Throughput Improvement of Multi-hop Wireless Mesh Networks with Cooperative Opportunistic Routing

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***Abstract*—This paper proposes cooperative opportunistic routing (COR), a throughput improvement scheme for the cooperative opportunistic routing in multi-hop wireless mesh networks (WMNs). We investigate the two major issues in opportunistic routing, the selection and the prioritization metric for the candidate set. The COR is presented to select and prioritize the candidate node with minimum expected cost. This candidate selection with low expected cost on each transmission constructs a throughput efficient routing path. The COR's robust packet handling strategy is also proposed to avoid duplicated transmission without forwarding list. With more efficient candidate set and packet handling, the average throughput improves by 76% and the end-to-end delay is reduced by 15% in our simulation results.**

Keywords-wireless mesh network; opportunistic routing; forwarding list; wireless routing.

I. INTRODUCTION

Routing protocols for multi-hop wireless mesh networks (WMNs) have been extensively studied. Most of the conventional routing algorithms, such as DSR [1], AODV [2], DSDV [3], and LQSR [4], select the best sequence of the nodes between the source and the destination, and forwards each packet through the selected route. However, these packets are always to be transmitted along the fixed sequence, which fails to exploit benefits of the wireless broadcast and stochastic propagation. A novel routing protocol called opportunistic routing is motivated for the multi-hop WMNs to exploit the broadcast feature of unreliable wireless medium [5-8]. In the opportunistic routing, a node that overhears the transmission and is closer to the destination is allowed to participate in forwarding the packet. Multiple weak links which have the same destination are combined into a strong link; therefore, the feature of multiple paths can be utilized. Besides, instead of predetermining the multi-hop path, the opportunistic routing improves throughput by exploiting the opportunistic reception of candidate nodes to reduce the overhead of transmitting the packet. The procedure of opportunistic routing begins when a source node requests to transmit the packet via broadcast medium. After a random set of receiver nodes receive the packet, the subset of receiver nodes can be chosen as the next relaying candidate nodes. Then the priority of the candidate nodes is set to deliver the packet. Only one of the candidate nodes is selected to forward the packet instead of duplicate transmissions.

The key design challenges of opportunistic routing include the selection and prioritization of candidate set [5]. The problem of candidate set selection has been considered by C. Lott and D. Teneketzis providing a Markov policy theoretic formulation for opportunistic routing in [9]. It is shown that the optimal routing decision is to select the next relaying candidate node based on the expected cost of relaying the packet along to the destination. In the framework of opportunistic routing in [9], the expected cost is adopted to optimize the routing decision of candidate set selection. The prioritization of candidate set also has a large impact on network performance since the candidate nodes will transmit the packet in the prioritized order.

M. Zorzi and R. R. Rao designed a geographical routing protocol called Geographic Random Forwarding (GeRaf) to utilize the location information as the cost metric [6]. GeRaf selects a forwarding list and prioritizes them based on their geo-distances to the destination. However, the metric of geo-distance selection leads to an undesirable deadlock if the packet is occasionally forwarded to a particular node where there is no other next-hop receiver closer to the destination. Additionally, the cost for acquiring location-based information may be too prohibitively high for implement. Without location-based selection, the opportunistic routing in ad hoc networks (OPRAH) proposed by C. Westphal uses the promiscuity of the air interface to overhear other transmissions [7]. The value of the hop count to the destination is suggested to choose and prioritize the forwarding node. But the destination may receive duplicate packets due to the spatially disjoint paths or partially disjoint paths from an intermediate node down to the destination. Besides, OPRAH requires relatively high power consumption. In [8], S. Biswas and R. Morris suggested an extremely opportunistic routing (ExOR) protocol, while impose a strict scheduler on the medium access control (MAC) layer. Owing to the strict scheduler tied with the MAC, each packet contains the forwarding list of nodes that can potentially be forwarded. The metric of expected transmission count (ETX) proposed by D. S. J. D. Couto et al. has been adopted to gather the expected total number of packet transmissions [10]. However, ExOR is short of spatial reuse since all neighboring nodes have to wait for the nodes with higher priority in the forwarding list after a transmission. Moreover, ETX only considers one path with the lowest expected cost and ignores an important aspect of multi-path diversity. In contrast to the highly structured scheduler of ExOR, MAC-independent opportunistic routing and encoding (MORE) introduced by S.

