Optimal Power Control MAC for Multi-hop Cognitive Radio Ad-hoc Networks

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***Abstract*—This paper presents a novel MAC protocol that allows the secondary links to optimally adjust their transmission power and persistence probability on an ingress rate basis regulated by cognitive users (CUs) for multi-hop cognitive radio ad hoc networks (CRAHNs). By introducing a unique collision probability constraint required by spectrum holder, we show that the CUs can opportunistically access the unused spectrum vacated by licensed users (LUs) to globally maximize the net revenue in a de-centralized manner. Finally, our illustrative results verify the efficiency of the proposed protocol.**

***Index Terms*—Power control MAC, cross-layer optimization, multi-hop CRAHNs, persistence probability.**

I. INTRODUCTION

The key rationale for opportunistic spectrum access (OSA) is how to exploit spectrum holes for the increasing demand for spectrum [1], [2]. Different from its counterpart in traditional wireless ad hoc networks, the contention-based medium access control (MAC) protocols in CRAHNs not only needs to provide a good performance (e.g., throughput and fairness), but it must also guarantee quality of service (QoS) of primary system [3], [4]. One of the key challenges in CRAHNs is an access mechanism to reduce collisions among CUs so as to utilize spectrum opportunities efficiently. Although IEEE 802.22 based MAC protocols have been studied extensively in literature (e.g., [5]), these efforts has not yet investigated the impact of contention resolution on other layers of protocol stack. In this paper, we focus on designing an optimal MAC scheme for multi-hop CRAHNs, in which CUs adaptively adjust their access strategy (i.e., power control and persistence probability control) to meet their ingress rates regulated by sources. Unlike the standardized MAC protocol in 802.11 [6] and binary exponential back-off mechanism which can face inefficient and unfair contention resolution, our proposed MAC protocol aims both energy efficiency and contention fairness in a unified optimization framework.

It is noteworthy that, in OSA-based CRAHNs, the persistence probabilities of CUs depend on not only the time-varying channel availability and the need to protect LUs from QoS's degradation but also contention resolution among links. In fact, the former is imperative while the latter should be done in such a way that it benefits the best. The more the number of links in a conflict domain, the less the persistence probabilities of those links. In a protocol interference model, two links belong to the same conflict domain if one link's transmission makes an adverse interference, which strongly depends transmit power, to the other link and/or vice verse. If one link's transmit power is high, its number of conflicting links increases and that link's persistence probability is decreased. Then, the contrapositive still holds. Hence, how to balance the transmit power and persistence probability among links on the basis of ingress rates regulated by sources motivates a new optimization framework of CRAHNs. In this paper, we propose a cross-layer optimization framework which is different from [7], [8] as follows: *i)* NUM-based contention resolution [7], [8] only focus on fairness among links while our solution can obtain the energy efficiency, fairness, and maximum social welfare/net revenue. *ii)* Our protocol can opportunistically exploit the licensed channel without degrading the LUs' QoS.

II. SYSTEM MODEL

We consider a multi-hop CRAHN modeled by a *unidirected* graph $G(\mathcal{N}, \mathcal{L})$ as shown in Fig.1, where $\mathcal{N}$ is the set of N CUs[1], $\mathcal{L}$ is the set of L links. Unlike [7], [8], the frequency band of width W is opportunistically exploited from a primary system including a pair of licensed users (LUs) and the its availability during a time slot is characterized as a two-state ergodic Markov Chain [9] with the idle probability π. We assume that π is obtained by CUs through a knowledge of the traffic statistics and/or the channel sensing. We further assume that the CRAHN is shared by a set of sources, $\mathcal{S}$. Each source $s \in \mathcal{S}$ emits one flow traveling through a pre-defined set of links, $\mathcal{L}_s \subseteq \mathcal{L}$, at rate $x_s \in \mathcal{X}_s \doteq [x_s^{min}, x_s^{max}]$ and obtains a utility $U_s(x_s) : R_+ \mapsto R$. Specifically, we focus on a slotted random access system (e.g., slotted ALOHA) where the contention resolution among links is performed at the beginning of each time slot on the basis of persistence probability $q_l \in \mathcal{Q}_l \doteq [q_l^{min}, q_l^{max}]$, where $0 \leq q_l^{min} \leq q_l^{max} \leq 1$.

