R3E: Reliable Reactive Routing Enhancement for Wireless Sensor Networks

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***Abstract*—Providing reliable and efficient communication under fading channels is one of the major technical challenges in Wireless Sensor Networks (WSNs), especially in Industrial WSNs (IWSNs) with dynamic and harsh environments. In this work, we present the Reliable Reactive Routing Enhancement (R3E) to increase the resilience to link dynamics for WSNs/IWSNs. R3E is designed to enhance existing reactive routing protocols to provide reliable and energy-efficient packet delivery against the unreliable wireless links by utilizing the local path diversity. Specifically, we introduce a biased backoff scheme during the route discovery phase to find a robust guide path, which can provide more cooperative forwarding opportunities. Along this guide path, data packets are greedily progressed toward the destination through nodes' cooperation without utilizing the location information. Through extensive simulations, we demonstrate that compared to other protocols, R3E remarkably improves the packet delivery ratio, while maintaining high energy efficiency and low delivery latency.**

***Index Terms*—Industrial wireless sensor networks; reliable forwarding; opportunistic routing; unreliable wireless links**

I. INTRODUCTION

WIRELESS Sensor Networks (WSNs) are replacing the traditional wired industrial communication systems since the Industrial Wireless Sensor Networks (IWSNs) offer several advantages including easy and fast installation and low-cost maintenance [1]. IWSN applications, such as factory automation, industrial process monitoring and control, and plant monitoring, require reliability and timeliness in forwarding messages among nodes [2]. However, the traditional routing protocols, such as AODV [3], AOMDV [4] and DSR [5], may find their limitations in industrial installations due to the harsh environmental conditions, interference issues, and other constraints [6].

In IWSNs, transmission failures can result in missing or delaying of process or control data. And missing the process or control deadline is normally intolerable for industrial applications, as it may cause chaos in industrial automation, or possibly terminate the automation, ultimately resulting in economic losses [7]. The sensed data should be reliably and timely transmitted to the sink node, and the programming or re-tasking data for sensor node operation, command, and query should be reliably delivered to the target nodes [8]. It is also required that these networks can operate for years without replacing the device batteries [9]. Therefore, the reliability, timeliness, and energy efficiency of data forwarding are crucial to ensure proper functioning of an IWSN. However, one of the major technical challenges for realization of IWSNs is to provide reliable and efficient communication in dynamic and harsh environments [1], [10]. This is because, in harsh industrial environments, sensor nodes may be subject to Radio Frequency (RF) interference, highly caustic or corrosive environments, high humidity levels, vibrations, dirt and dust, or other conditions that challenge network performance [8].

Since the varying wireless channel conditions and sensor node failures may cause network topology and connectivity changes over time, to forward a packet reliably at each hop, it may need multiple retransmissions. This results in undesirable delay as well as additional energy consumption. Opportunistic routing (OR) [11]–[16] has been proposed as an effective cross-layering technique to combat fading channels, thus improving the robustness and energy efficiency in wireless networks. The idea of opportunistic routing 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 neighbors. In the network layer, a set of forwarding candidates are specified in the data packet and these nodes will follow the assigned priorities to relay the packet. Essentially, only one node is chosen as the actual forwarder at the MAC layer in an *a posteriori* manner.

Reactive routing protocols [3], [4], [17] are designed to reduce the bandwidth and storage cost consumed in table driven protocols. These protocols apply 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 an RREQ (ROUTEREQUEST) through the network, i.e., when a node has data to send, it broadcasts an RREQ. When a route is found, the destination returns an RREP (ROUTEREPLY), which contains the route information (either the hop-by-hop information [3] or complete addresses from the source to the destination [5]) traversed by the RREQ.

In this work, we propose a *Reliable Reactive Routing Enhancement* (R3E) to increase the resilience to link dynamics for WSNs/IWSNs. Our design inherits the advantages of opportunistic routing, thus achieving shorter end-to-end delivery delay, higher energy efficiency and reliability. R3E is designed to augment existing reactive routing protocols to combat the channel variation by utilizing the local path diversity in the link layer. As a new addition to the cooperative forwarding

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*Corresponding author: chenglong@buaa.edu.cn design space in WSNs/IWSNs, our major contributions are as follows:

- We consider the effect of route discovery on the cooperative forwarding performance, and combine the solutions to reliable route discovery and efficient cooperative forwarding problems. A robust virtual path that can provide more cooperative forwarding opportunities is found with a low overhead in the route discovery phase, which not only implements the forward path setup in reactive routing, but also facilitates cooperative forwarding along the discovered path.
- We propose a simple yet effective cooperative forwarding scheme. Along the discovered virtual path, data packets can be greedily forwarded toward the destination through nodes' cooperation without utilizing location information.
- Through comprehensive performance comparisons, we demonstrate the effectiveness and feasibility of R3E design, which is compatible with most existing reactive routing protocols in WSNs/IWSNs.

The remainder of this work is organized as follows. Section II describes the network model and motivation. Section III elaborates the design of R3E. Section IV provides the simulation results followed by the related work in Section V. Finally, Section VI concludes the paper.

