Location-Aided Opportunistic Forwarding in Multirate and Multihop Wireless Networks

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***Abstract*—Routing in multihop wireless networks is challenging, mainly due to unreliable wireless links/channels. Geographic opportunistic routing (GOR) was proposed to cope with the unreliable transmissions by exploiting the broadcast nature of the wireless medium and the spatial diversity of the network topology. Previous studies on GOR have focused on networks with a single channel rate. The capability of supporting multiple channel rates, which is common in current wireless systems, has not carefully been studied for GOR. In this paper, we carry out a study on the impacts of multiple rates, as well as candidate selection, prioritization, and coordination, on the performance of GOR. We propose a new local metric, i.e., the opportunistic effective one-hop throughput (OEOT), to characterize the tradeoff between one-hop packet advancement and packet forwarding time. We further propose a local rate adaptation and candidate-selection algorithm to approach the optimum of this metric. The simulation results show that the multirate GOR (MGOR) incorporating the rate adaptation and candidate-selection algorithm achieves higher throughput and lower delay than the corresponding single-rate and multirate traditional geographic routing and single-rate opportunistic routing protocols.**

***Index Terms*—Geographic routing (GR), multihop wireless networks, multirate, opportunistic routing, throughput.**

I. Introduction

MULTIHOP wireless networks have attracted a lot of research interest in recent years since they can easily be deployed at low cost without relying on the existing infrastructure. Routing in such networks is very challenging mainly due to variable and unreliable wireless channel conditions [1].

Traditional routing schemes for multihop wireless networks have followed the concept of routing in wired networks by abstracting the wireless links as wired links and finding the shortest path between a source and a destination. However, the traditional shortest-path approach is not ideal for a wireless environment because fluctuations in the quality of any link along the predetermined path can cause excessive retransmissions at the link layer or reroutings at the network layer, thus consuming precious network resources such as bandwidth and energy.

Recently, a new routing paradigm, which is known as opportunistic routing (OR) [2]–[5], has been proposed to mitigate the impact of link quality variations by exploiting the broadcast nature of the wireless medium and the spatial diversity of the network topology. The general idea behind these schemes is that, for each destination, a set of next-hop forwarding candidates is 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 availability and reachability after the transmission. As more forwarding candidates are involved in helping relay the packet, the probability of at least one forwarding candidate having correctly received the packet increases, which results in higher forwarding reliability and lower retransmission cost. Some variants of opportunistic routing schemes [2], [6], [7] use the nodes' location information to define the forwarding candidate set and prioritize candidates. In this paper, we mainly focus on this kind of opportunistic routing by assuming that the nodes' location information is available.

Two important issues in opportunistic routing are candidate selection and relay priority assignment. The existing works on opportunistic routing typically address these issues in the network with a single channel rate. However, one of the current trends in wireless communication is to enable devices to operate on multiple transmission rates. For example, many existing wireless networking standards such as IEEE 802.11a/b/g include this multirate capability. Such multirate capability has shown its impact on the path throughput in multihop wireless networks [8]–[11]. There is an inherent tradeoff between transmission rate and effective transmission range. That is, low-rate communication usually covers a long transmission range, whereas high-rate communication must occur at a short range. This rate–distance tradeoff would also have an impact on the throughput performance of opportunistic routing because different rates imply different transmission ranges, which result in different one-hop neighbor sets, thus leading to a different level of exploitable spatial diversity.

In this paper, we carry out a comprehensive study on multirate, candidate selection, prioritization, and coordination, and examine their impacts on the performance of geographic opportunistic routing (GOR). Based on our analysis, we propose a new local metric, i.e., the *opportunistic effective one-hop throughput* (OEOT), to characterize the tradeoff between one-hop packet advancement and packet forwarding time under different data rates. We further propose a rate adaptation and candidate-selection algorithm to approach the local optimum of this metric. The simulation results show that the multirate GOR (MGOR) incorporating the rate adaptation and candidate-selection algorithm achieves higher throughput and lower delay than the corresponding single-rate and multirate traditional geographic routing (GR) and single-rate opportunistic routing protocols.

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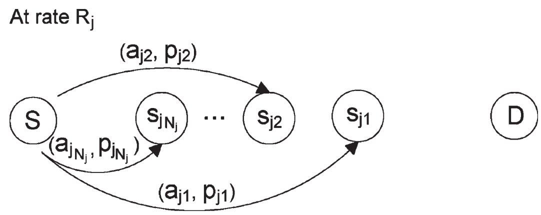

Fig. 1. Node S is forwarding a packet to a remote destination D with transmission rate R_j.

The rest of this paper is organized as follows. Section II introduces the system model. We discuss the impacts of multirate capability, forwarding strategy, and candidate coordination on the performance of opportunistic routing in Section III. The local metric is introduced in Section IV. We propose the heuristic algorithm in Section V. The simulation results are presented and analyzed in Section VI. Section VII discusses the related work, and conclusions are drawn in Section VIII.

II. System Model

In this paper, we consider the local MGOR scenario as the example in Fig. 1. Assume that node S, i.e., the sender, is forwarding a packet to a remote destination D. S can transmit the packet at k different rates $R_1, R_2, \ldots, R_k$. Each rate corresponds to a communication range, within which the nodes can receive the packet sent by S with some nonnegligible probability, which is larger than a threshold, e.g., 0.1. The available next-hop node set $\mathcal{C}_j (1 \leq j \leq k)$ of node S under a particular transmission rate R_j is defined as all the nodes in the communication range of S that are closer to D than S. We denote the nodes in $\mathcal{C}_j$ as $s_{j_1}, s_{j_2}, \ldots, s_{j_{N_j}}$, where $N_j = |\mathcal{C}_j|$. Similar to GR [12]–[14], we assume that S is aware of the location information of itself, its one-hop neighbors, and the destination D. Define the packet advancement as $a_{j_m} 1 \leq m \leq N_j$ in (1), which is the Euclidean distance between the sender and the destination $(d(S, D))$ minus the Euclidean distance between the neighbor s_{j_m} and the destination $(d(s_{j_m}, D))$

$$a_{j_m} = d(S, D) - d(s_{j_m}, D). \qquad (1)$$

Then, at each rate R_j, each node in $\mathcal{C}_j$ is associated with one pair (a_{j_m}, p_{j_m}), where p_{j_m} is the data packet reception ratio (PRR) from node S to s_{j_m}. Note that for different data rates, the PRR from node S to the same neighbor may be different. Let $\mathcal{F}_j$ denote the forwarding candidate set of node S at rate R_j, which contains the nodes that participate in the local opportunistic forwarding. Note that, here, $\mathcal{F}_j$ is a subset of $\mathcal{C}_j$, whereas in the existing pure opportunistic routing schemes [2], [4], $\mathcal{F}_j = \mathcal{C}_j$.

