

On End-to-end Throughput of Opportunistic Routing in Multirate and Multihop Wireless Networks

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Abstract—Routing in multi-hop wireless networks presents a great challenge mainly due to unreliable wireless links and interference among concurrent transmissions. Recently, a new routing paradigm, opportunistic routing (OR), is proposed to cope with the unreliable transmissions by exploiting the broadcast nature and spatial diversity of the wireless medium. Previous studies on OR focused on networks with a single channel rate. The performance of OR in a multi-rate scenario is not carefully studied. In addition, although simulation and practical implementation have shown that OR achieves better throughput performance than that of traditional routing, there is no theoretical results on capacity enhancement provided by OR or network capacity bounds of OR. In this paper, we bridge these gaps by carrying out a comprehensive study on the impacts of multiple rates, interference, candidate selection and prioritization on the maximum end-to-end throughput or capacity of OR. Taking into consideration of wireless interference, we propose a new method of constructing transmission conflict graphs - we propose transmitter based conflict graph in contrast to link conflict graph. Then, we introduce the concept of concurrent transmitter sets to represent the constraints imposed by the transmission conflicts of OR, and formulate the maximum end-to-end throughput problem as a maximum-flow linear programming problem subject to the transmission conflict constraints. We also propose a rate selection scheme, and compare the throughput capacity of multi-rate OR with single-rate ones. We validate the analysis results by simulation, and show that OR has great potential to improve end-to-end throughput and system operating at multi-rates achieves higher throughput than that operating at any single rate.

I. INTRODUCTION

Multihop wireless networks, such as mobile ad hoc networks (MANETs), wireless sensor networks (WSNs), and wireless mesh networks (WMNs), have received increasing attention in the past decade due to the easy deployment at low cost without relying on existing infrastructure and their broad applications, ranging from tactical communication in a battlefield, military sensing and tracking, disaster rescue after an earth quake, to real time traffic monitoring, wildlife monitoring and tracking, last-mile network access, etc.

Routing in multi-hop wireless networks presents a great challenge mainly due to the following facts. First, wireless links are not reliable because of channel fading [1]. Second, achievable channel rates may be different at different links because link quality depends on distance and path loss between

two neighbors. Third, since wireless medium is broadcast in nature, the transmission on one link may interfere with the transmissions on other neighboring links.

Traditional routing protocols for multihop wireless networks have followed the concept of routing in wired networks by abstracting the wireless links as wired links, and find the shortest, least cost, or highest throughput path(s) between a source and destination. However, this abstraction ignores the unique broadcast nature and spacial diversity of the wireless medium. Owing to these wireless natures, when a packet is unicast to a specific next-hop node of the sender at the network layer, all the neighboring nodes in the effective communication range of the sender will overhear the packet at the physical layer. It's likely that some of the neighbors may receive the packet correctly when the specified next-hop node doesn't. Then, a natural and innovative thought is "Can we make use of the successful receptions on these neighboring nodes in stead of retransmitting the packet on the specified link to save precious bandwidth and energy?"

Inspired by this idea, a new routing paradigm, known as opportunistic routing (OR) [2]–[5], has recently been proposed to mitigate the impact of unreliable wireless links by exploiting the broadcast nature and spatial diversity of the wireless medium. 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 on a per-packet basis according to its instantaneous availability and reachability at the time of transmission. As multiple forwarding candidates are involved to help relay the packet, the probability of at least one forwarding candidate correctly receiving the packet increases compared to the traditional routing that includes only one forwarding candidate. The increase of forwarding reliability in one transmission reduces the retransmission cost, which in turn improves the throughput [4]–[6] and energy efficiency [2], [7].

The existing works on OR mainly focused on a single-rate system. Researchers have proposed several candidate selection and prioritization schemes to improve throughput or energy efficiency. However, there is a lack of theoretical

analysis on the performance limit or the throughput bounds achievable by OR. In addition, one of the current trends in wireless communication is to enable devices to operate using multiple transmission rates. For example, many existing wireless networking standards such as IEEE 802.11a/b/g include this multi-rate capability. The inherent rate-distance trade-off of multi-rate transmissions has shown its impact on the throughput performance of traditional routing [8]–[10]. Generally, low-rate communication covers a long transmission range, while high-rate communication must occur at short range. It is intuitive to expect that this rate-distance tradeoff will also affect the throughput of OR. Because different transmission ranges also imply different neighboring node sets, which results in different spacial diversity opportunities. These rate-distance-diversity tradeoffs will no doubt affect the throughput of OR, which deserves a careful study. To the best of our knowledge, there is no existing work addressing the throughput problem of OR in a multi-rate network.

In this paper, we bridge these two gaps by studying the throughput bound of OR and the performance of OR in a multi-rate scenario. First, for OR, we propose the concept of concurrent transmitter sets which captures the transmission conflict constraints of OR. Then, for a given network with given opportunistic routing strategy (i.e., forwarding candidate selection and prioritization), we formulate the maximum end-to-end throughput problem as a maximum-flow linear programming problem subject to the constraints of transmitter conflict. The solution of the optimization problem provides the performance bound of OR. The proposed method establishes a theoretical foundation for the evaluation of the performance of different variants of OR with various forwarding candidate selection, prioritization policies, and transmission rates. We also propose a rate selection scheme, and compare the throughput of multi-rate OR with single-rate OR. Simulation results show that for OR, system operating at multi-rates achieves higher throughput than that operating at any single rate.

