MULTI-RATE GEOGRAPHIC OPPORTUNISTIC ROUTING IN WIRELESS AD HOC NETWORKS

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Abstract*—Routing in wireless ad hoc 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 and spatial diversity of the wireless medium. Previous studies on GOR has focused on networks with a single channel rate. The capability of supporting multiple channel rates, which is common in wireless systems, has not been carefully 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 throughput of GOR. We propose a new local metric, expected one-hop throughput (EOT), to characterize the trade-off between the packet advancement and medium time cost. We further propose a local rate adaptation and candidate selection algorithm to maximize this metric. Simulation results show that the multi-rate GOR (MGOR) incorporating the rate adaptation and candidate selection algorithm efficiently forwards the packet to the destination with higher throughput than the corresponding geographic routing and pure opportunistic routing operating at any single rate. EOT is shown to be a good local metric to achieve high path throughput for MGOR.

I. INTRODUCTION

Wireless ad hoc networks have attracted a lot of research interest in recent years since they can be easily deployed at low cost without relying on the existing infrastructure. They are often referred to as different names according to different applications, such as wireless mesh networks, wireless sensor networks, and mobile ad hoc networks.

Routing in such networks is a challenging issue 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, wireless medium is broadcast in nature, so the transmission on one link may interfere with the transmissions on other links.

Recently, a new routing paradigm, known as opportunistic routing [2]–[6], was proposed to mitigate the impact of link quality variations by exploiting the broadcast nature and spatial diversity of the wireless medium. The general idea behind these schemes is that, for each destination, 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 availability and reachability at that instant. As more forwarding candidates are involved to help relay the packet, the probability of at least one forwarding candidate correctly receiving the packet increases, which results in higher forwarding reliability and lower retransmission cost. Some variants of opportunistic routing protocols [2], [3], [6]–[8] use 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 nodes' location information are 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 using multiple transmission rates. For example, many existing wireless networking standards such as IEEE 802.11a/b/g include this multi-rate capability. Such multi-rate capability has shown its impact on the path throughput in multi-hop wireless ad hoc networks [9]–[12] because of the inherent trade-off between transmission rate and effective transmission range. That is, low-rate communication usually covers a long transmission range, while high-rate communication must occur at short range. This rate-distance trade-off 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 set, thus lead

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to different spatial diversity chances. However, to the best of our knowledge, there is no existing work studying the impact of multi-rate on the performance of opportunistic routing.

In this paper, we carry out a comprehensive study on multi-rate, candidate selection, prioritization, and coordination and examine their impacts on the throughput of GOR. Based on our analysis, we propose a new local metric, the *expected one-hop throughput* (EOT), to characterize the trade-off between the packet advancement and medium time cost under different data rates. We further propose a rate adaptation and candidate selection algorithm to approach the local optimum of this metric. Simulation results show that MGOR incorporating the proposed algorithm achieves better throughput than the corresponding opportunistic routing and geographic routing operating at any single rate, and indicate that EOT is a good local metric to achieve high path throughput for MGOR.

The rest of this paper is organized as follows. Section II introduces the system model. We study the impacts of multi-rate capability and forwarding strategy on the throughput of opportunistic routing in Section III. The local metric is introduced in Section IV. We propose the heuristic algorithm in Section V. Simulation results are presented and analyzed in Section VI. Conclusions are drawn in Section VII.

II. SYSTEM MODEL

In this paper, we consider the local MGOR scenario as the example in Fig. 1. Assume node S, i.e., the sender, is forwarding a packet to a remote destination D. S can transmit the packet at k different rates $R_1, R_2, ..., R_k$. Each rate corresponds to a **communication range**, within which the nodes can receive the packet sent by S with some non-negligible probability which is larger than a threshold, e.g., 0.1. The **available next-hop node set** $\mathcal{C}_j$ 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 $s_{j_1}, s_{j_2}, ..., s_{j_{N_j}}$, where $N_j = |\mathcal{C}_j|$. Similar to geographic routing [13]–[16], we assume 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} in equation (1), which is the Euclidian distance between the sender and destination ($d(S, D)$) minus the Euclidian distance between the neighbor s_{j_m} and destination ($d(s_{j_m}, D)$).

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

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, which contains the nodes that participate in the local opportunistic forwarding. Note that, here $\mathcal{F}_j$ is a subset of $\mathcal{C}_j$, while in the existing pure opportunistic routing protocols [2], [3], [5], $\mathcal{F}_j = \mathcal{C}_j$.

