Robust Forwarding for Reactive Routing Protocols in Wireless Ad Hoc Networks with Unreliable Links

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Abstract—Wireless ad hoc networks can experience significant performance degradation under fading channels. In this work, we present a robust forwarding extension (RFE) for reactive routing protocols in wireless ad hoc networks. RFE is designed to enhance existing reactive routing protocols to provide reliable and energy-efficient packet delivery against the unreliable wireless links. Specifically, we introduce a biased backoff scheme during the route discovery phase to find a robust virtual path, which can provide more cooperative forwarding opportunities. Along this virtual path, data packets are greedily progressed toward the destination through nodes cooperation. We extend the widely used AODV routing protocol with RFE to study its performance. Through extensive simulations, we demonstrate that AODV-RFE effectively improves the reliability, end-to-end energy efficiency and latency.

I. INTRODUCTION

Providing reliable and energy-efficient communication in wireless ad hoc networks is a challenging problem. This is because, in reality, the link conditions in wireless networks can be highly unreliable due to many factors such as interference, attenuation, and channel fading [1] [2]. To forward a packet reliably, it may need retransmissions at each hop. This results in undesirable delay as well as waste of energy. Cooperative forwarding has been considered as an effective strategy to combat fading channels, thus improving the robustness, end-to-end latency and energy efficiency in wireless ad hoc networks [3] [4].

The idea behind cooperative forwarding is to take advantage of the broadcast nature of wireless communication, involving multiple neighbors of the sender into local forwarding. Since the wireless medium is shared, each node can overhear data packets sent by its neighbor. Therefore, multiple neighbors could cooperatively cache the overheard data packet. When the intended receiver fails to receive the packet correctly, those neighbors could deliver the packet to the downstream node (possibly the intended receiver or the node closer to the destination). In this way, cooperative forwarding improves the transmission reliability, at the same time avoids the undesirable additional retransmissions.

Reactive (also referred to as on-demand) routing protocols [5] are designed to reduce the bandwidth and storage cost used in table driven protocols. This strategy applies the on-demand procedures to dynamically build the route between a source and a destination. Routes are generally created and maintained by two different phases, namely: route discovery and route maintenance. Route discovery usually occurs on-demand by flooding a Route Request (RREQ) through the network, i.e., when a node has data to send, it broadcasts a RREQ. When a route is found, the destination returns a Route Reply (RREP), which contains the route information (either the hop-by-hop information or complete addresses from the source to the destination) traversed by the RREQ.

In this work, we present the design of a robust forwarding extension (RFE) for reactive routing protocols in wireless ad hoc networks with unreliable links. RFE can augment most existing routing protocols to combat the channel variation by utilizing the local path diversity in the link layer. We demonstrate its effectiveness and feasibility by implementing RFE over the widely used AODV (ad hoc on-demand distance vector routing) [6] routing protocol in the NS-2 [7] simulator. As a new addition to the cooperative routing design space, two following contributions make RFE different from existing cooperative routing protocols.

(i) We introduce a biased backoff scheme in the route discovery phase, which enables the RREQ to travel faster along the path with more alternative forwarding candidates (also called helpers). The RREP is sent back to the source along the reverse route to implement the forward path setup, at the same time notify potential helpers to implement cooperation. In this way, a robust virtual path that can provide more cooperative forwarding opportunities is found with low overhead.

(ii) We propose a simple yet effective cooperative forwarding scheme. The discovered virtual path, also called guide path, points out the general direction toward the destination. Along the guide path, even without utilizing the location information, data packets can be greedily forwarded toward the destination through nodes cooperation.

The remainder of this work is organized as follows. Section II surveys the related work. Section III elaborates the detailed design of RFE. Section IV provides the simulation results followed by the conclusion in Section V.
II. RELATED WORK

Cooperative (also known as opportunistic) routing to combat fading channels in wireless networks has been an active research area. A number of routing protocols have been proposed for this purpose [8]–[12]. ExOR [8] is a representative opportunistic routing protocol. However, ExOR, as well as SOAR [12], requires every node to measure and maintain the global topology of the network.