The rest of this paper is organized as follows. Section II introduces the system model. We propose the framework of computing the throughput bounds of OR in Section III. Section IV studies the impact of multi-rate capability and forwarding strategy on the throughput of OR, and presents a rate and candidate selection scheme leveraging on node’s location information. Simulation results are presented and analyzed in Section V. Section VI discusses the related work, and conclusions are drawn in Section VII.

II. SYSTEM MODEL

We consider a multi-hop wireless network with N nodes arbitrarily located on a plane. Each node n_i ($1 \leq i \leq N$) can transmit a packet at J different rates R^1, R^2, \dots, R^J . We say there is a **usable** directed link l_{ij} from node n_i to n_j , when the **packet reception ratio** (PRR), denoted as p_{ij} , from n_i to n_j is larger than a non-negligible positive threshold p_{td} . We define the **effective transmission range** L_m at rate R^m as the sender-receiver distance at which the PRR equals p_{td} .

The basic module of opportunistic routing is shown in

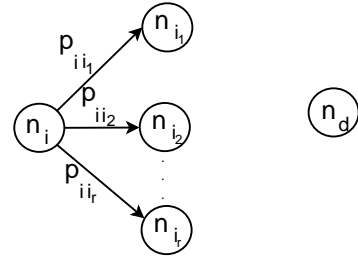


Fig. 1. Node n_i is forwarding a packet to a remote destination n_d with a chosen forwarding candidate set \mathcal{F}_i at some transmission rate.

Fig. 1. Assume node n_i is forwarding a packet to a sink/destination n_d . We denote the set of nodes within the effective transmission range of node n_i as the **neighboring node set** \mathcal{C}_i of node n_i . Note that, for different transmission rates, the corresponding effective transmission ranges are different, then we have different neighboring node sets of node n_i , and the PRR on the same link may be different at different rates. We define the set $\mathcal{F}_i := \langle n_{i_1}, n_{i_2}, \dots, n_{i_r} \rangle$ shown in Fig. 1, as **forwarding candidate set**, which is a subset of \mathcal{C}_i and includes all the nodes selected to be involved in the local opportunistic forwarding based on a particular selection strategy. \mathcal{F}_i is an ordered set, where the order of the elements corresponds to their priority in relaying a received packet.

The opportunistic routing works by the sender node n_s broadcasting the packet to the nodes in its forwarding candidate set \mathcal{F}_s . One of the candidate nodes continues the forwarding based on their relay priority – If the first node in the set has received the packet successfully, it forwards the packet towards the destination while all other nodes suppress 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 message only when all the nodes with higher priorities fail to do so¹. When no forwarding candidate has successfully received the packet, the sender will retransmit the packet if retransmission is enabled. The sender will drop the packet when the number of retransmissions exceeds the limit. The forwarding reiterates until the packet is delivered to the destination.

III. COMPUTING THROUGHPUT BOUND OF OR

The first fundamental issue we want to address is the maximum end-to-end throughput when OR is used. Any traffic load higher than the throughput capacity is not supported and even deteriorates the performance as a result of excessive medium contention. The knowledge of throughput capacity can be used to reject any excessive traffic in the admission control for real-time services. It can also be used to evaluate the performance of different OR variants. Furthermore, the derivation of throughput of OR may suggest novel and efficient candidate selection and prioritization schemes.

¹Several MAC protocols have been proposed in [2], [4], [5] to ensure the relay priority among the candidates.

In this section we present our methodology to compute the throughput bound between two end nodes in a given network with a given OR strategy (i.e., given each node’s forwarding candidate set, node relay priority, and transmission/broadcast rate at each node). We first introduce two concepts, transmitter based conflict graph and concurrent transmitter set, which are used to represent the constraints imposed by the interference among wireless transmissions in a multi-hop wireless network. We then present methods for computing bounds on the optimal throughput that a network can support when OR is used. In this paper, we assume that there is no power control scheme and the link quality²(PRR) is known before link scheduling.

A. Transmission Interference and Conflict

Wireless interference is a key issue affecting throughput. Existing wireless interference models generally fall into two categories: *protocol model* and *physical model* [13]. Under the protocol model, a transmission is considered successful when both of the following conditions hold: 1) The receiver is in the effective transmission range of the transmitter; and 2) No node that is in the carrier sensing range of the receiver is transmitting. This kind of protocol model requires only the receiver to be free of interference. To model an 802.11 like bidirectional communications, we can extend the protocol model by adding the requirement of interference free also at the transmitter side. Under the physical model, for a successful transmission, the aggregate power at the receiver from all other ongoing transmissions plus the noise power must be less than a certain threshold so that the SNR requirement at the ongoing receiver is satisfied. In this paper, we use the term “**usable**” to describe a link when it is able to make a successful transmission based on either the protocol model or the physical model. When two (or more) links are not able to be usable at the same time, they are having a “**conflict**”.

Link conflict graph has been used as a handy tool to model such interference [10], [14]. As shown in Fig. 3(b), in a link conflict graph, each vertex corresponds to a link in the original connectivity graph. There is an edge between two vertices if the corresponding two links may not be active simultaneously due to interference (e.g., having a “conflict”). However, this link-based conflict graph cannot be directly applied to study capacity problem of OR networks because by the nature of opportunistic routing, for one transmission, throughput may take place on multiple links. The throughput dependency among multiple links makes the subsequent maximum-flow optimization problem very difficult (if it is still possible). Therefore, in this paper, we propose a new construction of conflict graph to facilitate the computation of throughput bounds of OR. Instead of creating link conflict graph, we study the conflict relationship by transmitters (or nodes). As shown in Fig. 3(c), in the node conflict graph, each vertex corresponds to a node in the original connectivity graph. Each vertex is associated with a set of links, e.g., the links to its selected forwarding candidates. There is an edge (conflict) between two

²The link quality can be obtained by some measurement schemes [11], [12].

vertices if the two nodes cannot be transmitting simultaneously due to a conflict caused by one or more unusable links as we will define in section III-B.