Protocol interference model is assumed to adopt at the physical layer as in [7], [8]. More specifically, the spatial reuse is taken into consideration in this letter as the target to improve the network throughput. Without loss of generality, the kth link with transmission power P_k is supposed to make a considerable interference to the lth link if its harmful interference power at the receiver of the lth link, denoted by $I_{lk} \doteq G_{lk}P_k$, exceeds the specified threshold I_l^{th}. We assume that the channel fading changes very slowly so that the channel gain between the transmitter of link k and the receiver of link l (i.e, G_{lk}) remains constant during power

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[1] In this paper, the terms "CU" and "node" are used interchangeably.

update interval. Let $\mathcal{N}_l^I$ denote the set of other nodes whose transmissions remarkably cause an adverse interference to the lth link's reception, then $\mathcal{N}_l^I = \cup_{k\neq l}\{Tx_k : I_{lk} \geq I_l^{th}\}$, where Tx_k denotes the kth link's transmitter. Hence, the lth link and the kth link, $\forall k \in \mathcal{N}_l^I$, form an edge $e \in \mathcal{E}$ in a contention graph $G_c(\mathcal{V},\mathcal{E})$ where the vertices $v \in \mathcal{V}$ correspond to the unidirectional links. In order to reduce collisions, the number of edges that strongly depends on the allocated power P_l on each link should be relaxed.

To conserve capacity, the offered load on each link l does not overwhelm its average capacity $\bar{c}_l(\mathbf{q}, P_l)$:

$$\sum_{s\in\mathcal{S}_l} x_s \leq W\log(1+\gamma_l P_l)\pi q_l \prod_{n\in\mathcal{N}_l^I}(1-\sum_{k\in L_{out}^n} q_k) \qquad (1)$$

where $\mathcal{S}_l = \{s : l \in \mathcal{L}_s\}$ is the set of sources s using link l, L_{out}^n is the set of outgoing links from node n, and $\gamma_l = \frac{KG_{ll}}{N_0}$ is channel and processing gain-to-interference ratio (CIR) of link l. N_0 denotes the additive white noise power at the lth link's receiver and K is processing gain which depends on modulation/coding schemes and bit error ratio. For ease of exposition, we assume that W is unit henceforth.

The collision to LUs occurs when at least one link starts its transmission while channel is occupied by LUs. To guarantee LUs' quality of service (QoS), the maximum packet collision rate caused by the CUs' transmissions must be below the tolerable threshold $\mu \leq 1-\pi$, which is preset at each CU:

$$\left(1-\prod_{n\in\mathcal{N}}(1-\sum_{l\in L_{out}^n} q_l)\right)(1-\pi) \leq \mu. \qquad (2)$$

Therefore, given the spectrum opportunity (μ,π), the power control plays the important role in the spatial reusability.

III. OPTIMAL POWER CONTROL MAC DESIGN

Our MAC optimization framework is to globally maximize the total network revenue subject to link capacity conservation (1) and LU's QoS (2) as follows:

$$\max_{\boldsymbol{x}\in\mathcal{X},\mathbf{P}\in\mathcal{P},\mathbf{q}\in\mathcal{Q}} \sum_{s\in\mathcal{S}} U_s(x_s) - \text{CPP}\sum_{l=1}^{L} P_l \quad s.t. \quad (1),(2). \qquad (3)$$

where $\mathcal{X} = \{x_s; s \in \mathcal{S} | x_s^{min} \leq x_s \leq x_s^{max}\}$, $\mathcal{P} = \{P_l; l \in \mathcal{L}, |P_l^{min} \leq P_l \leq P_l^{max}\}$, $\mathcal{Q} = \{\mathcal{Q}_l, l \in \mathcal{L}\}$. $U_s(x_s)$ is assumed to be twice continuously differentiable, non-decreasing and strictly concave in its domain [10], [11]. CPP is the cost per unit of consumed power. The fairness in contention resolution can be characterized by a general α-fair utility function [12]. It is straightforward that (3) is an $\mathcal{NP}$-hard problem because of its non-linear and non-convex properties.

