcal{A}} \sum_{s \in \mathcal{S}} U_s(x_s) \tag{9}$$
$$\text{s.t.} \quad (1), (3), (4), (8).$$

where $\mathcal{X} = \{x_s; s \in \mathcal{S} | x_s^{min} \le x_s \le x_s^{max}\}$, $\mathcal{P} = \{P_l^m; l \in \mathcal{L}, m \in \mathcal{M} | P_l^{m,min} \le P_l^m \le P_l^{m,max}\}$, $\mathcal{A} = \{0, 1\}$. $U_s(x_s)$ is assumed to be twice continuously differentiable, non-decreasing and strictly concave in its domain. The fairness in the resource allocation can be characterized by the following general α-fair utility function [13]. It is straightforward that $\mathbf{P1}$ is mix-integer, non-linear, and non-convex. The optimal solution is known to be $\mathcal{NP}$-hard.

III. Equivalent Convex Problem and Duality

A. Equivalent Convex Problem

Without loss of optimality, the problem $\mathbf{P1}$ can be rewritten by using the log change of rate and power variables (i.e., $\hat{\mathbf{P}} = \log \mathbf{P}$ and $\hat{\mathbf{x}} = \log \mathbf{x}$) as follows:

$$(\mathbf{P2}) \qquad \max_{\hat{\mathbf{x}} \in \hat{\mathcal{X}}, \hat{\mathbf{P}} \in \hat{\mathcal{P}}, \mathbf{a} \in \mathcal{A}} \sum_{s \in \mathcal{S}} U_s(e^{\hat{x}_s}) \tag{10}$$

$$\text{s.t.} \qquad (1), (3),$$

$$\sum_{l=1}^{L} a_l^m \log(1 + \rho_l^m e^{\hat{P}_l^m}) \le \log \mu^m, \qquad \forall m, \tag{11}$$

$$\log \sum_{s \in \mathcal{S}_l} e^{\hat{x}_s} \le \log \sum_{m=1}^{M} a_l^m \log\left(1 + \gamma_l^m e^{\hat{P}_l^m}\right), \forall l \tag{12}$$

where $\hat{\mathcal{P}} = \{\hat{P}_l, l \in \mathcal{L} | \log P_l^{min} \le \hat{P}_l \le \log P_l^{max}\}$ and $\hat{\mathcal{X}} = \{\hat{x}_s, s \in \mathcal{S} | \log x_s^{min} \le \hat{x}_s \le \log x_s^{max}\}$.

Theorem 1. *Given* $\mathbf{a}$ *satisfying* (1) *and* (3), $\mathbf{P2}$ *is a convex optimization problem.*

Proof: It is straightforward that all constraints in $\mathbf{P2}$ is convex. Moreover, utility function is assumed concave. Given $\mathbf{a}$, $\mathbf{P2}$ hence is a convex problem [14]. ■

B. Lagrange Dual Problem

By augmenting the objective function with a weighted sum of the constraints (12) and (13), we obtain the partial Lagrangian of $\mathbf{P2}$:

$$L(\hat{\mathbf{x}}, \hat{\mathbf{P}}, \mathbf{a}, \boldsymbol{\lambda}, \boldsymbol{\nu}) = \sum_{s\in\mathcal{S}} U_s(e^{\hat{x}_s}) - \\ - \sum_l \lambda_l \left(\log \sum_{s\in\mathcal{S}_l} e^{\hat{x}_s} - \log \sum_m a_l^m \log\left(1+\gamma_l^m e^{\hat{P}_l^m}\right) \right) \\ - \sum_m \nu_m \left(\sum_l a_l^m \log(1+\rho_l^m e^{\hat{P}_l^m}) - \log \mu^m \right) \quad (13)$$

where congestion prices $\boldsymbol{\lambda} = [\lambda_1, ..., \lambda_L]$ and PU outage prices $\boldsymbol{\nu} = [\nu_1, ..., \nu_M]$ are the nonnegative multipliers.