II. NETWORK MODEL AND MOTIVATION

A. Network Model

We consider a dense multi-hop static WSN deployed in the sensing field. Since opportunistic routing is normally effective for wireless networks with higher node densities (e.g., more than 10 neighbors per node) [18], we assume each node has plenty of neighbors. When a node has packets to send to the destination, it launches the on-demand route discovery to find a route if there is not a recent route to a destination.

We assume that the MAC layer provides the link quality estimation service. There has been a lot of existing work on how to measure wireless link quality in an efficient and accurate manner. We can use a representative link estimation method, such as [19], [20]. In [21], through a set of real experiments, the authors reported that the size of the packets has a direct relationship with the Packet Reception Ratio (PRR) in wireless networks. Short control messages, such as RREQ and RREP, have higher PRRs than data packets.

Each node periodically sends HELLO messages to keep track of its neighborhood information. The HELLO message contains the IDs (addresses) of a node's one-hop neighbors and the PRRs of the corresponding links. After the HELLO message exchange, essentially, each node maintains the two-hop neighborhood information.

B. Motivation

Before providing the detailed design, we first illustrate the motivation behind R3E design. The idea of opportunistic routing is to utilize the path diversity for cooperative caching. That is, in each hop, neighboring nodes that hold the copies of a data packet serve as caches, thus the downstream node could retrieve the packet from any of them [22]. The rationale is that, the path with higher spatial diversity (more potential helper nodes) may possibly provide more reliable and efficient packet delivery against the unreliable links. With this observation, we aim to find such a reliable virtual path to guide the packets to be progressed toward the destination. We call this virtual path a *guide path*, in which the nodes are named as *guide nodes*. As shown in Fig. 1, $[S \rightarrow C \rightarrow G \rightarrow Dest]$ is a guide path, and nodes C and G are the guide nodes. The guide path points out the general direction toward the destination, and the routing decision is made a *posteriori*, i.e., the actual forwarders are chosen based on the packet reception results at each hop.

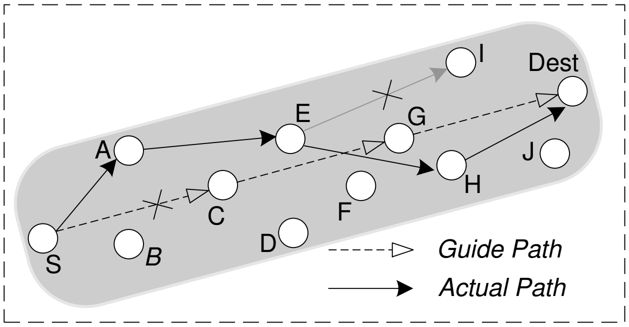


Fig. 1. An example of the guide path

III. MAIN DESIGN

In this section, we first present the R3E functional architecture overview, followed by a detailed description of R3E design, which is compatible with most existing reactive routing protocols in WSNs/IWSNs.

A. Architecture Overview

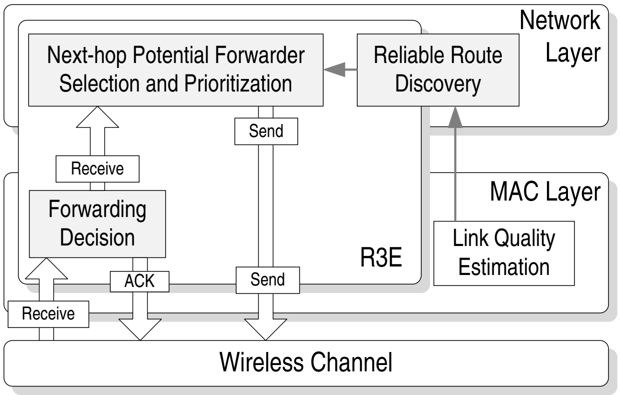


Fig. 2. Functional architecture overview of R3E

Fig. 2 illustrates an overview of the functional architecture of R3E, which is a middle-ware design across the MAC and the network layers to increase the resilience to link dynamics for WSNs/IWSNs. The R3E enhancement layer consists of three main modules, the reliable route discovery module, the potential forwarder selection and prioritization module, and the forwarding decision module. The helper node and potential forwarder are interchangeable in this work.

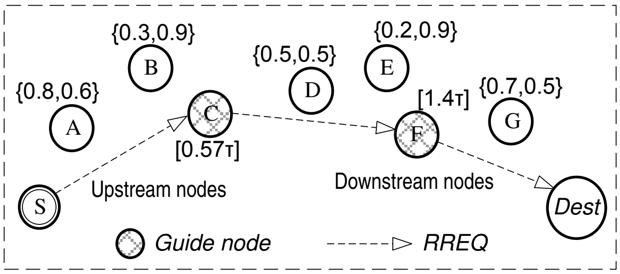


Fig. 3. An example illustrating the biased backoff scheme for RREQ propagation during the route discovery phase. The RREQ that travels along the path $[S \rightarrow C \rightarrow F]$ arrives at the $Dest$ first.

The reliable route discovery module finds and maintains the route information for each node. During the route discovery phase, each node involved in the cooperative forwarding process stores the downstream neighborhood information. That is to say, when a node serves as a forwarder, it already knows the next-hop forwarding candidates along the discovered path.

