Cross-Layer Cognitive MAC Design for Multi-hop Wireless Ad-hoc Networks with Stochastic Primary Protection

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***Abstract*—In this paper, we consider the probabilistic channel contention resolution problem for net revenue maximization in multi-hop wireless ad-hoc networks (MHAHNs) under collision-rate-constrained opportunistic spectrum access (OSA) approach. Specifically, we focus on the *interference-dependent* contention model, in which secondary users (SUs) must coordinate to each other to simultaneously balance between interference and collision, leading a more efficient MAC protocol than the *location-dependent* one proposed in the literature. By introducing some auxiliary variables and noisy channel estimations, we can then develop a novel heuristic cross-layer cognitive MAC protocol (HCC-MAC) in OSA-based MHAHNs to solve the formulated MAC optimization problem which is shown non-convex and inseparable. More importantly, our proposed protocol can achieve near-optimal throughput in a distributed manner without control overhead. Finally, the numerical results show that HCC-MAC can outperform the existing MAC protocols under OSA paradigm.**

***Index Terms*—cross-layer optimization, congestion and power control, contention control, multi-hop wireless ad-hoc networks.**

I. INTRODUCTION

In wireless ad-hoc networks, two well-known models used to characterize the mutual interference due to spectrum sharing among the active links are the physical model and the protocol model. However, in MHAHNs, the former's computational complexity dramatically increases for an optimal solution of the involved cross-layer problems whereas the latter simplifies the mathematical characterization that leads an inaccurate capture of physical layer [1]. In the literature, a large of MAC studies (e.g., [2]–[4]) resolved the channel contention under the protocol interference model in which the impact of interference from one link's transmitter to another link's receiver is binary and determined by the number of hops between them. The limitation of some above studies is that all outgoing links from a node are forced to transmit at the same fixed power, leading passive and inefficient MAC protocols.

In OSA-based MHAHNs, interference due to co-used dynamic spectrum, congestion due to link sharing, and contention due to multi-access are key obstacles that can fundamentally reduce the network performance. Since they interact in a complex way, the contention resolution requires a more sophisticated and adaptive MAC scheme. Studying of interaction effect of contention control at the MAC layer on power control at the physical layer and congestion control at the transport layer hence seems essentially urgent. The benefit of this cross-layer design is that we can essentially reduce the contention density thanks to the balance of interference and congestion among SUs while best-exploiting probabilistic spectrum opportunities vacated by primary users (PUs). In this paper, we investigate such a cross-layer MAC framework for OSA-based MHAHNs under a *mixed* interference model [1] which reconciles the physical model and protocol model. Our objective is to provide a good performance (i.e., maximum throughput, energy efficiency, and fairness) for OSA-based MHAHNs while ensuring PUs' QoS.

Several recent MAC studies under OSA paradigm (e.g., [5]–[11]) addressed how to utilize stochastic spectrum holes in time by jointly performing spectrum sensing and channel access at SUs in order to avoid possible collisions with PUs. The authors in [5] proposed an opportunistic-sensing-based multi-channel MAC protocol where SU-transmitter opportunistically senses all channels in collaboration with the other nodes and sufficiently regulates its power so that it can utilize spectrum holes even in mis-detecting the PU's presence. Thereby, SUs can fully utilize the spectrum opportunities without making harmful interference to PUs. Le at al. [8] designed an intelligent MAC protocol in which SUs' spectrum sensing must be done simultaneously in cooperation with contention resolution task. Tan and Le [6] addressed the design of optimal contention window and the sufficient sensing time allocation to enhance SUs' throughput and protect active PUs. More specifically, the studies [4], [9], [10], [12], [13] concentrated on the design of opportunistic multi-channel MAC protocols which can support ad-hoc network operations.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider an OSA-based MHAHN as Fig. 1 which consists of the set of N cognitive nodes (denoted by $\mathcal{N}$) and the set of L *unidirectional* cognitive links (denoted by $\mathcal{L}$). The whole channel is divided into the set of M orthogonal spectrum sub-bands (denoted by $\mathcal{M}$) and grouped into H non-overlapped sub-sets of contiguous sub-bands, so-called spectrum band denoted by $\mathcal{M}_h \in \mathcal{M} \mid \cup_h \mathcal{M}_h = \mathcal{M}$. Each band is correspondingly licensed to a pairs of PUs. For ease

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of presentation, we use the same index h to show the hth spectrum band and the hth pair of PUs. Each spectrum band h is characterized as a two-state ergodic Markov Chain [14] with the idle probability π^h.