In GeRaF (geographic random forwarding) [9], the forwarding node broadcasts data packets to a collection of neighbors which are prioritized according to their advancements toward the destination. The node that is closest to the destination will be chosen as next-hop forwarder in a distributed manner. In [10], the authors proposed a contention-based geographic routing protocol which incorporates the cooperative relaying and leapfrogging. RRP [4] was proposed to enhance the robustness of routing against path breakage, e.g., due to channel interference or node mobility. The issue addressed in RRP is how nearby nodes cooperatively forward packets for unreliable mobile wireless sensor networks. In CBF (cluster-based forwarding) [3], each node forms a cluster such that any node in the next-hop’s cluster can take the forwarding task. However, these existing works assume that a path has already been established between a source and a destination, leaving the robust end-to-end path discovery unaddressed.

In [13], which we refer to as REPF (reliable and efficient packet forwarding), the authors presented a cross-layer approach based on AODV and 802.11 MAC to utilize the local path diversity. However, REPF restricts the helpers within a very limited scope, i.e., only the nodes which can connect the two-hop away primary forwarding nodes are considered as helpers. Thus, it restricts the cooperative forwarding within a very limited scope.

In this section, we present the detailed design of the proposed robust forwarding extension (RFE), which is compatible with most existing reactive routing protocols in wireless ad hoc networks.

A. Assumptions

We assume the wireless network is densely deployed, each node has plenty of neighbors. Since cooperative routing is suitable only for networks with higher node densities (e.g., more than 10 neighbors per node) [14]. Each node periodically sends HELLO messages to keep track of their neighborhood information. The HELLO message contains the node id (address) of its one-hop neighbors and the packet reception ratio (PRR) of corresponding links, which can be estimated by the link quality indicator (LQI) or received signal strength indicator (RSSI) reported by the physical layer. After the HELLO message exchange, each node keeps the two-hop neighborhood information. In [15], through a set of real experiments, the authors reported that the size of the packets has a direct relationship with the PRR in wireless networks. RFE is also based on the assumption that small control messages, such as RREQ and RREP, have much higher PRRs than data packets.

B. Motivation

Before providing the detailed design, we first illustrate the motivation of RFE. We know the essential of cooperative forwarding is actually the cooperative caching in the neighborhood, by taking advantage of the overhearing of wireless communication. Nearby nodes that hold the copies of data could serve as caches, thus the downstream node could retrieve the packet from any of them [4]. Intuitively, the path with more nearby nodes (potential helpers) may possibly provide more reliable and efficient packet delivery against the unreliable links. RFE aims to find such a virtual path, which is used to guide the packets progressed toward the destination. This virtual path is called as a guide path, in which the nodes are called guide nodes. As shown in Fig. 1, nodes C and F are the guide nodes.

C. Robust guide path discovery

1) RREQ propagation: When a node receives a nonduplicate RREQ message, it stores the upstream node id and RREQ’s sequence number for reverse route learning. Instead of rebroadcasting the RREQ immediately in existing reactive routing protocols, we introduce a biased backoff scheme at the current RREQ forwarding node intentionally. The aim of this operation is to amplify the differences of RREQ’s traversing delays along different paths. This operation enables the RREQ to travel faster along the preferred path according to a certain defined metric.

Let \( v_i \) and \( v_j \) denote the last-hop node and current forwarding node of a RREQ, respectively. Let \( N(i) \) denote the set of \( v_i \)'s one-hop neighbors. We define a helper \( v_h \) between \( v_i \) and \( v_j \) as the common neighbor of \( v_i \) and \( v_j \), satisfying \( P_{lk} > P_{kj} \text{ and } P_{kj} > P_{lj} \), where \( P_{lj} \) is the PRR between \( v_l \) and \( v_j \). For cooperative routing, there exists an implicit constraint. That is, the nodes in the helper set should be able to hear from each other with a reasonably high probability. Let \( H(i,j) \) denote the set of helpers between \( v_i \) and \( v_j \). In other words, \( H(i,j) \) is the common neighbor set between \( v_i \) and \( v_j \) on the premise that any pair of nodes in \( H(i,j) \) can hear
from each other, and \( \forall v_k \in H(i,j), P_{ik} > P_{ij} \), \( P_{kj} > P_{ij} \). \( H(i,j) \subseteq \{N(i) \cap N(j)\} \).

![Diagram](image)

**Fig. 2.** An example illustrating the biased backoff scheme for RREQ propagation during the route discovery phase. The RREQ that travels along the path \([S\rightarrow C\rightarrow F]\) arrives at the Dest first.

