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

Mui Van Nguyen, Choong Seon Hong, Sungwon Lee
Dept. of Computer Engineering, Kyung Hee University, 449-701, Republic of Korea
Email: {nmui, cshong, drsungwon}@khu.ac.kr

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 need 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 undirected graph $G(N, L)$ as shown in Fig.1, where $N$ is the set of N CUs, $L$ 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 $\pi$. We assume that $\pi$ 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, $S$. Each source $s \in S$ emits one flow traveling through a pre-defined set of links, $L_s \subseteq L$, at rate $x_s \in X_s = [x_s^{min}, x_s^{max}]$ and obtains a utility $U_s(x_s) : R_+ \rightarrow R$. 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 $q_i \in Q_i = [q_i^{min}, q_i^{max}]$, where $0 \leq q_i^{min} \leq q_i^{max} \leq 1$.

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 $I_{lk} \geq G_{lk}P_k$, exceeds the specified threshold $I^p$. 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.

1In this paper, the terms “CU” and “node” are used interchangeably.
update interval. Let \( N_l^t \) denote the set of other nodes whose transmissions remarkably cause an adverse interference to the \( l \)-th node’s reception, then \( N_l^t = \bigcup_{k \in N_l} \{ x_k : I_k \geq I_l^t \} \), where \( T x_k \) denotes the \( k \)-th node’s transmitter. Hence, the \( l \)-th link and the \( k \)-th link, \( \forall k \in N_l^t \), form an edge \( e \in E \) in a contention graph \( G_t(V,E) \) where the vertices \( v \in V \) correspond to the unidirectional links. In order to reduce collisions, the number of edges that strongly depends on the allocated power \( P \) on each link should be relaxed.

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

\[
\sum_{s \in S_l} x_s \leq W \log \left( 1 + \gamma_l P_l \right) q_l \prod_{k \in L^m_\text{out}} (1 - \sum_{s \in S_l} q_k) \tag{1}
\]

where \( S_l = \{ s : l \in L_s \} \) is the set of sources \( s \) using link \( l \), \( L^m_\text{out} \) is the set of outgoing links from node \( n \), and \( \gamma_l = \frac{\alpha^l}{\alpha^m} \) is channel and processing gain-to-interference ratio (CIR) of link \( l \). \( N_0 \) denotes the additive white noise power at the \( l \)-th 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:

\[
\left( 1 - \prod_{s \in \mathcal{X}} \left( 1 - \sum_{l \in L^m_\text{out}} q_l \right) \right) (1 - \pi) \leq \mu. \tag{2}
\]

Therefore, given the spectrum opportunity \((\mu, \pi)\), 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 LUs’ QoS (2) as follows:

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

where \( \mathcal{X} = \{ x_s : s \in S | x^\text{min}_s \leq x_s \leq x^\text{max}_s \} \), \( \mathcal{P} = \{ P_l : l \in L, P^\text{min}_l \leq P_l \leq P^\text{max}_l \} \), \( \mathcal{Q} = \{ Q_l : l \in L \} \). \( U_s(x_s) \) 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 \( \alpha \)-fair utility function [12]. It is straightforward that (3) is an \( \mathcal{N}/\mathcal{P} \)-hard problem because of its non-linear and non-convex properties.

By using the log change of rate variables (\( \Delta = \log x \)), 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 \( \lambda^{(t+1)} \) 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 \( \max \| q^{(t)} - q^{(t+1)} \| \leq \varepsilon \), where \( \varepsilon \) is the error tolerance, is reached. For the sake of convenience, we use the same step size \( \kappa_l \) for all updates without loss of generality, henceforth.

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

<table>
<thead>
<tr>
<th>Source Algorithm:</th>
<th>For each source ( s \in S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>Receive the total price that characterizes the intermediate links’ price ( \lambda^{(t)}(l) ) along its path [1], [13]–[15].</td>
</tr>
<tr>
<td>2)</td>
<td>Update rate ( r^{(t+1)} = [\lambda^{(t)}(l) + \kappa^l_1 (U'_s(x^{(t)}_s) - \lambda^{(t)}_s)]^X ).</td>
</tr>
</tbody>
</table>

Link Algorithm: For each link \( l \in L^m_\text{out} \),

1) Broadcast message with \( q^{(t)}_l, \lambda^{(t)}_l \) on control channel. 
2) Update its power

\[
P^{(t+1)}_l = \left[ P^{(t)}_l + \kappa_1 \left( \frac{\lambda^{(t)}(l) \gamma_l}{(1 + \gamma_l P^{(t)}_l) \log(1 + \gamma_l P^{(t)}_l)} - \text{CPP} \right) \right]^P.
\]

3) Based on the interference power thresholds \( I^{bh}_k \), calculate its interference ranges to other links, then update \( L^m_\text{out} \).
4) Receive congestion probabilities \( \lambda^{(t)}_k, \ k \in L^m_\text{out} \), Update persistence probability \( q^{(t+1)}_l = \frac{(\lambda^{(t)}_l)^X}{\sum_{k \in L^m_\text{out}} (\lambda^{(t)}_k + \mu)} \).
5) Receive persistence probabilities \( q^{(t)}_l, \ k \in L, \) calculate average capacity \( \bar{c}_l(q^{(t)}_l, P^{(t)}_l) \). Get ingress rate \( \sum_{s \in S_l} x^{(t)}_s \) from input queue. Update its congestion price:

\[
\lambda^{(t+1)} = \left[ \lambda^{(t)}(l) + \kappa_1 \log \left( \sum_{s \in S_l} x^{(t)}_s / \bar{c}_l(q^{(t)}_l, P^{(t)}_l) \right) \right]^{+}.
\]

6) Update its spectrum price:

\[
\nu^{(t+1)} = \left[ \nu^{(t)}(l) + \kappa_1 \log \left( 1 - \frac{\mu}{1 - \pi} / \prod_{l=1}^L (1 - \gamma^{(t)}_l) \right) \right]^{+}.
\]
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.

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.

ACKNOWLEDGMENT

“This research was funded by the MSIP (Ministry of Science, ICT & Future Planning), Korea in the ICT R&D Program 2013”. Dr. CS Hong is the corresponding author.

REFERENCES