Joint Rate, Channel and Route Selection for Cognitive Radio Ad Hoc Networks

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***Abstract*—It is a difficult but fundamental goal to fully utilize various resources to deliver data as efficiently as possible in wireless networks. In CRAHNs, it becomes more challenging due to uncertain primary users' activities, time- and location-varying channels, and arbitrary traffic arrivals with unpredictable rate demand. In this paper, we propose a Joint Rate, Channel and Route Selection (*JRCRS*) approach to optimize the network resource utility in multi-hop, multi-channel CRAHNs, with the objective of maximizing social welfare. Our JRCRS jointly optimizes the data transmission rate adaptive to network condition, assigns interference-free channels and selects a route when a new flow arrives or a primary user activates. The routing metric in our JRCRS considers the relay workload, the distance between the relay and the destination node, and co-channel interference to primary and secondary users. Simulation results demonstrate that our JRCRS outperforms the most related solutions in terms of social welfare, average throughput, network stability and end-to-end delay.**

I. INTRODUCTION

With the explosive growth of modern wireless applications, cognitive radio has been considered as a promising solution to solve the spectrum scarcity problem. In cognitive radio ad hoc networks (CRAHNs), secondary nodes (SN) opportunistically use licensed spectrum of primary nodes (PN) through frequent sensing PN activities and immediately vacating the spectrum when the corresponding PN activates again [1].

To fully utilize various resources in CRAHNs, the following three key issues have to be addressed. The first one is the *data rate adaptation* [2]. As both the size of data buffer in networked nodes and the capacity of wireless links are limited, and most applications present specified data rate requirements. It is very challenging to adjust dynamically data transmission rate not only to avoid the network congestion but also to satisfy the rate requirement. The second issue is the *joint channel assignment and routing* [3]. In CRAHNs, available channels of a secondary node change with time and location. So, the channel assignment and the route selection should be jointly designed and optimized. Finally, it is also indispensable to design an *incentive* mechanism [4] to encourage collaboration among SNs for utilizing network resources efficiently.

Focusing on the above issues, in this paper, we propose a Joint Rate, Channel and Route Selection (JRCRS) approach to optimize various network resource utility in multi-hop multi-channel CRAHNs, with the objective of maximizing social welfare. In our target environments, channel conditions and capacities are fixed during any single time slot unless a PN communication appears; while traffics randomly arrive to the network. The JRCRS is initiated at the beginning of the time slot when a new data flow arrives or channels become unavailable. If a data flow arrives within a time slot, it will be scheduled at the next time slot. It will be initiated immediately, however, once any PN activates.

By exploiting the stochastic Lyapunov optimization theory [5], we propose a Joint Rate, Channel and Route Selection (*JRCRS*) approach to optimize the network resource utility. Main contributions are summarized as follows:

- We extend the queuing model of Lyapunov optimization from single radio to multi-radio, and propose a virtual queue concept to capture the cumulative difference between actual data rate and rate requirement, which can provide more applications with the specified rate requirement.
- We develop the JRCRS approach, which jointly optimizes the data rate, selects a route and assigns channels for links among the route. Simulation results demonstrate that our JRCRS outperforms related proposals.
- The routing metric in our JRCRS considers not only the relay workload and the distance between the relay and the destination node, but also unexpected PN activities and co-channel interference among SNs.

The remainder of this paper is organized as follows. Section II briefly reviews related work. In Section III, we present the network model and formulate the JRCRS problem. Section IV presents our JRCRS approach. We systematically evaluate our JRCRS in Section V. Finally, Section VI concludes this paper.

II. RELATED WORK

In this section, we briefly review the related work. The current related research efforts can be mainly classified into the following categories.

Cross-Layer Design in CRAHN. To improve the overall performance of CRAHN, quite a lot of recent work has focused on the direction of leveraging interactions between different layers of the protocol stack. Considering QoS requirements, [6] formulated the weighted network utility maximization problem, and proposed a cross-layer solution by performing

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joint routing, dynamic spectrum allocation and medium access. [7] investigated the joint routing and link scheduling problem of cognitive networks under uncertain spectrum supply, and developed a threshold coarse-grained fixing algorithm for a feasible solution.