Specifically, we focus on a slotted random access system in which the contention resolution among links at each time slot is performed on the basis of transmission persistence probability $q_l \in \mathcal{Q}_l = [q_l^{min}, q_l^{max}]$, where $0 \leq q_l^{min} \leq q_l^{max} \leq 1$. All cognitive nodes are synchronized and start their transmissions only at the beginning of each time slot. Similar to [2], [3], each cognitive node n with a random-access-based contention resolution protocol transmits data with a probability Υ_n, and it can not transmit or receive simultaneously. However, in this paper, when cognitive node n determines to transmit, to avoid collisions among its outgoing links (denoted by $L_{out}(n)$), it therefore choose link $l \in L_{out}(n)$ with a probability q_l/Υ_n, such that $\sum_{l \in L_{out}(n)} q_l = \Upsilon_n \leq 1$, and transmit data on the chosen link l at a power level per band P_l^m. The chosen link then transmits data on all spectrum bands by adopting spectrum pooling [15], [16]. We further assume that each source $s \in \mathcal{S}$ emits one flow traveling through a pre-defined set $L_s \subseteq \mathcal{L}$ of links at rate $x_s \in \mathcal{X}_s = [x_s^{min}, x_s^{max}]$ and obtains a utility $U_s(x_s)$.

We employ *mixed interference model* at the physical layer in which the link k is supposed to cause a harmful interference to the link l if its total interference power $\sum_m^M I_{lk}^m$ at the lth link's receiver is greater than the lth link's acceptable interference threshold I_l^{th}, where $I_{lk}^m = G_{lk}^m P_k^m$ is the kth link's interference power per sub-band m at the lth link's receiver. We assume that the channel fading changes very slowly so that the channel gain between the kth link's transmitter and the lth link's receiver on band m, G_{lk}^m, remains constant during time slot, but changeable over time slots. Then, we define $\mathcal{N}_l^I = \cup_{k \neq l} \{Tx_k : \sum_m^M I_{lk}^m \geq I_l^{th}\}$ as the set of other nodes whose transmissions generate a considerable interference to the receiver of link l. For a successful transmission of link l within a time slot, two following constraints must be satisfied: *i)* $P_l^{m,min} \leq P_l^m \leq P_l^{m,max}, \forall m$ and *ii)* no other cognitive nodes in $\mathcal{N}_l^I$ start their transmissions.

A. Constraints on Network Stability

From the link l's viewpoint with a transmit power per sub-band P_l^m, $\forall l \in L_{out}(n)$, the whole channel is idle if all other contending cognitive nodes and all pairs of PUs whose transmissions make an adverse interference to the lth link's reception are silent. Hence, the probability that the link l successfully transmits its data at q_l can be calculated as

$$q_l^{succ} = q_l \times \prod_{n' \in \mathcal{N}_l^I} \big(1 - \sum_{k \in L_{out}^l(n')} q_k\big) \times \prod_{h \in \mathcal{N}_{l,0}^I} \pi^h \qquad (1)$$

where $\mathcal{N}_{l,0}^I = \{Tx_h : \sum_m I_{lh,0}^m \geq I_l^{th}\}$ is the set of licensed transmitters which cause harmful interference at the lth link's receiver and $L_{out}^l(n')$ is the set of outgoing links from other node n' which cause a considerable interference at the lth link's receiver. Note that we use the special symbol "0" to denote those what is related to PUs. For its stability at the output buffer, the lth link's offered load avoids overwhelming its protocol Shannon capacity $c_l(\boldsymbol{q}, \boldsymbol{P}_l)$:

$$\sum_{s \in \mathcal{S}_l} x_s \leq \underbrace{\sum_m^M \log\left(1 + G_{MC}\gamma_l^m P_l^m\right) \times q_l^{succ}}_{c_l(\boldsymbol{q}, \boldsymbol{P}_l)}, \forall l \qquad (2)$$

where $\mathcal{S}_l = \{s : l \in \mathcal{L}_s\}$ is the set of sources s using link l and $\gamma_l^m = \frac{G_{ll}^m}{N_0^m}$ is the lth link's channel gain-to-interference ratio on sub-band m [1]. N_0^m denotes the additive white noise power per sub-band m. G_{MC} denotes the constant processing gain which will be absorbed into γ_l^m, henceforth.