The other two modules are responsible for the runtime forwarding phase. When a node successfully receives a data packet, the forwarding decision module checks whether it is one of the intended receivers. If yes, this node will cache the incoming packet and start a backoff timer to return an ACK message, where the timer value is related with its ranking in the intended receiver list (called forwarding candidate list). If there is no other forwarder candidate with higher priority transmitting an ACK before its backoff timer expires, it will broadcast an ACK and deliver the packet to the upper layer, i.e., trigger a receiving event in the network layer. Then, the potential forwarder selection and prioritization module attaches the ordered forwarder list in the data packet header for the next hop. Finally, the outgoing packet will be submitted to the MAC layer and forwarded towards the destination.

B. Reliable Guide Path Discovery

1) ROUTEREQUEST (RREQ) *propagation:* If a node has data packets to send to a destination, it initiates a route discovery by flooding an RREQ message. When a node receives a non-duplicate RREQ, 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. The aim of this operation is to intentionally 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 an RREQ, respectively. Let $N(i)$ denote the set of v_i's one-hop neighbors, and $CN(i,j)$ denote the common neighbor set between v_i and v_j. We define a helper v_k between v_i and v_j as the common neighbor of v_i and v_j, satisfying $P_{ik} > P_{ij}$ and $P_{kj} > P_{ij}$, where P_{ij} is the PRR between v_i 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 two nodes in $H(i,j)$ can overhear each other, and $\forall v_k \in H(i,j)$, $P_{ik} > P_{ij}, P_{kj} > P_{ij}$. $H(i,j) \subseteq \{N(i) \cap N(j)\}$.

Let t_{ij} denote the backoff delay at the current forwarding node v_j, which receives an RREQ from v_i. t_{ij} is calculated as defined in Eq. (1).

$$t_{ij} = \frac{HopCount}{\sum\limits_{k} P_{ik} P_{kj} + 1} \cdot \tau, \quad v_k \in H(i,j) \tag{1}$$

where τ is a time slot unit; the *HopCount* is the RREQ's hop distance from the source node thus far. The rationale is that, the neighbor with more forwarding candidates, better link qualities, as well as shorter hop-count will have a shorter backoff delay to rebroadcast the RREQ.

Fig. 3 illustrates the biased backoff scheme. Any node that forwards the RREQ will calculate the backoff delay by assuming itself as a guide node, and considering the last-hop node as its upstream guide node. For example, nodes A, B and C receive an RREQ from the source S. When node C calculates its backoff delay, 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 helper nodes. Then, it can calculate the value of backoff delay. In Fig. 3, the label $\{0.8, 0.6\}$ beside the helper node A means that $P_{sa} = 0.8$ and $P_{ac} = 0.6$. At node C, the backoff delay is about 0.57τ according to Eq. (1). Compared with A and B, C has a shorter backoff delay. When C's backoff timer first 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. Upon receiving an RREQ, a destination replies by sending an RREP message back to the source along the reverse route. In case of receiving the same RREQ multiple times, the destination shall only reply to the first received RREQ and neglect others. Algorithm 1 describes how a node handles a received RREQ.

2) ROUTEREPLY (RREP) *propagation:* When a node receives an RREP, it checks if it is the selected next-hop (the upstream guide node) of the RREP. If that is the case, the node realizes that it is on the guide path to the source, thus it marks itself as a guide node. Then, the node records 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 RREQ. Finally, this process finds a guide path from the source to the destination.

In our design, the RREP message 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 facilitate cooperative forwarding. Specifically, two sets of helpers and their relay priority assignments are included in the RREP. Suppose v_{i-1}, v_i and v_{i+1} are three adjacent guide nodes, the upstream link helper set $H(i-1,i)$

Algorithm 1: How a node v_j handles the RREQ received from node v_i.

```
Procedure: void RecvRREQ (Packet *p)
if Non-duplicate RREQ then
    if $v_j$ is the destination node then
        Send out RREP;
    else
        $CN(i,j) = N(i) \cap N(j)$;
        //get common neighbor set $CN(i,j)$,$v_k \in CN(i,j)$;
        Sort $CN(i,j)$ descendingly ordered by $P_{ik}P_{kj}$;
        $H(i,j) = \{cn_1\}$, $CN(i,j) = CN(i,j) - \{cn_1\}$;
        // $cn_1$ is always the first item of $CN(i,j)$;
        while $CN(i,j) \neq \emptyset$ do
            if CheckConnectivity($H(i,j)$, $cn_1$) then
                //$cn_1$ is within the transmission range of any
                node in $H(i,j)$;
                $H(i,j) = H(i,j) \cup \{cn_1\}$;
            end
            $CN(i,j) = CN(i,j) - cn_1$;
        end
        Calculate $t_{ij}$ and call Backoff($t_{ij}$, $p$);
        //schedule a timer whose value is $t_{ij}$, then call
        forwardRREQ($p$) when the timer expires;
    end
else
    Drop($p$);
end
```