B. Concurrent Transmitter Sets

We define the concepts of **concurrent transmitter sets (CTS’s)** for OR as follows. These concepts capture the impact of interference of wireless transmissions and OR’s opportunistic nature. They are the foundation of our method of computing the end-to-end throughput.

1) **Conservative CTS:** According to a specific OR policy, when one node is transmitting, the packet is broadcast to all the nodes in its forwarding candidate set. Let’s denote the links from a transmitter to all its forwarding candidates as links *associated* with the transmitter. We define a conservative CTS (CCTS) as a set of transmitters, when all of them are transmitting simultaneously, all links associated with them are still usable. If adding any one more node into a CCTS will result in a non-CCTS, the CCTS is called a maximum CCTS.

The conservative CTS actually requires all the opportunistic receivers to be interference-free for one transmission. This is probably true for certain protocols [5] where RTS/CTS-like mechanism is used to clear certain range within transmitter/receiver or confirm a successful reception. But this is a stricter requirement than necessary and will only give us a lower bound of end-to-end capacity. We define the following greedy CTS to compute the maximum end-to-end throughput.

2) **Greedy CTS:** In order to maximize the throughput, we permit two or more transmitters to transmit at the same time even when some links associated with them become unusable. The idea is to allow a transmitter to transmit as long as it can deliver some throughput to one of the next-hop forwarding candidate(s). Therefore, we define a greedy CTS (GCTS) as a set of transmitters, when all of them are transmitting simultaneously, at least one link associated with each transmitter is usable. If adding any one more node into a GCTS will result in changes in the usability status of any link associated with nodes in that set, the GCTS is called a maximum GCTS.

C. Effective Forwarding Rate

After we find a CTS, we need to identify the capacity on every link associated with a node in the CTS. We introduce the concept of **effective forwarding rate** on each link associated with a transmitter according to a specified OR strategy. Assume node n_i ’s forwarding candidate set $\mathcal{F}_i = \langle n_{i_1}, n_{i_2} \dots n_{i_r} \rangle$, with relay priorities $n_{i_1} > n_{i_2} > \dots > n_{i_r}$. Let ψ_q denote the indicator function on link l_{ii_q} when n_i is in a particular CTS: $\psi_q = 1$ indicating link l_{ii_q} is usable, and $\psi_q = 0$ indicating that link l_{ii_q} is not usable. Then the effective forwarding rate of link l_{ii_q} in that particular CTS is defined in Eq. (1):

$$\tilde{R}_{ii_q} = R_i \cdot \psi_q \cdot p_{ii_q} \prod_{k=0}^{q-1} (1 - \psi_k \cdot p_{ii_k}) \quad (1)$$

where R_i is the broadcast rate of transmitter i , and $p_{ii_0} := 0$.

In a conservative CTS, all the receptions are interference-free. Therefore, in each CCTS, every link associated with a transmitter is usable, i.e. $\psi = 1$, and the effective forwarding rate on each link is non-zero. And the effective forwarding rate for a particular link remains same when the link is in a different CCTS. The effective forwarding rate indicates that according to the relay priority, only when a usable higher forwarding candidates did not receive the packet correctly, a usable lower priority candidate may have a chance to relay the packet if it received the packet correctly. Note that this definition generalizes the effective rate for unicast in traditional routing, that is, when there is only one forwarding candidate, the effective forwarding rate reduces to the unicast effective data rate.

While for the greedy mode, some link(s) associated with one transmitter may become unusable, thus having zero effective forwarding rate. Furthermore, the effective forwarding rate on the links may be different when they are in different GCTS's. To indicate this possible difference, we use $\tilde{R}_{ii_w}^\alpha$ to denote the effective forwarding rate of link l_{ii_w} when it is in the α^{th} GCTS.

D. Lower Bound of End-to-End Throughput of OR

Assume we have found all the maximum CCTS's $\{T_1, T_2 \dots T_M\}$ in the network. At any time, at most one CTS can be scheduled to transmit. When one CTS is scheduled to transmit, all the nodes in that set can transmit simultaneously. Let λ_α denote the time fraction scheduled to CCTS T_α ($1 \leq \alpha \leq M$). Then the maximum throughput problem can be convert to an optimal scheduling problem that schedules the transmission of the maximum CTS's to maximize the end-to-end throughput. Therefore, considering communication between a single source, n_s , and a single destination, n_d , with opportunistic routing, we formulate the maximum achievable throughput problem between the source and the destination as a linear programming corresponding to a maximum-flow problem under additional constraints in Fig. 2:

In Fig. 2, f_{ij} denotes the amount of flow on link l_{ij} , \mathbf{E} is a set of all links in the connected graph G , and \mathbf{V} is the set of all nodes. The maximization states that we wish to maximize the sum of flow out of the source. The constraint (2) represents flow-conservation, i.e., at each node, except the source and the destination, the amount of incoming flow is equal to the amount of outgoing flow. The constraint (3) states that the incoming flow to the source node is 0. The constraint (4) indicates that the outgoing flow from the destination node is 0. The constraint (5) restricts the amount of flow on each link to be non-negative. The constraint (6) says there is no flow from the node to the neighboring nodes that are not selected as the forwarding candidates of it. The constraint (7) represents at any time, at most one CTS will be scheduled to transmit. The constraint (8) indicates the scheduled time fraction should be non-negative. The constraint (9) states the actual flow delivered on each link is constrained by the total amount of flow that can be delivered in all activity periods of this link.