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Chachulski et al. randomly mixes packets before forwarding them [11]. Although the scheduler is not required in MORE, it might induce the duplicated packet transmission and packet loss problems. Recently, X. Mao et al. proposed an energy efficient opportunistic routing (EEOR) protocol through rigorous expected cost analysis [12, 13]. The calculation of expected cost is proposed to select and prioritize the forwarding list. Unfortunately, the EEOR ignores the link probability between the sender and the candidate nodes, which fails to choose the optimal forwarder list. Furthermore, the suggested packet handling protocol losses the original edge of opportunistic routing since the characteristic of hop-by-hop decision is not supported.

This paper selects the candidate set with spatial reuse of neighboring nodes, and prioritizes the candidate list with the minimized total expected cost to perform the opportunistic routing in multi-hop WMNs. The selection of optimized candidate set is first designed in choosing the cost effective forwarding nodes in multi-hop WMNs. The packet handling is also introduced to avoid duplicated transmissions and packet losses. The introduced cooperative opportunistic routing (COR) chooses the candidate list of each node specifically for the optimized expected cost to forward the packet to the destination. The cost metric is designed to optimize the number of expected transmission to forward the packet to the destination in the multi-hop WMN topology. In order to make spatial reuse of neighboring nodes and avoid duplicate transmission, the same forwarding list is not applied for each packet. Instead, we record candidate nodes on each node, and the candidate node is selected from its neighboring nodes. The transmission overhead can also be reduced. We evaluate COR in a mesh grid topology to verify that the proposed strategy improves the average throughput and decrease the end-to-end delay compared with ExOR.

The remainder of the paper is organized as follows. Section II devises the description of the problem assumption, network model, and the metric of transmission cost of opportunistic routing. In section III, the COR algorithm of candidate set selection, expected cost calculation and packet handling is presented to optimize the multi-path WMNs. Then, the simulation is performed to evaluate the performance of our algorithm in section IV. Finally, section V concludes the paper.

II. PROBLEM ASSUMPTIONS AND MODEL

This paper establishes the network architecture to be a wireless multi-hop WMN with unreliable circumstances. The nodes with equal transmission power and cell coverage are uniformly deployed. Their movement is limited during each routing cycle. Each pair of nodes is possibly connected to form a communication link with a link probability. The link probability will periodically be analyzed and updated since each node will broadcast link probe packets and count the number of probes received from its neighbor regularly. The link probability is utilized to represent the probability of successful transmission rate of a communication link. Only the link with success probability above a certain threshold will be taken into account. For each node, any of other nodes with eligible link probability will be considered to be its neighbor. We assume that each transmission is delivered through the orthogonal channels, where the communication channel is symmetric. This assumption is often set in most of the existing routing protocols. Thus, the inter-channel interference is not taken into consideration, and the link probability of each node is independent in accordance with the orthogonal channel.

We divide the types of message in each packet into two categories: the data message and the control message. The data message will be transmitted through the interfered medium and followed with the defined link probability. In contrast, the control message is assumed to be transmitted through robust channel with better channel quality and coding mechanism.

A. Network Model

The multi-hop wireless network is modeled as a graph $G = (V, E)$, where V is the set of nodes and E is the set of bi-directional wireless links. We consider the scenario with $n + 1$ nodes in the network labeled by $V \in \{0, 1, 2, \ldots, |V|\}$, where node 0 is denoted to be the destination. A link between node i and node j is denoted as $(i, j) \in E$ if node j is in the coverage of node i. Let p_{ij} be the link probability that the packet transmitted by node i is successfully received by node j. Let $N(i)$ represent the set of neighboring nodes of node i. We refer to $N(i)$ as the neighboring list for node i, and $|N(i)|$ as the number of elements in $N(i)$. Let $\widehat{N}(i)$, a subset of $N(i)$, represent the candidate nodes of node i. The nodes in $\widehat{N}(i)$ are prioritized with decreasing order. We further assume $C(i)$ as the expected cost of node i to forward packets through prioritized $\widehat{N}(i)$.

B. Expected Cost

This subsection presents the main idea of calculating the expected cost for each node. With respect to the given destination, the expected cost of each node will be accumulated from the given destination denoted as node 0. We assume that the expected cost of node 0 is $C(0) = 0$. We calculate the expected cost of nodes in $V\backslash\{0\}$. Since each node in $V\backslash\{0\}$ is within at least one hop to the destination, each node in $V\backslash\{0\}$ needs to pay the price of its expected cost to send data to the destination.