Network Optimization Based on Queuing model. The stochastic network optimization by Neely is a universal scheduling framework for networks with arbitrary traffic, channels and mobility [8] [9]. The key techniques in these papers are Lyapunov drift and Lyapunov optimization, which enable system stability and performance optimization to be achieved simultaneously. At every time slot, each node carefully perturbs weights using the MaxWeight scheduling algorithm. However, the MaxWeight potentially causes long delay. Although [10] [11] have developed the delay-based scheduling to alleviate this drawback, these schemes can not maximize network resource utility.

Pricing and Incentive. Incentive pricing can encourage collaboration among network nodes so as to improve network resource utility because some intermediate nodes have no incentive to forward packets for other nodes [12] [13]. In [14], a log-based pricing scheme is designed for an unicast routing protocol, where the seller with the minimum price is selected as the next hop relay. The authors in [15] develop a route selection algorithm with minimum payment, and at the same time guarantees truthful cost reporting by secondary users.

In multi-hop CRAHNs, the above three categories of methods should be integratively considered to maximize the network resource utility. However, none of the exiting work jointly take them into account in their proposals, which is the motivation of our paper.

III. NETWORK MODEL AND PROBLEM FORMULATION

In this section, we first present the network model and introduce the pricing model, and then formulate the JRCRS problem in CRAHNs.

A. Network Model and Assumptions

We model a CRAHN as an undirected graph $G = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the union of the PN set $\mathcal{V}_P$ and SN set $\mathcal{V}_S$; $\mathcal{E}$ is the union of $\mathcal{E}_P$ and $\mathcal{E}_S$ (the set of logical links among PNs and SNs, respectively). Suppose each SN is equipped with $(q + 1)$ interfaces, among which one interface is designed to operate at the pre-defined common control channel. The remaining q interfaces are data interfaces.

Let $\mathcal{C}_m(t)$ and $\mathcal{C}_n(t)$ be the sets of available channels of SN m and n at a time slot t. A link e_{mn} belongs to $\mathcal{E}_S$ if and only if there exists a channel $c_i \in \mathcal{C}_m(t) \cap \mathcal{C}_n(t)$, and the euclidean distance $\|m - n\| \le R_T$. R_T and R_I refer to the transmission range and interference range of a SN. We consider two kinds of interference here: SN interference I_S and PN interference I_P. For two link-channels $e^{c_i}_{mn}$ and $e^{c_i}_{m'n'}$, $e^{c_i}_{m'n'} \in I_S(e^{c_i}_{mn})$ if and only if the condition $\|m - m'\| \le R_I \vee \|m - n'\| \le R_I \vee \|n - m'\| \le R_I \vee \|n - n'\| \le R_I$ is true. Similarly, $v_p \in I_P(e^{c_i}_{mn})$ implies $e^{c_i}_{mn}$ and PN v_p operate on the same channel and $\|m - v_P\| \le R_I \vee \|n - v_P\| \le R_I$.

A set of data flows is defined over the CRAHN. Let S and D be the sets of source and destination nodes respectively, and $|F|$ be the number of flows in a network. A flow $f \in F$ is of the form (s, d, r_f), where $s \in S \subset \mathcal{V}_S$ is the source node, $d \in D \subset \mathcal{V}_S$ is the destination node, and r_f is the minimum average rate requirement. The number of packets generated by s during a time slot t is denoted as $X_f(t) \in [0, X_f^{\max}]$. For the network stability, a rate adaptation algorithm is conducted at s, which only admits an amount of $A_f(t)$ packets each slot for f such that $A_f(t) \in [0, X_f(t)]$.