Let \( T_{\text{backoff}} \) denote the backoff delay at the current forwarding node \( v_j \), who receives a RREQ from \( v_i \). \( T_{\text{backoff}} \) is calculated as defined in Eq. (1).

\[
T_{\text{backoff}} = \frac{\text{HopCount}}{k} \cdot \tau, \quad v_k \in H(i,j)
\]

where \( \tau \) is a time slot unit; the \( \text{HopCount} \) is the RREQ’s hop distance from the source node thus far.

Fig. 2 illustrates the biased backoff scheme. The current RREQ forwarding node assumes itself as a guide node, and considers the last-hop node as its upstream guide node. For example, Nodes A, B, and C receive a RREQ from the source S. For node C, it considers itself as a guide node and S as the upstream guide node. From the local neighbor table, C knows that A and B are helpers. Then, it calculates its \( T_{\text{backoff}} \). The figures in braces represent a helper’s PRRs with the upstream guide node and the current forwarding node, respectively, e.g., \( \{0.8, 0.6\} \) besides the helper A means \( P_{sa} = 0.8 \) and \( P_{ac} = 0.6 \). At node C, the backoff delay is about 0.57\( \tau \). It has a shorter backoff delay compared with A and B. When the backoff timer expires, the RREQ is rebroadcasted. Consequently, node C has a higher priority to forward the RREQ. Similarly, node F forwards the RREQ before D and E. Thus, the RREQ that travels along the path \([S\rightarrow C\rightarrow F]\) arrives at the Dest first.

From Eq. (1), we can see that the higher priority is possibly given to the path with more potential helpers. When a RREQ reaches the destination, it replies a RREP message back to the source along the reverse route. In case of receiving the same RREQ several times, the destination shall only reply the first received RREQ and neglect others. Algorithm 1 describes how a node handles a received RREQ.

2) **RREP propagation:** When a node receives a RREP, it checks if it is the selected next-hop (the upstream guide node) of the RREP. If that is the case, it realizes that it is on the guide path to the source, thus it marks itself as a guide node. Then, it gets its upstream guide node id for this RREP and forwards it. In this way, the RREP is propagated by each guide node until it reaches the source via the reverse route of the corresponding helper.

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According to Algorithm 1, the node \( v_j \) that receives a RREQ \( R_{\text{RREQ}} \) from \( v_i \) first checks if the received RREQ is non-duplicate. If the RREQ is non-duplicate, it checks if the RREQ is destined to node \( v_j \). If the RREQ is destined to node \( v_j \), it sends out a RREP; otherwise, it drops the RREQ.

**Algorithm 1:** How a node \( v_j \) handles the RREQ received from node \( v_i \).

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In RFE, the RREP has two-fold functions. It not only implements the forward path setup, i.e., marking guide nodes along the reverse route, but also notifies the potential helpers to implement cooperative forwarding. Specifically, two sets of

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helpers and their relay priority assignment are included in the RREP. Supposing $v_{i-1}$, $v_i$ and $v_{i+1}$ are three adjacent guide nodes, the upstream link helper set $H(i-1, i)$ and downstream link helper set $H(i, i+1)$ together with their PRRs toward the corresponding downstream guide nodes are piggybacked onto the RREP when node $v_i$ forwards it. Thanks to the broadcast nature of wireless communication, all the helpers in $H(i-1, i)$ are expected to overhear this RREP. When the guide node $v_{i-1}$ receives the RREP from $v_i$, it records its downstream guide node $v_i$ and $H(i-1, i)$. While when the upstream link helpers in $H(i-1, i)$ receive the RREP, they record $v_{i+1}$, $H(i, i+1)$, $v_i$ and $H(i-1, i)$. Algorithm 2 describes how a node handles the RREP received from its downstream guide node $v_i$.

Fig. 3 is an example illustrating the RREP propagation corresponding to Fig. 2. When the guide node F forwards a RREP to its upstream guide node C, for example, helper D overhears this RREP and records the piggybacked information $\{\text{Dest}, G, F, E, D\}$. D’s one-hop neighbor set $N(D)$ is $\{B, C, E, F, G\}$. Therefore, its potential forwarding candidates when forwarding data packets toward the $\text{Dest}$ would be $N(D) \cap \{\text{Dest}, G, F, E, D\} = \{G, F, E\}$.