Consider the following situation, where a node s has the link probability p_{sd} with node d. Accordance to ETX [10], we can directly set the expected transmission times for node s transmitting packet successfully to node d as $1/p_{sd}$. The inverse of link probability taken as the expected transmission times is part of the expected cost in our work. Let ρ_i denote the probability that a packet sent by node i is received by at least one node in $\widehat{N}(i)$, expressed as

$$\rho_i = 1 - \prod_{j \in \widehat{N}(i)} (1 - p_{ij}). \qquad (1)$$

The transmission cost that node i must consume to send a packet to at least one node in $\widehat{N}(i)$ is denoted as $C_t(i)$. Using the inverse of ρ_i, $C_t(i)$ can be calculated as

$$C_t(i) = \frac{1}{\rho_i} = \frac{1}{1 - \prod_{j \in \widehat{N}(i)} (1 - p_{ij})}. \qquad (2)$$

After at least one node in neighboring list received the packet successfully, we then consider the forwarding cost to forward the packet. Here we assume that only one node from the candidate nodes receiving the packet will forward the packet. The forwarding cost that we calculate here could be slightly lower than the actual cost when multiple nodes from candidate nodes could forward the data packet. Let $C_f(i)$ denote forwarding cost that the chosen node could start to propagate the packet. We prioritize the candidate nodes $\widehat{N}(i)$of node i, denoted as

$$\widehat{N}(i) = \{v_1, v_2, \dots, v_{|\widehat{N}(i)|}\}. \quad (3)$$

Notice that [12, 13] sorts the forwarding list according to their expected cost in advance, where $C(v_m) < C(v_n)$ if $m < n$. In contrast, we only prioritize the nodes in $\widehat{N}(i)$ with decreasing order, where node v_m is prior to v_n if $m < n$.

In $\widehat{N}(i)$, node v_1 has the highest priority to forward the packet. Once the node v_1 has received the packet from node i, it will take the responsibility to propagate the packet. The probability that node v_1 forward the packet is p_{iv_1}/ρ_i as conditional probability, and the expected cost by v_1 is $C(v_1)$. Node v_2 will forward the packet only under the condition that node v_1 has not received the packet but v_2 does. So the probability is $\left(1 - p_{iv_1}\right) \cdot p_{iv_2}/\rho_i$ and the cost will be $C(v_2)$. Node v_k forwards the packet only if it receives the packet and node v_j does not receive the packet, where $0 < j < k$. In this case the cost will be $C(v_k)$. Therefore, the forwarding cost $C_f(i)$ can be computed as

$$C_f(i) = \frac{\sum_{j=1}^{|\widehat{N}(i)|}\left(\prod_{k=1}^{j-1}\left(1 - p_{iv_k}\right)\right)p_{iv_j}C(v_j)}{\rho_i}. \quad (4)$$

We let $C(i)$ denote the expected cost by the node i using opportunistic routing strategy to send a packet to the destination, which can be expressed as

$$C(i) = C_t(i) + C_f(i). \quad (5)$$

Both the transmission cost and the forwarding cost are included in the expected cost $C(i)$ of node i.

III. Proposed Method

In the following, the design details of our COR protocol is presented to find the optimized prioritization of candidate nodes to forward the packet such that the average throughput and the end-to-end delay can be improved. When a source node requests to transmit the packet via broadcast medium, a random set of receiver nodes may successfully receive the packet. A subset of receiver nodes will be selected as the forwarding candidates. One of the candidate nodes will be determined to bear the relay responsibility and to be the next source node. Since the candidate nodes will transmit the packet in the prioritized order, the algorithm of nodes selection and prioritization has a large impact on network performance. The node selection is dynamic and depends on the neighboring nodes' expected cost and the link probability to each neighboring node.