B. Queueing Model and Virtual Queues

Each SN n maintains a queue of $Q_n(t)$ packets, which are generated by itself or received from other nodes. $Q_n(t)$ complies with the following formulation with $Q_n(0) = 0$.

$$\begin{aligned} Q_n(t+1) = \max[Q_n(t) - \sum_{m \in N_\mathrm{n}(t)} \mu^{c_i}_{nm}(t), 0] \\ + \sum_{m \in N_n(t)} \mu^{c_i}_{mn}(t) + \sum_{f \in F} A_f(t) \delta_{n = n^s_f} \end{aligned} \tag{1}$$

where the indicator function $\delta_{n=n^s_f} = 1$ if n is the source node of f; otherwise, $\delta_{n=n^s_f} = 0$. $\mu^{c_i}_{mn}(t)$ is the actual number of packets routed over link e_{mn}, and it is usually less than the data rate $\hat{\mu}^{c_i}_{mn}(t)$ offered by the link. The number of packets that a single node transmits and receives can not exceed the upper bound, that is, $\sum_{m \in N_n(t)} \mu^{c_i}_{nm}(t) \le \mu_{\text{out}}$ and $\sum_{m \in N_n(t)} \mu^{c_i}_{mn}(t) \le \mu_{\text{in}}$.

Definition 1. *(Queue Stablity) A discrete time process* $Q_n(t)$ *is stable if* $\lim_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T-1} E\{Q_n(t)\} < \infty$ *, and a CRAHN is stable if all queues in the network are stable.*

Theorem 1. *(Necessity for Queue Stability) If* $Q_n(t)$ *is stable and* $E\{Q_n(0)\} < \infty$*, then* $\lim_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T-1} E\{a(t)\} \le \lim_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T-1} E\{b(t)\}$*, where* $a(t)$ *and* $b(t)$ *are the queue incoming rate and outgoing rate in time slot* t*.*

To meet the rate requirement, we introduce the concept of virtual queues and transform the minimum rate constraint into a queue stability problem. Specifically, each source node maintains a virtual queue $Y_f(t)$ for guaranteeing the minimum average rate constraint. Initially, $Y_f(0) = 0$, and the queueing update is:

$$Y_f(t + 1) = \max[Y_f(t) - A_f(t) + r_f, 0] \tag{2}$$

The virtual queue backlog $Y_f(t)$ is the cumulative difference between actual data rate $A_f(t)$ and rate requirement r_f. The virtual queue backlog $Y_f(t)$ will increase slot by slot if $A_f(t) < r_f$. Otherwise, $Y_f(t)$ will drop slot by slot and finally becomes zero so that $A_f(t)$ is set as the data arrival rate. By Theorem 1, if the virtual queue $Y_f(t)$ is stable, then we have for all $t > 0$, $\lim_{\mathrm{T} \to \infty} \frac{1}{T} \sum_{t=0}^{T-1} E\{A_f(t)\} \ge r_f$.

C. Incentive and Social Welfare

A node can make profits through transmitting packets generated by itself or forwarding packets for other nodes, and the specific trading processes are conducted as follows:

- If a source node $s \in S$ admits new generated packets at a sampling rate of $A_f(t)$, $G(A_f(t))$ amount of credits will be provided by the CRAHN, where $G(A_f(t))$ can be any differentiable, non-decreasing, non-negative and concave utility function of $A_f(t)$.
- If a node $n \in \mathcal{V}_S$ receives $\mu_{mn}^{c_i}(t)$ amount of data packets from node $m \in \mathcal{V}_S$, m pays $\mu_{mn}^{c_i}(t)\phi_n(t)$ amount of credits to n , where $\phi_n(t)$ is the service price per packet.