![Fig. 3. An example illustrating the RREP propagation to implement cooperative forwarding in RFE. $v_{i-2}$, $v_{i-1}$, $v_i$ and $v_{i+1}$ are adjacent guide nodes in sequence.](image)

### D. Cooperative forwarding

The cooperative forwarding procedure in RFE is described as follows. The source broadcasts a data packet, which includes the list of forwarding candidates (helpers and the downstream guide node) and their priorities. Those candidates follow the assigned priorities to relay the packet. For each candidate, if having received the data correctly, it will start a timer whose value depends on its priority. The higher the priority is, the shorter the timer will be. The candidate whose timer expires will reply an ACK to notify the sender, as well as to suppress other contenders’ backoff timers. Then it rebroadcasts the data packet toward its downstream link. If no forwarding candidate has successfully received the packet, the sender will retransmit the packet if the retransmission mechanism is enabled. Denote $t(k)$ as the backoff timer value of the $k^{th}$ candidate. Since the lower priority forwarding candidate needs to wait and confirm that no higher priority candidate has relayed the packet before it takes the forwarding task, $t(k)$ should be an increasing function of $k$. Suppose the link layer protocol is based on IEEE 802.11 MAC, $t(k)$ can be defined as Eq. (2).

$$ t(k) = (T_{SIFS} + T_{ACK} + T_{PropagationDelay}) \cdot k $$  \hspace{1cm} (2)

where $T_{SIFS}$ is the value of Short Inter Frame Space in 802.11 and $T_{ACK}$ is the transmission delay of an ACK.

In order to forward data toward the destination with minimum number of transmissions, the relay priority rule\(^2\) applies the basic greedy forwarding rule in geographic routing, i.e., data packets are greedily forwarded to the neighbor geographically closest to the destination. Note that RFE releases the necessity of utilizing location information, while enabling data packets to be greedily forwarded toward the destination with the help of the discovered robust guide path.

From the realistic link conditions in wireless networks, a helper with a higher PRR toward the downstream guide node possibly has a shorter distance from that guide node. Therefore, the relay priority rule is as follows. When a guide node $v_{i-1}$ takes the forwarding task, the downstream guide node $v_i$ has the highest priority; and the helpers in $H(i-1, i)$ are descendingly ordered according to their PRRs toward $v_i$. When a helper $v_k$ in $H(i-1, i)$ takes the forwarding task, the forwarding candidates include three parts: (1) the helpers who have higher priorities than $v_k$ in $H(i-1, i)$; (2) the downstream guide node $v_i$; and (3) $N(k) \cap \{H(i, i+1) \cup \{v_{i+1}\}\}$. Their relay priorities are $(3) > (2) > (1)$.

Revisiting the example in Fig. 2 and Fig. 3, we show the helpers and their priorities at each hop when forwarding data in Fig. 4(a). The helper set and their priorities at the first hop are $\{C, B, A\}$. Suppose guide node C fails to receive the packet correctly, while helper B successfully gets the packet, as shown in Fig. 4(b), B takes the forwarding task instead of C. Then B updates its helper set as $\{D, C\}$ and forwards the data to its downstream potential forwarders.

### IV. SIMULATION

In this section, we present performance evaluation results. We implement RFE as an extension for AODV [6], named AODV-RFE, using the NS-2 simulator, and compare the performance with AODV, REPF [13]. In order to show that RFE enables data packets to be greedily progressed toward

\(^2\)The relay priority rule can also adopt other variant metrics, e.g., the one-hop throughput metric [11] to achieve the best path throughput.
the destination, we also report the simulation results of the geographic opportunistic routing (GOR). All the results have been averaged over 100 runs, and the related standard deviations are provided as error bars.

A. Simulation settings

Since the relay priority rule in RFE aims to improve the energy efficiency, we implement GOR as follow: all the one-hop neighbors that are nearer than the current forwarding node toward the destination and can hear from each other are selected as helpers, and the nodes closer to the destination are given higher relay priorities. In AODV, the link layer retransmission is enabled, i.e., at most 3 retransmissions at each hop. The other protocols do not adopt the retransmission mechanism.

We carry out both grid topology and random topology tests in a 200m×200m square area. We define the node density as the number of nodes deployed in the 200m×200m field. The node transmission range r is set to 50m. The destination is positioned at bottom left (0m,0m), and the source is positioned at top right (200m,200m). In AODV-RFE, the system parameter τ is set 0.005s. Denote γ as the packet size ratio between a control message (the ACK) and a data packet, and γ is set 0.1. The link layer protocol is a modified version of IEEE 802.11 MAC, and T_{SIFS}=10μs.

