Opportunistic Routing in Multi-Radio Multi-Channel Multi-Hop Wireless Networks

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***Abstract*—Two major factors that limit the throughput in multi-hop wireless networks are the co-channel interference and unreliability of wireless transmissions. Multi-radio multi-channel technology and opportunistic routing (OR) have shown their promise to significantly improve the network capacity by combating these two limits. It raises an interesting problem on the tradeoff between multiplexing and spatial diversity when integrating these two techniques for throughput optimization. It is unknown what the capacity of the network could be when nodes have multiple radios and OR capability. In this paper, we present our study on optimizing an end-to-end throughput of the multi-radio multi-channel network when OR is available. First, we formulate the end-to-end throughput bound as a linear programming (LP) problem which jointly solves the radio-channel assignment, transmission scheduling, and forwarding candidate selection. Second, we propose an LP approach and a heuristic algorithm to find a feasible scheduling of opportunistic forwarding priorities to achieve the capacity. Simulations show that the heuristic algorithm achieves desirable performance under various number of forwarding candidates. Leveraging our analytical model, we find that 1) OR can achieve better performance than traditional routing (TR) under different radio/channel configurations, however, in particular scenario (e.g. bottleneck links exist between the sender and relays), TR is preferable; 2) OR can achieve comparable or better performance than TR by using less radio resource.**

***Index Terms*—Multi-radio multi-channel multi-hop wireless networks, opportunistic routing, capacity, throughput, radio channel assignment, scheduling, linear programming, heuristic algorithm.**

I. INTRODUCTION

MULTI-HOP wireless networks have attracted increasing attention in recent years owing to its easy deployment and wide range of applications. Two major factors that limit the throughput in multi-hop wireless networks are the co-channel interference and unreliability of wireless transmissions. With the spur of modern wireless technologies, a promising way to improve the system throughput is to allow more concurrent transmissions by installing multiple radio interfaces on one node with each radio tuned to a different orthogonal channel [1]–[3]. Other than the multi-radio multi-channel technology, opportunistic routing (OR) also shows its potential on significantly improving the network throughput [4]–[13]. OR is a network-MAC cross-layer design, which involves multiple forwarding candidates at each hop, and the actual forwarder is selected *after* packet transmission according to the instant link reachability and availability. It is quite different from the traditional routing (TR) that only one *pre-selected* next-hop node is involved to forward packets at each hop.

When integrating these two techniques, an interesting question arises that "what is the end-to-end throughput bound of the multi-radio multi-channel network when OR is available?". In this paper, we will propose a methodology to answer this question. However, it is a non-trivial task.

First, different from TR, OR has its unique nature that for each packet transmission, any one of the forwarding candidates of the transmitter can become the actual forwarder. Thus, effective throughput can take place from a transmitter to any one of its forwarding candidates at any instant. However, for TR, throughput can only happen from a transmitter to a pre-defined next-hop node even if other neighboring nodes overhear the transmission. Therefore, the previous work [1]–[3] on the throughput optimization in multi-radio multi-channel systems based on TR cannot be directly applied to OR.

Second, multi-radio multi-channel capability raises challenging issues on radio-channel assignment for OR. In a single-radio single-channel system, OR naturally takes advantage of the redundant receptions on multiple neighboring nodes without consuming or sacrificing any extra channel resource. When a node is sending packets, all of its one-hop neighbors usually cannot send or receive other packets at the same time due to co-channel interference. That is, these one-hop neighbors have no other choices but listen to the transmission. However, in multi-radio/channel systems, the one-hop neighbors have two choices: 1) they can operate on the same channel as the transmitter to improve the diversity gain on the receiver side, then more effective traffic can flow out of the transmitter and the system throughput can be increased; or 2) they can operate on other orthogonal channels, thus have chances to transmit/receive packets to/from other nodes, which may result in more concurrent effective traffic flowed in the network and can also increase the system throughput. This can be considered as a trade-off between multiplexing and spatial diversity. Which choice the neighboring nodes should make is non-trivial. The radio-channel assignment for optimizing the end-to-end throughput in multi-radio multi-channel systems when OR is available deserves careful study.

Third, due to the broadcast nature of the wireless medium,

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one transmission may interfere with the neighboring links operated on the same channel. Therefore, node's transmission should be optimally scheduled in order to maximize the throughput. Finally, even the radio-channel assignment and transmission scheduling are given, we still need to optimally (often dynamically) select forwarding candidates and assign relay priorities among them in order to maximize the end-to-end throughput. How to dynamically assign and schedule the forwarding priority among forwarding candidates has not been well studied in the existing literature.

In summary, in order to maximize the end-to-end throughput of the multi-radio multi-channel network when OR is available, we should jointly address multiple issues: radio-channel assignment, transmission scheduling, forwarding candidate selection, and forwarding priority scheduling. In this paper, we carry out a comprehensive study on these issues. First, we formulate the end-to-end throughput bound between a source-destination pair in multi-radio multi-channel multi-hop wireless networks with OR capability as a linear programming (LP) problem which jointly solves the radio-channel assignment, transmission scheduling, and forwarding candidate selection. Second, we propose an LP approach and a heuristic algorithm to find a feasible scheduling of opportunistic forwarding priority to achieve the throughput bound. The proposed heuristic algorithm achieves desirable performance under different number of forwarding candidates. Leveraging our analytical model, we gain the following two insights: 1) OR can achieve better performance than TR under different radio/channel configurations, however, in some scenario (e.g. bottleneck links exist between the sender and relays), TR is more preferable; 2) OR can achieve comparable or even better performance than TR by using less radio resource.

The rest of this paper is organized as follows. Section II discusses the related work. We introduce the system model and opportunistic routing in Section III. We propose the framework of computing the throughput bound between a source-destination pair in multi-radio multi-channel multi-hop wireless networks with OR capability in Section IV. The scheduling of opportunistic forwarding priorities is studied in Section V. Examples and simulation results are presented and analyzed in Section VI. Conclusions are drawn in Section VII.

II. Related Work

A. Opportunistic Routing

Opportunistic routing exploits the broadcast nature and spacial diversity of the wireless medium by involving multiple one-hop neighbors for packet forwarding. The increase in packet forwarding reliability improves throughput and energy efficiency. Existing studies on OR mainly focus on protocol design. Some variants of opportunistic routing, such as ExOR [6] and opportunistic any-path forwarding [7], rely on the path cost information or global knowledge of the network to select candidates and prioritize them. In the least-cost opportunistic routing (LCOR) [8], depending on the cost definition, it may need to enumerate all the neighboring node combinations to find the best forwarding candidates, while in some common cases it only introduces linear searching. Some other variants of OR [4], [5], [9]–[11], [14] use the location information of nodes to define the candidate set and relay priority. In GeRaF [14], the next-hop neighbors of the current forwarding node are divided into sets of priority regions with nodes closer to the destination having higher relay priorities. Similar to [14], in [5], the network layer specifies a set of nodes by defining a forwarding region in space that consists of the candidate nodes and the data link layer selects the first node available from that set to be the next hop node. [4] discussed three suppression strategies of contention-based forwarding to avoid packet duplication in mobile ad hoc networks. [9] revealed several important properties of the local behavior of OR, such as the maximum *expected packet advancement* (EPA) is an increasing and concave function of the number of forwarding candidates. [10], [11] proposed a local metric *expected one-hop throughput* (EOT) to balance the medium time cost and expected packet advancement. Recent work [12] combines OR with network coding to further improve the system throughput.