We use the price as the routing metric, and mainly considers the following two factors: the queue backlog and the node-to-destination distance.

$$\phi_n(t) = \alpha Q_n(t) + \beta D_n^d(t) \tag{3}$$

where α and β are weight of the queue backlog and the distance. The profits of a node $n \in \mathcal{V}_S$ at a time slot t can be summed as:

$$\eta_n(t)=\sum_{f\in F} G(A_f(t))\delta_{n=n_f^s}+\sum_{m\in N_n(t)}\mu_{mn}^{c_i}(t)\phi_n(t)-\sum_{m\in N_n(t)}\mu_{nm}^{c_i}(t)\phi_m(t) \tag{4}$$

As the whole social welfare only results from the external payments of the CRAHN, and it can be figured out using the following equation.

$$W(t) = \sum_{n\in\mathcal{V}_S}\eta_n(t) = \sum_{f\in F} G(A_f(t)) \tag{5}$$

D. JRCRS Problem Formulation

We next define the JRCRS problem, whose objective is to maximize the social welfare, while stabilize the network and meet the rate requirement at the same time. Since the arbitrary stochastic process of channel state, an infinite-horizon time-average of social welfare may not exist, we consider a finite series of time slot $t \in \{0, 1, \cdots, T-1\}$, and optimize the time-average social welfare over T slots,

$$max \quad \overline{W} = \frac{1}{T}\sum_{t=0}^{T-1} W(t) \tag{6}$$

such that, the admitted date rate $A_f(t)$ of any flow f is bounded by its arrival rate $X_f(t)$, and the assigned channel c_i for e_{mn} does not cause any SN interference and PN interference. Besides, the network should remain stable, and the minimum average rate requirement of each flow is guaranteed.

IV. JOINT RATE, CHANNEL AND ROUTE SELECTION APPROACH

In this section, we apply Lyapunov optimization techniques to design a distributed Joint Rate, Channel and Route Selection (JRCRS) approach.

A. Problem Analysis Based On Lyapunov Optimization

Denote $\Theta(t) = (Q(t), Y(t))$, where $Q(t)$ and $Y(t)$ are sets of actual queues in (1) and virtual queues in (2) respectively, and the *Lyapunov function* of CRAHN is defined as:

$$L(\Theta(t)) = \frac{1}{2}\sum_{n\in\mathcal{V}_S}(Q_n(t))^2+\frac{1}{2}\sum_{f\in F}(Y_f(t))^2 \tag{7}$$

where $L(\Theta(t))$ is a non-negative value which can be used as a scalar measure of queue backlogs in the network. Let ${}_t(\Theta(t))$ represent the *conditional Lyapunov drift* for slot t:

$${}_t(\Theta(t)) = E\{L(\Theta(t+1)) - L(\Theta(t))|\,\Theta(t)\} \tag{8}$$

which is the difference of values in the *Lyapunov function* over from the current slot t to the next. To jointly optimize the social welfare and stabilize the queues, we define the *drift-minus-penalty* expression which combines both of these two objectives:

$${}_t(\Theta(t)) - VE\{W(t)|\,\Theta(t)\} \tag{9}$$

where $V \geq 0$ represents an importance weight on how much we emphasize social welfare maximization. Our distributed JRCRS is motivated by minimizing a bound on (9), so that all queues are in a lower congestion state, and the social welfare is optimized.

According to queuing laws (1) and (2), we have the following inequalities:

$$\begin{aligned}&(Q_n(t+1))^2 - (Q_n(t))^2\\&\leq (\sum_{m\in N_n(t)}\mu_{nm}^{c_i}(t))^2 + (\sum_{m\in N_n(t)}\mu_{mn}^{c_i}(t) + \sum_{f\in F}A_f(t)\delta_{n=n_f^s})^2\\&-2Q_n(t)(\sum_{m\in N_n(t)}\mu_{nm}^{c_i}(t) - \sum_{f\in F}A_f(t)\delta_{n=n_f^s} - \sum_{m\in N_n(t)}\mu_{mn}^{c_i}(t))\end{aligned} \tag{10}$$

$$\begin{aligned}&(Y_f(t+1))^2 - (Y_f(t))^2\\&\leq (r_f)^2 + (A_f(t))^2 - 2Y_f(t)(A_f(t) - r_f)\end{aligned} \tag{11}$$