The MGOR procedure is as follows. Node S decides a transmission rate R_j and selects $\mathcal{F}_j$ based on its knowledge of $\mathcal{C}_j$ (a_{j_m}'s and p_{j_m}'s). Then, it broadcasts the data packet to the forwarding candidates in $\mathcal{F}_j$ at rate R_j after detecting that the channel is idle for a while. Candidates in $\mathcal{F}_j$ follow a specific priority to relay the packet, that is, a forwarding candidate will only relay the packet if it has correctly received the packet and all the nodes with higher priorities failed to do so. The actual forwarder will become a new sender and suppress all the other potential forwarders in $\mathcal{F}_j$. 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 retransmissions reach the limit. This procedure iterates until the packet arrives at the destination.

In this paper, we use a contention-based MAC protocol like 802.11 and apply a compressed slotted acknowledgement mechanism similar to that in [15] to coordinate the relay priority among the candidates, which is described as follows. After sensing that the channel has been idle for a distributed interframe space (DIFS), the sender broadcasts the data packet at the selected rate. In the header of the packet, the intended MAC addresses of the forwarding candidates and the corresponding relay priorities are identified. If the first-priority candidate correctly receives the packet, then it broadcasts an ACK with a delay of short interframe space (SIFS) after the successful data reception. The ACK is used for informing the sender of the data packet reception as well as suppressing lower-priority candidates from forwarding duplicated copies. If the first-priority candidate does not receive the packet, then it just remains silent. For the second-priority candidate, it sets a waiting period of $2T_{\mathrm{SIFS}} - T_{\mathrm{rx/tx}}$ after it correctly received the data packet, where T_{SIFS} and $T_{\mathrm{rx/tx}}$ are the time duration of SIFS and the radio receive/transmit status turnaround delay, respectively. If within the waiting period it detects that a transmission emerged (e.g., a significant signal strength increase) in the channel, then the ACK packet is considered as sent. Then, it just drops the received packet. On the other hand, if no transmission emergence is detected, then the second-priority candidate concludes that the highest prioritized candidate did miss the data packet. Therefore, the second-priority candidate will turn around its radio from receiving status to transmitting status and send out the ACK with $2T_{\mathrm{SIFS}}$ delay after it received the packet. Generally, the ith-priority $(i > 1)$ candidate that receives the data packet will set a waiting period as $i \times T_{\mathrm{SIFS}} - T_{\mathrm{rx/tx}}$ after the data packet reception. If it detects that a transmission emerged in this period, then it will suppress itself from forwarding the packet; otherwise, it will send out an ACK at $i \times T_{\mathrm{SIFS}}$ to claim its reception. In Section III-D, we will further elaborate on the impact of reliability of this ACK technique on the performance of OR.

III. Impact of Transmission Rate and Forwarding Strategy on OR Performance

In this section, we discuss the factors that affect the one-hop performance in terms of throughput and delay of OR. These factors include rate and forwarding strategy, which further includes candidate selection, prioritization, and coordination.

The impacts of transmission rate on the performance of opportunistic routing are twofold. On one hand, different rates achieve different transmission ranges, which lead to different neighborhood diversities. Explicitly, a high rate causes a short transmission range; then, in one hop, there are few neighbors around the sender, which presents low neighborhood diversity. A low rate is likely to have a long transmission range and, therefore, achieves high neighborhood diversity. Therefore, from the diversity point of view, a low rate may be better. On the other hand, although a low rate brings the benefit of a larger one-hop distance, which results in higher neighborhood diversity and fewer hop counts to reach the destination, it is still possible to achieve a low effective end-to-end throughput or high delay since it needs more time to transmit a packet at a lower rate. Therefore, it is nontrivial to decide which rate is indeed better.

In addition to the inherent rate–distance, rate–diversity, and rate–hop tradeoffs that affect the performance of opportunistic routing, the forwarding strategy will also have an impact on the performance. That is, for a given transmission rate, different candidate forwarding sets, relay priority assignments, and candidate coordinations will all affect the OR performance.

In the following sections, we will examine the impact of transmission rate and forwarding strategy on the one-hop performance of opportunistic routing, which leads us to the design of an efficient local rate adaptation and candidate-selection scheme. First, we will analyze the one-hop packet forwarding time introduced by opportunistic routing.

A. One-Hop Packet Forwarding Time of Opportunistic Routing

We define the one-hop packet forwarding time cost by the ith candidate as the period from the time when the sender is going to transmit the packet to the time when the ith candidate becomes the actual forwarder. Although the one-hop packet forwarding time varies for different MAC protocols, for any protocol, it can be divided into two parts. One part is introduced from the sender, and the other part is introduced from the candidate coordination, which are defined as follows.

1) T_s: The sender delay that can further be divided into three parts: channel contention delay (T_c), data transmission time (T_d), and propagation delay (T_p), i.e.,

$$T_s = T_c + T_d + T_p. \quad (2)$$

For a contention-based MAC protocol (like 802.11), T_c is the time needed for the sender to acquire the channel before it transmits the data packet, which includes the back-off time and DIFS. T_d is equal to the protocol header transmission time (T_h) plus data payload transmission time (T_{pl}), i.e.,

$$T_d = T_h + T_{\text{pl}} \quad (3)$$

where T_h is determined by physical layer preamble and MAC header transmitting time, and T_{pl} is decided by the data payload length L_{pl} and the data transmission rate. The payload may be transmitted at different rates.