The key difference of our maximum flow formulations from

$$\begin{aligned}
 & \text{Max} \sum_{l_{si} \in \mathbf{E}} f_{si} \\
 & \quad \text{s.t.} \\
 & \sum_{l_{ij} \in \mathbf{E}} f_{ij} = \sum_{l_{ji} \in \mathbf{E}} f_{ji} \quad \forall n_i \in \mathbf{V} - \{n_s, n_d\} \quad (2) \\
 & \sum_{l_{is} \in \mathbf{E}} f_{is} = 0 \quad (3) \\
 & \sum_{l_{di} \in \mathbf{E}} f_{di} = 0 \quad (4) \\
 & f_{ij} \geq 0 \quad \forall l_{ij} \in \mathbf{E} \quad (5) \\
 & f_{ij} = 0 \quad \forall l_{ij} \in \mathbf{E}, n_j \notin \mathcal{F}_i \quad (6) \\
 & \sum_{\alpha=1}^M \lambda_\alpha \leq 1 \quad (7) \\
 & \lambda_\alpha \geq 0, 1 \leq \alpha \leq M \quad (8) \\
 & f_{ij} \leq \sum_{n_i \in T_\alpha, n_j \in \mathcal{F}_i, 1 \leq \alpha \leq M} \lambda_\alpha \tilde{R}_{ij}^\alpha \quad \forall l_{ij} \in \mathbf{E} \quad (9)
 \end{aligned}$$

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

the formulations for traditional routing in [10], [14] lies in the methodology we use to schedule concurrent transmissions. With the construction of concurrent transmitter sets, we are able to schedule the transmissions based on node set rather than link set in traditional routing. When we schedule a transmitter, we effectively schedule the links from the transmitter to its forwarding candidates at the same time according to OR strategy. While for traditional routing, any two links share the same transmitter can not be scheduled simultaneously. When a packet is not correctly received by the intended sender but opportunistically received by some neighboring nodes of the sender, traditional routing will retransmit that packet in stead of making use of the correct receptions on some other links. OR takes advantage of the correct receptions. That's why OR achieves higher throughput than traditional routing. Our proposed model accurately captures OR's capability of delivering throughput opportunistically.

A Simple Example: Next, we give an example to show how our formulation helps us to find the end-to-end throughput bound of OR, and we compare this result with the maximum throughput derived from multipath traditional routing based on results in [14].

For simplicity, in the four node network shown in Fig. 3(a), we assume each node transmits at the same rate R , and each link is associated with a PRR indicated in the pair on each link. Assume every node is in the carrier sensing range of any other nodes. We are going to find the maximum end-to-end throughput from node a to d for traditional routing and OR.

For traditional routing, we first construct the link conflict graph as shown in Fig. 3(b). In the conflict graph, each vertex corresponds to each link in the original connectivity graph. There is an edge between two vertices when these two links conflict with each other. According to the protocol model,

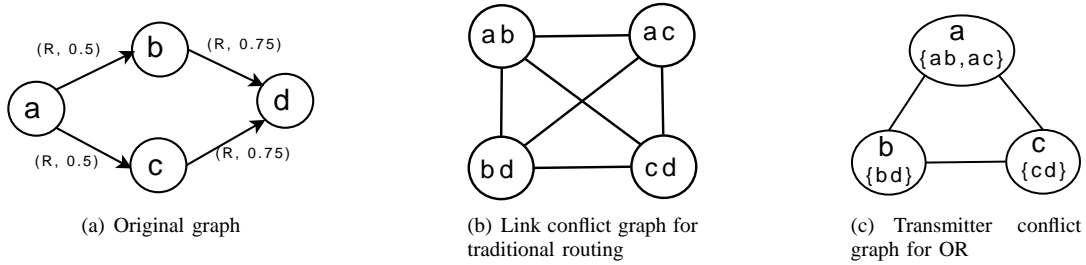


Fig. 3. Conflict Graph

any two links cannot be scheduled simultaneously. So the link conflict graph for traditional routing is a complete graph (clique). There are four independent sets each containing one node in the conflict graph. Each independent set corresponds to one concurrent schedulable link set. By running the linear programming formulations in [14], we can find an optimal schedule on links to maximize the throughput. Assuming the whole communication period is τ , one feasible solution is assigning $\frac{3}{10}\tau$, $\frac{3}{10}\tau$, $\frac{2}{10}\tau$, $\frac{2}{10}\tau$ to l_{ab} , l_{ac} , l_{bd} , l_{cd} , respectively. So the maximum end-to-end throughput between a and d is $\frac{2(\frac{3}{10}\tau \cdot R \cdot 0.5)}{\tau} = \frac{3}{10}R$ for the traditional routing.

