A Reward-based MAC layer scheduling For Co-operative Multi-Hop Cognitive Radio Networks

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ABSTRACT- Cognitive Radio Networks (CRNs) have recently emerged as a technology for secondary users (SUs) to opportunistically utilize the spectrum assigned to primary users (PUs). The purpose of this paper is to design a mac-layer optimal scheduling algorithm for cooperative multi-hop Cognitive Radio Networks (CRNs), where SUs assist PUs multi-hop transmissions and in return gain an immediate time-share of the channel proportional to their assistance.A time slotted multi hop co-operative CRN is where SUs relay PU data in return for the right to use the wireless spectrum is considered. The multi hop co-operative CRN is divided into two sub networks; a PU relay sub network and an SU sub network. The throughput optimal scheduling algorithm is designed with two mechanisms; Immediate- Reward Mechanism and Long-term Reward Mechanism. The algorithm is composed of two parts, namely, a congestion controller and a hop/link scheduler. The properties of proposed algorithm are illustrated through simulation studies.

Keywords - Cognitive Radio, Congestion Control, Finite Buffer, Multi-Hop Cognitive Radio Networks, Optimal Scheduling..

I. INTRODUCTION

Cognitive Radio Networks (CRNs) [3] have recently emerged as a new technology for unlicensed users to utilize the under-used spectrum opportunities. In a typical CRN, licensed users are referred to as primary users (PUs) and secondary users (SUs) denote the users dynamically utilizing spectrum opportunities. The concept of CRN is simple, but the design of CRNs imposes challenges that are not present in conventional wireless networks [3]. The traditional view on CRNs emphasizes point to- point connections for both PU and SU subsystems, and multi-hop CRNs have only been considered in recent past.

In this paper, a throughput-optimal mac-layer scheduling algorithm for a multi-hop cooperative CRN under a property-rights model [8] is proposed,where SUs relay data between PU pairs to gain access to the licensed spectrum. An illustrative example is shown in Figure 1, where the cooperative CRN is composed of an SU sub network and a PU sub network. The SU sub network consists of SUs communicating with a secondary base station over a single hop as assumed for IEEE 802.22. In the PU sub network, we consider a case where the channel condition is not desirable for the direct transmission between the PU and the primary base station due to physical separation. Thus, the PU is willing to –lease‖ a portion of the spectrum access to SUs in return for some form of service. Specifically, PU data is relayed by SUs from the source PU to PU base station, and SUs in return gain a time-share of the channel proportional to their assistance to the PU. The model illustrated in Figure 1 can be considered as a generalization of the overlay CRNs with two-hop relay [8]-[7].

In the proposed algorithm: the SUs are guaranteed a throughput proportional to the PU data they relay. An optimal opportunistic scheduling scheme has been proposed in [7] to guarantee each user a proportional share of the network resource for a non-cognitive setting, which is extended to scenario of two-hop relay CRNs [8].

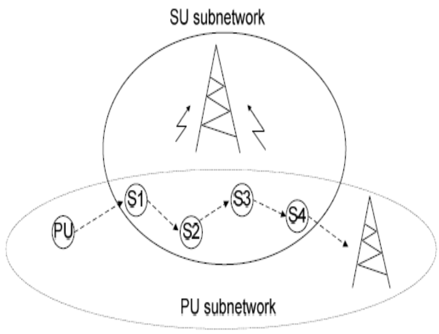

Fig.1: Co-operative CRN Model

II. NETWORK MODEL

The Cognitive Network

Consider a cognitive radio network of M primary users and N secondary users, all wishing to communicate with a common destination as shown in figure 2. This destination can be viewed as a base station in a single-cell of a cellular network or as an access point in a Wi-Fi network. A time-slotted system where the time slot is the resource to be shared among different nodes is considered and a non-interference model where only one node, either primary or secondary, is transmitting at any given time1 is adopted.

Fig.2: Network Model

Random channel gains between each node and other nodes in the network are assumed to be independent and identically distributed across time according to a general distribution and independent across users with values taken from a finite set.

Overall Network Elements and Constraints

In this paper, a time-slotted multi-hop cooperative CRN, as illustrated in Figure 1 is considered, where SUs relay PU data in return for the right to use the wireless spectrum. The multi-hop cooperative CRN in question can be divided into two sub networks: a ―PU relay sub network‖ and an ―SU sub network‖. The PU relay sub network is composed of one primary source node (*sP*), a corresponding primary destination node (*dP*) which is represented as a primary base station in Figure 1, and a set of SUs *S* that relay the PU traffic between *sP* and *dP* over possibly multiple hops, where | *S* |= *N*. This model can be considered as a generalization of the overlay CRNs with two-hop relay [5]-[7] and assumed that *sP* and *dP* cannot communicate directly. Thus, PU data is relayed solely by SUs.