T_p is the time for the signal propagating from the sender to the candidates, which can be ignored when an electromagnetic wave is transmitted in the air.

2) $T_f(i)$: The ith forwarding candidate coordination delay that is the time needed for the ith candidate to acknowledge the sender and suppress the other potential forwarders. Note that $T_f(i)$ is an increasing function of i, since the lower priority forwarding candidates always need to wait and confirm that no higher-priority candidates have relayed the packet before it takes its turn to relay the packet. For the protocol we introduced in Section II, $T_f(i) = i \times T_{\text{SIFS}} + T_{\text{ACK}}$, where T_{ACK} is the ACK transmission time.

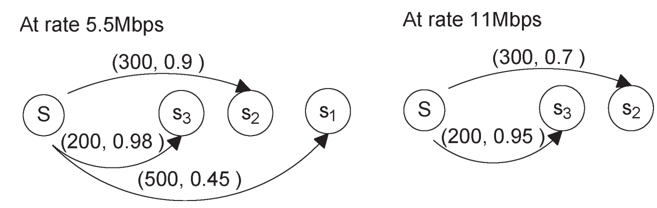

Fig. 2. Different transmission rates result in different next-hop neighbor sets.

Thus, the total medium time needed for a packet forwarding from the sender to the ith forwarding candidate is

$$t_i = T_s + T_f(i). \quad (4)$$

B. Impact of Transmission Rate

We examine the impact of the transmission rate on the one-hop throughput of OR by using two examples. In one example, transmission at a higher rate is better, whereas in the other example, a lower rate achieves a higher throughput. The one-hop throughput is defined as bit–meters successfully delivered per second (bmps). The one-hop delay per bit–meter is the inverse of the throughput. Therefore, a higher throughput implies a lower delay in this context.

Assume that the data payload $L_{\text{pl}} = 1000$ B, $T_{\text{SIFS}} = 10\ \mu$s, $T_{\text{ACK}} = 192\ \mu$s, $T_h = 200\ \mu$s, and the sender delay only includes the data transmission time (T_d). According to (2)–(4) and the MAC protocol we discussed in Section II, $t_i = (8000/R_j) + 10i + 392\ \mu$s. In Fig. 2, assume at each rate that the neighbor closer to the destination is assigned a higher relay priority. Suppose that S sends out N packets. Then, when $R_j = 11$ Mb/s, there are $L_{\text{pl}}(300 \cdot 0.7\ \text{N} + 200 \cdot 0.95 \cdot 0.3\ \text{N}) = 2.136$ N megabit–meters delivered, and the corresponding total packet forwarding time is $(t_1 \cdot 0.7\ \text{N} + t_2 \cdot 0.3\ \text{N}) = 1132.27$ N μs. Therefore, the one-hop throughput is 1.886 G bmps. Similarly, the one-hop throughput at 5.5 Mb/s is 1.651 G bmps, which is smaller than the throughput at 11 Mb/s. That is, in this example, although a lower rate introduces more spatial diversity (more neighbors), this benefit does not make up the cost on the longer medium time. Now, let us assume that the neighbor s_3 is removed from Fig. 2 for each rate. Then, the one-hop throughput is 1.60 and 1.49 G bmps at 5.5 and 11 Mb/s, respectively. Therefore, transmitting at a lower rate is better than transmitting at a higher rate in this case because the extra spatial diversity brought by a lower rate does help to improve the packet advancement but only introduces a moderate extra packet forwarding time.

C. Impact of Forwarding Strategy

We have seen that the multirate capability has an impact on throughput and delay. Other than this factor, for any given rate, a different candidate prioritization also results in different throughput and delay in opportunistic routing. Still use the example in Fig. 2 at rate 5.5 Mb/s. If we assign the relay priority as $s_2 > s_1 > s_3$, the one-hop throughput is 1.306 G bmps, which is lower than that achieved by assigning a higher priority to the candidate closer to the destination. It has been proved in [6] that giving candidates closer to the destination higher priorities achieves maximum expected packet advancement (EPA).

D. Impact of Candidate Coordination

Coordination delay is another key factor affecting the packet forwarding time and one-hop throughput. When this delay is much larger than the sender delay, then it would be better to retransmit the packet instead of waiting for other forwarding candidates to relay the packet to save the packet forwarding time. While when this delay is negligible, we should involve all the available next-hop neighbors into opportunistic forwarding because any extra candidate would help to improve the relay reliability but without introducing any extra delay. We should also give candidates closer to the destination higher relay priorities since larger-advancement candidates should always try first to maximize the EPA. If they failed to relay the packet, then the lower-priority candidates could instantaneously relay the correctly received packet without having to wait. Therefore, the coordination delay has a great impact on throughput. Since we use the compressed slotted acknowledgement, which introduces a small coordination delay among the candidates, it would be better to give candidates closer to the destination higher relay priorities.

In the compressed slotted acknowledgement mechanism, ACK plays two roles: One is to acknowledge the sender of data reception, and the other is to suppress the other candidates from forwarding duplicated packets. We discuss the reliability of this mechanism according to these two ACK roles. First, following the collision avoidance rule, each node should sense the channel to be clear for at least DIFS before transmission. Since the ith-priority candidate broadcasts the ACK with a short delay ($i \times T_{\mathrm{SIFS}}$, which is usually shorter than DIFS in our scheme) after a successful packet reception, the ACK is unlikely to collide with the other transmissions at the sender side. The empirical results in [16] also confirm that ACK can be received by the sender with high probability. Furthermore, since the ACK is transmitted at the basic rate (e.g., 1 Mb/s in 802.11b), the ACK link from the candidate to the sender should be more reliable than the data link from the sender to the candidate. So when the candidate correctly receives the data packet from the sender, the ACK can usually be correctly received by the sender with high probability. Second, since all of the forwarding candidates are in the data transmission range of the sender, the longest possible distance between any two candidates is twice of the data transmission range. Typically, the carrier sensing range is around double of the data transmission range. So any two forwarding candidates will be in the carrier sensing range of each other. Then, lower prioritized candidates should be able to detect that a transmission emerged in the channel if a higher-prioritized candidate does send out an ACK. A false positive could happen when a lower priority candidate senses a transmission emergence, but it is from the other transmission source. In this case, the lower priority candidate would drop its received packet. If all the lower-priority candidates who have received the packet correctly believe that there is a higher-priority candidate that has received the packet but actually there is not, then no ACK would be sent back to the sender, and the sender would retransmit the packet. However, the probability of other transmissions emerging in the short coordination period (multiple SIFS) and suppressing all the potential forwarding candidates should relatively be low.