B. Constraints on PU Packet Collision Rate

From the hth PU's viewpoint, the hth band is assumed to be busy during time slot if at least one cognitive node starts data transmission with an adverse interference to the hth PU's receiver. This probability of band state is calculated as

$$\zeta_h^{busy} = 1 - \prod_{n \in \mathcal{N}_{h,0}^I} (1 - \sum_{l \in L_{out}^h(n)} q_l), \forall h \qquad (3)$$

where $\mathcal{N}_{h,0}^I = \cup_l \{Tx_l : \sum_{m=m_h}^{m_{h+1}-1} I_{hl,0}^m \geq I_{h,0}^{th}\}$ and $L_{out}^h(n)$ is the set of outgoing links from node n which cause a considerable interference to the hth licensed link's receiver. The collision to the PU h occurs only when it starts data transmission while its band is being interfered by SUs. To guarantee PUs' quality of service (QoS), the maximum packet collision rate caused by the SUs' transmissions must be below the tolerable and preset threshold $\mu^h \leq 1 - \pi^h$:

$$\zeta_h^{col} = \zeta_h^{busy} \times (1 - \pi^h) \leq \mu^h, \forall h. \qquad (4)$$

It is clear that ζ_h^{col} depends on not only the cognitive link's persistence probabilities but also the interference level caused by them. Given stochastic spectrum opportunities $(\boldsymbol{\pi}, \boldsymbol{\mu})$ and the acceptable interference limits I_h^{th}, how to balance the interference and collision among SUs motivates a optimization control framework in the next section.

C. Optimization Framework of Cross-Layer MAC

Our objective is to achieve flexible tradeoff between energy efficiency and network utility maximization subject to network stability (2) and the PUs' QoS (4) as follows:

$$\max_{\boldsymbol{x} \in \mathcal{X}, \mathbf{P} \in \mathcal{P}, \mathbf{q} \in \mathcal{Q}} \sum_{s \in \mathcal{S}} U_s(x_s) - \text{CPP} \sum_{l=1}^{L} \sum_{m=1}^{M} P_l^m \qquad (5)$$
$$\textit{s.t.} \qquad (2),\ (4)$$

where $\mathcal{X} = \{x_s; s \in \mathcal{S} | x_s^{min} \leq x_s \leq x_s^{max}\}$, $\mathcal{P} = \{P_l^m; \forall l, m | P_l^{m,min} \leq P_l^m \leq P_l^{m,max}\}$, $\mathcal{Q} = \{\mathcal{Q}_l, l \in \mathcal{L}\}$. We assume $U_s(x_s)$ to be twice continuously differentiable, non-decreasing and strictly concave and can be characterized by a general α-fair utility function [17]. CPP is the cost per unit of consumed power. Note that the optimization problem (5) is non-convex and inseparable.

III. EQUIVALENT CONVEX PROBLEM AND SOLUTIONS

A. Equivalent Convex Problem

Let us denote $\chi^h = 1 - \frac{\mu^h}{1-\pi^h}$. By using the log change of rate variables ($\hat{\boldsymbol{x}} = \log \boldsymbol{x}$), taking logarithm both sides of (2) and (4), the optimization problem (5) can be equivalently transformed as

$$\max_{\hat{\boldsymbol{x}} \in \hat{\mathcal{X}}, \boldsymbol{P} \in \mathcal{P}, \mathbf{q} \in \mathcal{Q}} \quad \sum_{s \in \mathcal{S}} U_s(e^{\hat{x}_s}) - \text{CPP} \sum_{l=1}^{L} \sum_{m=1}^{M} P_l^m \quad \textit{s.t.} \tag{6}$$

$$\log \sum_{s \in \mathcal{S}_l} e^{\hat{x}_s} \leq \log \left(\sum_{m=1}^{M} \log\left(1 + \gamma_l^m P_l^m\right) \times \prod_{h \in \mathcal{N}_{l,0}^I} \pi^h \right) \tag{7}$$
$$+ \log \left(q_l \prod_{n' \in \mathcal{N}_l^I} (1 - \Upsilon_{n'}^l) \right), \forall l,$$

$$\log \chi^h \leq \sum_{n \in \mathcal{N}_{h,0}^I} \log(1 - \Upsilon_n^h), \forall h, \tag{8}$$

$$\sum_{k \in L_{out}^l(n)} q_k = \Upsilon_n^l, \quad \sum_{l \in L_{out}^h(n)} q_l = \Upsilon_n^h, \forall n \tag{9}$$

where Υ_n^l and Υ_n^h are interpreted as the interference weights in which cognitive node n interferes link l and PU h. It is clear that the equivalent optimization problem (6) is convex and separable in $(\hat{\boldsymbol{x}}, \boldsymbol{P}, \boldsymbol{q})$-space.