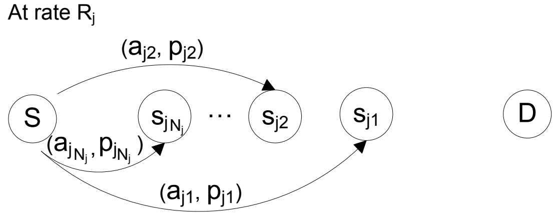

Fig. 1. Node S is forwarding a packet to a remote destination D with transmission rate R_j.

The multi-rate GOR (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 broadcasts the data packet to the forwarding candidates in $\mathcal{F}_j$ at rate R_j after detecting 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 received the packet correctly 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 will use the MAC protocol similar to those proposed in [2], [3], [6] to ensure the relay priority among the candidates, which is described as follows. When the channel is idle for a while, the sender broadcasts the data packet at the selected rate. In the head of the packet, the intended MAC addresses of the forwarding candidates and the corresponding relay priorities are identified. The candidate with i^{th} priority will wait $(i-1)T_{ACK}$ (T_{ACK} is time needed for transmitting an ACK packet) time before it sends out the ACK when it received the packet correctly or keep silent otherwise. Here the ACK message plays two roles, one is for acknowledgement to the sender, the other is for suppressing lower-priority candidates. That is, whenever a lower-priority candidate hears an ACK sent from a higher-priority candidate, it will suppress itself from relaying the packet. We assume that the ACK is broadcast at the basic rate of 1Mbps, and can be heard by the sender and other candidates correctly with probability 1. We emphasize that although the throughput will be analyzed based on this specific MAC protocol in this paper, the analysis methodology and framework apply to other MAC protocols.

III. IMPACT OF TRANSMISSION RATE AND FORWARDING STRATEGY ON THROUGHPUT

Both transmission rate and forwarding strategy (including candidate selection, prioritization and coordination) will affect the throughput of MGOR.

The impacts of transmission rate on the throughput of opportunistic routing are in two folds. On the one hand, different rates achieve different transmission ranges, which lead to different neighborhood diversity. Explicitly, high-rate causes short transmission range, then 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. So 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 is still possible to achieve a low effective path throughput when using low-rate communication links. Because the low rate disadvantage may overwhelm this benefit. So it is nontrivial to decide which rate is indeed better.

Besides the inherent rate-distance, rate-diversity and rate-hop trade-offs which affect the throughput performance of opportunistic routing, the forwarding strategy will also have an impact on the throughput. That is, for a given transmission rate, different candidate forwarding sets, relay priority assignments, and candidate coordinations will affect the throughput.

In the following subsections, we will examine the impact of transmission rate and forwarding strategy on the one-hop performance of opportunistic routing, which will provide important insight for us to design rate adaption and candidate selection algorithm. First we will analyze the one-hop medium time introduced by opportunistic routing.

A. *One-hop Medium Time of Opportunistic Routing*

In one transmission from the sender, we define the one-hop medium time cost by the i^{th} candidate as the time slot from the time when the sender is going to transmit the packet to the time when the i^{th} candidate becomes the actual forwarder. Although the one-hop medium time for forwarding a packet 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:

- T_s: the sender delay which can be further divided into three parts: channel acquisition time (T_c), data transmission time (T_d) and propagation delay (T_p):

  $$T_s = T_c + T_d + T_p \tag{2}$$

  For a contention-based MAC protocol (like 802.11), T_c is time needed for the sender to acquire the channel before it transmits the data packet, which may include the back-off time, Distributed Interframe Space (DIFS) and time for transmitting Ready-To-Send (RTS) packet. T_d is equal to protocol heads transmission time (T_h) plus data payload transmission time (T_{pl}), which is

  $$T_d = T_h + T_{pl} \tag{3}$$

  where T_h is determined by a certain protocol, 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 than the header.

  T_p is the time for the signal propagating from the sender to the candidates, which can be ignored when electromagnetic wave is transmitted in the air.
- $T_f(i)$: the i^{th} forwarding candidate coordination delay which is the time needed for the i^{th} candidate to acknowledge the sender and suppress 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.

Thus, the total medium time needed for a packet forwarding from the sender to the i^{th} forwarding candidate is

$$t_i = T_s + T_f(i) \tag{4}$$

B. *Impact of Transmission Rate on Throughput*

We examine the impact of transmission rate on throughput by using two examples. In one example, transmission at higher rate is better; while in the other example, lower rate achieves higher throughput. The throughput definition we use is the same as that proposed in [17] which is the bit-meters successfully delivered per second with unit bmps.