We refer to the problem $\mathbf{P2}$ as the *primal* problem, then its *dual* problem can be described as

$$(\mathbf{D}) \qquad \min_{\boldsymbol{\lambda}\succeq 0, \boldsymbol{\nu}\succeq 0} \; g(\boldsymbol{\lambda}, \boldsymbol{\nu}) \qquad (14)$$

$$\text{where} \quad g(\boldsymbol{\lambda}, \boldsymbol{\nu}) = \max_{\hat{\mathbf{x}}\in\hat{\mathcal{X}}, \hat{\mathbf{P}}\in\hat{\mathcal{P}}, \mathbf{a}\in\mathcal{A}} L(\hat{\mathbf{x}}, \hat{\mathbf{P}}, \mathbf{a}, \boldsymbol{\lambda}, \boldsymbol{\nu}) \qquad (15) \\ \textit{s.t.} \quad (1), (3).$$

IV. Joint Optimal Rate, Power, and Spectrum Allocation (JORPS) via Dual Decomposition

By dual decomposition, (15) can be decomposed into two subproblems as in (16) and (17).

A. Subproblem 1: Rate Allocation

Given $\boldsymbol{\lambda}$, each $s \in \mathcal{S}$ optimizes its data rate x_s such that $U_s(x_s)$ is maximized. Let $\lambda_s \doteq \sum_{l\in\mathcal{L}_s} \frac{\lambda_l}{\sum_{\acute{s}\in\mathcal{S}_l} x_{\acute{s}}}$, the optimal rate can be found by using a gradient ascent [15] with a sufficiently small step size $\kappa_t \geq 0$ as

$$x_s^{(t+1)} = \left[x_s^{(t)} + \kappa_t \left(U_s^{'}(x_s^{(t)}) - \lambda_s^{(t)} \right) \right]^{\mathcal{X}} \qquad (18)$$

where $U_s^{'}(.)$ is the first derivative of utility and $[x]^{\mathcal{X}}$ is the projection of x onto the set $\mathcal{X}$.

B. Subproblem 2: Power and Spectrum Allocation

Since $\hat{\mathbf{P}}$ and $\mathbf{a}$ appear in the sum of products, (17) can be further decomposed into two subproblems:

Subproblem 2.1: Power Allocation

Given (λ_l, ν_m), optimize $\hat{P}_l^m$ such that the weight $\Gamma_l^m(\hat{P}_l^m, \lambda_l, \nu_m)$ in (17) is maximized. The optimal powers

$$\hat{P}_l^{m,*} = \arg \max_{\hat{P}_l^m \in \hat{\mathcal{P}}} \Gamma_l^m(\hat{P}_l^m, \lambda_l, \nu_m). \qquad (19)$$

can be obtained by the iterative algorithm as follows:

$$P_l^{m,(t+1)} = \left[P_l^{m,(t)} + \kappa_t \left(\lambda_l^{(t)} A_l^{m,(t)} - \nu_m^{(t)} B_l^{m,(t)} \right) \right]^{\mathcal{P}} \qquad (20)$$

where $A_l^{m,(t)} = \frac{\gamma_l^m}{1+\gamma_l^m P_l^{m,(t)}} \frac{1}{\log(1+\gamma_l^m P_l^{m,(t)})}$ and $B_l^{m,(t)} = \frac{\rho_l^m}{1+\rho_l^m P_l^{m,(t)}}$.

Subproblem 2.2: Spectrum Allocation

Given Γ_l^m, the spectrum allocation problem in (17):

$$\max_{\mathbf{a}\in\mathcal{A}} \sum_{l=1}^{L} \sum_{m=1}^{M} a_l^m \Gamma_l^m \quad \text{s.t.} \;\; (1), (3). \qquad (21)$$

is equivalent to a *maximum weighted matching problem* on a multi-band weighted conflict graph $G^c = (\mathcal{V}, \mathcal{E})$. In graph G^c, each vertex corresponds to a pair of link-band (l, m) associated with its weight Γ_l^m, thereby we have $|\mathcal{V}| = M \times L$. For constraints (1), the edge between two vertices in G^c corresponds to the link-band pairs interfere with each other. For constraints (3), there will be additional edges between two vertices with the same link but different bands. Then, the global optimal solution $\mathbf{a}^*$ corresponds to the maximum independent set (MIS) of G^c achieved by an exhaustive search method in a centralized manner.