For OR, we construct the node conflict graph. Assume a chooses nodes b and c as its forwarding candidates, and b and c 's forwarding candidate is just the destination d . According to the protocol model, the node conflict graph is constructed in Fig. 3(c), which only contains three vertices and is also a clique. So the three conservative transmitter sets are $T_1 = \{a\}$, $T_2 = \{b\}$, and $T_3 = \{c\}$. Assume node b has higher relay priority than node c , then we have $\tilde{R}_{ab}^1 = 0.5R$, $\tilde{R}_{ac}^1 = 0.25R$, and $\tilde{R}_{bd}^2 = \tilde{R}_{cd}^3 = 0.75R$. By running the linear programming formulated in Fig. 2, we get an optimal schedule that assigns $\frac{1}{2}\tau$, $\frac{1}{3}\tau$ and $\frac{1}{6}\tau$, to nodes a , b and c respectively. So the throughput of OR under this optimal schedule is $\frac{\frac{1}{2}\tau(0.5R+0.25R)}{\tau} = \frac{3}{8}R$, which is 25% higher than that of the traditional routing.

E. Maximum End-to-end Throughput of OR

The throughput bound we find based on the maximum conservative CTS's in section III-D is a lower bound of maximum end-to-end throughput. The CCTS's can be constructed based on either the protocol model or the physical model. However, the interference freedom at every intended receiver is a stricter requirement than necessary. It may be applicable under some protocol scenario but it fails to take full advantage of opportunistic nature of OR, because it excludes the situations where concurrent transmission is able to deliver throughput on some of the links even though some other links are having conflicts. In order to compute the exact capacity, we apply the same optimization technique to the greedy CTS's. Since greedy CTS's include all the possible concurrent transmission scenarios that generate non-zero throughput, the bound found by the optimization technique based on all greedy CTS's will

be the maximum end-to-end throughput of OR.

Similar to the construction of CCTS's, GCTS's can be constructed based on either the protocol model or the physical model. Under the protocol model, the conflict between two links is binary, either conflict or no conflict. It is not difficult to construct the GCST's under the protocol model with the proposed node conflict graph. On the other hand, it is well known that the physical model captures the interference property more accurately. However, it is more complicated to represent the interference when multiple transmitters are active at the same time. In this section, we discuss the construction of GCTS's based on the physical interference model.

Under the physical interference model, a link l_{ij} , from node n_i to n_j , is usable if and only if the signal to noise ratio at receiver n_j is no less than a certain threshold, e.g., $\frac{Pr_{ij}}{P_N} \geq SNR_{th}$, where Pr_{ij} is the average signal power received at n_j from n_i 's transmission, P_N is the interference+noise power, and SNR_{th} is the SNR threshold, under which the packet can not be correctly received and above which the packet can be received at least with probability p_{td} . Note that, SNR_{th} is different for different data rates.

Under the physical model, the interference gradually increases as the number of concurrent transmitters increases, and becomes intolerable when the interference+noise level reaches a threshold. We define a weight function w_{ijq} , to capture the impact of a transmitter n_i 's transmission on a link l_{jjq} 's reception. Link l_{jjq} represents the data forwarding from node n_j to one of its forwarding candidates n_{jq} .

$$w_{ijq} = \frac{Pr_{ijq}}{\frac{Pr_{jjq}}{SNR_{th}} - P_{noise}} \quad (10)$$

where Pr_{ijq} and Pr_{jjq} are the received power at node n_{jq} from the transmissions of nodes n_i and n_j , respectively, P_{noise} is the ambient noise power, and $\frac{Pr_{jjq}}{SNR_{th}} - P_{noise}$ is the maximum allowable interference at node n_{jq} for keeping link l_{jjq} usable.

Then given a transmitter set S and $n_j \in S$, a link l_{jjq} is usable if and only if $\sum_{n_i \in S, i \neq j} w_{ijq} < 1$. It means that link l_{jjq} is usable even when all the transmitters in set S are simultaneously transmitting. For conservative mode, if this condition is true for every link associated with each transmitter in S , this set S is a CCTS. For greedy mode, if this condition

is true for at least one link associated with each transmitter in S , the set S is a GCTS.

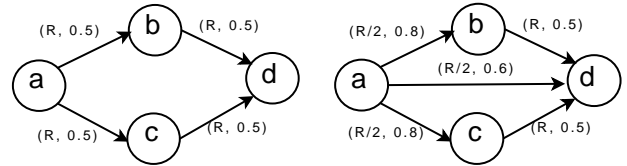
After finding all the GCTS's, we can apply the same optimization technique to the maximum flow problem based on all the GCTS's. The result is the exact bound of maximum end-to-end throughput.

When each node has only one forwarding candidate, OR degenerates to the traditional routing. Therefore, finding all the concurrent transmitter sets is at least as hard as the NP-hard problem of finding the independent sets in [10], [14] for traditional routing. Although it is a NP-hard problem, some brute-force algorithm can finish in a reasonable time when the network scale is not large. In addition, complexity can be further reduced by taking into consideration that interferences/conflicts always happen for nodes within certain range. Due to the space limitation, we will not elaborate on this in this paper.

IV. IMPACT OF TRANSMISSION RATE AND FORWARDING STRATEGY ON THROUGHPUT

The impact of the transmission rate on the throughput of OR is twofold. On the one hand, different rates have different transmission ranges, which lead to different neighborhood diversity. High-rate usually has short transmission range. In one hop, there are few neighbors around the sender, which presents low neighborhood diversity. Low-rate is likely to have long transmission range, therefore achieves high neighborhood diversity. From the diversity point of view, low rate may be better. On the other hand, although low rate brings the benefit of larger one-hop distance which results in higher neighborhood diversity and fewer hop counts to reach the destination, it may still end up with a low effective end-to-end throughput because the low rate disadvantage may overwhelm all other benefits. It is nontrivial to decide which rate is indeed better.

