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 unreliability of wireless transmissions and co-channel interference. One promising technique that combats lossy wireless transmissions is opportunistic routing (OR). OR involves multiple forwarding candidates to relay packets by taking advantage of the broadcast nature and spacial diversity of the wireless medium. Furthermore, recent advances in multi-radio multi-channel transmission technology allows more concurrent transmissions in the network, and shows the potential of substantially improving the system capacity. However, the performance of OR in multi-radio multi-channel multi-hop networks is still unknown, and the methodology of studying the performance of traditional routing (TR) can not be directly applied to OR. In this paper, we present our research on computing an end-to-end throughput bound of OR in multi-radio multi-channel multi-hop wireless networks. We formulate the capacity of OR as a linear programming (LP) problem which jointly solves the radio-channel assignment and transmission scheduling. Leveraging our analytical model, we gain the following insights into OR: 1) OR can achieve better performance than TR under different radio/channel configurations, however, in particular scenarios, TR is more preferable than OR; 2) OR can achieve comparable or even better performance than TR by using less radio resource; 3) for OR, the throughput gained from increasing the number of potential forwarding candidates becomes marginal.**

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 unreliability of wireless transmissions and co-channel interference. One promising network-MAC cross-layer design to improve the wireless network throughput is opportunistic routing (OR) [1]–[7], 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. It has been shown that OR achieves much higher throughput than TR in multi-hop wireless networks [1], [4], [7]. Furthermore, with the spur of modern wireless technologies, another way to improve 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 [8]–[10].

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When merging these two techniques, an interesting question arises that "what is the end-to-end throughput bound or capacity of OR in multi-radio multi-channel systems?". In this paper, we will propose a methodology to answer this question.

In order to maximize the end-to-end throughput of OR in multi-radio multi-channel multi-hop networks, we should jointly address multiple issues: radio-channel assignment, transmission scheduling, and opportunistic forwarding strategy. In this paper, we carry out a comprehensive study on these issues. We formulate the capacity of OR as a linear programming (LP) problem which jointly solves the radio-channel assignment and transmission scheduling. Leveraging our analytical model, we gain the following insights into OR: 1) OR can achieve better performance than TR under different radio/channel configurations, however, in particular scenarios, TR can be more preferable than OR; 2) OR can achieve comparable or even better performance than TR by using less radio resource; 3) for OR, the throughput gained from increasing the number of potential forwarding candidates becomes marginal.

The rest of this paper is organized as follows. Section II introduces the system model and opportunistic routing. We propose the framework of computing the throughput bounds of OR in multi-radio multi-channel multi-hop networks in Section III. Examples and simulation results are presented and analyzed in Section IV. Conclusions are drawn in Section V.

II. 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. For simplicity, we assume each node n_i transmits at the same data rate R_i among all its radios and channels. We also assume half-duplex on each radio, that is, a radio can not transmit and receive packets at the same time. There is a unified transmission range R_T and interference range R_I for the whole network. Typically, $R_I > R_T$. Two nodes, n_i and n_j, can communicate with each other if the Euclidean distance d_{ij} between them is less than R_T and they are operated on the same channel. Due to

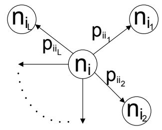


Fig. 1. A transmitter n_i is transmitting a packet, and its one-hop neighbors n_{i_q} $(1 \le q \le L)$ can correctly receive this packet with probability p_{ii_q}.

the unreliability of wireless links, there is a packet reception ratio (PRR) associated with each transmission link. In this paper, we assume that there is no power control scheme, and the link quality on each channel is independent and can be obtained by the existing measurement schemes [11]. 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 [7], [12], [13].