Algorithm 2: How a node v_j handles the RREP received from its downstream guide node v_i.

```
Procedure: void RecvRREP (Packet *p)
if Non-duplicate RREP then
    if $v_j == v_{i-1}$ then
        //$v_j$ is the selected next-hop & guide node $v_{i-1}$;
        Mark myself as a guide node;
        Record $v_i$ and $H(i-1,i)$;
        Get RREP's next-hop node id $v_{i-2}$;
        Attach $v_i$, $H(i-1,i)$, $v_{i-1}$ and $H(i-2,i-1)$ to
        RREP;
        /*$v_{i-2}$ is $v_{i-1}$'s upstream guide node; the helper set is
        ordered descendingly by the PRR toward the
        downstream guide node;*/
        Call forwardRREP($p$);
    else if $v_j \in H(i-1,i)$ then
        //$v_j$ is a helper in $H(i-1,i)$;
        Record $v_{i+1}$, $H(i,i+1)$, $v_i$ and $H(i-1,i)$;
        Drop($p$);
    else
        Drop($p$);
    end
else
    Drop($p$);
end
```

and downstream link helper set $H(i,i+1)$ together with their PRRs toward the corresponding downstream guide nodes are piggybacked to the RREP when node v_i forwards it. Due to the broadcast nature of wireless communication, all the helper nodes 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 $H(i-1,i)$. 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 $H(i-1,i)$, which will be useful in the data forwarding phase. Algorithm 2 describes how a node handles the RREP received from its downstream guide node.

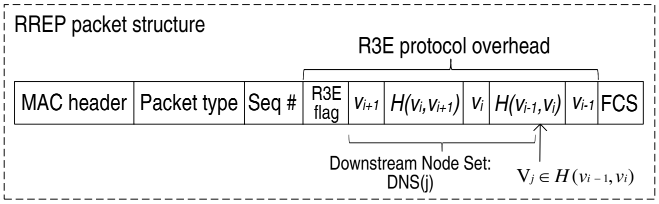


Fig. 4. RREP packet structure. Suppose guide node v_i sends out an RREP to the upstream guide node v_{i-1}, and node v_j ($v_j \in H(i-1,i)$) overhears this message

Since R3E is an enhancement layer over existing reactive routing protocols, a bit (the R3E flag) is used to indicate that the R3E function is enabled. There is not much protocol overhead for the RREQ message, where only the hopcount is included. R3E incurs a certain protocol overhead in RREP, i.e., a sequence of node IDs are piggybacked to the RREP, as shown in Fig. 4. However, the overhead will be eventually compensated by performance gain during the data transmission phase. Suppose the guide node v_i sends out an RREP to the upstream guide node v_{i-1}, and node v_j ($v_j \in H(i-1,i)$) overhears this message. We define the downstream node set of v_j, denoted by $DNS(j)$, as the sequential nodes that rank ahead of v_j in the piggybacked node list of RREP. As seen in Fig. 4, $N(j) \cap DNS(j)$ is the potential downstream helper set of v_j.

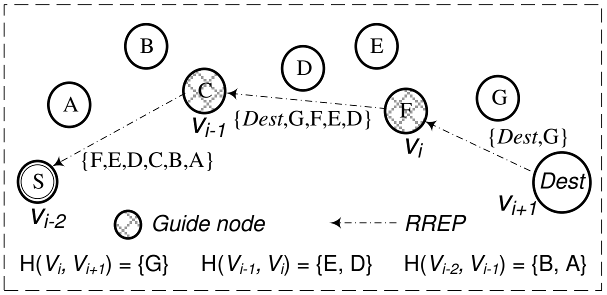


Fig. 5. An example illustrating the RREP propagation to implement cooperative forwarding, in which v_{i-2}, v_{i-1}, v_i and v_{i+1} are adjacent guide nodes in sequence.

Fig. 5 is an example illustrating the RREP propagation corresponding to Fig. 3. Suppose F is the current RREP forwarding guide node, C is F's upstream guide node, the upstream link helper set $H(C,F)$ and downstream link helper set $H(F,Dest)$ will be attached in the RREP. When the guide node F forwards the RREP to its upstream guide node C, for example, helper D overhears this RREP and records the piggybacked information $\{Dest,G,F,E,D\}$. 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 $Dest$ would be $N(D) \cap \{Dest,G,F,E,D\} = \{G,F,E\}$.

Since the wireless links are unreliable, especially in harsh IWSNs, we also consider the possibilities of RREQ and RREP transmission failures. R3E is fault-tolerant to the failure of RREQ, since there exist multiple paths between the source and the destination. However, the transmission reliability of RREP is desirable to be guaranteed, since the RREP returned by the destination node may collide with RREQs in the network, which will be shown in Section IV-C. In addition, if an RREP is lost, the source node probably needs to launch another route discovery process again, which will result in a long routing discovery delay.

C. Cooperative Forwarding

The cooperative forwarding procedure in R3E is described as follows. The source node broadcasts a data packet, which includes the list of forwarding candidates (helper nodes and the downstream guide node) and their priorities. Those candidates follow the assigned priorities to relay the packet. Each candidate, if having received the data packet correctly, will start a timer whose value depends on its priority. The higher the priority, the shorter is the timer value. The candidate whose timer expires will reply with an ACK to notify the sender, as well as to suppress other contenders. 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. We 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, $t(k)$ is an increasing function of k. Suppose the link layer protocol is based on CSMA/CA MAC, $t(k)$ can be defined as Eq. (2).

$$t(k) = (T_{SIFS} + T_{ACK}) \cdot k \tag{2}$$

where T_{SIFS} is the value of *Short Inter Frame Space*, T_{ACK} is the transmission delay for sending an ACK.