B. Lagrange Dual Problem

Now, we augment the objective in (6) with a weighted sum of the constraints (7) and (8), we achieve the Lagrangian:

$$L(\hat{\boldsymbol{x}}, \boldsymbol{P}, \boldsymbol{q}, \boldsymbol{\lambda}, \boldsymbol{\nu}) = L_x(\hat{\boldsymbol{x}}, \boldsymbol{\lambda}) + L_P(\boldsymbol{P}, \boldsymbol{\lambda}) + L_q(\boldsymbol{q}, \boldsymbol{\lambda}, \boldsymbol{\nu}) \tag{10}$$

where the multipliers $\boldsymbol{\lambda} = [\lambda_1, ..., \lambda_L]$ and $\boldsymbol{\nu} = [\nu^1, ..., \nu^H]$ are considered as congestion prices and spectrum prices, respectively. $L_x(\hat{\boldsymbol{x}}, \boldsymbol{\lambda}), L_P(\mathbf{P}, \boldsymbol{\lambda})$, and $L_q(\boldsymbol{q}, \boldsymbol{\lambda}, \boldsymbol{\nu})$ are defined as (11), (12), and (13).

$$L_x(\hat{\boldsymbol{x}}, \boldsymbol{\lambda}) \triangleq \sum_{s} U_s(e^{\hat{x}_s}) - \sum_{l \in \mathcal{L}} \lambda_l \log \sum_{s \in \mathcal{S}_l} e^{\hat{x}_s}. \tag{11}$$

The duality of the original problem (6) now is formulated as

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

$$\text{where} \quad g(\boldsymbol{\lambda}, \boldsymbol{\nu}) = \max_{\hat{\boldsymbol{x}}, \mathbf{P}, \mathbf{q}} L(\hat{\boldsymbol{x}}, \boldsymbol{P}, \boldsymbol{q}, \boldsymbol{\lambda}, \boldsymbol{\nu}) \quad \textit{s.t.}\ (9). \tag{15}$$

C. Dual Decomposition and Optimal Solution

Given $(\boldsymbol{\lambda}, \boldsymbol{\nu})$, by decomposing the objective (15) into three subproblems which correspond to the maximization of (12), (13), and (14), we then obtain the primal solution as follows:

1) Rate Control Subproblem : We use a gradient-ascent method [18] to obtain the optimal solution of sub-problem (11) with a sufficiently small step size $\kappa_t \geq 0$ as follows:

$$x_s^{(t+1)} = \left[x_s^{(t)} + \kappa_t \left(U_s^{'}(x_s^{(t)}) - \lambda_s^{(t)} \right) \right]^{\mathcal{X}} \tag{16}$$

where $U_s^{'}(.)$ is the first derivative of utility, $\lambda_s \doteq \sum_{l \in \mathcal{L}_s} \frac{\lambda_l}{\sum_{\acute{s} \in \mathcal{S}_l} x_{\acute{s}}}$, and $[x]^{\mathcal{X}}$ is the projection of x onto the set $\mathcal{X}$.

2) Power Control Subproblem: Given λ_l, the following iterative algorithm can maximize $L_P(\boldsymbol{P}, \boldsymbol{\lambda})$ in (12).

$$P_l^{m,(t+1)} = \left[P_l^{m,(t)} + \kappa_t \left(\lambda_l^{(t)} \Theta_l^{m,(t)} - \text{CPP} \right) \right]^{\mathcal{P}} \tag{17}$$

where $\Theta_l^{m,(t)} = \frac{\gamma_l^m}{(1+\gamma_l^m P_l^{m,(t)}) \sum_{m=1}^{M} \log(1+\gamma_l^m P_l^{m,(t)})}$.

3) Medium Access Control Subproblem: In this section, we adopt a novel heuristic method [16] to solve $\max_{\mathbf{q} \in \mathcal{Q}} L_q(\boldsymbol{q}, \boldsymbol{\lambda}, \boldsymbol{\nu})$ given by (15) with no control overhead. We assume that at the beginning of each time slot the lth link's ingress rate $\sum_{s \in \mathcal{S}_l} x_s$ and power $P_l^m, \forall m$ given by (16) and (17) are fixed. Then, q_l must be controlled in such a way that its capacity can meet the ingress rate demand. Accordingly, the constraints in (2) are re-expressed as

$$q_l \times \prod_{n' \in \mathcal{N}_l^I} (1 - \Upsilon_{n'}^l) \geq \frac{\sum_{s \in \mathcal{S}_l} x_s}{\sum_m^M \log(1 + \gamma_l^m P_l^m) \times \prod_{h \in N_{l,0}^I} \pi^h}. \tag{18}$$