Taking conditional expectations of inequalities (10) and (11), and summing over all of the queues in the network, then the *drift-minus-penalty* in equation (9) can be derived as:

$$\begin{aligned}&{}_t(\Theta(t)) - VE\{W(t)|\,\Theta(t)\}\\&\leq B + Z + E\{\sum_{f\in F}Y_f(t)r_f|\Theta(t)\}\\&-E\{\sum_{f\in F}(Y_f(t)A_f(t)+VG(A_f(t))-Q_n(t)A_f(t)\delta_{n=n_f^s})|\Theta(t)\}\\&-E\{\sum_{n\in\mathcal{V}_S}(Q_n(t)+\frac{\beta}{\alpha}D_n^d(t))(\sum_{m\in N_n(t)}\mu_{nm}^{c_i}(t)-\sum_{m\in N_n(t)}\mu_{mn}^{c_i}(t))|\Theta(t)\}\end{aligned} \tag{12}$$

where

$$\begin{aligned}B = &\frac{1}{2}|\mathcal{V}_S|(|\mathcal{V}_S|-1)((\mu_{out})^2 + (\mu_{\text{in}} + |F|X^{\max})^2)\\&+\frac{1}{2}\sum_{f\in F}((r_f)^2 + (X^{\max})^2)\end{aligned} \tag{13}$$

$$\begin{aligned} Z &= \frac{\beta}{\alpha}|\mathcal{V}_S|(|\mathcal{V}_S|-1)\mu^{\max}D^{\max} \\ &\geq E\{\sum_{n\in\mathcal{V}_S}\frac{\beta}{\alpha}D_n^d(t)(\sum_{m\in N_n(t)}\mu_{nm}^{c_i}(t)-\sum_{m\in N_n(t)}\mu_{mn}^{c_i}(t))|\boldsymbol{\Theta}(t)\} \end{aligned} \tag{14}$$

and $X^{\max}$, $\mu^{\max}$, and $D^{\max}$ refer to as the maximum value of flow rate, link capacity and node-to-destination distance respectively.

To this end, we can observe that since the first item $E\{\sum\limits_{f\in F} Y_f(t)r_f|\boldsymbol{\Theta}(t)\}$ on the right hand side of inequality (12) is a constant in each time slot, so the underlying objective of minimizing the upper bound of the *drift-minus-penalty* transfers to maximizing the second and third item of equation(12) in each time slot, which is just the rate adaptation decision, and the joint channel assignment and route selection decision. Note that we introduce the node-to-destination distance into the route selection, which looks like it will increase the minimum value of inequality (12), and directly affect the queue stability and optimal social welfare. However, if such a factor can reduce the average hops of each data packet experiences in the network, then obviously it will promote concurrent transmission ability, which in turn optimizes the *drift-minus-penalty*.

B. Distributed JRCRS Algorithm

Based on the above analysis, our distributed control algorithm can be conducted as follows:

1) Adaptive rate control: For each $n \in S$, adapts its admitted data rate $A_f(t)$ to solve the following problem:

$$\max \quad Y_f(t)A_f(t) + VG(A_f(t)) - Q_n(t)A_f(t) \tag{15}$$

satisfy constraints in (6).

Since $G(A_f(t))$ is concave, its first derivative $G'(A_f(t))$ is a monotonically decreasing function of $A_f(t)$. Therefore, it is easy to get the optimal value of equation (15). Given the value of V, $X_f(t)$, the current queue backlog $Q_n(t)$ and $Y_f(t)$, and the utility function $G(A_f(t))$, the optimal rate can be calculated by

$$A_f(t) = min[max[(G')^{-1}((Q_n(t)-Y_f(t))/V), 0], X_f(t)] \tag{16}$$

where $(G')^{-1}((Q_n(t)-Y_f(t))/V)$ is the inverse function of the first derivative of $G(A_f(t))$.