We now use a simple example in Fig. 4 to illustrate transmitting at lower rate may achieve higher throughput than transmitting at higher rate for OR. In this example, we assume all the nodes operate on a common channel, but each node can transmit at two different rates R and $R/2$. We compare the throughput from source a to destination d when the source transmits the packets at the two different rates. Fig. 4(a) shows the case when all the nodes transmit at rate R , and the packet delivery ratio on each link is 0.5. So the effective data rate on each link is $0.5R$. There is no link from a to d because d is out of a 's effective transmission range when a operates on rate R . Assume the four nodes are in the carrier sensing range of each other, so they can not transmit at the same time. Assuming b and c are the forwarding candidates of a , and b has higher relay priority than c . Then link l_{ac} has effective forwarding rate of $0.25R$. By using the formulations in Fig. 2, we obtain an optimal transmitter schedule such that a , b and c are scheduled to transmit for a fraction of time 0.4, 0.4 and 0.2, respectively. So the maximum end-to-end throughput from a to d is $0.3R$. While in Fig. 4(b), when a is transmitting at a lower rate $R/2$, it can reach d directly with packet delivery ratio of



(a) Source broadcasts at rate R (b) Source broadcasts at rate $R/2$

Fig. 4. End-to-end throughput comparison at different transmission rates

0.6, also we get higher packet deliver ratio from a to b and c as 0.8. Then in this case, lower rate achieves longer effective transmission range and brings more spacial diversity chances. Assume d , b , and c are forwarding candidates of a , and with priority $d > b > c$. Similarly, we calculate the maximum throughput from a to d as $0.36R$, which is 20% higher than the scenario in Fig. 4(a) where system operates on a single rate.

Besides the inherent rate-distance, rate-diversity and rate-hop tradeoffs which affect the throughput of OR, the forwarding strategy will also have an impact on the throughput [6]. How to select the transmission rates and forwarding strategy for each node such that the network capacity can be globally optimized is still an open research issue. Towards the development of distributed and localized OR protocol that maximize the capacity, in this section, we examine the impact of transmission rate, candidate selection, prioritization, and coordination on the throughput of OR on a per-hop basis. We propose a localized rate selection algorithm that finds local optimal transmission rate and forwarding candidate set.

A local metric: Expected Advancement Rate The location information is available to the nodes in many applications of multihop wireless networks, such as sensor networks for monitoring and tracking purposes [2] and vehicular networks [5]. Geographic opportunistic routing (GOR) [2], [5]–[7] has been proposed as an efficient routing scheme in such networks. In GOR, nodes are aware of the location of itself, its one-hop neighbors, and the destination. A packet is forwarded to neighbor nodes that are geographically closer to the destination. In [7], we have proposed a local metric, *expected packet advancement (EPA)* for GOR to achieve efficient packet forwarding. EPA for GOR is a generalization of EPA for traditional routing [15], [16]. It represents the expected packet advancement achieved by opportunistic routing in one transmission without considering the transmission rate. In this paper, we extend it into a bandwidth adjusted metric, *expected advancement rate (EAR)*, by taking into consideration of various transmission rates.

Given a transmitter n_i , one of its forwarding candidates n_{i_q} , and the destination n_d , we define the **packet advancement** a_{i_q} in Eq. (11), which is the Euclidian distance between the transmitter and destination subtracting the Euclidian distance between the candidate n_{i_q} and the destination.

$$a_{i_q} = \text{dist}(n_i, n_d) - \text{dist}(n_{i_q}, n_d) \quad (11)$$

This definition represents the advancement in distance made

toward the destination when n_{i_q} forwards the packet sent by n_i . Then we define the EAR as follows.

$$EAR_{n_i}^{\mathcal{F}_i} = R_i \sum_{q=1}^r a_{ii_q} p_{ii_q} \prod_{k=0}^{q-1} (1 - p_{ii_k}) \quad (12)$$

The physical meaning of EAR is the *expected bit advancement per second* towards the destination when the packet is forwarded according to the opportunistic routing procedure introduced in section II.

The definition of EAR is very similar to that of EPA except that EPA does not have the term R_i . According to the proved relay priority rule for EPA [7], we have the following theorem for EAR:

Theorem 4.1: (Relay priority rule) For a given transmission rate at n_i and \mathcal{F}_i , the maximum EAR can only be achieved by giving the candidates closer to the destination higher relay priorities.

This Theorem indicates how to prioritize the forwarding candidates when a transmission rate and the forwarding candidate set are given. From the definition of EAR, it is also not difficult to find that adding more neighboring nodes with positive advancement into the existing forwarding candidate set will lead to a larger EAR. Therefore, we conclude that *an OR strategy that includes all the neighboring nodes with positive advancement into the forwarding candidate set and gives candidates with larger advancement higher relay priorities will lead to the maximum EAR* for a given rate.

Then a straightforward way to find the best rate is: for node n_i , at each transmission rate R^m ($1 \leq m \leq J$), we calculate the largest EAR according to the above conclusion, then we pick the rate that yields maximum EAR. This would be the local optimal transmission rate and the corresponding forwarding candidate set. Note that for a node n_i , it is possible that no neighboring nodes are closer to the destination than itself. In this case we need some mechanism like face routing [17] to contour the packet around the void. However, solving the communication voids problem is out of the scope of this paper.