IV. Opportunistic Effective One-Hop Throughput

According to the analysis above, for a given next-hop neighbor set $\mathcal{C}_j$, we now introduce the local metric OEOT [in (5)] to characterize the local behavior of GOR in terms of bit–meter advancement per second, i.e.,

$$\mathrm{OEOT}(\mathcal{F}_j) = L_{\mathrm{pl}} \cdot \frac{\sum_{i=1}^{r} a_{j_i} p_{j_i} \cdot \prod_{w=0}^{i-1} \overline{p}_{j_w}}{t_r \overline{P}_{\mathcal{F}_j} + \sum_{i=1}^{r} t_i p_{j_i} \cdot \prod_{w=0}^{i-1} \overline{p}_{j_w}} \tag{5}$$

where $\mathcal{F}_j = \langle s_{j_1}, \ldots, s_{j_r} \rangle$, which is an ordered subset of $\mathcal{C}_j$ with priority $s_{j_1} > \cdots > s_{j_r}$; $r = |\mathcal{F}_j|$; $p_{j_0} := 0$; $\overline{p}_{j_w} = 1 - p_{j_w}$; and

$$\overline{P}_{\mathcal{F}_j} = \prod_{i=1}^{r} (1 - p_{j_i}) \tag{6}$$

which is the probability of none of the forwarding candidates in $\mathcal{F}_j$ successfully receiving the packet in one physical transmission from the sender.

The physical meaning of the OEOT defined in (5) is the expected bit advancement per second for a local GOR procedure when the sender S transmits the packet at rate R_j. The OEOT integrates the factors of packet advancement, relay reliability, and one-hop packet forwarding time. Now for MGOR, our goal is to select an R_j and the corresponding $\mathcal{F}_j$ to locally maximize this metric. The intuitions to locally maximize the OEOT are as follows. 1) As the end-to-end achievable throughput is smaller than the per-hop throughput on each link, maximizing the local OEOT is likely to increase the path throughput. 2) The path delay is the summation of per-hop delay, which is actually relative to the delay introduced by transmitting the packet and coordinating the candidates. As the per-hop delay factors [T_s and $T_f(i)$] are integrated in the denominators of OEOT, maximizing OEOT is also implicitly decreasing the per-hop delay, which may further decrease the path delay. 3) As the transmission reliability of $\mathcal{F}_j$ is also implicitly embedded in OEOT, maximizing OEOT also tends to improve the reliability. Reliability is a key factor affecting throughout and delay for the following reason. If a packet is transmitted on a low reliable link, then several retransmissions are needed to make a successful packet forwarding at one hop. These retransmissions not only harm the throughput and delay performance of the flow that the packet belongs to but also introduce huge medium contentions to other flows, thus further decreasing the whole system performance. However, maximizing the one-hop reliability does not necessarily lead to better end-to-end throughput. Because reliable links likely have a short hop distance, this short hop distance may result in taking many hops to deliver a packet from the source to the destination, which may also introduce a large delay or more medium contention to other flows. Our OEOT metric jointly takes into account the hop advancement, reliability, and packet forwarding time.

V. Heuristic Candidate-Selection Algorithm

A straightforward way to get the optimal R_j and $\mathcal{F}_j$ to maximize the OEOT is to try all the ordered subset of $\mathcal{C}_j$ for each R_j, which runs in $O(keN!)$ time, where k is the number of different rates, e is the base of natural logarithm, and N is the largest number of neighbors at all rates. It is, however, not feasible when N is large. In this section, we propose a heuristic algorithm to get a solution approaching the optimum.

As there are a finite number of transmission rates, a natural approach is to decompose the optimization problem into two parts. First, we find the optimal solution for each R_j; then, we pick the maximum among them. Therefore, we only need to discuss how to find the solution approaching the optimum for a given rate R_j and the corresponding available next-hop neighbor set $\mathcal{C}_j$. The following lemma guides us to design the heuristic algorithm.

Lemma 1: For a given R_j and $\mathcal{C}_j$, define $\mathcal{F}_j^r$ as one feasible candidate set that achieves the maximum OEOT by selecting r nodes; then, $\forall r\ (1 \leq r \leq |\mathcal{C}_j|)$, $\exists \mathcal{F}_j^r$, s.t. $\mathcal{F}_j^1 \subseteq \mathcal{F}_j^r$.

Proof: We prove this lemma by contradiction. Assume $\forall r (1 \leq r \leq |\mathcal{C}_j|)$ that we could find a feasible $\mathcal{F}_j^r$, s.t. $\mathcal{F}_j^1 \nsubseteq \mathcal{F}_j^r$. Then, from that $\mathcal{F}_j^r$, we can obtain a new ordered set by substituting the lowest priority candidate in $\mathcal{F}_j^r$ as the node in $\mathcal{F}_j^1$. According to (5) and the fact that $\mathcal{F}_j^1$ achieves the maximum OEOT by selecting 1 node, we can derive that the OEOT of the new set is larger than that of the $\mathcal{F}_j^r$. It is a contradiction, so the assumption is false, and the lemma is true. ■

Lemma 1 basically indicates that for the given R_j and $\mathcal{C}_j$, the candidate achieving the maximum OEOT by selecting one node from $\mathcal{C}_j$ is contained in the candidate set achieving the maximum OEOT by selecting more number of nodes from $\mathcal{C}_j$.