Assume the data payload $L_{pl} = 1000$ bytes. For simplicity, we assume the sender delay only includes the data transmission time (T_d), and T_h in Eq. (3) is fixed at $200\mu s$. So $T_s = \frac{1000 \cdot 8}{R_j} + 200\mu s$. Recall that R_j is the data transmission rate. According to the MAC protocol we discussed in the previous section, we assume $T_f(i) = 200i\ \mu s$. Then $t_i = T_s + 200i$. In Fig. 2, the sender S transmits the data at 5.5Mbps and 11Mbps respectively. The next-hop neighbor set at each transmission rate and the corresponding

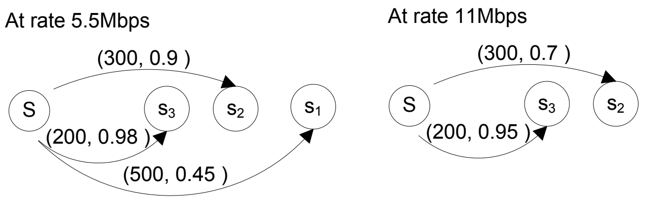

Fig. 2. Different transmission rates result in different next-hop neighbor sets

(distance, PRR) pairs associated with each neighbor are indicated in the figure. Assume at each rate, the neighbor closer to the destination is assigned higher relay priority. For a long term, S sends out a sufficient large number of packets, say N. Then at 11Mbps, there are $L_{pl}(300 \cdot 0.7N + 200 \cdot 0.95 \cdot 0.3N)$ bit-meters are delivered, and the corresponding medium time is $(t_1 \cdot 0.7N + t_2 \cdot 0.3N)\mu s$. So there are $1.799G$ bit-meters successfully transmitted per second. We name it as the one-hop throughput. Similarly, the one-hop throughput at 5.5Mbps is $1.556G$ bmps, which is smaller than the throughput at 11Mbps. That is, in this example, although lower rate introduces more spatial diversity (more neighbors), this benefit does not make up the cost on the longer medium time. Now let's assume the neighbor s_3 is removed from the Fig. 2 for each rate. Then when S is transmitting at 5.5Mbps, the one-hop throughput is $1.52G$ bmps. While when S is transmitting at 11Mbps, the it achieves $1.49G$ bmps, which is smaller than that using rate 5.5Mbps. So transmitting at lower rate is better than higher rate in this case, because the extra spatial diversity brought by lower rate does help to improve the packet advancement but only introduce moderate medium time.

C. Impact of Forwarding Strategy on Throughput

We have seen that multi-rate capability has an impact on throughput. Other than this factor, for any given rate, different candidate prioritization also results in different throughput in opportunistic routing. Assume S transmits the data packet at 11Mbps, and it has four next-hop neighbors s_1 to s_4. The advancement associated with each neighbor is 480, 400, 350, and 250m respectively, and the PRR is 0.1, 0.35, 0.55, and 0.85 respectively. We first assume all the neighbors are selected as candidates and the neighbor that is closer to the destination has higher relay priority. Then we get the one-hop throughput as $1.86G$ bmps. However, if we assign the forwarding priority as $s_3 > s_2 > s_4 > s_1$, we get a larger one-hop throughput as $1.99G$ bmps. This result contradicts the common sense that candidates closer to the destination should relay packets first. The reason behind this result is that since the largest-advancement candidate has poor link quality from the sender, in most of the times, it does not receive the packet correctly, but lower-priority candidates always have to wait for a period of time to confirm this situation before they have chances to relay the packet, thus increase the total medium time, which in result degrades the throughput. It should be noted that, in the previous multi-rate examples, it happens to be the instance that assigning nodes closer to the destination higher relay priorities achieves the largest one-hop throughput.

Besides multi-rate and candidate prioritization, for a given transmission rate, different candidate sets also result in different throughput. We use the same settings as in the last four-neighbor example. First, we may get different throughput for different candidate sets with the same number of candidates. For example, candidate set $\langle s_1, s_4 \rangle$ achieves throughput of $1.46G$ bmps, while candidate set $\langle s_3, s_2 \rangle$ achieves higher throughput of $1.67G$ bmps. So we should carefully select forwarding candidates that indeed help improve the throughput. Furthermore, involving different number of forwarding candidates will also result in different throughput. Actually, candidate set $\langle s_3, s_2, s_4 \rangle$ achieves the largest throughput among all the candidate combination and prioritization in this example. When all the available next-hop nodes are involved as forwarding candidates, the throughput does not increase while slightly drops. This implies that it may be sufficient to just involve a few of "good" candidates to achieve the maximum one-hop throughput.