Note that the above discussion does not take into consideration of protocol overhead. As we have shown in [6], [7], including as many as possible nodes might not be the optimal strategy when overheads, such as the time used to coordinate the relay contention at MAC layer, are taken into consideration. However, in this paper, since our objective is to study the performance bound and capacity limit, we assume the existence of a somewhat idealistic scheduling mechanism which encounters zero protocol overhead. This is a very useful and commonly used assumption for such theoretical study.

V. PERFORMANCE EVALUATION

In this section, we use Matlab to investigate the performance of two OR variants: ExOR [4] and GOR in both conservative and greedy modes, and compare their end-to-end throughput with that of traditional single and multipath routing. We also evaluate the end-to-end throughput of GOR in single rate and multi-rate scenarios. For ExOR [4], each transmitter selects the

neighbors with lower ETX (Estimated Transmission count) to the destination than itself as the forwarding candidates, and neighbors with lower ETX have higher relay priorities. For GOR, the forwarding candidates of a transmitter are those neighbors that are closer to the destination, and candidates with larger advancement to the destination have higher relay priorities. The EAR metric proposed in section IV is used to select the transmission rate for each node in the multi-rate scenario.

A. Simulation Setup

The simulated network has 36 stationary nodes uniformly distributed in a $900m \times 900m$ square region. The data rates 18, 11, and 6 Mbps are studied, and their effective transmission radii are 183, 304 and 396m [18], respectively. The PRR threshold p_{td} is set to 0.1. We assume the PRR is inversely proportional to the distance with random gaussian deviation of 0.1. As discussed in [9], 802.11 systems have very close interference ranges and the optimum carrier sensing ranges for different channel rates, so we use a single interference range 500m for all channel rates for simplicity. We fix the node nearest to the lower left corner as the destination, and find the paths from all other nodes to it. Therefore, there are 35 different source-destination pairs considered in the evaluation. The performance metric is the end-to-end throughput.

B. Throughput Bounds of OR and Traditional Routing

Fig. 5 shows the simulation results of ExOR, GOR and traditional routing in a single rate (11Mbps) system. For traditional routing, we compute the exact end-to-end throughput bound between the source-destination pairs according to the LP formulations in [14], which normally result in multiple paths from the source to the destination. So we call it “multipath traditional routing”. We also compute the end-to-end throughput of a single path that is found by minimizing the medium time (delay), and we call it “single path traditional routing”. The bound of single path traditional routing is calculated according to the formulations in [10]. For the two OR variants, we compute the throughput bounds under both conservative and greedy modes as we discussed in Section III-B.

From Fig. 5, we can observe that both ExOR and GOR achieve much higher end-to-end throughput than traditional routing, especially when source and destination are separated by several hops. The key difference of OR from traditional routing is that, by allowing multiple nodes to opportunistically forward a packet, the medium time utility is improved, thus the throughput is enhanced. We can see that the throughput of OR almost doubles that of traditional routing. Fig. 5 also indicates that when source-destination distance is far, greedy modes result in higher end-to-end throughput than conservative modes, while when the source-destination distance is short, they represent nearly the same performance due to severe interference between transmitters. Greedy mode makes the most use of any chance to deliver a packet to the next hop.

Fig. 5 also presents two interesting results. One is that GOR performs as well as ExOR, and even better for some

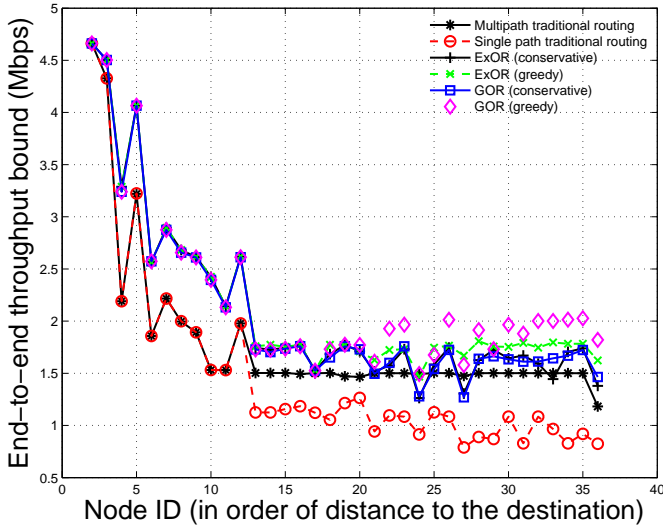


Fig. 5. End-to-end throughput bound of OR and traditional routing in a single rate (11Mbps) network

node pairs. This validates that the per-hop greedy behavior (maximizing the EPA) of GOR is a good routing metric which approaches global optimality. The other is that the throughput bound of multipath traditional routing is nearly the same as the single path routing when the distance between the source and destination is short. This indicates that multipath traditional routing does not really help to improve the wireless network throughput when the source-destination distance is short (less than 3 hops). This is because, even when there are multiple paths between nodes, we still can not schedule the links in different paths at the same time due to interference among transmissions. For wireless traditional routing, one sender can not concurrently transmit different packets to different neighboring nodes. Thus the maximum achievable outgoing capacity of one node is upper bounded by the highest capacity of a single outgoing link. However, OR can achieve higher throughput than traditional routing even when the link interference is high. Because for OR, throughput can virtually take place concurrently on multiple outgoing links of the same sender, thus making real use of multipath.

We also observe that when the distance between the source and destination is larger, multipath traditional routing performs better than single path one by making use of some non-interference links. However its throughput is still lower than that of OR, especially when OR is in greedy mode.