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. We introduce the concept of **opportunistic module** for OR. As illustrated in Fig. 1, it consists of a transmitter (n_i), all of its **one-hop neighbors** $\{n_{i_1}, ..., n_{i_L}\}$ (denoted as $\mathcal{C}_i$), and the corresponding wireless links from the transmitter to the candidates with each link (denoted as l_{ii_q}) associated with a PRR p_{ii_q} $(1 \le q \le L)$. A subset of the one-hop neighbors will be selected as **forwarding candidates**. Only the forwarding candidates will help forward the packet. 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 an ordered set $\mathcal{F}_i$, the **forwarding candidate sequence**, which is one permutation of the forwarding candidates, to represent the forwarding priority. The order of the elements in $\mathcal{F}_i$ corresponds to their priority in relaying a received packet. For example, $\mathcal{F}_i = \langle n_{i_1}, n_{i_2}, ..., n_{i_r} \rangle$ indicates n_{i_1} has the highest forwarding priority, then n_{i_2}, ..., then n_{i_r}. We call the candidate selection and prioritization a **forwarding strategy**. Denote a forwarding strategy as $\mathcal{H} = (\mathbf{\Phi}, \mathcal{P})$, where $\mathbf{\Phi}$ is an indicator function on the one-hop neighbors defined in Eq. (1), and $\mathcal{P}$ is a permutation function of the one-hop neighbors. So $\mathbf{\Phi}$ represents selection of forwarding candidates and $\mathcal{P}$ represents prioritization of forwarding candidates. We denote $\mathcal{P}(i_j) < \mathcal{P}(i_k)$ if n_{i_j} has higher forwarding priority than n_{i_k}. Thus, a specified $\mathcal{H}$ can uniquely decide a forwarding candidate sequence $\mathcal{F}_i$.

$$\mathbf{\Phi}(i_q) := \phi_{i_q} = \begin{cases} 1, & n_{i_q} \text{ is a forwarding candidate;} \\ 0, & \text{otherwise.} \end{cases} \quad (1)$$

The opportunistic routing works by letting the source n_s forward the packet to the receivers in its forwarding candidate sequence $\mathcal{F}_s$. One of the candidate nodes continues the forwarding based on their relay priorities – If the first node in the set has received the packet successfully, it forwards the packet towards the destination while all other nodes suppress themselves from duplicate forwarding. Otherwise, the second node in the set is arranged to forward the packet if it has received the packet correctly. Otherwise the third node, the fourth node, etc. A forwarding candidate will forward the packet only when all the other candidates with higher priorities failed to do so. Existing MAC protocols have been proposed to ensure the relay priority among the candidates. For example, in [1], 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.

III. 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. 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 capacity of OR as an LP problem which jointly solves the radio-channel assignment and transmission scheduling.

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 [12] and concurrent transmission patterns in [10]. 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 [10], [12] 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 the 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 $E = \{l_{ij}^k | i,j = 1...N, i \neq j, k = 1...K\}$.

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

$$\psi_{ij}^{k\alpha} = \begin{cases} 1, & l_{ij}^k \text{ is usable in CTS } T_\alpha; \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

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

$$\eta_i^{k\alpha} = \begin{cases} 1, & v_i^k \text{ is usable in CTS } T_\alpha; \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

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:

$$\eta_i^{k\alpha} = \min(1, \sum_{l_{ij}^k \in E} \psi_{ij}^{k\alpha} + \sum_{l_{ji}^k \in E} \psi_{ji}^{k\alpha}), \forall\ i = 1...N, k = 1...K \quad (4)$$

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

$$\sum_{k=1}^{K} \eta_i^{k\alpha} \leq t_i, \forall\ i = 1...N \quad (5)$$

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

$$\psi_{ij}^{k\alpha} + \psi_{pq}^{k\alpha} \leq 1 + I(l_{ij}^k, l_{pq}^k), \forall\ k = 1...K \quad (6)$$

where

$$I(l_{ij}^k, l_{pq}^k) = \begin{cases} 1, & i == p,\ or\ l_{ij}^k \text{ and } l_{pq}^k \text{ do not interfere;} \\ 0, & \text{otherwise.} \end{cases} \quad (7)$$

According to Eq. (4), (5), and (6), we can construct 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 [14], or column generation technique [10] can be applied to find a subset of all the CTS's to approach the throughput bound. We will not go into detail of the technologies of finding CTS's. Next we discuss which link rate (or rate vector) is supportable by OR in an opportunistic module.

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 [7] 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 one-hop neighbor set $\mathcal{C}_i$, under an OR strategy $\mathcal{H} = (\mathbf{\Phi}, \mathcal{P})$, the effective forwarding rate on link l_{ii_q} is defined in Eq. (8):

$$\widetilde{R}_{ii_q} = R_i \cdot \phi_{i_q} \cdot p_{ii_q} \prod_{\mathcal{P}(i_k) < \mathcal{P}(i_q), n_{i_k} \in \mathcal{C}_i} (1 - \phi_{i_k} \cdot p_{ii_k}) \quad (8)$$

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.