A. Candidate Node Selection

Algorithm 1 is proposed to find the optimum candidate nodes. The description of Algorithm 1 is shown in Figure 1. Before the detailed description of Algorithm 1, some notations should be clarified. Let node i be the forwarding node who wants to select its candidate nodes. The neighboring nodes of node i are expressed as $N(i)$, where their expected costs are already given. The input also includes the link probability p_{ij} of node i and its neighbor node v_j, $\forall v_j \in N(i)$. Denote $\widehat{N}(i)$ as the candidate nodes, which is also the subset of neighboring nodes. Nodes in $\widehat{N}(i)$ are prioritized with the decreasing forwarding order. Denote X_i as a subset of neighboring nodes of node i. Then, $Opt_i(X_i, p_{ij})$ is used to generate the optimized expected cost in accordance with the node v_j, and the link probability between node i and node v_j, $\forall v_j \in X_i$. All permutations of nodes in $\widehat{N}(i)$ are compared to find the minimum expected cost $Opt_i(\widehat{N}(i))$ in the descendant order. Moreover, we denote $C(i)$ as the expected cost calculated by equation (5) with the candidate nodes in $\widehat{N}(i)$. To select the proper candidate nodes, we revise the algorithm in [12, 13] with the consideration of the link probability.

In Figure 1, we initializes the candidate nodes to be an empty set, and then inspect each node in the neighboring list in lines 1~2. Lines 3~7 are used to find the optimized permutation and combination of neighboring nodes $N(i)$. Furthermore, this algorithm is inherent in selecting another node with lower expected cost. By this mechanism, we can prevent redundant transmissions from the nodes far from the destination.

Algorithm 1: For a node i selecting the candidate nodes
Input: i: *forwarding node*
$N(i)$: *neighboring nodes of node i*
p_{ik}: *link probability of node i and its neighbor*
Output: $\widehat{N}(i)$: *the candidate nodes of node i*
1: $\widehat{N}(i) = \emptyset$
2: $\Delta = N(i), \forall \{v_j\} \in N(i)$
3: **repeat**
4: **if** $Opt_i(\widehat{N}(i) \cup \{v_j\}, p_{ij}) < C(i)$
5: $\widehat{N}(i) = \widehat{N}(i) \cup \{v_j\}$
6: $\Delta = \Delta \backslash \{v_j\}$
7: **until** $\Delta = \emptyset$

Figure 1. Algorithm of candidate node selection.

B. Expected Cost Calculation

Algorithm 2 shows the pseudo code we address to calculate the expected cost for all nodes. The description of Algorithm 2 is shown in Figure 2. Let $G(V, E)$ be a graph contains multiple nodes in V and link paths in E. For each node i, both neighboring nodes $N(i)$ and link probability p_{ij} are the inputs of this algorithm, where $\forall i \in V$ and $\forall j \in N(i)$. We assume that S be the processing list and $S[1]$ be the node with minimum expected cost in S.

We run Algorithm 2 when the network is just started up. Moreover, it could become more flexible. When a new node comes in or an old node drops out, system can just add its neighboring nodes to the set processing list S, and periodically call Algorithm 2 to update their expected cost. In Figure 2, lines 1~2 initialize the expected cost of each node $i, \forall i \in V$. Then, line 3 calculates the expected cost of the neighboring nodes $C(k)$ of the destination, $\forall k \in N(0)$. Accumulated from the given destination denoted as node 0, lines 4~10 continuously calculate the expected cost through the returned $\widehat{N}(i)$ by Algorithm 1. Until there is no update of all the expected cost, each node i contains its expected cost $C(i)$ and their prioritized candidate neighbor $\widehat{N}(i), \forall i \in V$.

Algorithm 2: For all nodes i calculating the expected costs
Input: $G(V, E)$: *underlying graph*
$N(i)$: *neighboring nodes of each node*
p_{ij}: *link probability of each link*
Output: $C(i)$: *the expected cost for each node*
$C(0) = 0, C(i) = \infty, \forall i \in V$
$S = V$
calculate $C(k)$ *based on* p_{0k} *and* $C(0), \forall k \in N(0)$
repeat
$i = S[1]$, *run Algorithm 1 to find its* $\widehat{N}(i)$
calculate $C(i)$ *based on* p_{ij} *and* $C(j), \forall j \in \widehat{N}(i)$
$S = S \backslash i$
if $C(i)$ *is updated*
$S = S \cup N(i)$
until $S = \emptyset$

Figure 2. Algorithm of expected cost calculation.