2) Joint channel assignment and route selection: Similar to rate adaptation, the joint channel assignment and route selection decision is determined by optimizing the following problem:

$$\max \sum_{n\in\mathcal{V}_S}(Q_n(t)+\frac{\beta}{\alpha}D_n^d(t))(\sum_{m\in N_n(t)}\mu_{nm}^{c_i}(t)-\sum_{m\in N_n(t)}\mu_{mn}^{c_i}(t)) \tag{17}$$

satisfy constraints in (6).

By switching the sums in (17), it is easy to show that the joint channel assignment and route selection can be reduced to the following max-weight algorithm, which has the same property as equation (17): every slot, choose $\mu_{mn}^{c_i}(t)$ to maximize:

$$\sum_{e_{mn}\in\mathcal{E}_S}\mu_{mn}^{c_i}(t)\chi_{mn}(t) \tag{18}$$

where $\chi_{mn}(t)$ is the link weight of e_{mn} , and can be denoted by:

$$\chi_{mn}(t) = \quad Q_{mn}(t) + \frac{\beta}{\alpha} \quad D_{mn}(t) = (\phi_m(t)-\phi_n(t))/\alpha \tag{19}$$

and $Q_{mn}(t)$, $D_{mn}(t)$ represent the difference of queue backlog and node-to-destination distance between node m and n.

Algorithm 1 describes how a SN n finds out an available channel $c_i(t)$ for e_{nm} at a slot t, where $m \in N_n(t)$. Note the link-channel pair $e_{mn}^{c_i}$ will not interfere any PN or SN. In Algorithm 1, the function $\mathsf{F}(C_{nm}(t))$ extracts the first element in $C_{nm}(t)$. If there is not any $c_i(t)\in C_{nm}(t)$ at this slot, Algorithm 1 will return -1.

Algorithm 1: Channel assignment

```
Input: $e_{nm}$ ($m \in N_n(t)$), $C_n(t)$ and $C_m(t)$
Output: $c_i(t)$
$C_{nm}(t) = C_n(t) \cap C_m(t)$;
while ($C_{nm}(t) \neq$  ) do
    $c_i(t)$=F($C_{nm}(t)$)
    set up $I_S(e_{nm}^{c_i})$, $I_P(e_{nm}^{c_i})$ based on section III-A;
    if ($I_S(e_{nm}^{c_i}) =$   && $I_P(e_{nm}^{c_i}) =$  )
        Return $c_i(t)$;
    $C_{nm}(t)$=$C_{nm}(t)$-$\{c_i(t)\}$
end while
Return -1;
```

Algorithm 2 focuses on seeking the optimal solution to the expression (18). The channel assignment has to be jointly considered during the route setup. A working node n finds out the best next hop $m\in N_n(t)$ with the highest $\chi_{nm}(t)$ among all neighbors of n. Obviously, the selected SN m also has the lowest service price, i.e., $\phi_m(t)=\min\ \{\phi_i(t)|\forall i \in N_n(t)\}$, where both m and n have to have available interface(s). Then, n transmits a number of $\min[Q_n(t), \mu_{nm}^{c_i}(t)]$ packets in the head of $n's$ queue to the next hop m. Finally, the queue backlog is updated with $Q_n(t) = Q_n(t)-\mu_{nm}^{c_i}(t)$. Particularly, if $\chi_{nm}(t)\leq 0$ for all $m\in N_n(t)$ in Algorithm 2, n will not transmit any packet to m at the slot t because it will bring negative profits in our profit-driven systems.