In fact, the right-hand side of (18) is considered constant. Therefore, the medium access control subproblem $\max_{\mathbf{q} \in \mathcal{Q}} L_q(\boldsymbol{q}, \boldsymbol{\lambda}, \boldsymbol{\nu})$ given by (15) can be approximately rewritten as follows:

$$\max_{\mathbf{q} \in \mathcal{Q}} \sum_{h=1}^{H} \nu^h \sum_{n \in \mathcal{N}_{h,0}^I} \log(1 - \Upsilon_n^h) \quad \textit{s.t.} \quad (9), (18). \tag{19}$$

Then we can reform (19) as:

$$\max_{\mathbf{q} \in \mathcal{Q}} \sum_{h=1}^{H} \nu^h \sum_{n \in \mathcal{N}_{h,0}^I} \log(1 - \sum_{l \in L_{out}^h(n)} q_l) \quad \textit{s.t.} \quad (18). \tag{20}$$

Under observing from (4), the problem (20) states that how to seek $\mathbf{q}$ for minimizing the PUs' collision probability while balancing the bandwidth supply and rate demand at each cognitive link. Now let us take the log change of persistence variables (i.e., $\hat{\mathbf{q}} = \log \mathbf{q} \preceq 0$) and the logarithm both sides of (18), we then obtain an equivalent problem of (20):

$$\max_{\hat{\mathbf{q}} \in \hat{\mathcal{Q}}} \ \Psi(\hat{\mathbf{q}}) \triangleq \sum_{h}^{H} \nu^h \sum_{n \in \mathcal{N}_{h,0}^I} \log \left(1 - \sum_{l \in L_{out}^h(n)} e^{\hat{q}_l} \right) \tag{21}$$

$$\textit{s.t.} \quad \hat{q}_l \geq \Phi_l(\hat{\mathbf{q}}), \forall l. \tag{22}$$

where $\Phi_l(\hat{\mathbf{q}}) \triangleq \log \left(\frac{\sum_{s \in \mathcal{S}_l} x_s}{\sum_{m}^{M} \log(1+\gamma_l^m P_l^m) \times \prod_{h \in N_{l,0}^I} \pi^h} \right) - \sum_{n' \in \mathcal{N}_l^I} \log\left(1 - \sum_{k \in L_{out}^l(n')} e^{\hat{q}_k}\right)$.

$$L_P(\boldsymbol{P},\boldsymbol{\lambda}) \triangleq \sum_{l=1}^{L} \lambda_l \log\left(\sum_{m=1}^{M} \log\left(1+\gamma_l^m P_l^m\right) \times \prod_{h\in\mathcal{N}_{l,0}^I} \pi^h\right) - \mathrm{CPP}\sum_{l=1}^{L}\sum_{m=1}^{M} P_l^m. \tag{12}$$

$$L_q(\boldsymbol{q},\boldsymbol{\lambda},\boldsymbol{\nu}) \triangleq \sum_{l=1}^{L} \lambda_l \log\left(q_l \prod_{n'\in\mathcal{N}_l^I} (1-\Upsilon_{n'}^l)\right) + \sum_{h=1}^{H} \nu^h \left(\sum_{n\in\mathcal{N}_{h,0}^I} \log(1-\Upsilon_n^h) - \log\chi^h\right). \tag{13}$$

Proposition 1. *Given* $(\boldsymbol{x},\boldsymbol{P},\boldsymbol{\nu})$*, the approximate MAC subproblem* (21) *is convex. Hence, its optimal solution can be found via the following iterative algorithm in* **q***-space as*

$$q_l^{(t+1)} = \left[q_l^{(t)} + \kappa_t\left(\frac{\partial\Psi(\boldsymbol{q}^{(t)})}{\partial q_l}\frac{1}{q_l^{(t)}} + \Phi_l(\boldsymbol{q}^{(t)})\right)\right]^{\mathcal{Q}_l}. \tag{23}$$

Proof: We omit the detailed proof due to space constraints and refer the reader to the technical report [19]. ■

IV. HEURISTIC CROSS-LAYER COGNITIVE RADIO MAC PROTOCOL (HCC-MAC)

In this section, we describe an HCC-MAC protocol in which the links update their transmission parameters without message passing. It is straightforward that the number of time slots in which link l experiences to obtain a successful transmission is an independent and identically distributed geometric random variable, denoted by $\xi_l \sim Geo(q_l^{succ})$. Hence, each link l can estimate q_l^{succ} by observing its success events over a time window T (time slots). We assume that there exist K bursts of successive failures during T. Let b_k denote the number of successive failures of the k^{th} burst, link l then can calculate the mean number of successive failures preceding a success during T. In this regard, the noisy estimation of q_l^{succ} is given by using maximum log-likelihood (ML) estimate:

$$\check{q}_l^{succ} = \frac{\sum_{k=1}^{K} b_k}{K+\sum_{k=1}^{K} b_k}. \tag{24}$$