B. Capacity of Multi-hop Wireless Networks

The theoretical study on the capacity of multi-hop wireless networks can be classified into two directions. One is on the asymptotic bounds of the network capacity [15]–[17]. These studies derive the capacity trend with regard to the size of a wireless network [15] or with respect to the number of radios and channels [17]. The other direction on wireless network capacity is to compute the exact performance bounds for a given network. Our work falls into this direction. Jain *et al* proposed a framework to calculate the throughput bounds of traditional routing between a pair of nodes by adding wireless interference constraints into the maximum flow formulations [18]. Zhai and Fang studied the path capacity of traditional routing in a multi-rate scenario [19]. There has been recent work [1]–[3] on capacity bound computation in multi-radio multi-channel networks. However, they are all based on the assumption of using traditional routing at the network layer, where one transmitter can only deliver traffic to one receiver. There is one work [13] addressing the end-to-end throughput of OR in multi-rate wireless networks, and it computes the throughput bound when opportunistic forwarding strategy is given at each node. This paper is based on our recent work on computing the end-to-end throughput bound of opportunistic routing in multi-radio multi-channel multi-hop wireless networks [20]. We advance the state-of-the-art by addressing the priority scheduling problem in the local opportunistic forwarding to satisfy the rate/traffic demand on each link. Our study is the first integrated work of radio-channel assignment, transmission scheduling, candidate selection and prioritization for OR in multi-radio multi-channel multi-hop wireless networks. Our analysis provides insights into the performance and behavior of OR in multi-radio multi-channel systems.

III. System Model and Opportunistic Routing Primer

We consider a multi-hop wireless network with N nodes. Each node n_i ($1 \leq i \leq N$) is equipped with one or more wireless interface cards, referred to as radios in this work. Denote the number of radios in each node n_i as t_i ($i = 1...N$). Assume K orthogonal channels are available in the network without any inter-channel interference. We consider the system with channel switching capability, such that a radio can dynamically switch across different channels. We assume there is no performance gain to assign the same channel to the different radios on the same node (i.e. we do not consider MIMO). For simplicity, we assume each node n_i transmits at the same data rate R_i among all its radios and channels. However, our model can be easily extended to the multi-rate case. We also assume half-duplex on each radio, that is, a radio can not transmit and receive packets at the same time. It is usually true in practice. There is a unified transmission range and interference range for the whole network. The transmission range and interference range are largely dependent on the transmission power, which is fixed in our model. Typically, the interference range is larger than the transmission range. Two nodes, n_i and n_j, can communicate with each other if the Euclidean distance between them is less than the transmission range and they are operated on the same channel. Due to the unreliability of the wireless links, there is a packet reception ratio (PRR) associated with each transmission link. In this paper, we assume that the link quality on each channel is independent and can be obtained by the existing measurement schemes [21], [22]. In order to analyze the throughput bound, we assume that packet transmission/forwarding at an individual node and radio/channel allocation can be perfectly scheduled by an omniscient and omnipotent central entity. Thus, we do not concern ourselves with issues such as MAC contention or coordination overhead that may be unavoidable in a distributed network. This is a very commonly used assumption for theoretical studies [13], [18], [19].

A. Opportunistic Routing Primer

Different from TR, OR basically runs in such a way that for each local packet forwarding, a set of next-hop forwarding candidates are selected at the network layer and one of them is chosen as the actual relay at the MAC layer according to their instantaneous availability and reachability at the time of transmission. Using Fig. 1 as an example, the **one-hop neighbor set** of a transmitter n_i is $\mathcal{C}_i = \{n_{i_1}, ..., n_{i_5}\}$, which consists of nodes that operate on the same channel as node n_i and are in its transmission range. A subset $\mathcal{F}_i = \{n_{i_1}, ..., n_{i_3}\}$ of $\mathcal{C}_i$ is selected as the **forwarding candidate set** of n_i. We name $(n_i, \mathcal{F}_i)$ as an **opportunistic module**.

To avoid packet duplication, only one of the forwarding candidates becomes the actual forwarder of each packet. There is a forwarding priority among these forwarding candidates to decide who should forward the packet if multiple forwarding candidates correctly receive the same packet. We use $\mathcal{P}$ to represent the forwarding priority among the forwarding candidate, such that $\mathcal{P}(i_j) > \mathcal{P}(i_k)$ indicates n_{i_j} has higher forwarding priority than n_{i_k}.

To send a packet from the source n_s to a destination n_d, the opportunistic routing works by the source n_s sending the packet to the receivers in its forwarding candidate set $\mathcal{F}_s$. One of the candidate nodes continues the forwarding based on their relay priorities – If the first-priority node in the set has received the packet successfully, it forwards the packet towards

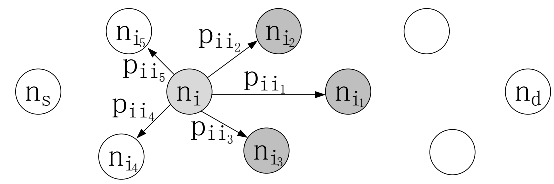


Fig. 1. An example of opportunistic module $(n_i, \mathcal{F}_i)$, where $\mathcal{F}_i = \{n_{i_1}, n_{i_2}, n_{i_3}\}$.

the destination while all other nodes suppress themselves from duplicate forwarding. Otherwise, the second-priority node in the set is arranged to forward the packet if it has received the packet correctly. Otherwise the third-priority node, the fourth-priority node, etc. A forwarding candidate will forward the packet only when all the other candidates with higher priorities failed to do so.

Several MAC protocols [4], [6], [14] have been proposed to ensure the relay priority among the candidates. For example, in [6], a batch map is used to indicate the packets known to have been received by higher-priority candidates, thus prohibit the lower-priority candidates from relaying duplicate copies of the packets. Only when none of the forwarding candidates has successfully received the packet, the sender will retransmit the packet if retransmission is enabled. The forwarding reiterates until the packet is delivered to the destination n_d.

IV. Problem Formulation

In this section we present our methodology to compute the throughput bound between two end nodes in a multi-radio multi-channel multi-hop wireless network when OR is available. We first study which opportunistic modules can coexist at the same time under the constraints of wireless interference and radio interface limits. We then formulate the end-to-end throughput bound as an LP problem which jointly solves the radio-channel assignment, transmission scheduling, and forwarding candidate selection. We further propose an LP approach and a heuristic algorithm to find a feasible scheduling of opportunistic forwarding priorities to achieve the capacity.