C. Lagrange Multiplier Update

Since $L(\hat{\mathbf{x}}, \hat{\mathbf{P}}, \mathbf{a}, \boldsymbol{\lambda}, \boldsymbol{\nu})$ is affine in $(\boldsymbol{\lambda}, \boldsymbol{\nu})$, the optimal multipliers (λ_l^*, ν_m^*) to minimize $g(\boldsymbol{\lambda}, \boldsymbol{\nu})$ can be obtained using the projected gradient-descent method [15] as (22) and (23).

$$\nu_m^{(t+1)} = \left[\nu_m^{(t)} - \kappa_t \log(\mu^m / \Psi_l^{m,(t)}) \right]^{\mathbf{R}+}, \qquad (22)$$

$$\lambda_l^{(t+1)} = \left[\lambda_l^{(t)} + \kappa_t \log(\sum_{s\in\mathcal{S}_l} x_s^{(t)} / \Theta_l^{m,(t)}) \right]^{\mathbf{R}_+} \qquad (23)$$

where $\Psi_l^{m,(t)} = \prod_{l\in\mathcal{L}} (1 + a_l^{m,(t)} \rho_l^m P_l^{m,(t)})$ and $\Theta_l^{m,(t)} = \sum_{m=1}^{M} a_l^{m,(t)} \log(1 + \gamma_l^m P_l^{m,(t)})$.

D. JORPS Algorithm

The above dual solution motivates the following JORPS algorithm, where we use the same step-size k_t for all updates without loss of generality:

Theorem 2. *For any initial values of the primal and dual variables in their domains, the sequence of primal-dual variables generated by **JORPS** converges to the global optimum of the original problem* $\mathbf{P1}$ *provided that the stepsize satisfies*

$$\kappa_t \geq 0, \quad \sum_{t=0}^{\infty} (\kappa_t) = \infty, \quad \sum_{t=0}^{\infty} (\kappa_t)^2 < \infty \qquad (25)$$

Proof: When each $\mathbf{a}$ is fixed during T, $\mathbf{x}$ and $\mathbf{P}$ are always adjusted toward global optimality since $\mathbf{P2}$ is convex [**Theorem 1**]. Moreover, $\mathbf{a}$ is always optimized by the central node via finding MIS on G^c over T. JORPS hence converges to the global optimum if the step sizes satisfying (25) [15]. ■

$$\max_{\mathbf{x}\in\mathcal{X}} \left\{ L_x(\hat{\mathbf{x}},\boldsymbol{\lambda}) \triangleq \sum_s U_s(e^{\hat{x}_s}) - \sum_{l\in\mathcal{L}} \lambda_l \log \sum_{s\in\mathcal{S}_l} e^{\hat{x}_s} \right\}. \quad (16)$$

$$\max_{\hat{\mathbf{P}}\in\hat{\mathcal{P}},\mathbf{a}\in\mathcal{A}} \left\{ L_{P,a}(\hat{\mathbf{P}},\mathbf{a},\boldsymbol{\lambda},\boldsymbol{\nu}) \triangleq \sum_{l=1}^{L}\sum_{m=1}^{M} a_l^m \underbrace{\left[\lambda_l \log(\log(1+\gamma_l^m e^{\hat{P}_l^m})) - \nu_m \log(1+\rho_l^m e^{\hat{P}_l^m})\right]}_{\Gamma_l^m(\hat{P}_l^m,\lambda_l,\nu_m)} \right\} \quad \text{s.t.} \quad (1),(3). \quad (17)$$

Algorithm 1: JORPS Algorithm

Sources and links initialize $\mathbf{x}^{(0)},\mathbf{P}^{(0)},\boldsymbol{\lambda}^{(0)},\boldsymbol{\nu}^{(0)}$.

Source Algorithm: For each source $s\in\mathcal{S}$, at time t:

1) Receive the total price $\lambda_s^{(t)}$ which accumulates $\lambda_l^{(t)}/\sum_{\acute{s}\in\mathcal{S}_l} x_{\acute{s}}^{(t)}$ of the intermediate links l along its path through a feedback message from its destination.
2) Update rate $x_s^{(t+1)}$ using (18) with $\lambda_s^{(t)}$.