We denote $T_{omd}(k)$ as the one-hop medium delay [23] of the k^{th} candidate, which is the time interval between the sender broadcasting a data packet and the k^{th} candidate claiming that it has received the packet. Eq. (3) defines this:

$$T_{omd}(k) = T_{DIFS} + T_{DATA} + (T_{SIFS} + T_{ACK}) \cdot k \tag{3}$$

where T_{DIFS} is the value of *Distributed Interframe Space* (DIFS), T_{DATA} is the transmission delay of data packet, and the signal propagation delay is ignored. For sender v_i, given n sequential forwarding candidates $(j_1 > j_2 > ... > j_n)$, we have the expected one-hop media delay $E_{omd}(i)$ as Eq. 4.

$$E_{omd}(i) = \sum_{k=1}^{n} \{T_{omd}(k) P_{ij_k} \prod_{m=0}^{k-1} \overline{P}_{ij_m}\} + T_{omd}(n) \prod_{m=1}^{n} \overline{P}_{ij_m} \tag{4}$$

where $\overline{P}_{ij_m} = 1 - P_{ij_m}$ and $\overline{P}_{ij_0} = 1$.

In order to forward data toward the destination with minimum number of transmissions, we can apply the basic greedy forwarding rule in geographic routing [24] as the relay priority rule in R3E, i.e., data packets are greedily forwarded to the neighbor geographically closest to the destination. In this way, R3E obviates the necessity of utilizing location information, while enabling data packets to be greedily forwarded toward the destination with the help of the robust guide path. Note that the relay priority rule can also adopt other variant metrics, e.g., the one-hop throughput metric [23] to achieve the best path throughput.

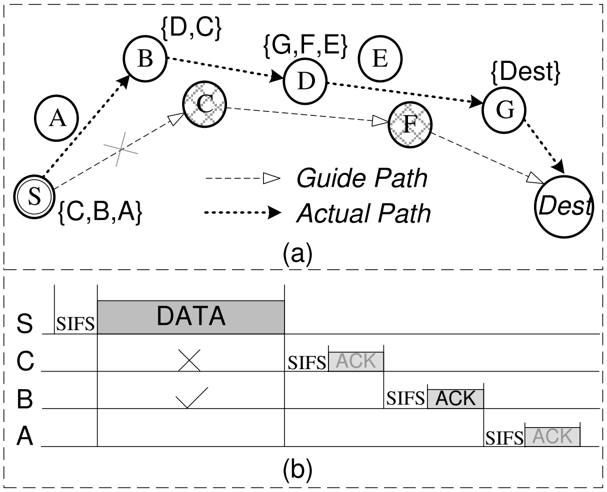


Fig. 6. (a) An example illustrating the forwarding candidates and their priorities at each hop; (b) The corresponding cooperative forwarding procedure at the first hop in the MAC layer

From the realistic link conditions in wireless networks, a potential forwarder with a higher PRR toward the downstream guide node possibly has a shorter distance from that guide node, as longer distances normally result in lower received signal strength and thus increased probability of packet loss [25]. Therefore, the relay priority rule is as follows. When a guide node v_{i-1} transmits the data packet, the downstream guide node v_i has the highest priority; and the helper nodes in $H(i-1,i)$ are ordered descendingly according to their PRRs toward v_i. Suppose the downstream guide node v_i fails to receive the packet, while a helper v_j in $H(i-1,i)$ receives the packet and takes the forwarding task. The forwarding candidates of v_j are given by $N(j) \cap DNS(j)$. More specifically, the forwarding candidate set of v_j is composed of three parts: (1) the helper nodes who have higher priorities than v_j in $H(i-1,i)$; (2) the downstream guide node v_i; and (3) $N(j) \cap (H(i,i+1) \cup \{v_{i+1}\})$. To achieve the minimum number of transmissions, the relay priorities are ordered as: Priority of (3) > Priority of (2) > Priority of (1).

Revisiting the examples in Fig. 3 and Fig. 5, we show the helper nodes and their priorities at each hop in the data forwarding phase in Fig. 6(a). The helper nodes 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 receives the packet, as shown in Fig. 6(b). B takes the forwarding task instead of C. Then B updates its helper set as $\{D, C\}$ and forwards the data packet to its downstream potential forwarders. It can be seen that R3E is resilient to the wireless link dynamics.

IV. PERFORMANCE EVALUATION

In this section, we present performance evaluation results. We implement R3E as an extension to AODV [3], named AODV-R3E, using the ns-2 simulator [26], and compare the performance with three baseline routing protocols. All the results have been averaged over 100 runs, and the related standard deviations are provided as error bars.

A. Comparison Baselines

We first introduce the comparison baselines. We choose three routing protocols, shown as following.