A. Concurrent Transmission Sets

In this subsection, we will discuss which opportunistic modules in the network can be activated at the same time. The set of opportunistic modules which can be activated at the same time is named as **concurrent transmission set** (CTS). The motivation of building concurrent transmission set is similar to those of building independent set in [18] and concurrent transmission patterns in [3]. That is, taking the benefit of time-sharing scheduling of different concurrent transmission sets, we could achieve a collection of capacity graphs, associated with capacity constraint on each link. OR can be performed on the underlying capacity graph to achieve the maximum throughput. However, the methodology of constructing CTS for OR is quite different from those in [3], [18] for TR. Because for OR, any of the forwarding candidates can become the actual forwarder for each transmission, and the instantaneous throughput can take place on any link from the transmitter to any forwarding candidate. So the CTS is constructed based on opportunistic modules (involving multiple links sharing the same transmitter) instead of individual links. Furthermore, besides the co-channel interference, radio interface limits in the multi-radio system also impose constraint on concurrent transmissions in the network.

We introduce the concept of **transceiver configuration**, v_i^k, which indicates node n_i operating on channel k $(1 \le k \le K)$. Each transceiver configuration can be in either transmission or reception state, and we call it transmitter or receiver, respectively. We say there is a wireless link l_{ij}^k $(i \ne j)$ when v_i^k is a transmitter and v_j^k is a receiver and v_j^k is in the transmission range of v_i^k. Link l_{ij}^k is **usable** when v_j^k is not in the interference range of any other transmitters; otherwise, it is **unusable**. When a link is usable, its transmitter and receiver are also usable. Let $V = \{v_i^k | i = 1...N, k = 1...K\}$, and $E = \{l_{ij}^k | i, j = 1...N, i \ne j, k = 1...K\}$.

A CTS T_α can be represented by an indicator vector on all wireless links, written as $T_\alpha = \{\psi_{ij}^{k\alpha} | l_{ij}^k \in E\}$.

$$\psi_{ij}^{k\alpha} = \begin{cases} 1, & l_{ij}^k \text{ is usable in CTS } T_\alpha; \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

Denote the following indicator variable to represent the transceiver configuration status in CTS T_α:

$$\eta_i^{k\alpha} = \begin{cases} 1, & v_i^k \text{ is usable in CTS } T_\alpha; \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

where v_i^k can be a transmitter or receiver.

An opportunistic module in a CTS T_α can be represented as $(v_i^k, \{v_j^k | l_{ij}^k \in \mathbf{E}, \psi_{ij}^{k\alpha} == 1\})$. Note that according to the unique property of OR, when a transmitter v_i^k is usable, its multiple receivers can be usable at the same time. While a usable receiver can only correspond to one transmitter. This can be formally represented by:

$$\eta_i^{k\alpha} = \min(1, \sum_{l_{ij}^k \in E} \psi_{ij}^{k\alpha}) + \sum_{l_{ji}^k \in E} \psi_{ji}^{k\alpha}, \forall\ i = 1...N, k = 1...K \tag{3}$$

Although any two active links operating on different channels do not interfere with each other, due to radio interface constraint, the number of channels being used on one node cannot exceed the number of radios installed on this node. To satisfy this constraint, we have

$$\sum_{k=1}^{K} \eta_i^{k\alpha} \le t_i, \forall\ i = 1...N \tag{4}$$

If two wireless links are concurrently usable on the same channel, they should either share the same transmitter or do not interfere with each other. This can be represented by

$$\psi_{ij}^{k\alpha} + \psi_{pq}^{k\alpha} \le 1 + I(l_{ij}^k, l_{pq}^k), \forall\ k = 1...K \tag{5}$$

where

$$I(l_{ij}^k, l_{pq}^k) = \begin{cases} 1, & i == p,\ or\ l_{ij}^k \text{ and } l_{pq}^k \text{ do not interfere;} \\ 0, & \text{otherwise.} \end{cases} \tag{6}$$

According to Eqs. (3), (4), and (5), we can enumerate all the CTS's. One CTS represents one radio-channel assignment. Note that the number of all the CTS's is exponential in the number of nodes, radios and channels. However, it may not be necessary to find all of them to maximize an end-to-end throughput. Some heuristic algorithm similar to that in [23], or column generation technique [3] can be applied to find a subset of all the CTS's to approach the throughput bound. Applying these technologies to find CTS's is out of the scope of this paper. In this paper, we simply enumerate all the CTS's. Next, we discuss which link rate (or rate vector) is supportable by OR from a transmitter to its forwarding candidates.

B. Effective Forwarding Rate

A fundamental difference of OR from TR is that effective throughput can take place from a transmitter to any of its forwarding candidates at any instant. To capture the unique property of OR, we apply the definition of **effective forwarding rate** in [13] to represent the throughput on each link from a transmitter to each of its forwarding candidate according to a forwarding strategy. For a given transmitter n_i and its forwarding candidate set $\mathcal{F}_i$, under a forwarding priority $\mathcal{P}$, the effective forwarding rate on link l_{ii_q} is defined in Eq. (7):

$$\widetilde{R}_{ii_q} = R_i \cdot p_{ii_q} \prod_{\mathcal{P}(i_k) > \mathcal{P}(i_q), n_{i_k} \in \mathcal{F}_i} (1 - p_{ii_k}) \tag{7}$$

where R_i is the data transmission rate at transmitter n_i.

The effective forwarding rate indicates that according to the relay priority, only when higher-priority forwarding candidates do not receive the packet correctly, a lower-priority candidate may have a chance to relay the packet if it does. Similar methodology is used to define the remaining path cost for a forwarding candidate set in [8] and compute the expected number of packets a transmitter must forward in [12].

Then the effective forwarding rate from a transmitter n_i to its forwarding candidate set $\mathcal{F}_i$ is the summation of the effective forwarding rate to each forwarding candidate in the sequence:

$$\widetilde{R}_{i\mathcal{F}_i} = \sum_{n_{i_q} \in \mathcal{F}_i} \widetilde{R}_{ii_q} = R_i \cdot (1 - \prod_{n_{i_q} \in \mathcal{F}_i} (1 - p_{ii_q})) \tag{8}$$

Note that, the effective forwarding rate from a transmitter to a set of its forwarding candidates only depends on the transmission rate and the PRRs on the corresponding links, but does not depend on the priority among the forwarding candidates. We will show that this property eases the LP formulation in Section IV-D by avoiding enumerating all the possible prioritizations among the forwarding candidates. Furthermore, it will be used to design a heuristic scheduling of opportunistic forwarding priorities to satisfy a rate vector in Section V-B.

C. Capacity Region of An Opportunistic Module

In this subsection, we study the capacity region of an opportunistic module $(n_i, \mathcal{F}_i)$. This capacity region will serve as a bound of a rate vector corresponding to the links in the opportunistic module.

By applying the proved result in [24], we have the capacity region of $(n_i, \mathcal{F}_i)$ indicated in the following Inequality (9).

$$\sum_{q=1}^{r} \mu_{ii_q} \cdot \phi_{i_q} \leq R_i(1-\prod_{q=1}^{r}(1-p_{ii_q} \cdot \phi_{i_q})), \forall\, [\phi_{i_1}, ..., \phi_{i_r}] \in \{0,1\}^r \tag{9}$$

where μ_{ii_q} $(1 \leq q \leq r)$ is the rate from n_i to n_{i_q} in $\mathcal{F}_i$, and $r = |\mathcal{F}_i|$.