Similarly, SUs can also estimate the collision probability of each pair of PUs by overhearing RTS collisions taken place over each band. Let N_h^T denote the number of collisions of the hth PU observed by SUs during T and R_h denote the hth PU's packet rate during T. Then, the noisy estimation of the hth PU collision probability can be calculated as [16, Eq.27]:

$$\check{\zeta}_h^{col} = \begin{cases} 1/(R_h\times T), & \text{if } N_h^T = 0, \\ N_h^T/(R_h\times T), & \text{otherwise} \end{cases} \tag{25}$$

In HCC-MAC, each source s locally adjusts its rate based on the feedback of the aggregate congestion price $\lambda_s \doteq \sum_{l\in\mathcal{L}_s} \frac{\lambda_l}{\sum_{\acute{s}\in\mathcal{S}_l} x_{\acute{s}}}$. Each link l individually calculates its congestion price and spectrum price, then adjusts its transmission power and probability. Note that the updates $\lambda_l^{(t+1)}$ and $\nu^{(t+1)}$ are obtained by solving the dual problem with the gradient-descent method [18]. The HCC-MAC algorithm will converge to the optimum if $\max\|\mathbf{q}^{*(t)} - \mathbf{q}^{*(t-1)}\| \le \varepsilon$, where ε is the error tolerance, is reached.

Algorithm 1: HCC-MAC Protocol

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Sources and links initialize $\boldsymbol{x}^{(0)}, \boldsymbol{P}^{(0)}, \boldsymbol{q}^{(0)}, \boldsymbol{\lambda}^{(0)}, \boldsymbol{\nu}^{(0)}$. At time $t$:
Cognitive Source Algorithm: For each source $s \in \mathcal{S}$:
    1) Update rate $x_s^{(t+1)}$ using (16) with $\lambda_s^{(t)}$.
Cognitive Link Algorithm: For each link $l \in L_{out}(n); n \in \mathcal{N}$.
    1) Update power $P_l^{(t+1)}$ using (17).
    2) Calculate $\tilde{c}_l(\mathbf{q}^{(t)}, P_l^{(t)})$ using (2) with ML estimation $\check{q}_l^{succ,(t)}$.
    3) Get $\sum_{s\in S_l} x_s^{(t)}$ from queue and locally calculate $\Upsilon_n^{h,(t)} = \sum_{l\in L_{out}^h(n)} q_l^{(t)}, \forall h$.
    4) Update persistence probability $q_l^{(t+1)}$ by using (23):
       $q_l^{(t+1)} = \left[q_l^{(t)} + \kappa_t\left(\log\left(\frac{\sum_{s\in\mathcal{S}_l} x_s^{(t)} q_l^{(t)}}{\tilde{c}_l(\mathbf{q}^{(t)}, P_l^{(t)})}\right) - \sum_{h}^{H} \frac{a_n^{h,(t)}\nu^{h,(t)}}{1-\Upsilon_n^{h,(t)}}\right)\right]^{\mathcal{Q}_l}.$
    5) Update congestion prices by solving dual problem (14):
       $\lambda_l^{(t+1)} = \left[\lambda_l^{(t)} + \kappa_t \log\left(\sum_{s\in\mathcal{S}_l} x_s^{(t)}/\tilde{c}_l(\mathbf{q}^{(t)}, P_l^{(t)})\right)\right]^{\mathbb{R}^+}.$
    6) Update spectrum price by solving dual problem (14):
       $\nu^{h,(t+1)} = \left[\nu^{h,(t)} + \kappa_t\left(\log\chi^h - \log\left(1-\check{\zeta}_h^{col,(t)}/(1-\pi^h)\right)\right)\right]^{\mathbb{R}^+}.$
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Theorem 1. *The **Algorithm 1** converges to an equilibrium which has a negligible gap compared to the global optimum of* (5) *provided that the step sizes* κ_t *satisfy*

$$\kappa_t \ge 0, \quad \sum_{t=0}^{\infty}\kappa_t = \infty, \quad \sum_{t=0}^{\infty}(\kappa_t)^2 < \infty. \tag{26}$$

Proof: Rate updates (16) and power updates (17) optimally solve the rate and power control subproblems in (15). Moreover, MAC algorithm (23) solving the approximate MAC subproblem (21) always converges to the unique optimum [Proposition 1]. Hence, Algorithm 2 totally solves the original problem (6) and converges to to an equilibrium which is close to the global optimum. Due to the space constraint, detailed proof can be found on the online technical report [19]. ■