- **AODV-ETX** [3]: The route discovery phase finds a least-ETX (*expected transmission count*) path from a source to a destination. In AODV-ETX, the link layer retransmission is enabled, i.e., at most 3 retransmissions at each hop are sanctioned. Note that the other routing protocols do not adopt the retransmission mechanism.
- **REPF** [27]: REPF (Reliable and Efficient Packet Forwarding) protocol is designed to improve the AODV routing performance by utilizing local path diversity. The route discovery phase finds an efficient primary path (composed of a set of primary forwarding nodes) in terms of the accumulated path ETX, and alternative paths which have similar cost. However, REPF restricts the helper nodes to a very limited scope, i.e., only the nodes which can connect the two-hop away primary forwarding nodes are considered as helper nodes, as shown in Fig. 7. As a result, it does not fully utilize the forwarding opportunities provided by available neighboring nodes in evenly distributed networks.
- **GOR** [24]: In order to show that R3E enables data packets to be greedily progressed toward the destination, we also report the evaluation results of the Geographic Opportunistic Routing (GOR). In our simulation, both R3E and GOR follow the same relay priority rule, i.e., minimizing the number of end-to-end data transmissions. We implement GOR as follows: all the one-hop neighbors that are nearer from the destination than the current forwarding node and can hear from each other are selected as helper nodes, and the nodes closer to the destination are given higher relay priorities. Since the network is densely deployed, the routing recovery mechanism bypassing "holes" is not considered in the simulations.

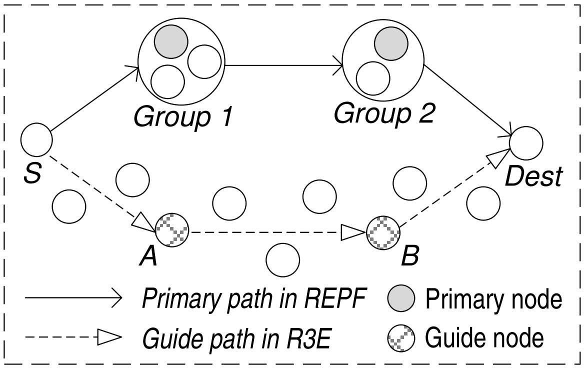


Fig. 7. An example illustrating the primary path in REPF [27]. Only the nodes which can connect the two-hop away primary forwarding nodes are considered as helper nodes. Thus, it restricts the cooperative forwarding to a very limited scope.

B. Simulation Setup

We define the node density as the number of nodes deployed in a 200m×200m square area. 100 randomly connected topologies for each node density setting are generated using the *setdest* tool in ns-2, ranging from 100 to 200. The node transmission range r is set to 50m. The destination node is positioned at bottom left (0m,0m), and the source node is positioned at top right (200m,200m). In AODV-R3E, the system parameter τ is set to 0.005s. In order to highlight the potential collision problem between the returning RREP and RREQs, RREP is not acknowledged by the guide nodes at each hop in our simulation.

We use the Nakagami distribution defined as (5) to describe the power x of a received signal:

$$f(x, m, \Omega) = \frac{m^m x^{m-1}}{\Gamma(m)\Omega^m} \exp(-\frac{mx}{\Omega}) \tag{5}$$

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 (6) as a function of d, the distance between the sender and receiver.

$$\Omega(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^n L} \tag{6}$$

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 n 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 (5) and (6), we can derive the PRR at a certain distance d [28].

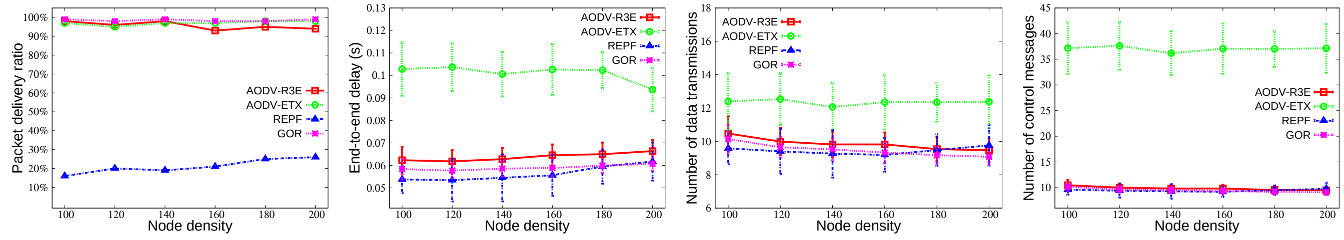
We choose four main evaluation metrics.

- *Packet delivery ratio*: the ratio of the number of packets received by the destination to the total number of packets sent by the source.
- *End-to-end delay*: the time taken for a packet to be transmitted from the source node to the destination node.
- *Data transmission cost*: it is measured as the total number of data transmissions for an end-to-end delivery per packet.
- *Control message cost*: it is defined as the total number of control message transmissions (such as RTS, CTS and ACK) for sending a single packet to the destination.

C. Performance Overview

We evaluate the impact of network density on the performance of the different protocols. The evaluation results are shown in Fig. 8, where the node density is varied from 100 to 200.

