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I. Problem Model

We consider a Cognitive Radio Ad Hoc Network (CRAHN). We have a set of primary users V_P and a set of secondary users V_S. The CRAHN is defined over the set of secondary users and $\mathcal{E}$ denotes the set of directed edges such that $e_{ij} \in \mathcal{E}$ implies that node $i \in V_S$ can transmit directly to node $j \in V_S$ if a common available channel exists between them. For each primary user $v \in V_P$, a dedicated channel is subscribed by it. So we have the channel set $\mathcal{C}$ with $|V_P|$ channels in total.

We consider a generic interference model. Let I denote the set of interference relations among potential transmissions in the network, which includes two types of pairs: (1) $(e_{ij}, e_{kl}) \in I$ (with $e_{ij}, e_{kl} \in \mathcal{E}$) denotes that transmission along link e_{ij} cannot be scheduled on the same channel concurrently with that along link e_{kl}; (2) $(v_p, e_{ij}) \in I$ (with $v_p \in V_P$ and $e_{ij} \in \mathcal{E}$) means that when primary user v_p is actively using its subscribed channel, transmission e_{ij} cannot simultaneously happen on the channel due to interference. We also assume that each secondary user is equipped with one radio only, such that it may either transmit or receive data on one channel at each time.

A set of unicast sessions $\mathcal{M}$ is defined over the CRAHN. Let $s_m \in V_S$ and $d_m \in V_S$ be the source and destination of session $m \in \mathcal{M}$, respectively. The data delivery from s_m to d_m may need multihop routing and relaying, assisted by other secondary users.

In cognitive radio networks, we know that the primary users may not be active all the time. Let $\mathbf{1}_{\{v_p\}}(t) = 1$ if primary user $v_p \in V_P$ is idle in time slot t, and 0 otherwise. There are two mainstream approaches for the secondary users to access the licensed channels when the primary users are idle: opportunistic access and negotiated access.

- For the first approach, each secondary user listens to the licensed spectrum and judge whether the primary user is active or not, by spectrum sensing. They opportunistically occupy the licensed spectrum when it is sensed to be idle. However, there are several drawbacks of this approach, e.g., inaccurate spectrum sensing and packet erasure caused by the unexpected return of primary users.
- The other approach, negotiated one, receives intensive research in recent years. In this approach, the secondary users negotiate with the primary users for the spectrum management. The secondary users pay for the usage of the licensed spectrum while the primary users get the revenue for the spectrum leasing correspondingly. Auction is usually applied to set the price for spectrum leasing. With this approach, not only the primary users are motivated to share the spectrum when they are idle, but also can the secondary users safely occupy the leased spectrum without the risk of interference from primary users.

A. Unique feature of this work

In this work, we focus on the negotiated spectrum access. Different from our previous work, which is based on the opportunistic access, we should consider the cost to complete the end-to-end data delivery. That is to say, the cross-layer design with end-to-end rate control, routing and channel allocation (with link scheduling) should either explicitly or implicitly reflect the payment made for relaying service and spectrum leasing over each hop. On the other hand, different from current literature on spectrum leasing, which is mostly focused on the auction or pricing over each single hop while assuming the routing and link scheduling have been decided, we consider a joint design of routing, channel allocation and spectrum leasing.

We may formulate two optimization problems to be discussed shortly. Before that, some definitions should be made.

V_P	Set of primary users	V_S	Set of secondary users
$\mathcal{C}$	Set, orthogonal channels	$\mathcal{M}$	Set of unicast sessions
E	Set of links	I	Set, interference relations
M	# of data sessions	e_{ij}	Directed $i \to j$ link
$\mathbb{E}(\cdot)$	The expectation	$U(\cdot)$	Utility function
s_m	Source of session m	d_m	Destination of session m
$p_{ij}^{(m)}(t)$	Price to relay unit data of session m over e_{ij} in time slot t		
$p_{ij}^{(c)}(t)$	Price to relay unit data on channel c over e_{ij} in time slot t		
$A_m(t)$	Data arrival rate of session m in time slot t		
$A_{max}^{(m)}$	Maximum arrival rate of session m		
$r_m(t)$	Admissible data rate of session m in time slot t		
$\bar{r}_m$	Average admissible data rate of session m		
$\mu_{ij}^{(m)}(t)$	Binary var: data session m is routed over e_{ij} in time slot t?		
$\alpha_{ij}^{(c)}(t)$	Binary var: channel c is assigned to e_{ij} in time slot t?		
$Q_n^{(m)}(t)$	Data queue of session m on user n in time slot t		

TABLE I: Notation table.

II. Some definitions

A. Transport layer data arrivals

In each time slot, an arbitrary amount of data $A_m(t) \in [0, A_{max}^{(m)}]$ is generated and to be admitted into the network at source s_m ($\forall m \in \mathcal{M}$). For congestion control, $r_m(t) \in [0, A_m(t)]$ is admitted into the packet queues on the network layer.