We use the Nakagami distribution defined as (3) to describe the power x of a received signal:

\[
f(x,m,\Omega) = \frac{m^m x^{m-1}}{\Gamma(m)\Omega^m} \exp\left(-\frac{mx}{\Omega}\right) \tag{3}\]

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 TwoRayGround signal propagation, Ω can be expressed in (4) as a function of d, the distance between the sender and receiver.

\[
\Omega(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^\alpha L} \tag{4}
\]

where \(P_t\) is the transmission power, \(G_t\) and \(G_r\) are the antenna gains, \(h_t\) and \(h_r\) are the antenna heights, \(L\) is the loss factor, and \(\alpha\) is the path-loss exponent. We set \(G_t = G_r = 1\), \(h_t = h_r = 1.5m\), \(L = 1\), 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. Then by using (3) and (4), we can derive the PRR at a certain distance \(d\) [11].

We choose three evaluation metrics. (i) Packet delivery ratio: the ratio of the amount of packets received by the destination to the total amount of packets sent by the source. (ii) Normalized sending cost: we define the normalized energy cost for sending a data packet as one cost unit. Therefore, the energy cost for sending a control message is 0.1 (when \(\gamma = 0.1\)) cost unit. The cost of a transmission consists of the sending cost of the sender, and the receiving cost of its one-hop neighbors. Given an evenly distributed network, the transmission cost is proportional to the sending cost. Thus, the sending cost metric reflects the communication overhead and energy efficiency. (iii) End-to-end delay: the time taken for a packet to be transmitted from the source to the destination.

B. Simulation results

1) Grid topology test: In the grid topology, nodes are uniformly placed. Fig. 5 shows the results when we vary the node density from \(9 \times 9\) to \(14 \times 14\).

Fig. 5(a) illustrates the packet delivery ratio under different node densities. We observe that, AODV-RFE and GOR achieve almost 100% packet delivery ratio. This is because they take full advantage of the local forwarding opportunities. With the increase of the node density, the packet delivery ratio in both AODV and REPF increases. Although 3 retransmissions are allowed in AODV, the packet delivery ratio is around 70% on average. REPF can only provide about 20% packet delivery ratio averagely. The reason is that REPF restricts the helpers within a very small scope.

Fig. 5(b) and Fig. 5(c) report the changes of the normalized sending cost and end-to-end delay when increasing the node density, respectively. Note that we only consider the successful end-to-end transmissions. REPF may yield even worse results if the failed end-to-end transmissions are counted. Even this, AODV-RFE shows the performance improvement.

We also observe that the grid topology influences the routing performance a lot. For example, in \(12 \times 12\) grid topology, AODV achieves up to 94% packet delivery ratio. In \(14 \times 14\) grid topology, AODV behaves much better than in other grid topologies. This is because, according to our lossy link model, the available one-hop neighbors can provide better accumulative PRRs on average in these grid topologies.

2) Random topology test: In the random topology, we vary the node density from 100 to 200. The random topologies are generated by the setdest tool in NS-2. The evaluation results are shown in Fig. 6.

Fig. 6(a) depicts the performance comparison on the packet delivery ratio. AODV-RFE shows obvious improvements compared with AODV and REPF. Fig. 6(b) and Fig. 6(c) illustrate the results of the normalized sending cost and end-to-end delay, respectively. They clearly show that the performance of AODV-RFE approaches to GOR (used as a comparison in ideal condition), although without utilizing the location information.

From Fig. 5 and Fig. 6, we see that AODV-RFE is comparable to GOR. Compared with AODV and REPF, it remarkably improves the packet delivery ratio. Although only counting the successful end-to-end transmissions, AODV-RFE yields satisfactory results in terms of the end-to-end energy efficiency and latency. Besides, we also compare the route discovery overhead, we find that REPF incurs much higher communication overhead and increased network load during the route discovery phase, since it allows duplicate RREP packets propagating in order to find a better virtual path.

V. CONCLUSION

In this work, we presented RFE, which can augment most existing reactive routing protocols in wireless ad hoc networks to provide reliable and energy-efficient packet delivery against
the unreliable wireless links. We introduced a biased backoff scheme in the route discovery phase to find a robust virtual path with low overhead. Although without utilizing the location information, data packets can be still greedily progressed toward the destination along the virtual path, thus RFE provides very close routing performance to the geographic opportunistic routing protocol. We extended AODV with RFE to demonstrate its effectiveness and feasibility. Simulation results showed that AODV-RFE can significantly improve robustness, it achieves nearly 100% packet delivery ratio in dense networks, and it also effectively improves the end-to-end energy efficiency and latency.

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