The PU relay sub network is represented as (*N*, *L*) where *N* = *{sP , dP} ∪ S* denotes the node set of the PU relay sub network and *L* denotes the link set for PU data relay, i.e., *L* = *{*(*m, n*) : *m, n ∈ N*, and there exists a link between nodes *m* and *n}*. The SU sub network is composed of a set of SUs *S* and secondary base station dS as their one hop destination. Then, the SU sub network can be represented by (*S ∪ {dS},L_*), where *L_* = *{*(*l, dS*): *l ∈ S}* is the set of uplinks in the SU sub network. Let *V* = *L ∪ L_*. The CRN interference model is represented by an interference graph *G* = (*V, E*), a pair of links in *V* is in *E* if the links interfere with each other when scheduled simultaneously. Let *µmn* be the scheduled link rate for PU data over link (*m, n*) *∈ L*, and the scheduled SU link rate denoted as *sl* over link (*l, dS*) *∈ L_*. For analytical simplicity, a scheduled link rate takes a value from *{*0, 1*}* in units of packets per time slot.

A link schedule represented by a vector ((*µmn*)(*m,n*)*∈L*, (*sl*)*l∈S*) *∈ {*0, 1*}*|*L*|+*N* is said to be *feasible* iff any pair of scheduled links does not belong to the interference edge set *E*. With a time slot system, a feasible link scheduler chooses a feasible link schedule ((*µmn*(*t*))(*m,n*)*∈L*, (*sl*(*t*))*l∈S*) *∈ I* for each time slot *t*, where *I* is the set of all feasible link schedules.

III. PROPOSED ALGORITHM FOR THE CRN

In this section, the throughput-optimal scheduling algorithm with the immediate reward mechanism [1] is described; the algorithm is composed of two parts, namely, a congestion controller and a hop/link scheduler. The formalized algorithm description is provided in Figure 3. The congestion controller generates and admits PU packets into the PU relay sub network, and a corresponding fraction of SU packets are admitted to their sources according to the immediate reward mechanism. The hop/link scheduler regulates the link transmission rates of the cooperative CRN.

Step 1. Congestion Controller:
$k^* = \arg\min_k \left(\rho_k \sum_{l\in P_k} Q_l(t) + U_0^k(t)\right)$;
for $k = 1,\dots,K$
  if $k = k^*$ **do:**
    if $\rho_{k^*} \sum_{l\in P_{k^*}} Q_l(t) + U_0^{k^*}(t) \le V_2$ **do:**
      $\mu_{-1,0}^k(t) = \mu_M$;
      for $m \in \{1,\dots,H_k\}$
        do: admit $\rho_k \mu_M$ packets to SU v_k^m;
      end for
    else do: $\mu_{-1,0}^k(t) = 0$;
    end if
  else do: $\mu_{-1,0}^k(t) = 0$;
  end if
end for
Step 2. Hop/Link Scheduler:
  Find $\{(\mu_{mn}(t))_{(m,n)\in\mathcal{L}}, (s_l(t))_{l\in S}\} \in \mathcal{I}$ that maximizes:
  $\sum_{k=1}^K \sum_{m=0}^{H_k} \mu_{m,m+1}^k(t)(U_m^k(t) - U_{m+1}^k(t))$
  $+ \sum_{l\in S} Q_l(t) s_l(t)$;
Update $(U_m^k(t+1))$ and $(Q_l(t+1))$ according to (3)(4).

Fig.3: Optimal algorithm with immediate reward mechanism in time slot.