The physical meaning of Inequality (9) is that any subset summation of the rates on the outgoing links from a transmitter to its forwarding candidates must be bounded by the effective forwarding rate from the transmitter to the corresponding forwarding candidate subset. Now we are ready to formulate the end-to-end throughput bound of OR in multi-radio multi-channel systems by making use of the CTS and the capacity region of the opportunistic module.

D. Maximum End-to-end Throughput in Multi-Radio Multi-channel Multi-hop Networks with OR Capability

Assume we have found all the CTS's $\{T_1, T_2...T_M\}$ in the network. At any time, we activate all the transmitters in one CTS. Let λ_α denote the time fraction scheduled to CTS T_α $(\alpha = 1...M)$. Then the maximum throughput problem can be converted to an optimal scheduling problem that schedules the activation of the CTS's to maximize the end-to-end throughout. Therefore, considering communication between a single source, n_s, and a single destination, n_d, with opportunistic routing, we formulate the throughput capacity problem between the source and the destination as a linear programming problem corresponding to a maximum-flow problem under additional constraints in Fig. 2.

$$Max \sum_{k=1}^{K} \sum_{l_{si}^k \in \mathbf{E}} \sum_{\alpha=1}^{M} \mu_{si}^{k\alpha} \tag{10}$$

$$s.t.$$

$$\sum_{k=1}^{K} \sum_{l_{ij}^k \in \mathbf{E}} \sum_{\alpha=1}^{M} \mu_{ij}^{k\alpha} = \sum_{k=1}^{K} \sum_{l_{ji}^k \in \mathbf{E}} \sum_{\alpha=1}^{M} \mu_{ji}^{k\alpha},$$
$$\forall\; i = 1...N, i \neq s, i \neq d \tag{11}$$

$$\sum_{k=1}^{K} \sum_{l_{is}^k \in \mathbf{E}} \sum_{\alpha=1}^{M} \mu_{is}^{k\alpha} = 0 \tag{12}$$

$$\sum_{k=1}^{K} \sum_{l_{di}^k \in \mathbf{E}} \sum_{\alpha=1}^{M} \mu_{di}^{k\alpha} = 0 \tag{13}$$

$$\mu_{ij}^{k\alpha} \geq 0, \quad \forall\; k = 1...K, l_{ij}^k \in \mathbf{E}, \alpha = 1...M \tag{14}$$

$$\sum_{\alpha=1}^{M} \lambda_\alpha \leq 1 \tag{15}$$

$$\lambda_\alpha \geq 0,\; \forall\; \alpha = 1...M \tag{16}$$

$$\sum_{\mathcal{C}} \mu_{ii_q}^{k\alpha} \cdot \phi_{i_q} \leq \lambda_\alpha R_i(1 - \prod_{\mathcal{C}}(1 - p_{ii_q}^k \cdot \phi_{i_q})),$$
$$\mathcal{C} = \{n_{i_q} | l_{ii_q}^k \in \mathbf{E}, \psi_{ii_q}^{k\alpha} == 1\},$$
$$\forall\; v_i^k \in \mathbf{V},\; \alpha = 1...M, \forall\; \Phi(\mathcal{C}) \in \{0,1\}^{|\mathcal{C}|} \tag{17}$$

Fig. 2. LP formulations to optimize the end-to-end throughput between two end nodes in multi-radio multi-channel multi-hop wireless networks with OR capability.

In Fig. 2, $\mu_{ij}^{k\alpha}$ and $\mu_{ii_q}^{k\alpha}$ denote the rate on link l_{ij}^k and $l_{ii_q}^k$ in the CTS T_α, respectively. Recall that $\mathbf{E}$ is the set of all the wireless links, and $\mathbf{V}$ is the set of all the transceiver configurations. The maximization states that we wish to maximize the sum of the flow rates out of the source, which is the accumulated flow rates on all outgoing links and all channels from the source in all CTS's. The constraint (11) represents flow-conservation, i.e., at each node, except the source and the destination, the accumulated incoming flow rate is equal to the accumulated outgoing flow rate. The constraint (12) states that the incoming accumulated flow rate to the source node is 0. The constraint (13) indicates that the outgoing accumulated flow rate from the destination node is 0. The constraint (14) restricts the amount of flow rate on each link to be non-negative. The constraint (15) represents that at any time, at most one CTS will be scheduled to be active. The constraint (16) indicates that the scheduled time fraction should be non-negative.

In the constraint (17), $\Phi(\mathcal{C})$ is an indicator vector of ϕ_j's with length $|\mathcal{C}|$. The constraint (17) states that no matter which forwarding candidates are selected, the flow rates from a transmitter v_i^k to its usable one-hop neighbors in $\mathcal{C}$ should be in the capacity region of the opportunistic module $(v_i^k, \mathcal{C})$. That is, in any CTS T_α, any subset-summation of the flow rates from a transmitter to its usable one-hop neighbors is bounded by the effective forwarding rate from the transmitter to the corresponding neighbor set. So constraint (17) actually contains $2^{|\mathcal{C}|}$ inequalities.

The solution of the objective function (10) is the upper bound of the throughput between two nodes in multi-radio multi-channel multi-hop wireless networks when OR is available. The byproduct of the LP in Fig. 2 is the radio-channel assignment (CTS's $\{T_\alpha | \alpha = 1...M\}$) and transmission scheduling ($\{\lambda_\alpha | \alpha = 1...M\}$). We also get the rate $\mu_{ij}^{k\alpha}$ on each link l_{ij}^k in each CTS T_α. When $\mu_{ij}^{k\alpha} \neq 0$, node j operating on channel k is selected as a forwarding candidate of v_i^k in the CTS T_α; otherwise, it is not. Therefore, the candidate selection is also solved by the LP. Note that only one forwarding candidate being selected indicates the usage of TR. So our model is general for OR and TR cases. However, the LP does not tell us how to achieve the link rate $\mu_{ij}^{k\alpha}$ in the opportunistic module, which is a forwarding priority scheduling problem.

In the following section, we propose an LP approach and a heuristic algorithm to satisfy the flow rate $\frac{\mu_{ij}^{k\alpha}}{\lambda_\alpha}$ on each link l_{ij}^k by scheduling the forwarding priorities among the forwarding candidates in an opportunistic module in a CTS T_α.