Link Algorithm: For each link $l\in\mathcal{L}$,

1) At time t:
   a) Receive $\mathbf{P}_k^{(t)}, k\neq l$ from other links. Update the new outage prices $\nu^{m,(t+1)},\forall m$ using (22).
   b) Get ingress rates $\sum_{s\in S_l} x_s^{(t)}$ from input queue. Update new congestion price $\lambda_l^{(t+1)}$ using (23).
   c) Update and broadcast the new $P_l^{m,(t+1)}$ using (20).
   d) Compute new weights $\Gamma_l^{m,(t)},\forall m\in\mathcal{M}$ as in (17) and average weights with $0<\beta<1$:
   $$\bar{\Gamma}_l^{m,(t+1)} = (1-\beta)\Gamma_l^{m,(t)} + \beta\Gamma_l^{m,(t+1)} \quad (24)$$
2) At time $T\geq t$: Send its average weights $\overline{\Gamma_l}^{m,(T)},\forall m\in\mathcal{M}$ and receive the new $\mathbf{a}_l^{(T)}$ to/from central node.

Central node Algorithm: At time $T\geq t$,

1) Receive the links' average weights $\overline{\Gamma_l}^{m,(T)},\forall m,l$.
2) Construct multi-band conflict graph G^c. Perform exhaust search algorithm on G^c to find new $(\mathbf{a}_l^{(T)})$.
3) Broadcast the new $\mathbf{a}^{(T)}$ to all links.

V. Performance Evaluation

A. Simulation Settings

We consider a simplified MHCRN system with 5 SUs, 3 pairs of PUs, and 4 sources at $d=1m$ as illustrated in Fig.1. Each CR link with a transmit power range from $1.76dBm$ to $27dBm$ is allocated one band and a power level at each period. Bandwidth of each band is $125KHz$. The minimum data rate for each source is assumed to be $100bps$. For PUs, we predefine the tolerable outage thresholds for the three non-overlap bands 1, 2 and 3 as $\mu_{th}^1=12\%$, $\mu_{th}^2=19\%$, and $\mu_{th}^3=14\%$ at SIR thresholds $\gamma_{th}^1=11.7dB$, $\gamma_{th}^2=9dB$, and $\gamma_{th}^3=12.8dB$, respectively. We assume all PUs transmit at the same power $20dBm$ and PSD of AWGN is -174dBm/Hz.

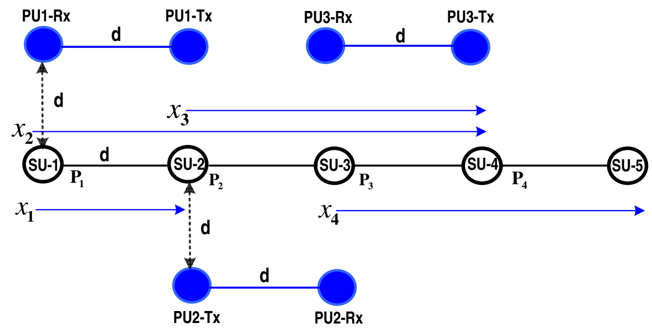

Fig. 1: Physical and logical topologies for simulation.

B. Numerical Results

In Fig. 2, JORPS is compared with scheme JORPS-FSA, where we randomly assign the licensed bands to all links satisfying (1) and (3), then fix them during power and rate update period to validate its optimality. JORPS outperforms any JORPS-FSA algorithms in terms of aggregate utility for all different fixed spectrum settings. In fact, the solution of JORPS is globally optimal, and its total utility is the highest.

We also investigate the impact of timescale T on the performance of our proposed algorithm. Fig. 4 shows that there is a significant difference in terms of convergence speed at different timescales $T=t$, $T=50t$, and $T=100t$. This is because it will take a longer time to update spectrum allocation vector from the central node. However, our proposed algorithm brings the central node the freedom to track only the average weight. More importantly, this scheme reduces the induced computation burden on the central node so that our algorithm is much more scalable and implementable.