V. PERFORMANCE EVALUATION

A. System Setup

10 primary nodes and 100 secondary nodes are randomly deployed and randomly move at a speed distributed in $[0, 10m/s]$. The transmission range and interference range of network nodes are set as $150m$ and $300m$ respectively. Every SN has 6 data channels. In the simulation, we tested four key

Algorithm 2: Joint channel assignment and route selection

```
Input: $Q_n(t)$, $q_n^{used}$, $q_m^{used}$
Output: $\mu_{nm}^{c_i}(t)$ and the next hop $m$
$m_{\min} = -1$; $\chi_{\max} = -\infty$;
while ($q_n^{used} < q$ && $Q_n(t) > 0$ ) do
  for ($\forall m \in N_n(t)$)
    if ($q_m^{used} < q$)
      get $c_i(t)$ using Algorithm 1;
      if ($c_i(t) \neq -1$)
        $\chi_{nm}(t) = (\phi_n(t) - \phi_m(t))/\alpha$;
        if ($\chi_{nm}(t) > 0$ && $\chi_{nm}(t) > \chi_{\max}$)
          $m_{\min} = m$; $\chi_{\max} = \chi_{nm}(t)$;
  end for
  if ($m_{\min} \neq -1$)
    $m = m_{\min}$;
    $\alpha_{nm}^{c_i}(t) = 1$;
    $q_n^{used} + +$;
    $q_m^{used} + +$;
    $\mu_{nm}^{c_i}(t)$=min[$Q_n(t), \hat{\mu}_{nm}^{c_i}(t)$];
    send $\mu_{nm}^{c_i}(t)$ packets in head of queue to $m$;
    $Q_n(t) = Q_n(t) - \mu_{nm}^{c_i}(t)$;
end while
```

performance metrics for a duration of 10^5 time slots. In each scenario, we have two categories of flows. In the first category, we set $r_f = 5pkt/slot$, and $G(A_f(t)) = 50\ln(A_f(t) + 1)$, and in the second category, we set $r_f = 7pkt/slot$, and $G(A_f(t)) = 70\ln(A_f(t) + 1)$, respectively.

We compare our JRCRS with the following two solutions.

- *Back Pressure Routing (BPR)* [8]. The routing decision in BPR only considers the queue backlog, and the neighbor with the smallest queue backlog is selected as the next hop.
- *Greedy Perimeter Stateless Routing (GPSR)* [16]. In GPSR, the optimal next hop is the neighbor geographically closest to the destination.

We evaluate our JRCRS in terms of queue stability, social welfare, average throughput and end-to-end delay.

B. Queue Stability

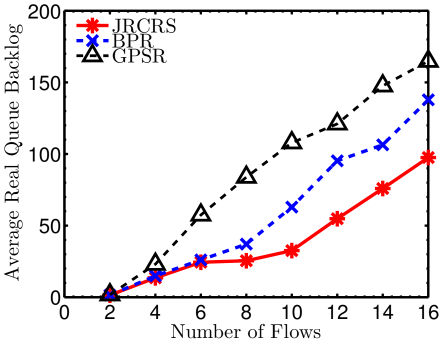

Fig. 1. Real queue backlog with flow number.

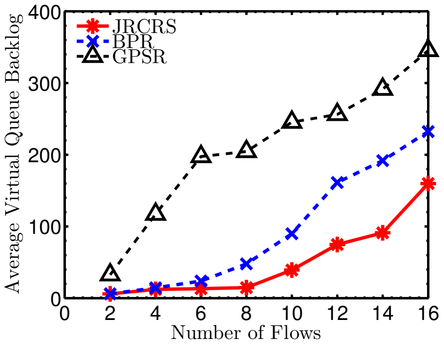

Fig. 2. Virtual queue backlog with flow number.

Fig. 1 and Fig. 2 indicate that both the real queue backlog and virtual queue backlog of our JRCRS are always less than BPR and GPSR, which reflects the fact that our JRCRS can effectively control the network congestion and guarantee the minimum rate requirement. As at every time slot, each source node monitors its real queue backlog and virtual queue backlog, and it will make a trade-off between queue stability and flow's rate requirement, then it carefully adjusts its optimal admitted rate $A_f(t)$. In such a dynamic and distributed manner, the network congestion is prevented, and the transmission rate is promoted.