The coordination delay is another key factor affecting the one-hop throughput. We use two extreme cases to illustrate the impact of this factor. First, we assume 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 in order to save the medium time. In this case, one candidate may be optimal. On the other hand, we assume this delay is negligible, that is, the lower-priority candidates can relay the packet immediately when higher-priority candidates failed to do so. In this case, it is not difficult to imagine that we should involve all the available next-hop neighbors into opportunistic forwarding, because any extra included candidates 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 in order to maximize the expected packet advancement, even if they were unlikely to receive the packet correctly. If they failed to relay the packet, the lower-priority candidates could instantaneously relay the correctly received packet without needing to wait. Therefore, the coordination delay has a great impact on throughput.

IV. EXPECTED ONE-HOP THROUGHPUT (EOT)

According to the analysis above, for a given next-hop neighbor set $\mathcal{C}_j$, we now define a new local metric, *expected one-hop throughput* (EOT) (in Eq. 5), to characterize the local behavior of GOR in terms of bit-meter advancement per second.

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

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

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

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 EOT defined in Eq. (5) is the expected bit advancement per second for a local GOR procedure when the sender S transmits the packet at rate R_j. EOT integrates the factors of packet advancement, relay reliability, and MAC medium time cost. Now for multi-rate GOR, our goal is to select an R_j and the corresponding $\mathcal{F}_j$ to locally maximize this metric. The intentions to locally maximize the EOT are for the following: 1) as the whole path achievable throughput is less than per-hop throughput on each link, to maximize the local EOT 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 EOT, to maximize EOT is also implicitly to decrease per-hop delay, which may further decrease the path delay. 3) as EOT also takes into account the packet advancement to the destination, maximizing it potentially decreases hop counts needed to relay the packet to the destination, which may lead to fewer transmissions, alleviated interference to other flows, and decreased delay.

V. HEURISTIC CANDIDATE SELECTION ALGORITHM

A straightforward way to get the optimal R_j and $\mathcal{F}_j$ to maximize the EOT is to try all the ordered subset of $\mathcal{C}_j$ for each R_j, which runs in $O(N!)$ time, where N is the largest number of $|\mathcal{C}_j|$'s. 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 find the optimal solution for each R_j then pick the maximum one. So we only need to discuss how to find the solution approaching the optimum for given R_j and $\mathcal{C}_j$. The following Lemma guides us to design the heuristic algorithm.

```
FindMEOT($\mathcal{C}_j$'s, $R_j$'s)
$R^* \leftarrow 0$; $\mathcal{F}^* \leftarrow \emptyset$; $EOT^* \leftarrow 0$;
for each $\mathcal{C}_j$
  $\mathcal{F}_m \leftarrow \emptyset$; $EOT_m \leftarrow 0$; $\mathcal{A} \leftarrow \mathcal{C}_j - \mathcal{F}_m$;
  while ($\mathcal{A} \neq \emptyset$) do
    $\mathcal{F} \leftarrow \mathcal{F}_m$;
    for each node $s_n \in \mathcal{A}$
      for $i$ from 0 to $|\mathcal{F}_m|$
        $\mathcal{F}_t \leftarrow$ Insert $s_n$ between $F(i)$ and $F(i+1)$;
        Get $EOT$ on $\mathcal{F}_t$ according to Eq. (5);
        if ($EOT > EOT_m$)
          $EOT_m \leftarrow EOT$; $\mathcal{F}_m \leftarrow \mathcal{F}_t$
      end for
    end for
    $\mathcal{A} \leftarrow \mathcal{C}_j - \mathcal{F}_m$;
  end while
  if ($EOT_m > EOT^*$)
    $R^* \leftarrow R_j$; $\mathcal{F}^* \leftarrow \mathcal{F}_m$; $EOT^* \leftarrow EOT_m$;
end for
return($R^*$, $\mathcal{F}^*$);
```

TABLE I

PSEUDOCODE OF FINDING AN TRANSMISSION RATE R^* AND FORWARDING CANDIDATE SET $\mathcal{F}^*$

Lemma 5.1: For given R_j and $\mathcal{C}_j$, define $\mathcal{F}_j^r$ as one feasible candidate set that achieves the maximum EOT 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 $\forall\ r$ ($1 \leq r \leq |\mathcal{C}_j|$), we find a feasible $\mathcal{F}_j^r$, s.t. $\mathcal{F}_j^1 \nsubseteq \mathcal{F}_j^r$. Then for 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 Eq. (5) and the fact that $\mathcal{F}_j^1$ achieves the maximum EOT by selecting 1 node, we can derive that the EOT of the new set is larger than that of the $\mathcal{F}_j^r$. It is a contradiction, so the assumption is false, then the Lemma is true. ■