The numerator of OEOT is the EPA defined in [6]. The EPA has three nice properties, i.e., priority rule, containing property, and concavity. We present these properties as follows without proof. Please refer to [6] for a detailed proof. These properties also help us design the rate and candidate-selection algorithm.

Property 1—Relay Priority Rule: Given a forwarding candidate set $\mathcal{F}$, the maximum EPA can only be achieved by giving candidates closer to the destination higher relay priorities.

The *Relay Priority Rule* guides us to prioritize the forwarding candidates by only examining their advancement to the destination. Next, we present the relationship among the optimal forwarding candidate sets (in the sense of maximizing EPA) with a different number of candidates selected from a given candidate set $\mathcal{C}$.

Property 2—Candidate Set Containing Property: Given an available forwarding candidate set $\mathcal{C}(N = |\mathcal{C}|)$, let $\mathcal{F}_r^*$ be a feasible ordered candidate set that achieves the maximum EPA by selecting r candidates from $\mathcal{C}$, $\forall \mathcal{F}_{r-1}^*$, $\exists \mathcal{F}_r^*$, s.t.

$$\mathcal{F}_{r-1}^* \subset \mathcal{F}_r^* \quad \forall 1 \leq r \leq N. \tag{7}$$

Property 2 indicates that an $r-1$-candidate set that achieves the maximum EPA is a subset of at least one of the feasible r-candidate sets that achieves the maximum EPA. The reliability in one opportunistic forwarding is shown in (8). The property also implies that the increase of the maximum EPA is consistent with the increase of the forwarding reliability

$$P_{\mathcal{F}_j} = 1 - \prod_{i=1}^{r} (1 - p_{j_i}). \tag{8}$$

We also have the following concave property of the maximum EPA.

Property 3—Maximum EPA Concavity: The maximum EPA is an increasing and concave function of the number of forwarding candidates.

This property indicates that involving more forwarding candidates will increase EPA, but the gained EPA becomes marginal when we keep doing so. It has been shown in [6] that the maximum EPA nearly does not increase when the number of forwarding candidates is larger than 4. Furthermore, involving more forwarding candidates may increase the probability of a false positive, that is, lower-priority candidates are more likely to be falsely suppressed by other transmissions in the network. So in our algorithm design, we set a maximum allowable forwarding candidate number $r_{\max}$.

Now we examine the denominator of the OEOT in (5). For the compressed slotted ACK mechanism, the denominator can further be simplified as $T_s(j) + T_{\mathrm{ACK}} + T_{\mathrm{SIFS}}(\sum_{i=1}^{r} i \cdot p_{j_i} \prod_{w=0}^{i-1} \overline{p}_{j_w} + r \cdot \overline{P}_{\mathcal{F}_j})$, where $T_s(j)$ is the delay at the sender side when the data packet is transmitted at rate R_j. The third part of this summation is the expected time introduced by candidate coordination, which is upper bounded by $r \cdot T_{\mathrm{SIFS}}$. Since $T_{\mathrm{SIFS}} \ll T_s(j) + T_{\mathrm{ACK}}$, and r is a small number, the denominator can be seen as a constant at a fixed rate R_j. So maximizing the OEOT is equivalent to maximizing its numerator EPA.

Therefore, according to Properties 1–3 and the preceding analysis, we propose a heuristic greedy algorithm that finds the transmission rate and the corresponding forwarding candidates approaching the maximum OEOT. This heuristic algorithm FindMOEOT is described in Algorithm 1, where the input is the multirate R_j, the corresponding $\mathcal{C}_j$, and the maximum allowable forwarding candidate number $r_{\max}$, and the output is the selected rate R^* and the forwarding candidate set $\mathcal{F}^*$. For each rate R_j, this algorithm first finds the set $\mathcal{F}_m$ with one candidate that maximizes the OEOT, and then, it augments the current $\mathcal{F}_m$ by one more candidate in each iteration (line 6). Whenever adding a new candidate, it calculates the OEOT (line 7) and then updates the $\mathcal{F}_m$ when finding a new set that achieves a higher OEOT than the existing one. Note that, according to Lemma 1, when the final returned set contains no more than two nodes, it is indeed the global optimum. Otherwise, it is an approximate optimal solution. An interesting finding is that this algorithm almost surely returns the global optimal solution, even when the returned set contains more than two candidates.

Algorithm 1 FindMOEOT($\mathcal{C}_j$'s, R_j's, $r_{\max}$)

$R^* \leftarrow 0$; $\mathcal{F}^* \leftarrow \emptyset$; $OEOT^* \leftarrow 0$;
for {each $\mathcal{C}_j$} **do**
  $\mathcal{F}_m \leftarrow \emptyset$; $OEOT_m \leftarrow 0$; $\mathcal{A} \leftarrow \mathcal{C}_j - \mathcal{F}_m$;
  while ($\mathcal{A} \neq \emptyset \&\& |\mathcal{F}_m| < r_{\max}$) **do**
    for each node $s_n \in \mathcal{A}$ **do**
      $\mathcal{F}_t \leftarrow$ Insert s_n into $\mathcal{F}_m$ according to ***Relay Priority Rule***;
      Get $OEOT$ on $\mathcal{F}_t$ according to (5);
      if ($OEOT > OEOT_m$) **then**
        $OEOT_m \leftarrow OEOT$; $\mathcal{F}_m \leftarrow \mathcal{F}_t$
      end if
    end for
    $\mathcal{A} \leftarrow \mathcal{C}_j - \mathcal{F}_m$;
  end while
  if ($OEOT_m > OEOT^*$) **then**
    $R^* \leftarrow R_j$; $\mathcal{F}^* \leftarrow \mathcal{F}_m$; $EOT^* \leftarrow EOT_m$;
  end if
end for
return ($R^*, \mathcal{F}^*$);

VI. Performance Evaluation

In this section, we evaluate the performance of MGOR by simulation and compare the performance of MGOR with multirate GR (MGR), single-rate GR, and single-rate opportunistic routing. Our MGOR degenerates into MGR when we only choose one forwarding candidate, and further degenerates into GR when we also fix the transmission rate. For all the OR protocols, candidates closer to the destination are assigned higher relay priorities. The performance metrics we evaluate include throughput, delay, and hop count. To get insight into our rate and candidate-selection algorithm, for MGOR, we show the number of packets transmitted at each rate in the whole network and the average number of forwarding candidates used at each node on each data rate.