C. Packet Handling

Algorithm 3 performs the flows for each node to deal with the packets in its backlog. During each time slot, every node will check its backlog. If there are packets queued in the backlog, the node has the responsibility to transmit the packet toward destination. The routing path is not designed in advance; instead, we choose the next hop just after the packet have been broadcasted. We apply the control message includes the information of acknowledgement (ACK) and forwarding order (FO). After a source node transmits a packet via broadcast medium, each node which has successfully received the packet sends an ACK packet to the source node. The source node chooses a node to bear the relay responsibility and to be the next source node, and then announces this decision using a control FO packet.

The description of Algorithm 3 is shown in Figure 3. In Algorithm 3, a node i intends to forward a packet p through one of the nodes in the prioritized candidate nodes $\widehat{N}(i)$. Let $BroadcastPacket(\alpha)$ be the function to broadcast packet α. Denote Y as a set of nodes. Denote y as the type of packet to be responded. Then, $ReceivedACK(y, Y)$ is defined as the set of nodes in Y who receives the packet y and responds the $ACK(y)$ information. In addition, the function $f_d(\widehat{N}(i), Y)$ is used to generate a descendant ordered list L by prioritizing the set of nodes in Y according to the priority of $\widehat{N}(i)$. The node $L[1]$ denotes the node with the highest priority in L. The function $SendFO(L[1])$ is used to send the FO information to node $L[1]$, and $Drop(\alpha)$ is used to drop the packet α.

In Figure 3, a node i broadcasts the packet and then waits for a while in lines 1~4. Line 5 checks if there are ACKs sent back from $\widehat{N}(i)$. In lines 6~7, if the node i has received ACKs, it collects the nodes that has sent ACK message back, and extract the highest priority one. Lines 8~10 then send the FO information to the selected node and wait for the feedback ACK. If the node i receives the ACK of FO, the packet α will be dropped, and this process will be terminated in lines 11~13. Otherwise, the packet will be broadcasted again.

Algorithm 3: For a node i handling the packet in backlog
Input: α: *a packet to be sent out*
$\widehat{N}(i)$: *prioritized candidate nodes of node i*
01: **repeat**
02: $\Omega_1 = \Omega_2 = L = \emptyset$
03: $BroadcastPacket(\alpha)$
04: *wait for* $ACK(\alpha)$ *from* $\widehat{N}(i)$
05: $\Omega_1 = ReceivedACK\left(\alpha, \widehat{N}(i)\right)$
06: **if** $\Omega_1 \neq \emptyset$
07: $L = f_d(\widehat{N}(i), \Omega_1)$
08: $SendFO(L[1])$
09: *wait for* $ACK(FO)$ *from* $L[1]$
10: $\Omega_2 = ReceivedACK(FO, L[1])$
11: **if** $\Omega_2 \neq \emptyset$
12: $Drop(\alpha)$
13: **until** $\Omega_2 \neq \emptyset$

Figure 3. COR packet handling protocol.

IV. Performance Evaluation

In this section, we evaluate the performance of the proposed algorithm in the case where there is a source that has to route packet to a given destination in multi-hop WMNs. We implement our algorithm with OMNet++ 4.1 on Ubuntu 10.10. We compare our simulation results with ExOR in terms of average throughput and end-to-end delay. Denote n as the dimension of a grid topology. We perform the proposed algorithm with the topology consisting of a random grid topology of $n \times n$ nodes, where the simulated terrain is divided into $n \times n$ cells and each node is placed randomly within a cell. For example, node 0 is assumed to be the destination and node 15 is the source node in a 4×4 grid topology. We randomly generate the link probabilities between these nodes. The probabilities are divided into three ranges, which are uniformly distributed between 0.1-0.3 as weak quality, 0.4-0.6 as median quality, and 0.7-0.9 as high quality. We also implement the ExOR as the baseline comparison, by using the ETX-based shortest-path routing protocol. To avoid the inconsistence in current evaluation methodologies, we take one packet per batch. At each run of the simulation, we use the same random seed. This can make sure that we compare two strategies fairly.