V. PERFORMANCE EVALUATION

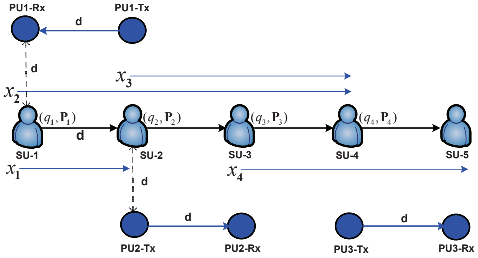
A. Simulation Settings

In this section, we consider a simplified OSA-based MHAHN as Fig. 1 with 3 bands licensed to 3 corresponding pairs of PUs. Each band with bandwidth of 20MHz is divided

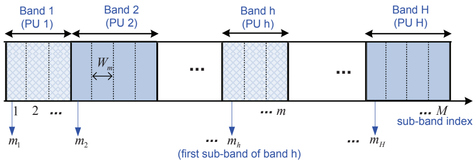
TABLE I
PERFORMANCE COMPARISON OF PROTOCOLS VERSUS **CPP**† AT $P_l^{m,max} = 50mW$

Protocols	**SocialWelfare** (CPP)			**TEC*** (CPP)			**NetRevenue** (CPP)		
	CPP = 2	CPP = 3	CPP = 4	CPP = 2	CPP = 3	CPP = 4	CPP = 2	CPP = 3	CPP = 4
HCC-MAC	68.89	68.85	68.78	$8.32W$	$6.97W$	$5.75W$	52.25	47.94	45.78
FPC-MAC	68.22	68.22	68.22	$9.60W$	$9.60W$	$9.60W$	49.02	39.42	29.82

* Total Energy Consumption (W); † Cost Per unit of consumed Power (1/W)



(a) Physical topology for a coexistence of PUs and SUs.



(b) Spectrum allocation in OSA-based MHAHN systems.

Fig. 1: OSA-based MHAHN systems for simulation.

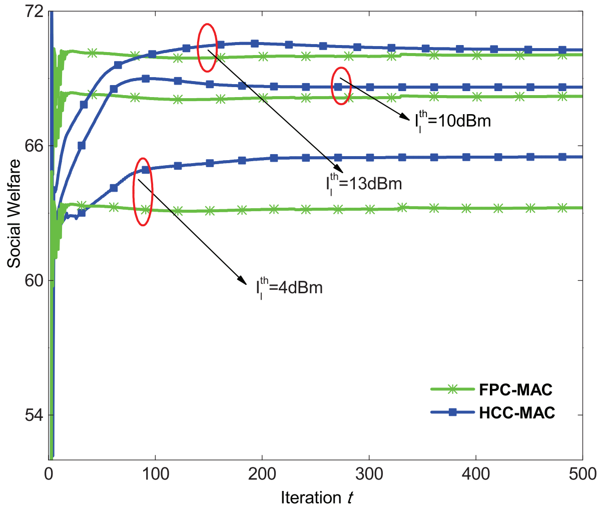


Fig. 2: Social welfare versus I_l^{th}.

into 16 orthogonal sub-bands for spectrum pooling which merges dynamic spectral ranges from these licensed bands. Each SU with $P_l^m \in [-10, 20]$dBm and $q_l \in [0.01, 0.9]$ accesses all 3 licensed bands characterized by an ON/OFF Markov Chain with the idle probabilities as $\pi^1 = 60\%$, $\pi^2 = 80\%$, and $\pi^3 = 55\%$. We assume $x_s^{min} = 200$bps while the maximum rate is dynamically updated to the achievable link capacity at each time slot. The tolerable collision probabilities of licensed bands are $\mu^1 = 15\%$, $\mu^2 = 8\%$, and $\mu^3 = 6\%$. We choose $G_{MC} = -1.5/\log(5\text{BER})$, for all l where target bit error rate BER$= 10^{-5}$. We further assume that the power spectral density of white noise is -174dBm/Hz at both SU and PU receivers, the path loss exponent is 4, and $d = 1m$. For a proportional fair allocation, we choose $U_s(x_s) = \log x_s$ as source's utility function (i.e., $\alpha = 1$) for all SUs.