C. Multi-Rate vs. Single Rate

In this subsection, we illustrate that by allowing multiple rates at each nodes, and using our EAR metric to select rate and forwarding candidates, GOR can achieve higher throughput than using any single rate. For single rate scenario, 18, 11 or 6Mbps is allowed, and for multi-rate scenario, each node locally chooses the rate that maximizes the EAR defined in Eq. (12). All the capacities are calculated under the greedy mode.

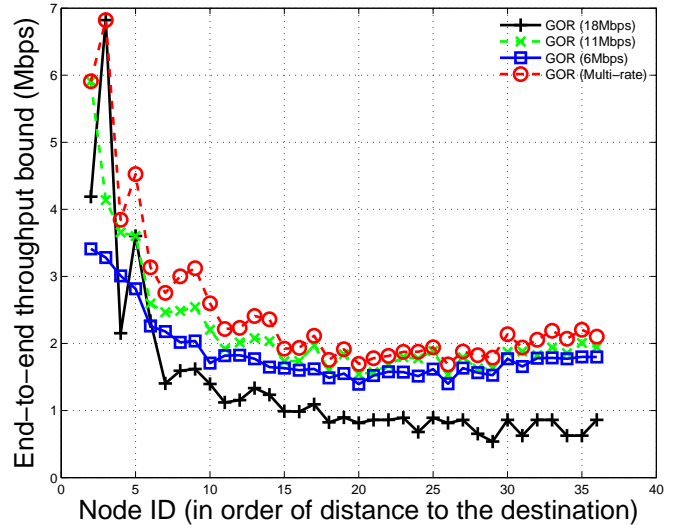


Fig. 6. End-to-end throughput bound of GOR for single and multi-rate networks

Fig. 6 shows that GOR operating on multi-rates performs better than operating on any single rate. The proposed local metric EAR appears to be a good metric. Another interesting result is that system operating at 18Mbps shows lower throughput capacity compared to those operating at 11Mbps and 6Mbps in this scenario. It indicates that the disadvantage of short transmission range and lower spacial diversity of 18Mbps overwhelms its higher data rate advantage.

VI. RELATED WORK

A. Capacity of Multi-hop Wireless Networks

The theoretical capacity study on multi-hop wireless networks mainly focuses on two directions. One is on the asymptotic bounds of the network capacity [13], [19]. These works study the capacity trend with regard to the size of a wireless network under specific assumptions or scenarios. Another direction on wireless network capacity is to compute the exact performance bounds for a given network. 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 [14]. Zhai and Fang studied the path capacity of traditional routing in a multi-rate scenario [10]. Our work falls into this direction. However, distinguished from the previous works, we propose a method to compute the end-to-end throughput bounds of opportunistic routing, which is much different from the traditional routing in that we construct the transmitter conflict graph instead of link conflict graph to capture the local broadcast nature of OR. Our framework can be used as a tool to calculate the end-to-end throughput bound of different OR variants, and is an important theoretical foundation for the performance study of OR.

B. Opportunistic Routing

Opportunistic routing exploits the spacial diversity of the wireless medium by involving a set of forwarding candidates

instead of only one in traditional routing, then improves the reliability and efficiency of packet relay. Some variants of opportunistic routing, such as ExOR [4] and opportunistic any-path forwarding [20], relying on the path cost information or global knowledge of the network to select candidates and prioritize them. In the least-cost opportunistic routing (LCOR) [21], it needs to enumerate all the neighboring node combinations to get the least cost OR paths. Some other variants of OR [2], [3], [5] use the location information of nodes to define the candidate set and relay priority. In GeRaF [2], 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 [2], in [3], 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. [5] discussed three suppression strategies of contention-based forwarding to avoid packet duplication in mobile ad hoc networks. However, there is no theoretical work on determining the end-to-end throughput bounds of OR.

C. Multi-rate Routing

Multirate wireless network has started attracting research attention recently. In [22], Draves, Padhye and Zill proposed to use the weighted cumulative expected transmission time (WCETT) as a routing metric. In [8], Awerbuch, Holmer and Rubens adopted the medium time metric (MTM). In [9], Zhai and Fang studied the impact of multirate on carrier sensing range and spatial reuse ratio and demonstrated that the bandwidth distance product and the end-to-end transmission delay (the same as the medium time) are better routing metrics than the hop count. They also proposed the metric of interference clique transmission time to achieve a high path throughput in [10].

However, these metrics or protocols are proposed for routing on a fixed path following the concept of the traditional routing. There is no metric proposed for multi-rate opportunistic routing. The rate-distance-diversity impact on the throughput of opportunistic routing is not well studied.

VII. CONCLUSION

In this paper, we studied the impact of multiple rates, interference, candidate selection and prioritization on the maximum end-to-end throughput of OR. Taking into consideration of wireless interference, we proposed a new method of constructing transmission conflict graphs, and presented a methodology for computing the end-to-end throughput bounds (capacity) of OR. We formulate the maximum end-to-end throughput problem of OR as a maximum-flow linear programming problem subject to the transmission conflict constraints. To the best of our knowledge, this is the first theoretical work on capacity problem of OR for multihop and multirate wireless networks. We also proposed a local metric, *expected advancement rate*, and a local rate and candidate selection scheme. We validate the analysis results by simulation, and show that OR has great potential to improve end-to-end throughput, and system

operating at multi-rates achieves higher throughput than that operating at any single rate for OR.

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