V. Forwarding Priority Scheduling

In this section, we will answer the question "in the time fraction λ_α assigned to T_α, how can we schedule the forwarding priorities among the forwarding candidates $\mathcal{F}_{v_i^k} = \{v_j^k | \mu_{ij}^{k\alpha} \neq 0\}$ of the transmitter v_i^k to satisfy $\mu_{ij}^{k\alpha}$?". Note that $\mu_{ij}^{k\alpha}$ is the normalized link rate over the whole scheduling period, thus, during the time fraction λ_α, the link rate on l_{ij}^k is $\frac{\mu_{ij}^{k\alpha}}{\lambda_\alpha}$. For simplicity, we denote v_i^k as n_i, and v_j^k as n_{i_q}

$$Min \sum_{k=1}^{r!} \beta_k \tag{19}$$
$$s.t.$$
$$\mu_q \leq \sum_{k=1}^{r!} \beta_k \widetilde{R}_{ii_q}^k, \ \forall \ q = 1...r \tag{20}$$
$$0 \leq \beta_k \leq 1, \ \forall \ k = 1...r! \tag{21}$$

Fig. 3. LP formulations for finding a forwarding priority scheduling to satisfy a rate vector $[\mu_1, ..., \mu_r]$.

in the following discussion. Furthermore, we denote the rate vector $[\frac{\mu_{ij}^{k\alpha}}{\lambda_\alpha} | v_j^k \in \mathcal{F}_{v_i^k} \ in \ T_\alpha]$ as $\overrightarrow{\mu} = [\mu_1, ..., \mu_r]$, where $r = |\mathcal{F}_{v_i^k}|$. Therefore, the **forwarding priority scheduling problem (FPSP)** can be formally defined as follows.

Definition 5.1: FPSP: Given $\overrightarrow{\mu}$, find a forwarding priority scheduling $[(\mathcal{P}_m, \beta_m) | m = 1...L]$, such that on link l_{ii_q}, the accumulated effective rate $R_{ii_q} \geq \mu_q \ \forall \ 1 \leq q \leq r$.

In the definition, $\mathcal{P}_m$ and β_m are the m^{th} forwarding priority $\mathcal{P}_m$ and its time fraction, respectively. So $\beta_m \geq 0$ $\forall \ 1 \leq m \leq L$, and $\sum_{m=1}^{L} \beta_m \leq 1$. L is the total number of different priority assignment. Under the scheduling, R_{ii_q} can be computed as follows.

$$R_{ii_q} = \sum_{m=1}^{L} \beta_m \widetilde{R}_{ii_q}^m \tag{18}$$

where $\widetilde{R}_{ii_q}^m$ is the effective forwarding rate on link l_{ii_q} defined in Eq. (7) under the forwarding priority $\mathcal{P}_m$.

A. A Scheduling based on LP

One way to get a scheduling of opportunistic forwarding priorities for a rate vector $\overrightarrow{\mu}$ is by solving a linear programming problem in Fig. 3. The basic idea of this linear programming is to enumerate all possible $r!$ opportunistic forwarding priorities to see if we can find a feasible solution. If the solution of the objective function (19) is no greater than 1, then the flow vector is schedulable, and $[(\mathcal{P}_m, \beta_m) | m = 1...r!]$ is a feasible scheduling; otherwise, the flow vector is not schedulable.

The linear programming in Fig. 3 provides a way to judge the schedulability of a rate vector corresponding to an opportunistic module, and find a schedule of forwarding priorities if the rate vector is schedulable. r is at most the number of all the one-hop neighbors of a transmitter, so it tends to be a relatively small number. However, it may not be necessary to enumerate all the possible forwarding priorities to find a feasible scheduling. In the following subsection, we propose a heuristic algorithm to solve the FPSP in a more efficient way.

B. A Heuristic Scheduling

Table I describes the heuristic recursive algorithm that finds a schedule of opportunistic forwarding priorities satisfying the rate vector $\overrightarrow{\mu}$. The basic idea of this algorithm is to satisfy each rate one-by-one by using two priority settings: assigning

TABLE I
PSEUDOCODE OF A HEURISTIC RECURSIVE ALGORITHM FOR FINDING A SCHEDULING OF OPPORTUNISTIC FORWARDING STRATEGIES

	(S,Γ) = PS($\overrightarrow{\mu}, \overrightarrow{p}, \overrightarrow{I}, r, \beta, \omega$)
1	**if** $r == 1$
2	**return**($\langle I_1 \rangle$,β)
3	**else**
4	**if** $\exists \ \mu_q == \omega R_i p_q \ \|\| \ \mu_q \leq \omega R_i p_q \prod_{j \neq q} (1 - p_j)$
5	swap(μ_1, μ_q); swap(p_1, p_q); swap(I_1, I_q);
6	$P_2 = 1 - \prod_{q=2}^{r} (1 - p_q)$;
7	β_2 =min($\frac{R_i p_1 \cdot \omega - \mu_1}{R_i P_2 p_1 \cdot \omega}$, 1); $\beta_1 = 1 - \beta_2$; $\omega' = \omega(1 - p_1 \beta_1)$;
8	(S_{11}, Γ_{11}) = PS($\mu_1, p_1, I_1, 1, \beta\beta_1, \omega$);
9	(S_{12}, Γ_{12}) = PS($\mu_1, p_1, I_1, 1, \beta\beta_2, \omega$);
10	(S_{21}, Γ_{21}) = PS($[\mu_2...\mu_r], [p_2...p_r], [I_2...I_r], r-1, \beta\beta_2, \omega'$);
11	(S_{22}, Γ_{22}) = PS($[\mu_2...\mu_r], [p_2...p_r], [I_2...I_r], r-1, \beta\beta_1, \omega'$);
12	(S_1, Γ_1)=Merge(S_{11},S_{22},Γ_{11},Γ_{22});
13	(S_2, Γ_2)=Merge(S_{21},S_{12},Γ_{21},Γ_{12});
14	**return**($S_1 \bigcup S_2, \Gamma_1 \bigcup \Gamma_2$);

the corresponding candidate the highest and lowest priority in the existing subset of the candidates. In the algorithm, we take advantage of the property of OR that the effective forwarding rate of a lower-priority candidate is not affected by the priority relationships among the higher-priority candidates. Then we can consider a group of forwarding candidates $\mathcal{F}$ as a virtual candidate, whose PRR is the probability of at least one forwarding candidate receiving the packet correctly, and the rate to this virtual candidate can be computed using Eq. (8).

In Table I, the input of the prioritizing and scheduling algorithm PS includes: $\overrightarrow{\mu}$, the rate vector; $\overrightarrow{p}$, the corresponding PRR vector; $\overrightarrow{I}$, the corresponding forwarding candidate index vector; r, the number of candidates; β, the active time fraction of the links corresponding to candidates in $\overrightarrow{I}$; ω, a scalar on the PRR which is used to calculate time fraction β_1 and β_2 in line 7. Initially, $\beta = \omega = 1$. The output of this algorithm is a set of opportunistic forwarding priorities, S, and the corresponding time fraction vector, Γ.