Lemma 5.1 basically indicates that for given R_j and $\mathcal{C}_j$, the candidate achieving the maximum EOT by selecting 1 node from $\mathcal{C}_j$ is contained in the candidate set achieving the maximum EOT by selecting more number of nodes from $\mathcal{C}_j$. Then, we can design an algorithm that greedily adds a new node into the current $\mathcal{F}_j^r$ containing r nodes to get $\mathcal{F}_j^{r+1}$ with $r+1$ nodes. We calculate the EOT for each $\mathcal{F}_j^r$, then returns the maximum one. When the returned set contains no more than 2 nodes, it is indeed the global optimum. Otherwise, it is a suboptimal solution. An interesting finding is that this algorithm almost surely returns the global optimal solution even when the returned set contains more than 2 nodes. This heuristic algorithm FindMEOT is described in Table I, where the input is the multi-rates R_j's and the corresponding $\mathcal{C}_j$'s, and the output is the selected rate R^* and forwarding candidate set $\mathcal{F}^*$.

This algorithm runs in $O(kN^3)$ time, where k is the number of different rates and N is the maximum number of nodes in $\mathcal{C}_j$'s.

VI. PERFORMANCE EVALUATION

We evaluate the one-hop performance as well as the path performance of MGOR that incorporates the FindMEOT algorithm by simulation. We examine the impact of coordination delay on the throughput. We compare the performance of MGOR with the single-rate geographic routing which selects one neighbor with maximum $(Advancement \times PRR)$ [15], [16], and the pure single-rate opportunistic routing which involves all the available next-hop nodes with nodes closer to the destination having higher relay priorities.

A. Simulation Setup

We assume $T_s = T_h + L_{pl}/R_j$, where $T_h = 200\mu s$ and $L_{pl} = 1000 bytes$, and $T_f(i) = i \cdot T_{ACK}$. The simulated network has stationary 36 nodes uniformly distributed in a 1500×1500 m^2 square region. The data rates are 11, 5.5, and 2Mbps. The ACK is transmitted at the basic rate 1Mbps. We also assume an ideal collision-free MAC such that packet loss is only due to the randomness of link quality, and at any time there is only one transmission scheduled. The source and the destination nodes are fixed at two corners across the diagonal of the square area. The source delivers 500 packets to the destination under 10 different node deployments for each protocol.

We use the Nakagami distribution [18] to describe the power x of a received signal:

$$f(x; m, \Omega) = \frac{m^m x^{m-1}}{\Gamma(m)\Omega^m} exp(-\frac{mx}{\Omega}) \tag{7}$$

where Γ is the Gamma function, m denotes the Nakagami fading parameter and Ω is the average received power. We set $m = 1$ in our simulation. Assuming two-ray signal propagation, Ω can be expressed in Eq. (8) as a function of d, the distance between the sender and receiver.

$$\Omega(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^n} \tag{8}$$

where P_t is the transmission power, G_t and G_r the antenna gains, h_t and h_r the antenna heights, and n the path-loss exponent. We set $P_t = 15dbm$, $G_t = G_r = 1$, $h_t = h_r = 1.5m$, and $n = 4$ in our simulation.

We assume a packet is received successfully if the received signal power is greater than the receiving power threshold (P_{Th}). According to 802.11b [19], the P_{Th} for 11, 5.5, and 2Mbps data rates are -82, -87, and -91dbm, respectively. Then by using Eq. (7) and (8), we can derive the PRR at a certain distance d for each data rates.

B. Evaluation Metrics

We define the following evaluation metrics:

- One-hop throughput: number of bit-meters successfully delivered per second medium time in one-hop with unit of $bmps$.
- Path throughput: number of bit-meters successfully delivered per second from the source to the destination in the whole duration of simulation with unit of $bmps$.