In our simulation, we mainly use two metric to evaluate the protocol performance: the average throughput and the end-to-end delay. The first metric for comparison is the average throughput. Since the COR and the ExOR are multi-path routing strategies, the main goal is to improve the average throughput in wireless multi-hop networks. We let the source node send up to 100 packets toward its destination in sequence. In most cases, packets will be relayed to the destination node through different paths. We take the average throughput to be the total number of received packets divided by total processing times. Sometimes the packet will not be transmitted successfully, and then it will be queued in the job backlog, which increases the processing time. The COR chooses better

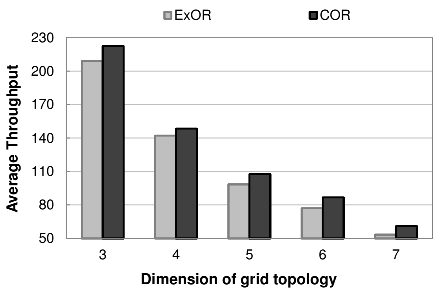

Figure 4. Avg. throughput with high link quality.

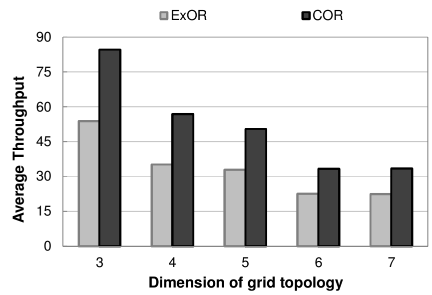

Figure 5. Avg. throughput with medium link quality.

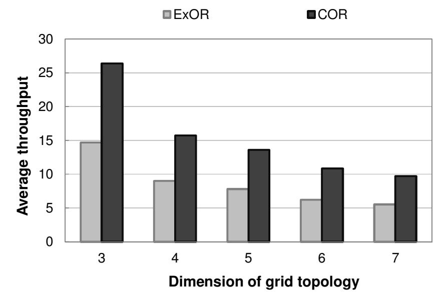

Figure 6. Avg. throughput with weak link quality.

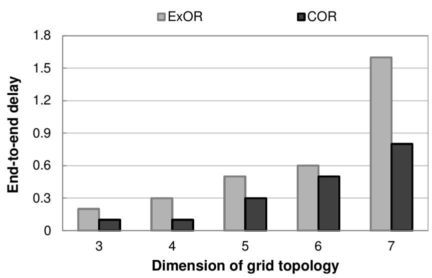

Figure 7. End-to-end delay with high link quality.

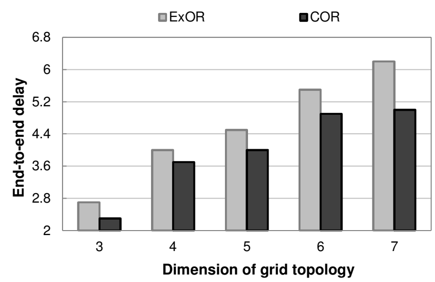

Figure 8. End-to-end delay with medium link quality.

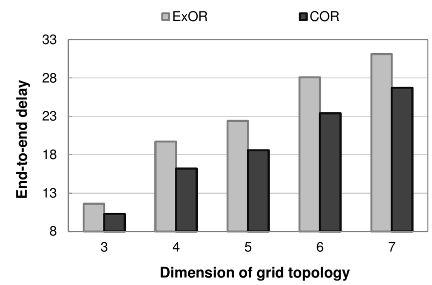

Figure 9. End-to-end delay with weak link quality

relay nodes, and thus we can have more chances to prevent the halting time. Figure 4, Figure 5 and Figure 6 shows the comparisons of average throughput with ExOR. We observe that the network size dominates the average throughput, which decreases with the growth of grid dimension n. The significant improvement is observed under the noisy channels. The proposed method gets much better throughput than ExOR in weak channel quality. The delay time is another criterion used to evaluate the performance of a routing protocol. We measure the average end-to-end delay time for a pair of source and destination. The end-to-end delay of a packet is defined as the average time duration in the queuing backlog until the transmission is completed. We illustrate the average end-to-end delay time in Figure 7, Figure 8 and Figure 9. As shown in those figures, the end-to-end delay of the proposed method is shorter than ExOR. This is mainly because ExOR chooses the relay nodes only based on ETX metric. In comparison, we simultaneously utilize multiple path features and therefore the performance becomes more stable.

V. Conclusion

To select and prioritize the neighboring nodes, we explore the expected cost metric to select the optimum candidate set. We propose algorithms to select candidate set and calculate the expected cost for each node. The packet handling protocol is also proposed to forward packets without unnecessary transmissions. The simulation results show that the proposed strategy improves the average throughput by 76% and end-to-end delay by 15% with weak link quality.

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