B. Numerical Results

In Fig. 2, our HCC-MAC's social welfare is compared with Fixed-Power Cognitive MAC scheme (named FPC-MAC), where we adopt MAC protocols [2], [3] into our OSA-based MHAHN scenario and fix the link power per sub-band at $P_l^{m,max}$ to validate the optimality. In fact, HCC-MAC outperforms FPC-MAC for all different settings of interference threshold I_l^{th}. This is achieved because our MAC protocol balance the interference level and the contention level among cognitive links to best-utilize spectrum opportunities in a unified optimization framework whereas FPC-MAC's fixed interference levels force its location-dependent contention resolution to become passive. In addition, the smaller the links' interference power budgets are, the bigger the optimal gap between HCC-MAC and FPC-MAC. This is because, in the small interference power budget region, all cognitive nodes of FPC-MAC make an adverse interference to each other and their performance are hence seriously worse. Table I shows the comparative performance of HCC-MAC with FPC-MAC in terms of net revenue versus the different values of CPP. First of all, we can see that the achievable social welfare of FPC-MAC is smaller but the total energy consumption is higher. As a consequence, FPC-MAC's net revenue is becoming dramatically worse as CPP inflicted on each unit of consumed power is increasing. In economic aspects, the power resource wastage leads an inefficiency of FPC-MAC. Next, it is straightforward that the higher CPP will force the link power per sub-band to decrease proportionally as pointed out in (17). As a result, in HCC-MAC, the links' reduced sum power consumptions due to the increase in CPP makes their congestion prices become higher such that sources must decrease their rates according to (16). However, the increase in CPP slightly decreases the HCC-MAC's net revenue while the FPC-MAC's net revenue is significantly decreased. To observe benefits of HCC-MAC over FPC-MAC, let us consider their net revenues at the fixed CPP. Table II shows the performance comparison for three different aspects of $P_l^{m,max}$ at CPP$= 5$. At $P_l^{m,max} = 7mW$, the performance gap of two considering protocols is almost negligible. However, their gap gradually becomes bigger at $P_l^{m,max} = 40mW$. When $P_l^{m,max}$ falls into contention-limited regime (i.e., $P_l^{m,max} = 100mW$),

TABLE II
PERFORMANCE COMPARISON OF PROTOCOLS VERSUS $P_l^{m,max}$ AT $\mathbf{CPP}^{\dagger} = \mathbf{5}$

Protocols	**SocialWelfare** ($P_l^{m,max}$)			**TEC*** ($P_l^{m,max}$)			**NetRevenue** ($P_l^{m,max}$)		
	$7mW$	$40mW$	$100mW$	$7mW$	$40mW$	$100mW$	$7mW$	$40mW$	$100mW$
HCC-MAC	68.67	68.75	68.83	$1.15W$	$5.30W$	$6.32W$	62.92	42.25	37.23
FPC-MAC	68.56	68.20	67.03	$1.20W$	$7.20W$	$21.60W$	62.56	32.20	−40.97

* Total Energy Consumption (W); † Cost Per unit of consumed Power (1/W)

the FPC-MAC's net revenue becomes negative whereas HCC-MAC still achieves good performance. This is because the HCC-MAC's operation point always moves towards balancing between interference and contention whereas the FPC-MAC's contention level significantly increases.

It is interesting to find from Fig. 3 that the sources and links in HCC-MAC can adaptively control their parameters to get the higher network utility when the stochastic spectrum opportunities (e.g., PU1's idle probability π^1 and PU1' tolerable collision probability μ^1) are further relaxed by PUs.

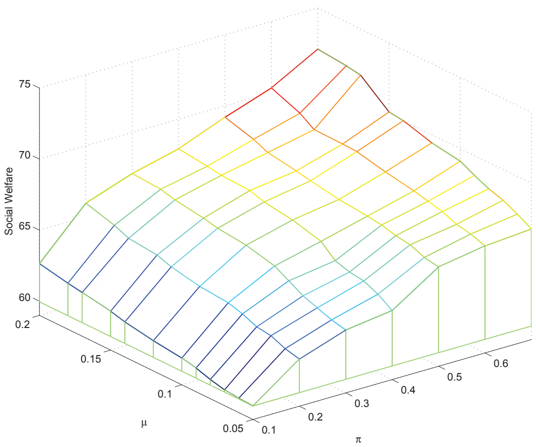


Fig. 3: Social welfare of HCC-MAC versus the PU1's idle probability π^1 versus the PU1's tolerable collision probability μ^1 while fixing the other PUs' spectrum opportunities.

VI. CONCLUSION

In this paper, we have proposed a novel optimal MAC framework for interference-dependent contention resolution problem considering the co-existence of the licensed and unlicensed users in OSA-based MHAHNs. By taking into account the interaction effect of congestion control and power control on contention control at MAC layer, we developed a distributed cross-layer cognitive MAC protocol without message passing. Our novel solution can achieve both energy consumption minimization and social welfare maximization while best-utilizing stochastic spectrum opportunities without downgrading primary system's performance.

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