B. Network Layer Packet Queues

On each secondary user $n \in V_P$, it maintains the following data packet queue for each session $m \in \mathcal{M}$ except when n is the destination d_m,

$$Q_n^{(m)}(t+1) = \max\{Q_n^{(m)}(t) - \sum_{e_{ij}\in\mathcal{E}} \mu_{ij}^{(m)}(t)\} + \sum_{e_{ji}\in\mathcal{E}} \mu_{ji}^{(m)}(t) + \mathbf{1}_{\{n=s_m\}} r_m(t),\ \forall m \in \mathcal{M}, n \in V_S, n \neq d_m. \tag{1}$$

Here, $\mu_{ij}^{(m)}(t)$ is the amount of data routed over link e_{ij} for session m at time slot t. And $\mathbf{1}_{\{n=s_m\}}$ is an indicator function with

$$\mathbf{1}_{\{n=s_m\}} = \begin{cases} 1 & n = s_m, \\ 0 & \text{otherwise.} \end{cases}$$

Apart from the packet queues, the network layer should also decide the price to relay unit of data for session m over link e_{ij}, *i.e.,* $p_{ij}^{(m)}(t)$, which will be discussed separately later.

C. MAC layer

Let $\alpha_{ij}^{(c)}(t)$ indicate whether link e_{ij} is scheduled on channel $c \in \mathcal{C}$ or not in time slot t:

$$\alpha_{ij}^{(c)}(t) = \begin{cases} 1 & \text{if } e_{ij} \text{ is scheduled on channel } c \text{ in time slot } t, \\ 0 & \text{otherwise.} \end{cases}$$

Clearly, the assignments to each $\alpha_{ij}^{(c)}(t)$ should satisfy the interference constraints. Besides, we know that the overall routed data for all sessions on network layer over each link is just the overall capacity on all channels of that link:

$$\sum_{c\in\mathcal{C}} \alpha_{ij}^{(c)}(t) = \sum_{m\in\mathcal{M}} \mu_{ij}^{(m)}(t), \forall e_{nj} \in \mathcal{E}. \tag{2}$$

D. Time average

Definition 1: For each time-varying variable $x(t)$, its time-averaged value is

$$\bar{x} = \lim_{t\to\infty} \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}(x(\tau)).$$

Here, $\mathbb{E}(\cdot)$ is the expectation.

E. Queue and network stability

Definition 2 (Queue and Network Stability): A queue Q is *strongly stable* (or *stable* for short) if and only if

$$\lim_{t\to\infty} \sup \frac{1}{t} \sum_{\tau=0}^{t-1} \mathbb{E}(Q(\tau)) < \infty,$$

where $Q(\tau)$ is the queue size at time slot τ and $\mathbb{E}(\cdot)$ is the expectation. A network is *strongly stable* (or *stable* for short) if and only if all queues in the network are strongly stable.

Theorem 1 (Necessity and Sufficiency for Queue Stability): For any queue Q with the following queuing law,

$$Q(t+1) = Q(t) - b(t) + a(t),$$

where $a(t)$ and $b(t)$ are the queue incoming rate and outgoing rate in time slot t, respectively, the following results hold:

Necessity: If queue Q is strongly stable, then its average incoming rate $\bar{a} = \lim_{t\to\infty} \frac{1}{t}\sum_{\tau=0}^{t-1}\mathbb{E}(a(\tau))$ is no larger than the average outgoing rate $\bar{b} = \lim_{t\to\infty} \frac{1}{t}\sum_{\tau=0}^{t-1}\mathbb{E}(b(\tau))$.

Sufficiency: If the average incoming rate $\bar{a}$ is strictly smaller than the average outgoing rate $\bar{b}$, *i.e.*, $\bar{a} + \epsilon \leq \bar{b}$ with $\epsilon > 0$, then queue Q is strongly stable.

III. Utility-Maximization with Bounded Budget Problem

The first optimization problem is to maximize the overall throughput utility with the constraint that the average cost for deliver each unit of data from source to destination is bounded by some budget of the session.

$$\begin{aligned} \max \quad & \sum_{m\in\mathcal{M}} U(\bar{r}_m) \\ s.t. \quad & \sum_{e_{ij}\in\mathcal{E}} \bar{p}_{ij}^{(m)} \leq B_m, \ \forall m \in \mathcal{M}, \qquad (3) \\ & \mathbf{r} \in \Lambda. \qquad (4) \end{aligned}$$

Here, $U(\cdot)$ is the utility function for average end-to-end data rates. $\bar{p}_{ij}^{(m)}$ is the time-averaged price to relay one unit of data for session $m \in \mathcal{M}$ over link $e_{ij} \in \mathcal{E}$ while $p_{ij}^{(m)}(t)$ is the corresponding price made in time slot t. B_m is the given budget for session m. Λ is the capacity region and $\mathbf{r} \in \Lambda$ means that there exists feasible routing and channel allocation schemes to stabilize the network with throughput $\mathbf{r}$. (Each $Q_n^{(m)}$ is stable with queueing law Eqn. (1), and each $\mu_{ij}^{(m)}(t)$ and $\alpha_{ij}^{(c)}(t)$ satisfy constraint (2) and all interference constraints.)

The problem for this story is that the budget B_m is hard to justify. It is not a trivial work to derive a proper budget such that it is enough to pay all the costs and successful deliver the data all the way to the destination.