By using the log change of rate variables ($\hat{\boldsymbol{x}} = \log \boldsymbol{x}$), taking logarithm both sides of (1) and (2), we obtain the equivalent problem which is convex. Then we globally solve it in a decentralized manner as Algorithm 1:

Note that the updates $\lambda_l^{(t+1)}$ and $\nu^{(t+1)}$ are obtained by the primal solution using the projected gradient-descent method [16]. The algorithm will stop whenever the convergence criterion $\max\|\mathbf{q}^{*(t)} - \mathbf{q}^{*(t-1)}\| \leq \varepsilon$, where ε is the error tolerance, is reached. For the sake of convenience, we use the same step-size k_t for all updates without loss of generality, henceforth.

Algorithm 1: Optimal Power Control MAC (OPC-MAC)

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

Source Algorithm: For each source $s \in \mathcal{S}$

1) Receive the total price that accumulates the intermediate links' price $\lambda_l^{(t)}$ along it's path [1], [13]–[15].
2) Update rate $x_s^{(t+1)} = \left[x_s^{(t)} + \kappa_t\left(U_s'(x_s^{(t)}) - \lambda_s^{(t)}\right)\right]^{\mathcal{X}}$.

Link Algorithm: For each link $l \in \mathcal{L}_{out}^n; n \in \mathcal{N}$.

1) Broadcast message with $(q_l^{(t)}, \lambda_l^{(t)})$ on control channel.
2) Update its power

$$P_l^{(t+1)} = \left[P_l^{(t)} + \kappa_t\left(\frac{\lambda_l^{(t)}\gamma_l}{(1+\gamma_l P_l^{(t)})\log(1+\gamma_l P_l^{(t)})} - \text{CPP}\right)\right]^{\mathcal{P}}$$

3) Based on the interference power thresholds I_k^{th}, calculate its interference ranges to other links, then update $\mathcal{L}_{out-}^n$.
4) Receive congestion prices $\lambda_k^{(t)}, k \in \mathcal{L}_{out-}^n$. Update persistence probability $q_l^{(t+1)} = \left[\frac{\lambda_l^{(t)}}{\sum_{k\in L_{out-}^n}\lambda_l^{(t)} + \sum_{l\in L_{out}^n}\lambda_l^{(t)} + \nu^{(t)}}\right]^{\mathcal{Q}}$.
5) Receive persistence probabilities $q_k^{(t)}, k \in \mathcal{L}$, calculate average capacity $\bar{c}_l(\mathbf{q}^{(t)}, \mathbf{P}^{(t)})$. Get ingress rate $\sum_{s\in S_l} x_s^{(t)}$ from input queue. Update its congestion price:

$$\lambda_l^{(t+1)} = \left[\lambda_l^{(t)} + \kappa_t \log\left(\sum_{s\in\mathcal{S}_l} x_s^{(t)}/\bar{c}_l(\mathbf{q}^{(t)}, P_l^{(t)})\right)\right]^{\mathbb{R}^+}$$

6) Update its spectrum price:

$$\nu^{(t+1)} = \left[\nu^{(t)} + \kappa_t \log\left((1-\frac{\mu}{1-\pi})/\prod_{n=1}^{N}(1-\Upsilon_n^{(t)})\right)\right]^{\mathbb{R}^+}$$

IV. PERFORMANCE EVALUATION

In this section, we evaluate our proposed protocol through a simplified CRAHN as Fig. 1. Each CR link with $P_l \in [20,30]$dBm, $q_l \in [0.01, 0.9]$ and $I_l^{th} = 9.76dBm$ opportunistically accesses the licensed channel characterized by an ON/OFF Markov Chain with $\pi = 0.9$. The system bandwidth and the minimum data rate for each source is assumed to be $125KHz$ and $100bps$, respectively. We further assume that the maximum collision rate $\mu = 0.07$ and the distances between two consecutive nodes, d, are identical and equal to $1.1m$.