Lines 1 and 2 indicate the basic case where there is only one candidate, then the candidate index and the corresponding time fraction β are returned. When the number of candidates is larger than 1, we first pre-process the rate vector (in lines 4 and 5) such that if there is a rate equal to its corresponding scaled PRR timing the transmission rate or no grater than the scaled effective forwarding rate when the corresponding candidate is assigned the lowest priority, we put this candidate at the first place of the candidate vector. We then split the candidates into two parts, part 1: I_1 and part 2: $[I_2...I_r]$. Next, we calculate the accumulated PRR P_2 of candidates $[I_2...I_r]$. In line 7, we calculate the time fractions β_1 and β_2 corresponding to prioritization $\langle I_1, [I_2...I_r] \rangle$ and $\langle [I_2...I_r], I_1 \rangle$, respectively. Note that $\langle I_1, [I_2...I_r] \rangle$ indicates the candidate I_1 has higher relay priority than the group of candidates $[I_2...I_r]$, and vice versa. Then we recursively call the function PS on I_1 and $[I_2...I_r]$ (in lines 8 to 11). The returned S_{ij} is the set of forwarding strategies when part i is in the j^{th} place ($j = 1, 2$ indicates higher and lower priority, respectively). Then we combine the sequences in S_{11} and S_{22} to get S_1 which are sequences of candidates with I_1 having higher priority than

TABLE II
PSEUDOCODE OF MERGING TWO PRIORITIZED SUB-SETS OF CANDIDATES

```
(S,Γ)=Merge(S1,S2,Γ1,Γ2);
1  S = ∅; Γ = ∅;
2  while (S1 ≠ ∅ || S2 ≠ ∅)
3   push(S,top(S1)|top(S2));
4   if (top(Γ1)>top(Γ2))
5    push(Γ,top(Γ2)); pop(Γ2); pop(S2); top(Γ1)=top(Γ1)−top(Γ2);
6   else if (top(Γ2)>top(Γ1))
7    push(Γ,top(Γ1)); pop(Γ1); pop(S1); top(Γ2)=top(Γ2)−top(Γ1);
8   else
9    push(Γ,top(Γ1)); pop(Γ1); pop(S1); pop(Γ2); pop(S2);
10 end while
11 return(S, Γ);
```

$[I_2...I_r]$ (in line 12). Similarly, we combine S_{21} and S_{12} with group of candidates $[I_2...I_r]$ having higher priority than I_1 (in line 13). Finally, we return the whole series of prioritizations by taking the union of S_1 and S_2.

Next, we explain the Merge algorithm in Table II. We assume both input (S_1, S_2, Γ_1 and Γ_2) and output (S and Γ) are stored in stacks. The basic idea of this Merge algorithm is to concatenate the sequence (corresponding to a prioritization) in the top of S_1 with that in the top of S_2 (in line 3) to create a new sequence (prioritization). The time fraction of this new sequence is the minimum of the time fractions of these two subsequences. After creating a new sequence, we pop the sequence with smaller time fraction, and update the time fraction of the other sequence by subtracting the used time fraction (in lines 5, 7, and 9). When all the sequences in S_1 and S_2 are popped out, a series of new sequences S and the corresponding time fraction vector Γ are returned (in line 11).

The computation complexity of Merge algorithm is $\Theta(|S_1| + |S_2|)$, where $|S_i|$ $(i = 1, 2)$ is the number of sequences in S_i. For S_i with x elements, we have at most $O(2^x)$ and at least $\Omega(1)$ sequences in it. So the complexity of the algorithm PS is $O(2^{r-1})$ in the worst case and $\Omega(r)$ in the best case, where r is the number of forwarding candidates.

1) Correctness of the Heuristic Algorithm: This heuristic algorithm does not guarantee to return a feasible schedule of opportunistic forwarding priorities even when the rate vector is schedulable. When this happens, we need to run the LP in Fig. 3 to get a feasible scheduling. However, we will prove that this heuristic algorithm does return a feasible scheduling for a schedulable rate vector $\overrightarrow{\mu}$ when $r \leq 2$. We will also show numerical results that this heuristic algorithm works well for larger number of forwarding candidates in terms of achieving low unsatisfied rate ratio.

Proposition 5.2: When $r = |\overrightarrow{\mu}|$ is no greater than 2, any rate vector $\overrightarrow{\mu} = [\mu_1, ..., \mu_r]$ in the capacity region defined in Inequality (9) can be satisfied by the scheduling obtained by the heuristic algorithm PS in Table I.

Proof: First, when $r = 1$, it is obvious that any μ_1, s.t. $\mu_1 \leq R_i p_{ii_1}$, is schedulable. Lines 1 and 2 in Table I deal with this case.

Second, when $r = 2$, there are two forwarding priorities: $\mathcal{P}_1 : \mathcal{P}_1(i_1) > \mathcal{P}_1(i_2)$ and $\mathcal{P}_2 : \mathcal{P}_2(i_2) > \mathcal{P}_2(i_1)$. Assuming

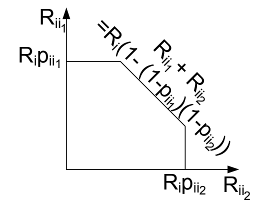


Fig. 4. Capacity region for two forwarding candidates.

the whole transmission period is unit 1, we allocate β_1 and β_2 time fraction for $\mathcal{P}_1$ and $\mathcal{P}_2$, respectively. Then according to Eq. (18), we have

$$R_{ii_1} = R_i(\beta_1 \cdot p_{ii_1} + \beta_2 \cdot p_{ii_1}(1 - p_{ii_2})) \quad (22)$$
$$R_{ii_2} = R_i(\beta_1 \cdot p_{ii_2}(1 - p_{ii_1}) + \beta_2 \cdot p_{ii_2}) \quad (23)$$

Then we only need to prove, for any μ_1 and μ_2, s.t. $0 \leq \mu_1 \leq R_i p_{ii_1}$, $0 \leq \mu_2 \leq R_i p_{ii_2}$, and $\mu_1 + \mu_2 \leq R_i(1 - (1 - p_{ii_1})(1 - p_{ii_2}))$, $\exists$ β_1 and β_2, s.t. $0 \leq \beta_1 \leq 1$, $0 \leq \beta_2 \leq 1$, and $\beta_1 + \beta_2 = 1$, to make $\mu_1 \leq R_{ii_1}$ and $\mu_2 \leq R_{ii_2}$.

With $\mu_2 \leq R_{ii_2}$, $\mu_2 \leq R_i p_{ii_2}$, Eq. (23) and $\beta_1 = 1 - \beta_2$, we have

$$0 \leq \beta_1 \leq \frac{R_i p_{ii_2} - \mu_2}{R_i p_{ii_1} p_{ii_2}} \quad (24)$$

With $\mu_1 \leq R_{ii_1}$, $\mu_1 \leq R_i p_{ii_1}$, Eq. (22) and $\beta_2 = 1 - \beta_1$, we have

$$0 \leq \beta_2 \leq \frac{R_i p_{ii_1} - \mu_1}{R_i p_{ii_1} p_{ii_2}} \quad (25)$$

By satisfying μ_1, we set

$$\beta_2 = \min(\frac{R_i p_{ii_1} - \mu_1}{R_i p_{ii_1} p_{ii_2}}, 1), \;\; \beta_1 = 1 - \beta_2 \quad (26)$$

By substituting Eq. (26) into Eq. (22) and (23), we can verify that $\mu_1 \leq R_{ii_1}$ and $\mu_2 \leq R_{ii_2}$. Note that, the setting of β_1 and β_2 makes inequalities (24) and (25) hold. Eq. (26) exactly corresponds to the first two equations in line 7 in Table I. So we proved the correctness of the heuristic algorithm PS for $r = 2$. ■

The proof of the correctness of the heuristic algorithm also indicates that any rate vector in the capacity region shown in Fig. 4 is schedulable.