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

$$\widetilde{R}_{i\mathcal{F}_i} = \sum_{n_{i_q} \in \mathcal{F}_i} \widetilde{R}_{ii_q} = R_i \cdot (1 - \prod_{n_{i_q} \in \mathcal{C}_i} (1 - \phi_{i_q} p_{ii_q})) \quad (9)$$

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.

C. Capacity Region of An Opportunistic Module

In this subsection, we study the capacity region of the opportunistic module shown in Fig. 1. 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 [15], we have the capacity region of the outgoing links from a transmitter n_i to its one-hop neighbors indicated in Inequality (10).

$$\sum_{q=1}^{L} \mu_q \cdot \phi_{i_q} \leq R_i (1 - \prod_{q=1}^{L} (1 - p_{ii_q} \phi_{i_q})), \forall\ [\phi_{i_1}, ..., \phi_{i_L}] \in \{0,1\}^L \quad (10)$$

where μ_q $(1 \leq q \leq L)$ the rate from n_i to n_{i_q}.

The physical meaning of Inequality (10) is that any subset summation of the rate vector $\overrightarrow{\mu}$ must be bounded by the effective forwarding rate from the transmitter to the corresponding forwarding candidate set. Now 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. Capacity of OR in Multi-radio Multi-channel Multi-hop Networks

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.

In Fig. 2, $\mu_{ij}^{k\alpha}$ and $\mu_{ii_q}^{k\alpha}$ denote the flow rate on link l_{ij}^k and $l_{ii_q}^k$ in the CTS T_α, respectively. Recall that $\mathbf{E}$ is a set of all the wireless links, and $\mathbf{V}$ is the set of all the transceiver configurations. The maximization states that we

$$Max \sum_{k=1}^{K} \sum_{l_{si}^{k} \in \mathbf{E}} \sum_{\alpha=1}^{M} \mu_{si}^{k\alpha} \tag{11}$$

$$s.t.$$

$$\sum_{k=1}^{K} \sum_{l_{ij}^{k} \in \mathbf{E}} \sum_{\alpha=1}^{M} \mu_{ij}^{k\alpha} = \sum_{k=1}^{K} \sum_{l_{ji}^{k} \in \mathbf{E}} \sum_{\alpha=1}^{M} \mu_{ji}^{k\alpha},$$

$$\forall\ i = 1...N, i \neq s, i \neq d \tag{12}$$

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

$$\sum_{k=1}^{K} \sum_{l_{di}^{k} \in \mathbf{E}} \sum_{\alpha=1}^{M} \mu_{di}^{k\alpha} = 0 \tag{14}$$

$$\mu_{ij}^{k\alpha} \geq 0, \ \ \forall\ k = 1...K, l_{ij}^{k} \in \mathbf{E} \tag{15}$$

$$\sum_{\alpha=1}^{M} \lambda_{\alpha} \leq 1 \tag{16}$$

$$\lambda_{\alpha} \geq 0, \ \forall\ \alpha = 1...M \tag{17}$$

$$\sum_{\mathcal{C}} \mu_{ii_q}^{k\alpha} \cdot \phi_{i_q} \leq \lambda_{\alpha} R_i (1 - \prod_{\mathcal{C}} (1 - p_{ii_q}^{k} \cdot \phi_{i_q})),$$

$$\mathcal{C} = \{n_{i_q} | l_{ii_q}^{k} \in \mathbf{E}, \psi_{ii_q}^{k\alpha} == 1\},$$

$$\forall\ v_i^k \in \mathbf{V},\ \alpha = 1...M, \forall\ \Phi(\mathcal{C}) \in \{0,1\}^{|\mathcal{C}|} \tag{18}$$

Fig. 2. LP formulations to optimize the end-to-end throughput of OR

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 (12) 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 (13) states that the incoming accumulated flow rate to the source node is 0. The constraint (14) indicates that the outgoing accumulated flow rate from the destination node is 0. The constraint (15) restricts the amount of flow rate on each link to be non-negative. The constraint (16) represents that at any time, at most one CTS will be scheduled to be active. The constraint (17) indicates that the scheduled time fraction should be non-negative. In the constraint (18), $\Phi(\mathcal{C})$ is a vector of ϕ_j's with length $|\mathcal{C}|$. The constraint (18) states that the flow rates out of a transmitter in an opportunistic module within a CTS must be in the capacity region discussed in Section III-C. That is, in any CTS, any sub-summation of the flow rates from a transmitter to its usable receivers is bounded by the effective forwarding rate from the transmitter to the corresponding receivers.