Another problem is how to fulfill the budget constraint (3) with a distributed algorithm. We see that each price $\bar{p}_{ij}^{(m)}$ is decided hop-by-hop by each relay node while the budget B_m is some end-to-end control. If there is no central control, (*e.g.*, one server collects all prices together and judges whether the constraint is satisfied) how can each relay node decide the local price without knowing the precise pricing on other links? The solution may be the "Cash-on-delivery" mechanism as discussed in last meeting: each relay maintains two virtual queues for each session such that the payment and revenue on it for each session is balanced while the total cost is cashed at the destination; the destination maintains a virtual for its session with the cost as the incoming item and the budget as the outgoing item; according to the necessity of queue stability (theorem 1), if the virtual queue on the destination is stable, the budget constraint is achieved.

IV. Cost-Minimization with Fixed Throughput Problem

If we check the topic from another angle, we may get the cost-minimization with fixed throughput problem. That is to say, we replace the previous assumption of arbitrary data arrival rate $A_m(t)$ by a new setting that a fixed end-to-end data rate $\bar{r}_m$ is generated and admitted into the network at the source s_m, $\forall m \in \mathcal{M}$. So, we have no end-to-end rate control here. The problem is to minimize the overall average cost to delivery each unit data to its destination along the multihop paths.

$$\begin{aligned} \min \quad & \sum_{m \in \mathcal{M}} \sum_{e_{ij} \in \mathcal{E}} \bar{p}_{ij}^{(m)} \\ s.t. \quad & r_m(t) = \bar{r}_m,\ \forall m \in \mathcal{M}, t \geq 1, \\ & \mathbf{r} \in \Lambda. \end{aligned}$$

Here, $\bar{r}_m$ is the fixed end-to-end data rate for session $m \in \mathcal{M}$.

The problem with this story is similar with the previous utility-maximization one. It is not trivial to derive the fixed end-to-end rate for each session which is known to be in the capacity region.

Besides the above concern, this problem is technically easier to solve than the previous one with Lypapunov optimization theory. Since no rate control is in need, a joint routing, channel allocation and pricing algorithm can be derived with some minor alteration to the classic back-pressure mechanism.

V. Concerns on the pricing

The pricing mechanism is of most importance in both optimization problems.

Up to now, only the service prices ($p_{ij}^{(m)}(t),\ \forall e_{ij} \in \mathcal{E}, m \in \mathcal{M}, t \geq 0$) occur in the two optimization problems. The spectrum leasing prices ($p_{ij}^{(c)}(t),\ \forall e_{ij} \in \mathcal{E}, c \in \mathcal{C}, t \geq 0$) should also be involved. However, any relationship, or constraint, between the service prices and spectrum leasing prices depends on the detailed pricing mechanism between data session and relay nodes. We have several choices to set the prices: fixed, randomized and auction-based.

Technically, the above two optimization problems are not hard to solve if the service prices are either fixed or randomly generated. However, if we consider the application scenario more practically, *e.g.*, both primary users (who lease spectrum to relay nodes) and relay nodes (who provide service to data sessions) are selfish, we can see that all participants in the problem want to maximize its revenue (or minimize its cost). This phenomenon makes the pricing problem more complicated.

A. Without Collusion

If there is no collusion among neither the primary users nor the relay nodes, both auctions for relaying service and spectrum leasing are games.

- *Auction for spectrum leasing*: Relay nodes propose their bidding prices to the primary users based on the "true value" of the spectrum and previous bidding result. Meanwhile, the primary users also contend with each other to lease the spectrum. So, a double auction may be in need.

- *Auction for relaying service*: Data sessions propose their bidding prices to the relay nodes based on the "true value" of the relaying service and previous bidding result. Meanwhile, the relay nodes also compete with each other to relay the packets. Thus, a double auction may also exist here.

In the above, the "true value" of the spectrum or relaying service is hard to define. In previous literature, the "true value" is just assumed to be readily calculated with some known but unspecified function. In this work, we have to design a proper function for "true value" to reflect the "urgency" of spectrum leasing over each link, since the spectrum leasing result directly affects the routing and channel allocation (including link scheduling) which indirectly influences the end-to-end rate control. One intuitive option is to set the "true value" according to the differentiate backlogs of the packet queues. If a bounded budget is considered as in the utility-maximization problem, the "true value" should also take the remaining budget or current deficit into account.

B. With Collusion

The case without collusion is quite challenging since two double auctions exist. If we assume the possible collusion in the network, we may simplify the problems,

- If the primary users collude, we can treat all the individual revenue-maximization problems of each primary user, which is a multi-objective optimization, into a global revenue-maximization problem with scalarization. So, there is no competition among the primary users. Once the relay nodes propose their bidding prices, the spectrum leasing prices can be decided.
- If the relay nodes further collude, we can treat all the individual revenue-minus-cost-maximization (revenue paid by the data sessions while cost charged by the primary users) problems of each relay node, which is a multi-objective optimization, into a global revenue-minus-cost-maximization problem with scalarization. So, there is no competition among the relay nodes. Once the data sessions propose their bidding prices, the relaying service prices can be decided.