A. Multirate Link Quality Measurement

To make multirate protocols work, we need to estimate the link quality (PRR) at different data rates. We extend the single-rate link quality measurement mechanism in [17] to a multirate mechanism. In multirate protocols, each node maintains k neighbor tables that correspond to k data rates. The jth table stores the bidirectional PRR information about its neighbors at rate R_j. For every τ second, each node broadcasts k "Hello" messages each transmitted at a different data rate, e.g., 11, 5.5, and 2 Mb/s. Whenever a node n receives a "Hello" message sent from a node m at rate R_j, it will include node m into the corresponding neighbor table. Two events drive the updating of PRR_{mn} at R_j on node n: one is the periodical updating event set by node n, for example, every t_u seconds node n will update PRR_{mn}. The other is the event that node n receives a "Hello" packet sent from m at rate R_j. The Exponentially Weighted Moving Average (EWMA) method is used to update the PRR information. See [17] for details about how each node updates the link quality at a particular data rate.

TABLE I
Simulation Parameters

Simulation Parameter	Value
Nodes Number	50
Transmission Power	15dbm
Data Transmission Rates	11Mbps, 5.5Mbps, 2Mbps
ACK Transmission Rate	1Mbps
Retry limit	5
Carrier Sensing Threshold	-100dbm
11Mbps Receiving Threshold	-83dbm
5.5Mbps Receiving Threshold	-87dbm
2Mbps Receiving Threshold	-91dbm
1Mbps Receiving Threshold	-94dbm
Pathloss Model	Two-ray
Fading Model	Ricean with $K = 4$
Hello Packet Interval	1s

TABLE II
Average Number of Neighbors per Node at Each Rate Under Different Network Densities

Data rate (Mbps)	Terrain side length			
	1500	1800	2100	2400
2	19.7	14.4	11.3	8.8
5.5	16.3	11.9	8.8	6.8
11	11.1	7.9	5.8	4.3

B. Simulation Setup

We implement the multirate link quality measurement mechanism and the MGOR protocol with a compressed slotted ACK in GlomoSim. The FindMOEOT algorithm proposed in Section V is used to select the transmission rate and the forwarding candidates for MGOR. This algorithm is also used to select the forwarding candidates for a single-rate GOR by fixing the transmission rate. According to the analysis in Section V and considering the candidate coordination overhead, the maximum allowable forwarding candidate number ($r_{\max}$) is set as 3. Other than the candidate coordination scheme, our OR protocol follows the same carrier sense multiple access with collision avoidance (CSMA/CA) medium-access mechanism as that in 802.11b. The simulated network has 50 stationary nodes randomly uniformly distributed in a $d \times d\,\mathrm{m}^2$ square region. When the SNR is larger than a defined threshold, and the signal receiving power is above the corresponding threshold, the packet is received without error. Otherwise, the packet is dropped. Table I lists the related simulation parameters. According to the findings in [16] and the discussion in Section III-D, we assume that the candidate coordination can be ensured by the compressed slotted ACK mechanism.

We examine the impact of node density on performance by setting $d = 1500, 1800, 2100, 2400$. The corresponding network density in terms of average number of neighbors per node at each rate is summarized in Table II. We randomly choose 25 communication pairs in the network. The sources are constant bit rate (CBR). We examine two different packet sizes. All the results shown in Sections VI-C1–4 are under 512-B packet size, and Section VI-C5 discusses the performance with a packet size of 1024 B. We examine two traffic

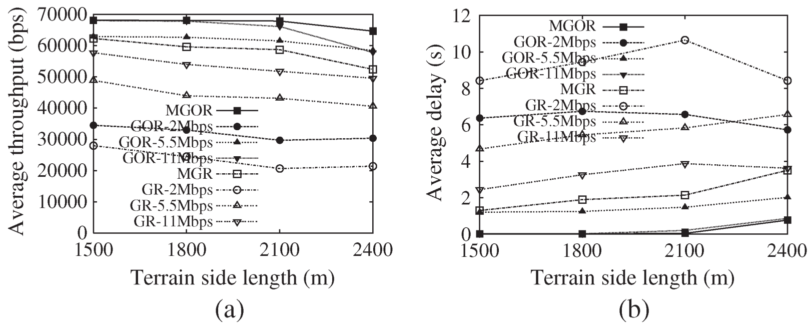

Fig. 3. Performance of MGOR, single-rate GOR, MGR, and single-rate GR under different network densities with CBR interval at 60 ms. (a) Throughput. (b) Delay.

demands with a CBR interval at 60 and 75 ms. The User Datagram Protocol (UDP) is used as the transport layer protocol. Each communication session continues for 40 s. All the simulation results are averaged over 25 flows under five simulation runs with different seeds.

C. Simulation Results and Analysis

1) Throughput and Delay: The throughput is measured as the average throughput per flow in the communication period. We first set the CBR packet interval as 60 ms to push the traffic demand approaching to the capacity of MGOR. Fig. 3(a) shows the throughput of MGOR, single-rate GOR, MGR, and single-rate GR. We can see that MGOR achieves the highest throughput among all the protocols and yields up to 20% higher throughput than MGR (when the terrain side length is 2400 m). Generally, opportunistic routing protocols achieve a higher throughput than the corresponding traditional routing protocols at each rate. The spatial diversity gain introduced by involving multiple forwarding candidates in opportunistic routing does increase the probability of a successful transmission at each hop, which reduces the retransmission overhead. The reduction of retransmission can alleviate the medium contention and allow more packets to get through in the network, and result in higher throughput. We would like to point out that due to the randomness of the network topology and limited transmission range, the packet lost in 11-Mb/s GOR and GR is partially due to the communication void, where a forwarding node cannot find any neighbor that is geographically closer to the destination. Solving the communication void problem in GR is out of the scope of this paper. However, we note that lowering the transmission rate (from 11 to 5.5 Mb/s) increases the transmission range and improves the network connectivity, which in turn alleviates the void problem. This can be seen as a side effect or advantage of MGR protocols over single-rate protocols. That is, by using our local candidate-selection and rate adaptation schemes, the multirate protocols take advantage of the higher transmission rate (11 Mb/s) whenever there is sufficient spatial diversity or node density but switch to a lower rate to improve the spatial diversity and connectivity in a sparser area.