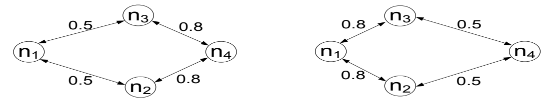
The solution of the objective function (11) is the upper bound of the throughput between two nodes for OR. The byproduct of the LP in Fig. 2 is the radio-channel assignment (CTS's $\{T_\alpha | \alpha = 1...M\}$) and transmission scheduling ($\{\lambda_\alpha | \alpha = 1...M\}$). We also get the flow rate $\mu_{ij}^{k\alpha}$ on each link l_{ij}^{k} in each CTS T_α from the LP.

IV. 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. Two Scenarios with Different Link Qualities

Consider two four-node network scenarios in Fig. 3 with different link qualities. Suppose each node has one radio which



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

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 Section III, 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. 3(a) and Fig. 3(b) in Table I and II, respectively. The optimal throughput from n_1 to n_4 for each figure is 0.58 and 0.5, respectively. An interesting observation in Table II is that the opportunistic routing is not used when n_1 is transmitting packets. Since in Fig. 3(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. 3(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 multi-hop wireless networks.

B. Simulation of Random Networks

In this subsection, we investigate the throughput bound of OR and TR in multi-radio multi-channel multi-hop networks and compare the results with that in single-radio single-channel systems. In the simulation, we randomly deploy 12 nodes in a rectangle area of 200 units $\times$ 300 units. We select node n_1 at the left corner of the network 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. In all the simulations, we assume the packet reception ratio is inversely proportional to the distance with Gaussian random variation, which simulates the log-normal fading and two-ray path loss model. The interference range $R_I = 2R_T$. The transmission range R_T is set as 100 units. The performance metric is the normalized end-to-end throughput bound (by assuming the transmission rate is unit one).

Fig. 4 shows the simulation result. In the legend, "TR" represents traditional routing, "OR" represents opportunist routing, "xRyC-z" represents x radios and y channels, with z maximal number of forwarding candidates. We can see that 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

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

TABLE I

CHANNEL ASSIGNMENT, ROUTING, AND SCHEDULING OF OPPORTUNISTIC FORWARDING STRATEGIES FOR FIG. 3(A).

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

TABLE II

CHANNEL ASSIGNMENT, ROUTING, AND SCHEDULING OF OPPORTUNISTIC FORWARDING STRATEGIES FOR FIG. 3(B).

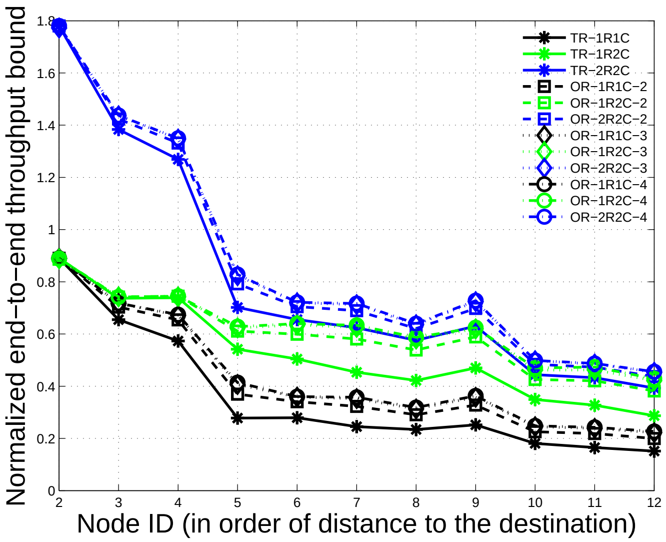


Fig. 4. Normalized end-to-end throughput bound under different number of radios, channels and potential forwarding candidates in rectangle topology.

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 [3], [4]. 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 optimal throughput. This theoretical observation may help us design practical protocols.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we proposed a unified framework to compute the throughput bound of opportunistic routing between two end nodes in multi-radio multi-channel multi-hop wireless networks. 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. 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 insights into OR that 1) OR can achieve better performance than TR under different radio/channel configurations. However, in particular scenarios (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; 3) for OR, the throughput gained from increasing the number of potential forwarding candidates becomes marginal. Just involving a few "good" forwarding candidates is enough to approach optimal throughput. As for the future work, we are interested in designing practical 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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