Fig. 8(a) illustrates the end-to-end packet delivery ratio under different node densities. GOR achieves very high packet delivery ratio, since the node density is always high, and it takes full advantage of the local forwarding opportunities, involving maximum possible number of neighbors which are closer to the destination. For AODV-ETX, it already finds a more efficient path using the ETX metric than using the



(a) Packet delivery ratio (b) End-to-end delay (c) Data transmission cost (d) Control message cost

Fig. 8. Performance comparison, only the successful end-to-end transmissions are counted

hop-count metric [3]. In addition, packets are forwarded using unicast transmission, and 3 retransmissions at each hop are allowed in the link layer in AODV-ETX. That is why it also achieves a high packet delivery ratio. We observe that AODV-R3E shows above 95% packet delivery ratio on average, which is comparable to that of AODV-ETX and GOR, without enabling the MAC layer retransmission mechanism. However, REPF only provides around 20% packet delivery ratio on average. The main reason is that REPF restricts the node cooperation to a very limited scope.

With the increase of node density, the intuition is that the packet delivery ratio should also increase. However, it is surprising that the delivery ratio drops a little as the node density increases in AODV-R3E, as shown in Fig. 8(a). An examination of the simulation traces in MAC layer reveals that, as the network becomes more congested, the RREP returned by the destination node may collide with RREQs in the network. Therefore, it is better that each guide node acknowledges the reception of the RREP.

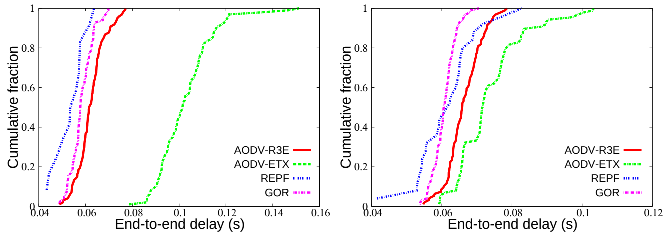
Fig. 8(b) depicts the performance comparison on the end-to-end packet delivery delay. We know that the delay incurred by retransmission is much larger than the coordination delay introduced by the cooperative forwarding. Therefore, AODV-ETX requires longer time to finish the end-to-end transmission, because it requires several retransmissions to forward a packet to the destination. AODV-R3E shows very close performance to the GOR. Note that only the successful end-to-end transmissions are counted in Fig. 8. From Fig. 8(b), it seems that REPF yields the best performance. Actually, this is not true. Because it only shows the results for around 20% successful transmissions. REPF should yield worse results if the failed end-to-end transmissions are counted, which we will discuss in Section IV-D. Overall, AODV-R3E can provide 50% improvement over REPF in terms of the delivery delay.

Fig. 8(c) and Fig. 8(d) report the changes of the data transmission cost and control message cost, respectively, under different node densities. From Fig. 8(c), it clearly shows that REPF requires 2 or 3 retransmissions to finish the transmission task. As expected, AODV-R3E only incurs approximately 5% higher transmission cost than the ideal baseline scheme GOR. However, GOR requires the location information. Since the traffic is transmitted using unicast in AODV-ETX, it incurs a higher control message overhead compared with other protocols, as shown in Fig. 8(d).

Another interesting observation about AODV-R3E and GOR is that, in Fig. 8(b), as the node density increases, the end-to-end delay also slowly increases, whereas the number of data transmissions slightly decreases, as can be seen in Fig. 8(c). It is because of the relay priority rule applied in AODV-R3E and GOR. As the node density increases, more available forwarding candidates can be involved into the cooperative forwarding. However, the higher forwarding priorities will be assigned to neighbors with better advancements towards the destination, but with relatively lower PRRs. Consequently, it increases the one-hop medium time [23], which is defined as the interval between the sender broadcasting a data packet and the forwarding candidate's first claim of receiving the packet.

D. Insights

In this section, we investigate the internal state of each routing protocol and understand the underlying reasons why AODV-R3E provides better performance than other alternative solutions.

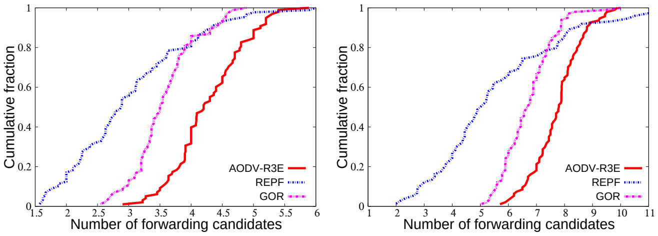


(a) 100-node networks (b) 200-node networks

Fig. 9. CDF of end-to-end delay

Fig. 9(a) and Fig. 9(b) illustrate the CDF (Cumulative Distribution Function) curves of end-to-end delivery delay in 100-node networks and 200-node networks, respectively. Since REPF only achieves around 20% successful transmissions, for a fair comparison, we compare the top 20% simulation rounds with lower end-to-end delivery delay of AODV-R3E and GOR with all the results of REPF. For example, the average delivery delays for GOR, AODV-R3E and REPF in 100-node networks are 0.0513s, 0.0528s, and 0.0538s. From Fig. 9, we observe that GOR and AODV-R3E experience shorter delivery delays than REPF.