2) An Example: We use an example to illustrate how the PS algorithm works. Assume n_i has three forwarding candidates $\{n_{i_1}, n_{i_2}, n_{i_3}\}$, the corresponding rate on each link l_{ii_q} (q=1,2,3) is $0.2R_i$, $0.3R_i$, and $0.46R_i$, and the corresponding PRR on these links are 0.5, 0.6, and 0.8, respectively. Fig. 5 shows the running result of algorithm PS. In the first stage, μ_1 is satisfied, and in the second stage μ_2 is satisfied, then μ_3. The time fraction β of each forwarding priority is listed at the right of the priority.

3) Performance of the Heuristic Algorithm: We conducted numerical simulations to evaluate the performance of the PS algorithm. We propose the metric of **unsatisfied rate ratio** γ to indicate how well the heuristic algorithm can satisfy the rate vector $\overrightarrow{\mu}$.

$$\gamma = \frac{\sum_{q=1}^{r}(\mu_q - R_{ii_q}) I(R_{ii_q} < \mu_q)}{\sum_{q=1}^{r} \mu_q} \quad (27)$$

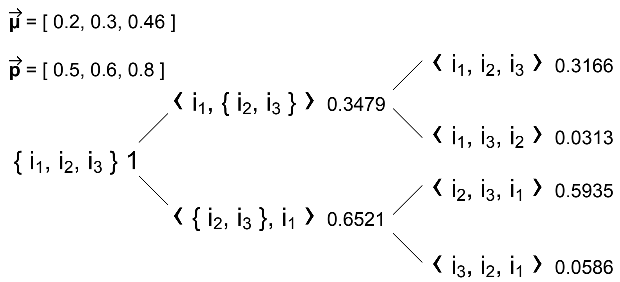


Fig. 5. An example of opportunistic forwarding strategy scheduling for three forwarding candidates.

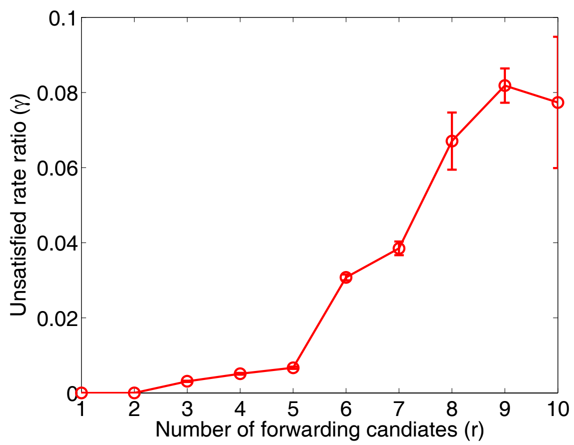


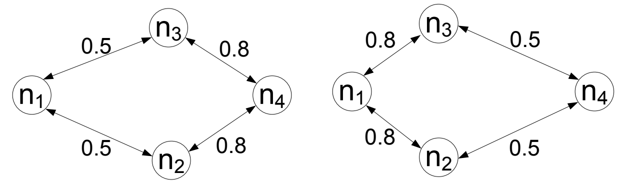
Fig. 6. Unsatisfied rate ratio vs. number of forwarding candidates using PS algorithm for forwarding priority scheduling.

where R_{ii_q} is the accumulated effective rate on link l_{ii_q} defined in Eq. (18) under a scheduling of forwarding priorities, and $I()$ is an indicator function. When the input expression of $I()$ is true, $I() = 1$; otherwise $I() = 0$. According to Eq. (27), $0 \leq \gamma \leq 1$. Smaller γ indicates better performance.

In the simulation, we vary the number of forwarding candidates from 1 to 10. For each number of forwarding candidates, we conducted 10^4 runs. In each run, we randomly assign the PRR on the links in the opportunistic module, and generates a rate vector that reaches the capacity of that opportunistic module. Then we run PS algorithm on the rate vector and opportunistic module, and compute the corresponding γ. Fig. 6 shows the mean of γ with 95% confidence interval under different number of forwarding candidates. We can see that the PS algorithm works well in terms of having low γ. It satisfies the rate vector almost all the time with unsatisfied ratio as low as 0.7% when there are no more than five forwarding candidates. When the number of forwarding candidates increases, γ is increased. However, even when there are 10 forwarding candidates, γ is below 10%.

VI. Performance Evaluation

In this section, we show the results of joint radio-channel assignment, routing, and scheduling for optimizing an end-to-end throughput solved by our methodology for two simple scenarios, and simulation results for more general networks. All the simulations are implemented in Matlab.



(a) PRRs from the source (n_1) to relays (n_2 and n_3) are worse than that from the relays to the destination (n_4)

(b) PRRs from the source (n_1) to relays (n_2 and n_3) are better than that from the relays to the destination (n_4)

Fig. 7. Four-node networks under different channel conditions (link PRRs).

A. Two Scenarios with Different Link Qualities

We consider two four-node network scenarios in Fig. 7 with different link qualities. Suppose each node has one radio which can be operated on two orthogonal channels. The PRR is indicated on each link. For simplicity, we assume the PRR is identical under different channels in each network. We assume each node is in the interference range of each other. So there is only one transmitter can be active on the same channel at any instant in the network. By applying the methodology in Sections IV and V, we solve the joint radio-channel assignment, routing, scheduling problem for maximizing the throughput from n_1 to n_4. We summarize the results for Fig. 7(a) and Fig. 7(b) in Table III. The optimal throughput from n_1 to n_4 for these two scenarios are 0.58 and 0.5, respectively. An interesting observation from Table III is that the opportunistic routing is not used when n_1 is transmitting packets in the scenario of Fig.7(b). Since in Fig. 7(b), the channel conditions from the source to the relays are better than that from the relays to the destination, the maximum throughput is constrained by the bottleneck links from the relays to the destination. So we should allow more concurrent transmissions to saturate the bottleneck links instead of making use of OR to push more flows out of the sender. Differently, when the bottleneck links are between the sender and relays (Fig. 7(a)), OR is used to push more flows out the sender. This observation is expected to provide a guideline on designing distributed radio-channel assignment for OR in multi-radio multi-channel systems.