Specifically, to differentiate from the other proposals (e.g., [7], [8]) for optimality and effectiveness of OPC-MAC, we assume all links have the same capacity at P_{max} for simulating the optimal MAC based on [7], [8] without power control, so-called OPT-MAC. Fig. 2 illustrates the effect of joint consideration of congestion control, power control and MAC on energy consumption, social welfare and net revenue. In OPT-MAC, total energy consumption is $3.2W$ since all links transmit at the fixed power, P_{max} while OPC-MAC consumes the least amount of energy as shown in Fig. 3. Moreover, OPC-MAC's social welfare and net revenue is significantly better than those of OPT-MAC. The reason is that the number of other links causes a harmful interference to one link in OPT-MAC is greater than that in OPC-MAC. Consequently, according to (1), all link average capacity in OPT-MAC will tend to be smaller. On the other hand, since the link 3 is the most congested, its persistence probability in OPT-MAC must be higher than that in OPC-MAC as shown in Fig. 3. Moreover, the link 3's fixed and high power makes a remarkable interference to all other links, hence the link 3 conflicts with all other links. This makes all other links' persistence probabilities smaller than those in OPC-MAC.

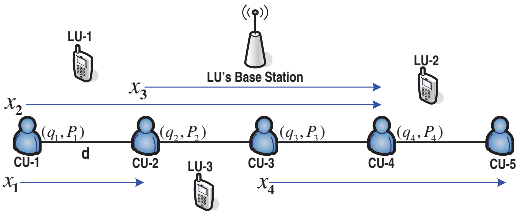
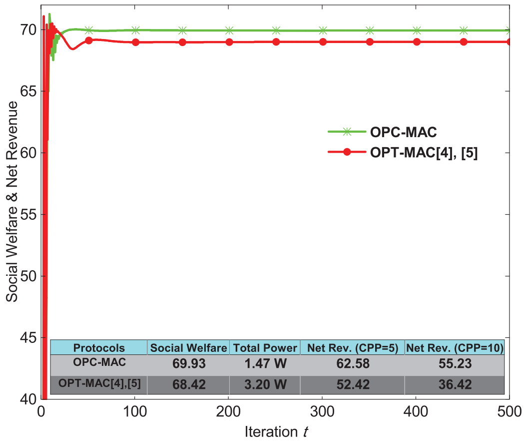


Fig. 1: Physical and logical topologies for a CRAHN.



Protocols	Social Welfare	Total Power	Net Rev. (CPP=5)	Net Rev. (CPP=10)
OPC-MAC	69.93	1.47 W	62.58	55.23
OPT-MAC[4],[5]	68.42	3.20 W	52.42	36.42

Fig. 2: Social welfare and net revenue.

V. CONCLUSION

In this paper, by taking into joint consideration power control and medium access control on the basis of congestion control, an OPC-MAC protocol is proposed. Our protocol can not only save energy consumption of CUs but also increase the spatial reusability of spectrum and avoid collisions for CRAHNs. As a result, OPC-MAC is an efficient power control MAC which can achieve both the optimal social welfare and net revenue.

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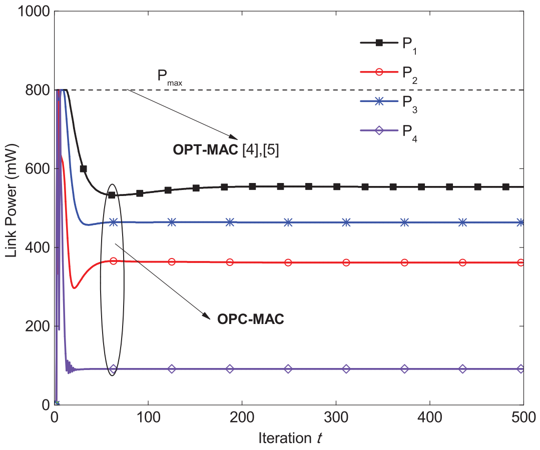

Fig. 3: Efficient energy consumption of OPC-MAC.

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