C. Simulation Results and Analysis

Fig. 3 shows the one-hop throughput of MGOR, opportunistic routing and geographic routing operating at various transmission rates under various T_{ACK} (which implies different candidate coordination delay). We can observe that the MGOR that incorporates our rate adaptation and candidate selection algorithm achieves better one-hop throughput than the opportunistic and geographic routing protocols transmitting at any single rate. Because it adapts to the channel condition and chooses the best transmission rate for each packet, judiciously selects the forwarding candidates that do help improve the throughput, and carefully prioritize the candidates. For geographic routing, transmitting at higher rate achieves higher one-hop throughput, which indicates that without making use of spatial diversity, it is desirable to transmit packet at higher rate in order to minimize the medium time. However, for opportunistic routing, different rates results in different transmission ranges, which implies different neighborhood diversity chances. Lower rate brings more spatial diversity benefit for opportunistic routing, then gives more chances for the packet to make larger progress to the destination. This benefit may complement its disadvantage of longer medium time. As shown in Fig. 3, opportunistic routing operating at 5.5Mbps even achieves better one-hop throughput than that operating at 11Mbps when the coordination delay becomes larger. It's not surprising to see that opportunistic routing protocols achieves much better throughput than the corresponding geographic protocols under each transmission rates.

Fig. 4 indicates the path throughput of these protocols under various T_{ACK}. It presents the similar trend as the one-hop throughput. An interesting observation is that the path throughput of geographic routing degrades much from the one-hop throughput, while MGOR and opportunistic routing degrade gracefully. Because geographic routing selects only one next-hop forwarding candidate, it has the lowest forwarding reliability in one transmission, then needs more physical transmissions make a packet delivered at the network layer. These retransmissions not only decrease its one-hop throughput, but also introduce more interference to the transmissions on the other links on the path, so

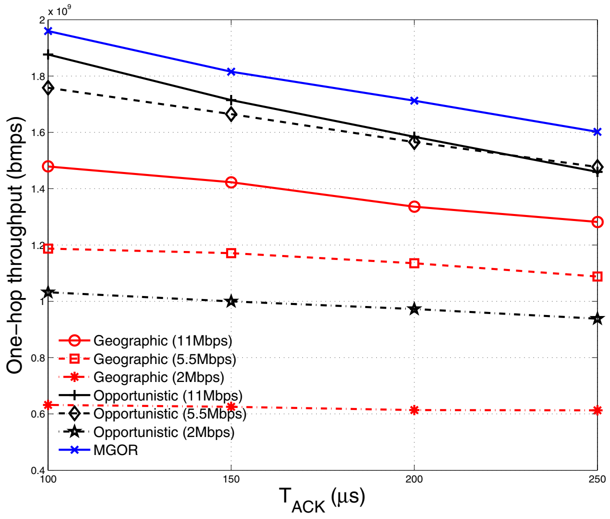

Fig. 3. One-hop throughput under various T_{ACK}

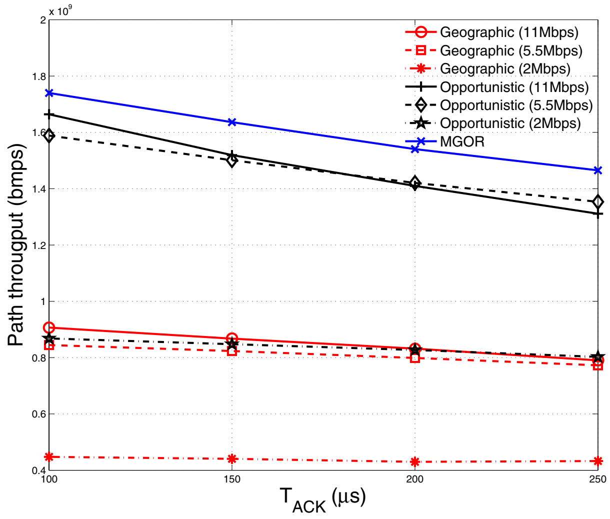

Fig. 4. Path throughput under various T_{ACK}

worsen the path throughput. MGOR and opportunistic routing include multiple forwarding candidates, thus increase the transmission reliability and reduce the retransmissions, then alleviate this intra-flow interference.

VII. CONCLUSION

In this paper, we study multi-rate geographic opportunistic routing (MGOR), and examine the factors that affect its throughput, which includes multi-rate capability, candidate selection, prioritization, and coordination. Based on our analysis, we propose a new local metric, the *expected one-hop throughput* (EOT), to characterize the trade-off between the packet advancement and medium time cost under different data rates. We further propose a rate adaptation and candidate selection algorithm to approach the local optimum of this metric. Simulation results show that MGOR incorporating our algorithm achieves better throughput than the corresponding opportunistic routing and geographic routing operating at any single rate. It indicates that EOT is a good local metric to achieve high path throughput for MGOR.

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