C. Social Welfare

With the increase of concurrent data flows (F), social welfare in the three solutions grows up, but with different growth rate. Fig. 3 shows that JRCRS outperforms BPR and GPSR. When $|F|$ grows up to 8, BPR and GPSR have little increase while our JRCRS still exhibits significant improvements. The reason is that in order to achieve the network-wide optimal social welfare, BPR dynamically selects its route where long paths are utilized even under a light traffic load. For GPRS, it just explores the shortest path no matter how overloaded the next hop is.

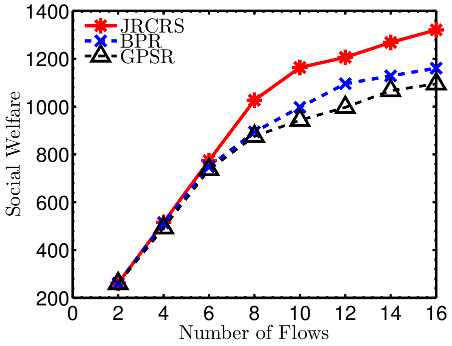

Fig. 3. Social welfare with flow number.

D. Average Throughput

In Fig.4, the results show that our JRCRS exhibits the highest aggregated throughput in two categories of flows and can satisfy specified rate requirements. For the 4 flows in second category, for example, average data rate of each flow in our JRCRS is around 32/4=8 pkt/slot, which is higher than the rate requirement r_f=7 pkt/slot. Instead, average data rate of each flow in BPR and GPSR in the same category is around 26/4=6.5 pkt/slot and 20/4=5 pkt/slot, respectively. It demonstrates that our JRCRS can provide more applications with the specified rate requirement, and improve the user experience.

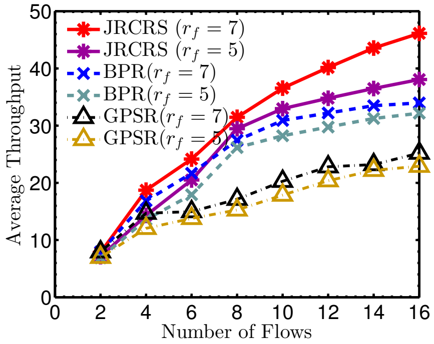

Fig. 4. Average throughput with flow number.

E. End-to-End Delay

Fig. 5 shows the increase of average end-to-end delay with the number of flows, and our JRCRS has the lowest end-to-end delay. The reason is similar to Fig. 3. As BPR may route packets over longer pathes to balance traffic load, and GPSR may cause longer wait time. Thus, both of them inevitably lead to longer end-to-end delay. While the routing metric in our JRCRS considers not only the traffic load but also the distance between the relay and the destination node. Besides, the results also demonstrate our analysis in section IV-A, that such a routing metric will not affect the joint optimization.

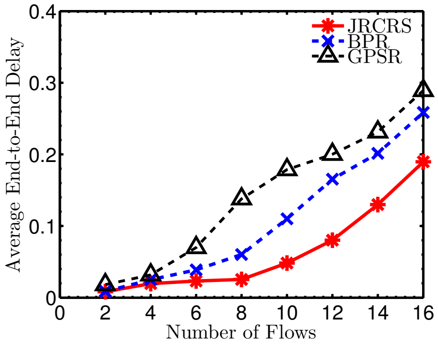

Fig. 5. End-to-End delay with flow number.

VI. CONCLUSION

We presented a JRCRS approach that jointly considers rate adaptation, channel assignment and route selection to optimize various network resource utility in multi-hop, multi-channel CRAHNs. It adaptively optimizes the data rate at each time slot, selects a route and assigns channels for all links among the route when a new flow arrives or a primary user actives. The routing metric in our JRCRS considers not only the relay workload and the distance between the relay and the destination node, but also unexpected PN activities and co-channel interference among SNs. Numeric results demonstrate that our JRCRS outperforms the most related BPR and GPSR in terms of social welfare, average throughput, network stability and end-to-end delay.

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