The delay performance of these protocols with the CBR interval at 60 ms is shown in Fig. 3(b). We can see that all the opportunistic routing protocols achieve a much lower delay than the corresponding traditional ones. Generally, MGOR achieves the lowest delay among all the protocols. When the network density is high, an 11-Mb/s GOR achieves almost the same delay (0.01 and 0.015 s with the terrain side length being 1500 and 1800 m, respectively) as MGOR. When the network becomes sparser, MGOR outperforms the 11-Mb/s GOR. In the saturated network, the end-to-end delay consists of per hop queuing delay, data transmission and retransmission delay, and medium access delay. Opportunistic routing makes use of multiple forwarding candidates to relay the packets, thus improving the per transmission reliability. This enhancement of reliability reduces the retransmission delay, which in turn reduces the queuing and medium access delay, thus reducing the end-to-end delay.

To conduct a "fairer" comparison between MGOR and GOR at 11 Mb/s and separate the impact of the transmission reliability on the end-to-end delay from other factors (such as excessive medium contention and long queuing delay due to high traffic demand, and communication voids), we run another simulation with a lower traffic demand, where the CBR interval is set as 75 ms, and only count the cases without communication voids. This traffic demand is below the capacity of MGOR and GOR at 11 and 5.5 Mb/s, so they achieve nearly the same throughput as shown in Fig. 4(a). Fig. 4(b) shows the delay performance of these three protocols. We can see that MGOR achieves a lower delay than the other two protocols, particularly when the network becomes sparser. MGOR can tune its transmission rate at each hop according to different network conditions to maximize OEOT. When the number of neighbors at 11 Mb/s is small, MGOR transmits packets at 5.5 Mb/s to involve more forwarding candidates to harvest the opportunistic gain (e.g., achieve higher transmission advancement and reliability). When transmitting at 11 Mb/s already introduces sufficient spatial diversity, MGOR chooses to transmit at a higher rate (11 Mb/s). We will show the proportion of packets transmitted at each rate in MGOR later.

We also find that although MGR can support at least 96% of this lower traffic demand, it still presents one or two orders of longer delay than MGOR. The difference of transmission reliability is the essential reason of this observation. That is, MGR has only one predefined forwarding candidate, and therefore, it usually needs more than one transmission to deliver a packet at each hop, whereas MGOR usually needs only one transmission since it introduces multiple forwarding candidates and improves the transmission reliability.

Since the relative performance of hop count, average number of forwarding candidates, and proportion of packets transmitted

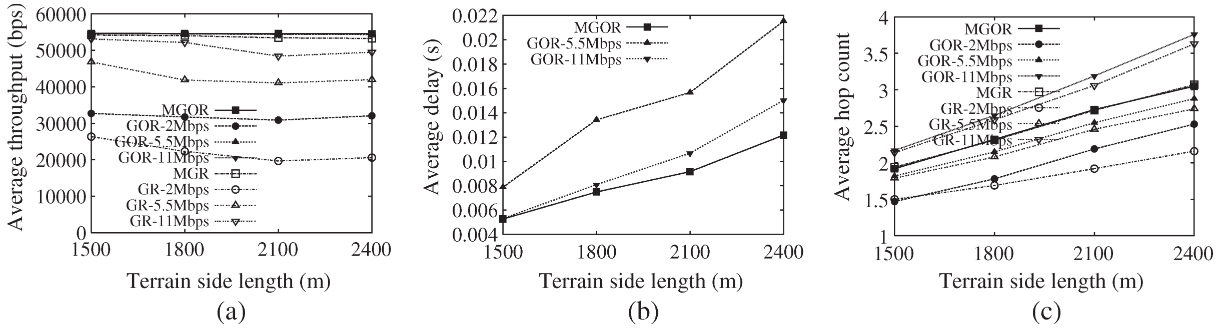

Fig. 4. Performance of MGOR, single-rate GOR, MGR, and single-rate GR under different network densities with CBR interval at 75 ms. (a) Throughput. (b) Delay. (c) Hop count.