Congestion Controller:

$$\min \sum_{k=1}^{K} \mu_{-1,0}^k(t)(\rho_k \sum_{l\in P_k} Q_l(t) + U_0^k(t) - V_2)$$

$$\text{s.t. } \sum_{k=1}^{K} \mu_{-1,0}^k(t) \le \mu_M.$$

The congestion controller (7) is a threshold based optimization problem, with the control parameter *V*2 as the threshold. The congestion controller (7) is developed to deterministically upper -bound the PU buffer size. Specifically, we will show later that *V*2 determines the finite PU buffer size and tradeoffs between throughput optimality and delay performance. For time slot *t*, we define

$k^* \triangleq \arg\min_k(\rho_k \sum_{l\in P_k} Q_l(t) + U_0^k(t))$. Then, to solve (7), we set

$$\mu_{-1,0}^{k^*}(t) = \begin{cases} \mu_M, & \text{if } \rho_{k^*} \sum\limits_{l\in P_{k^*}} Q_l(t) + U_0^{k^*}(t) \le V_2, \\ 0, & \text{otherwise.} \end{cases} \quad (8)$$

For $k \neq k^*$, we set $\mu_{-1,0}^k(t) = 0$. With a centralized control, $\rho_k \mu_{-1,0}^k(t)$ packets are admitted to SUs v_k^m, $m = 1, \cdots, H_k$.

Hop/Link Scheduler:

In the hop/link scheduler (9), each SU link rate is weighted by the SU queue backlog and each PU hop rate is weighted by a –hop back-pressure‖, i.e., the difference between the PU queue backlogs across a hop where the optimization is taken over all feasible ((µk m,m+1(t))m,k,(sl(t))l∈S.

$$\max\{\sum_{k=1}^{K}\sum_{m=0}^{H_k} \mu_{m,m+1}^k(t)(U_m^k(t) - U_{m+1}^k(t)) + \sum_{l\in S} Q_l(t)s_l(t)\}, \quad (9)$$
$$\text{s.t. } \{(\mu_{mn}(t))_{(m,n)\in\mathcal{L}}, (s_l(t))_{l\in S}\} \in \mathcal{I},$$

The structure of the hop/link scheduler favors hops/links with higher weights for resource allocation, where we note that a higher weight implies a higher congestion level for a hop/link. When the hop back-pressure $U_m^k(t) - U_{m+1}^k(t) \le 0$, $m \in \{0, \cdot \cdot \cdot, H_k\}$, we set $\mu^k_{m,m+1}(t) = 0$, without loss of optimality.

IV. FURTHER DISCUSSION

With the immediate reward mechanism, the optimal backpressure- based algorithm requires simultaneous admission of both PU and SU packets. This requirement of simultaneous admission can be relaxed for an optimal algorithm with a long-term reward mechanism.

Proposed Algorithm with A Long-Term Reward Mechanism

In the original algorithm proposed in Section III with the immediate reward mechanism, SUs are assigned a channel share *proportional to* the relayed PU data, i.e., there may exist additional unutilized channel opportunities left by the PU. In addition, the congestion controller (7) is centralized to simultaneously admit both PU and SU packets. In this section, we extend our analysis to a CRN model with a more general ***long-term reward mechanism*** [1].The formalized algorithm description is provided in Figure 4.

PU Congestion Controller:

Redefining $k* \triangleq$ arg min*k*(*ρk*_ *l∈Pk Dl*(*t*)+*Uk* 0(*t*)), we admit the PU packets on the *k*∗-th route as follows

$$\mu_{-1,0}^{k^*}(t) = \begin{cases} \mu_M, & \text{if } \rho_{k^*} \sum\limits_{l\in P_{k^*}} D_l(t) + U_0^{k^*}(t) \le V_2, \\ 0, & \text{otherwise,} \end{cases} \quad (16)$$

where *V*2 is the same control parameter as in Section III. For route *k* _= *k*∗, we set *µk*−1,*0*(*t*) = 0. Compared to the original congestion controller (7), we utilize the virtual queue *Dl*(*t*) instead of the actual SU queue backlog *Ql*(*t*).

Step 1. PU Congestion Controller:
$k^* = \arg\min_k \left(\rho_k \sum_{l\in P_k} D_l(t) + U_0^k(t)\right)$;
for $k = 1, ..., K$
  if $k = k^*$ **do:**
    if $\rho_{k^*} \sum_{l\in P_{k^*}} D_l(t) + U_0^{k^*}(t) \le V_2$
      do: $\mu_{-1,0}^k(t) = \mu_M$;
    else do: $\mu_{-1,0}^k(t) = 0$;
    end if
  else do: $\mu_{-1,0}^k(t) = 0$;
  end if
end for
Step 2. SU Congestion Controller:
for SU $l \in \mathcal{S}$ **do:**
  if $Q_l(t) \le D_l(t)$
    do: $A_l(t) = A_M$;
  else do: $A_l(t) = 0$;
  end if
end for
Step 3. Hop/Link Scheduler:
  Find $\{(\mu_{mn}(t))_{(m,n)\in\mathcal{L}}, (s_l(t))_{l\in\mathcal{S}}\} \in \mathcal{I}$ that maximizes:
  $\sum_{k=1}^{K}\sum_{m=0}^{H_k} \mu_{m,m+1}^k(t)(U_m^k(t) - U_{m+1}^k(t))$
  $+ \sum_{l\in\mathcal{S}} Q_l(t)s_l(t)$;
Update $(U_m^k(t+1))$ and $(Q_l(t+1))$ according to (3)(14).