VI. Conclusion

In this paper, we have proposed a new cross-layer framework for JORPS problem considering co-existence of the licensed and unlicensed users in MHCRNs using OFDMA. By applying the dual decomposition and introducing a novel multi-band conflict graph, we develop a partially distributed algorithm, which is proved to globally converge to an optimal solution despite $\mathcal{NP}$-hardness of the problem. Fair resource allocation also is achieved by using a utility-based scheme.

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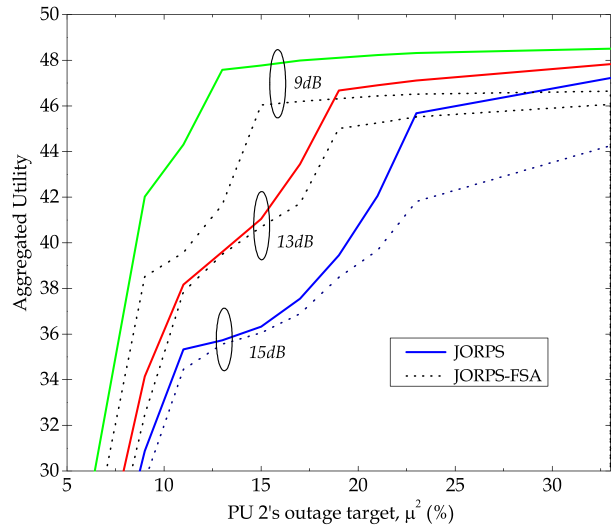

Fig. 2: Comparison of the aggregate utilities versus the PU 2's outage margin and SIR margin.

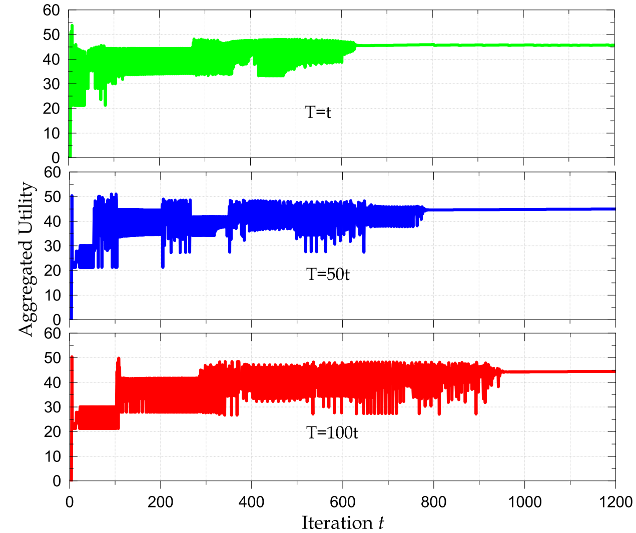

Fig. 4: Effect of timescales on trajectory of aggregated utility.

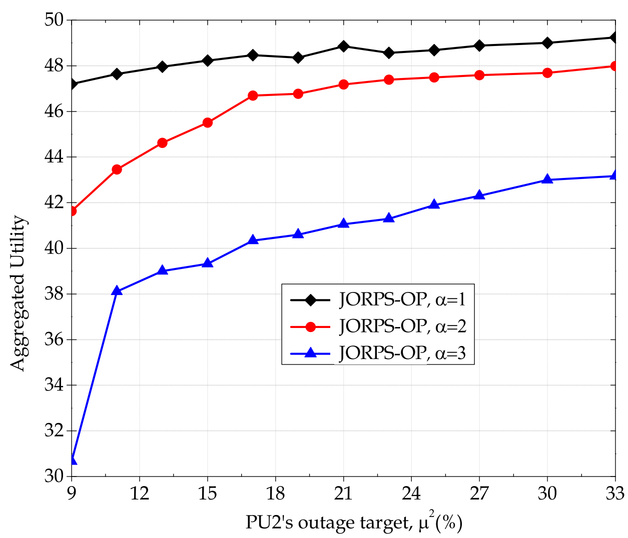

Fig. 3: Comparison of aggregated utility with different fairness policies for resource sharing.

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