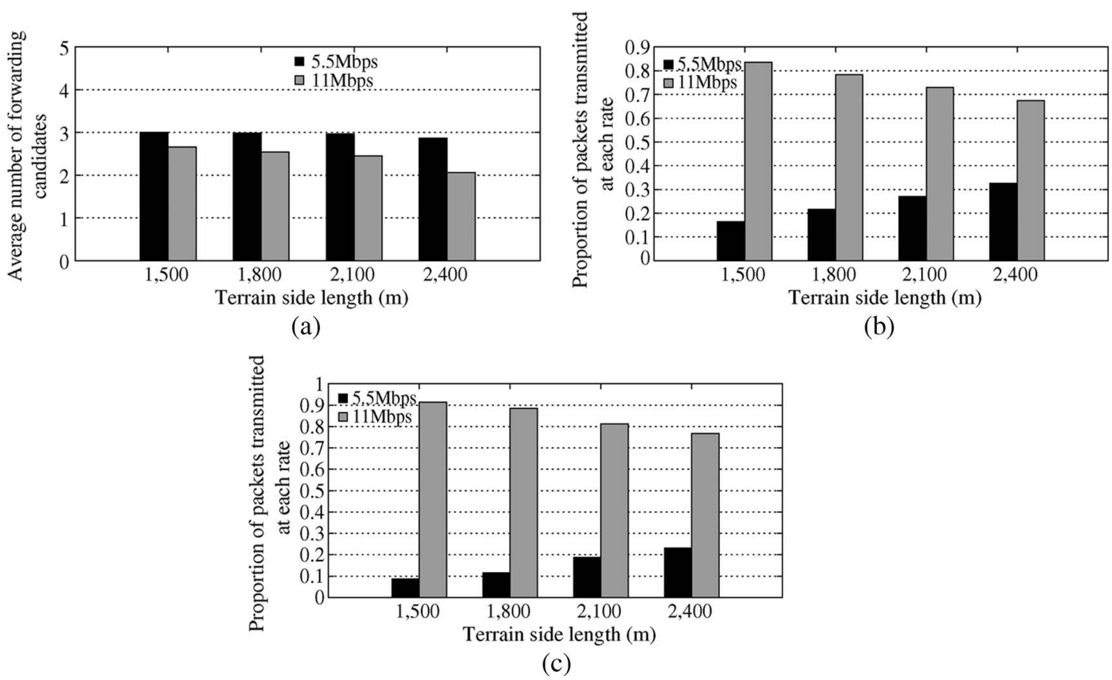

Fig. 5. Performance of MGOR under different network densities with CBR interval at 75 ms. (a) Average number of forwarding candidates. (b) Proportion of packets transmitted at each rate, packet size = 512 B. (c) Proportion of packets transmitted at each rate, packet size = 1500 B.

at each rate of each protocol is similar under these two traffic demands, we only show the simulation results with CBR interval at 75 ms in the following discussions.

2) Hop Count: From Fig. 4(c), we can see that GOR has a larger hop count than GR at each single rate. Although GOR allows packets to be forwarded on long-distance links, some forwarding candidates with a smaller advancement may also be chosen as the actual forwarder, which results in a larger hop count. The hop count of MGOR is nearly the same as MGR and is between those of GOR at 11 and 5.5 Mb/s but closer to that at 5.5 Mb/s. The rate–distance tradeoff is explicitly shown in the figure for both GR and GOR, that is, the hop count of the lower rate is smaller than that of the higher rate since lower rates result in longer transmission ranges.

3) Average Number of Forwarding Candidates: Fig. 5(a) shows the average number of forwarding candidates at each rate for MGOR. We can see that the number of forwarding candidates at each rate decreases when the network density is decreased. Furthermore, transmission at a lower rate (5.5 Mb/s) results in more forwarding candidates than transmission at a higher rate (11 Mb/s). In our MGOR, we do not choose a 2-Mb/s transmission rate since the traffic demand is already larger than the capacity that 2 Mb/s can provide.

4) Proportion of Packets Transmitted at Each Rate per Node: Fig. 5(b) shows the proportion of packets transmitted at each rate per node. We can observe that when the network becomes sparser, more packets are selected to be transmitted at 5.5 Mb/s in our MGOR protocol than when the network is dense. A lower transmission rate results in a longer transmission range, which leads to more number of neighbors [shown in Fig. 5(a)] and increases the spatial diversity. The increased diversity gain does improve the probability of a successful transmission, which reduces the retransmission overhead, and then improves the throughput [shown in Fig. 3(a)] and decreases the delay [shown in Fig. 4(b)].

5) Impact of Packet Size: We also evaluated the impact of packet size on the selection of transmission rate. By comparing Fig. 5(c) with Fig. 5(b), we notice that when the packet size is larger (such as 1500 B, in contrast to 512 B), more packets are transmitted at a higher data rate (i.e., 11 Mb/s). Because when the packet payload size is increased, the time of protocol overhead (such as packet header, preamble and ACK transmission time) becomes relatively smaller compared to the payload transmission time. Therefore, a higher transmission rate will be more favorable when the packet size becomes larger.

VII. Related Work

GR has widely been suggested as an efficient routing paradigm in multihop wireless networks. A key advantage of GR is that the nodes are not required to maintain extensive routing tables and can make simple routing decisions based on the local geographic position of its neighboring nodes. More recent works [13], [14] on GR focus on designing a local metric in lossy channel situations. Unfortunately, these metrics only apply to GR, which involves a single forwarding candidate and cannot directly be used for GOR. The OEOT metric that we introduced can be applied to both opportunistic routing with multiple forwarding candidates and GR with only one forwarding candidate.

Opportunistic routing exploits the spatial diversity of the wireless ad hoc networks by involving a set of forwarding candidates instead of only one in traditional routing. It improves the reliability and efficiency of packet relay. Some variants of opportunistic routing [2], [3], [5], [8] use the location information to define the candidate set and relay priority. Our work belongs to this kind of variant but provides a more insightful understanding of the tradeoff among packet advancement, coordination time cost, and reliability associated with node collaboration under a multirate scenario. We explore the rate–distance–diversity impact on the throughput and delay of opportunistic routing, which has not been well studied in the foregoing works.

Several papers [8]–[11] in the literature have already started to design routing metrics in a multirate wireless ad hoc network. However, these metrics are proposed for routing along a fixed path following the concept of traditional routing. Recently, a theoretical study [19] has shown that without considering the protocol overhead and with collision-free transmission scheduling, the multirate OR can achieve higher end-to-end throughput bound than any single-rate OR. Zeng *et al.* [7] also show the advantage of a multirate OR over a single-rate OR with collision-free MAC by using a slotted ACK coordination scheme. In this paper, we study the multirate OR with a contention-based MAC similar to 802.11 by using the compressed slotted ACK coordination mechanism.

VIII. Conclusion

In this paper, we have studied MGOR and examined the factors that affect its performance, which include multirate capability, candidate selection, prioritization, and coordination. Based on our analysis, we proposed the local metric, i.e., the OEOT, to characterize the tradeoff between packet advancement and medium time cost under different data rates. We further proposed a rate and candidate-selection algorithm to approach the local optimum of this metric. We presented a multirate link quality measurement mechanism to provide the link PRR information for the network layer to assist with the routing decision. We compared the performance of MGOR with single-rate GOR, single-rate GR, and multirate GR. The simulation results show that the MGOR incorporating the rate adaptation and candidate-selection algorithm achieves the highest throughput and the lowest delay among all the protocols.

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