Fig. 4 :Optimal algorithm with Long-term reward mechanism in time slot t.

SU Congestion Controller:

For each SU *l* ∈ *S*, The threshold-based SU congestion controller has a time varying threshold, i.e, the virtual queue *Dl*(*t*).

$$A_l(t) = \begin{cases} A_M, & \text{if } Q_l(t) \le D_l(t), \\ 0, & \text{otherwise.} \end{cases} \quad (17)$$

Hop/Link Scheduler:

The hop/link scheduler remains the same as (9).

V. MEDICAL USE CASES OF NFC

In this section, we present a simulation-based performance evaluation for the algorithm proposed in Section III. Simulation results are obtained using the topology shown in Figure 1, which consists of a PU source (sP) and a PU destination (dP). In Figure 5, by fixing $V2$ = 10, we illustrate the throughput and congestion level performance of the algorithm against the route-specific reward parameters $\rho 1 = \rho 2 = \rho$, where we recall that the number of admitted secondary packets for each SU is ρ times the admitted PU packets and note that SU throughput is the sum for all SUs.

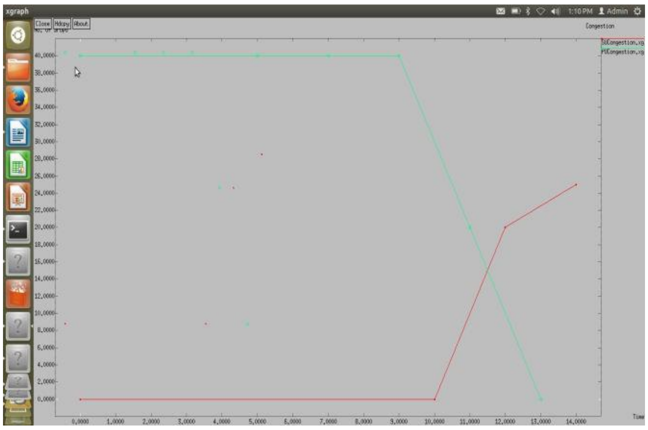

Fig. 5: Comparison of PU and SU Congestion.

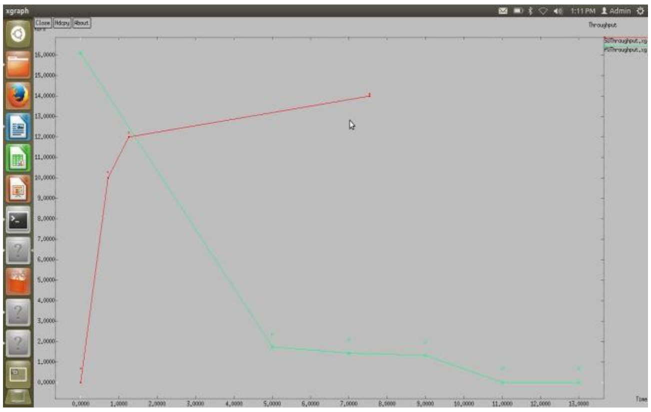

Fig. 6: Comparison of PU and SU Throughput.

According to the topology and the immediate reward mechanism, we must have the following relation between PU and SU throughput:

SU throughput= $2\rho \times$ (PU throughput), (18)

Noting that there are 2 SUs along each pre-determined route.

VI. CONCLUSIONS AND FUTURE WORKS

In this paper, a cross-layer scheduling algorithm for multi-hop cooperative cognitive radio networks is introduced. The algorithm can achieve a PU throughput arbitrarily close to the optimum, with a trade-off in the deterministically upper bounded PU buffer sizes. The algorithm is then scrutinized with respect to its feasibility for distributed implementation. In our future work, new methods of relaxing the fixed route assumption and the interference graph model will be investigated and also a proof-of- concept implementation of the propOsed distributed algorithm with the long-term reward mechanism will be implemented.

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