B. Simulation of Random Networks

In this subsection, we investigate the throughput bound of OR and TR in multi-radio multi-channel systems and compare the results with that in single-radio single-channel systems. We examine both linear topology and rectangle topology. For the linear topology, we uniformly deploy 12 nodes in a line with 300 units of length. For the rectangle topology, we randomly deploy 12 nodes in a rectangle area of 200 units × 300 units. We select node n_1 at the left end (for the linear topology) and left corner (for the rectangle topology) of the networks as the destination, then calculate the throughput bound from other nodes to the destination using the LP formulations in Fig. 2. Therefore, there are 11 different source-destination pairs considered in the evaluation for each topology. In all the simulations, we assume the packet reception ratio is inversely proportional to the distance with Gaussian random

TABLE III
CHANNEL ASSIGNMENT, ROUTING, AND SCHEDULING OF OPPORTUNISTIC FORWARDING STRATEGIES FOR FIG. 7(A) AND FIG. 7(B)

Fig. 7(a)	CTS	$\{(v_1^1, \langle v_2^1, v_3^1\rangle)\}$	$\{(v_1^1, \langle v_3^1, v_2^1\rangle)\}$	$\{(v_1^1, \langle v_2^1\rangle), (v_3^2, \langle v_4^2\rangle)\}$	$\{(v_1^1, \langle v_3^1\rangle), (v_2^2, \langle v_4^2\rangle)\}$
	Time fractions	0.14	0.14	0.36	0.36
Fig. 7(b)	CTS	$\{(v_1^1, \langle v_3^1\rangle), (v_2^2, \langle v_4^2\rangle)\}$	$\{(v_1^1, \langle v_2^1\rangle), (v_3^2, \langle v_4^2\rangle)\}$	$\{(v_2^1, \langle v_4^1\rangle)\}$	$\{(v_3^1, \langle v_4^1\rangle)\}$
	Time fractions	0.354	0.354	0.146	0.146

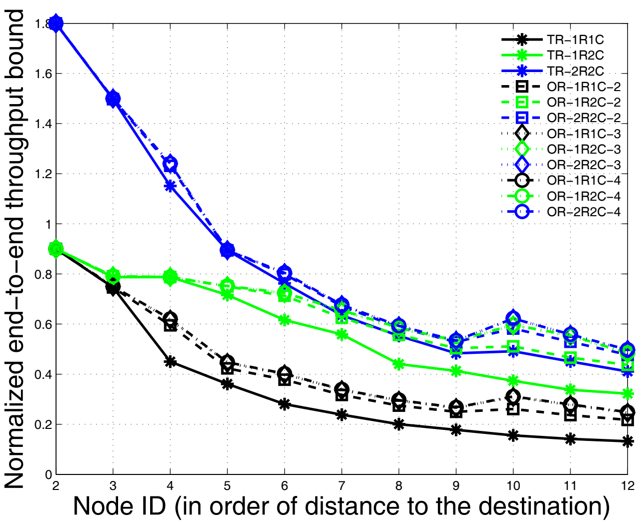


Fig. 8. Normalized end-to-end throughput bound under different number of radios, channels and potential forwarding candidates in linear topology.

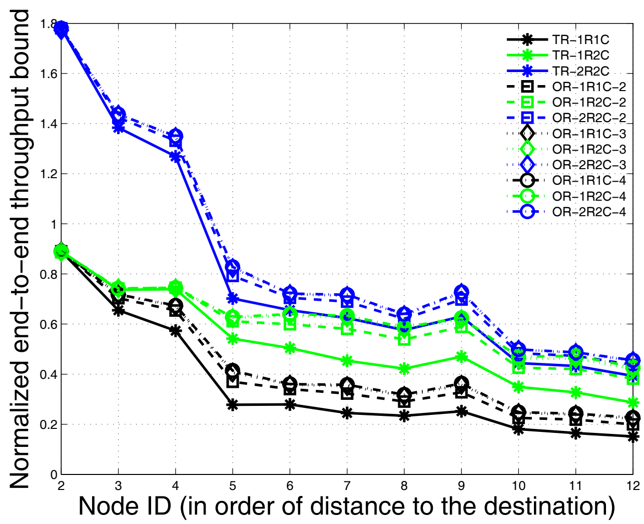


Fig. 9. Normalized end-to-end throughput bound under different number of radios, channels and potential forwarding candidates in rectangle topology.

variation, which simulates the log-normal fading and two-ray path loss model. The transmission range is set as 100 units, and the interference range is set as twice of the transmission range. The performance metric is the normalized end-to-end throughput bound (by assuming the transmission rate is unit one). Note that although the network size is limited at 12 nodes in our simulation due to the exponential complexity of finding all the CTS's, this small network size is sufficient to allow us to gain insight of the opportunistic routing in multi-radio multi-channel networks. According to the simulation settings, the longest path between node 12 and 1 can be 6 hops and 11 hops in the rectangle and linear topologies, respectively. The shortest path between the node 12 and 1 can be 4 hops and 3 hops in the two topologies, respectively. So reasonable multihop network scenarios are simulated.

Figs. 8 and 9 show the simulation result under linear topology and rectangle topology, respectively. In the legend, "TR" represents traditional routing, "OR" represents opportunistic routing, "$xRyC - z$" represents x radios and y channels, with z maximal number of forwarding candidates. That is, in the CTS enumeration, we only consider the opportunistic module that contains at most z number of forwarding candidates. We can see that the performance shows similar trends under both topologies. With the number of radios and channels increasing, the throughput of TR and OR are both increased. Generally OR achieves higher throughput than TR, and the multi-radio/channel capability has greater impact on the throughput of TR than OR. When the source is farther away from the destination, the OR presents more advantage than TR. The opportunistic forwarding by using multiple forwarding candidates do help increase the throughput. An interesting result is that, for nodes 7 to 12, the throughput of 1R2C case for OR is comparable with or even greater than that of 2R2C case for TR. This result indicates that OR can achieve comparable or even better performance as TR by using less radio resource.

Another interesting observation is that the throughput gained decreases as the number of forwarding candidates increases. This result is consistent with that found in [9], [10]. So it is not necessary to involve all the usable receivers of the transmitter into the opportunistic forwarding, and selecting a few "good" forwarding candidates is enough to approach the optimal throughput. This theoretical observation may help us design practical protocols.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a unified framework to compute the throughput bound between two end nodes in multi-radio multi-channel multi-hop wireless networks when OR is available. Our model accurately captures the unique property of OR that throughput can take place from a transmitter to any one of its forwarding candidates at any instant. We also studied the capacity region of an opportunistic module, and proposed an LP approach and a heuristic algorithm to obtain an opportunistic forwarding priority scheduling that satisfies a rate vector. Numerical simulations show that the heuristic algorithm achieves desirable performance under various number of forwarding candidates. It can satisfy the rate vector with unsatisfied rate ratio below 0.7% when there are no more than 5 forwarding candidates. Even when there are

10 forwarding candidates, the unsatisfied rate ratio is below 10%. Our methodology can be used to calculate the end-to-end throughput bound of OR and TR in multi-radio multi-channel multi-hop wireless networks, as well as to study the OR behaviors (such as candidate selection and prioritization). Leveraging our analytical model, we gained the following two insights: 1) OR can achieve better performance than TR under different radio/channel configurations. However, in some scenario (e.g. bottleneck links exist between the sender to relays), TR can be more preferable than OR; 2) OR can achieve comparable or even better performance than TR by using less radio resource. We also confirm that just involving a few "good" forwarding candidates is enough to approach optimal throughput. As for the future work, we are interested in designing practical distributed joint radio-channel assignment and opportunistic routing protocols in multi-radio multi-channel systems based on our theoretical study and observations in this paper.

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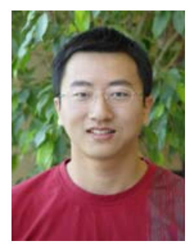

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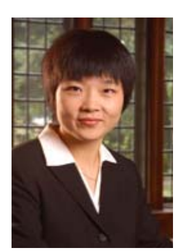

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