Fig. 10(a) and Fig. 10(b) report the CDF of forwarding candidates at each hop for GOR, AODV-R3E and REPF. It is obvious that AODV-R3E explores a larger cooperation opportunity than the other two schemes. The reason is that, AODV-R3E finds a routing path with more cooperative forwarding opportunities in the route discovery phase, whereas



(a) 100-node networks

(b) 200-node networks

Fig. 10. CDF of forwarding candidates at each hop

GOR applies the greedy forwarding scheme with only local information. Therefore, choosing the optimal routing direction is not guaranteed in GOR. REPF has the least number of forwarding candidates at each hop, which confirms our argument that REPF restricts the cooperative forwarding to a very limited area. For example, when the node density is 100, REPF involves 3 forwarding candidates at each hop, whereas GOR and AODV-R3E, on average, have 3.6 and 4.3 forwarding candidates, respectively. In 200-node networks, REPF has 5.5 forwarding candidates, whereas GOR and AODV-R3E on average involve 6.7 and 7.5 forwarding candidates at each hop, respectively.

Although having more cooperative forwarding opportunities per hop than GOR, AODV-R3E still generates a little larger delivery delay and transmission cost than that of GOR. The reason is that, AODV-R3E prioritizes forwarding candidates based on only the PRRs toward the downstream guide node. In some cases, the potential forwarder with the highest PRR toward the downstream guide node is not necessarily the closest node to the destination node. Therefore, AODV-R3E does not always find the optimal order of forwarding candidates without utilizing the location information.

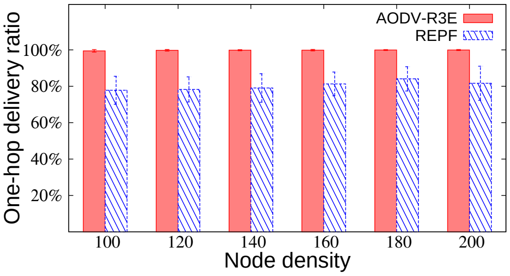


Fig. 11. One-hop delivery ratio

Fig. 11 plots the one-hop delivery ratio for AODV-R3E and REPF, which is defined as the probability that at least one forwarding candidate successfully receives the packet at each hop. From the figure, we can see that as compared to REPF, AODV-R3E yields a remarkable increase of 20% in one-hop delivery ratio. It reveals the reason why REPF only achieves a very low packet delivery ratio on average when the retransmission mechanism is disabled.

Fig. 12 compares the route discovery overhead between AODV-R3E and REPF, which measures the total number of routing discovery control message transmissions, e.g., RREQ and RREP. REPF incurs much higher communication overhead and increases the network load during the route discovery phase, since it allows duplicate propagating RREP packets in order to find a better virtual path. We observe that the route discovery overhead in both AODV-R3E and AODV-ETX is $O(n)$, where n is the number of nodes. However, the route discovery overhead in REPF increases exponentially as the network size increases.

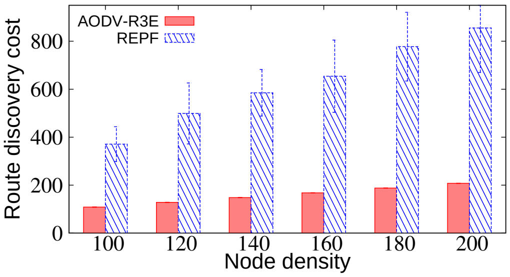


Fig. 12. Route discovery cost

E. Results with Increased Packet Losses

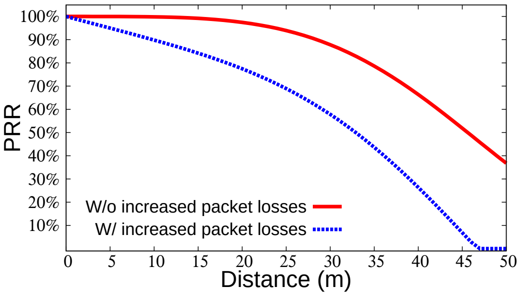
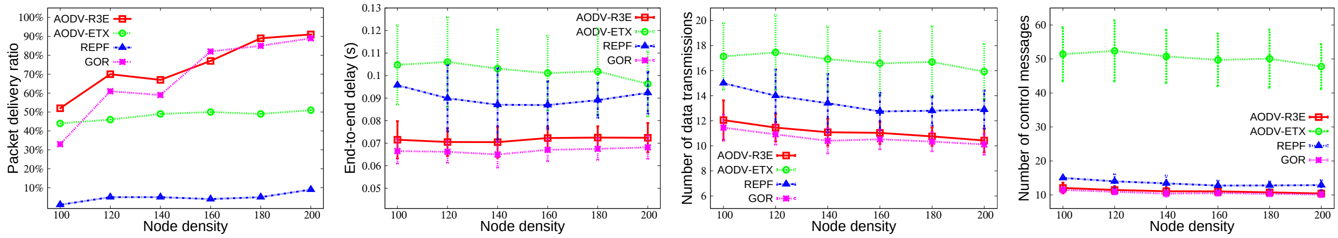


Fig. 13. Unreliable link models in the simulations

In an industrial wireless sensor network, the harsh industrial environments may result in very unreliable wireless links due to many factors [1], [8]. To evaluate the effect of increased packet losses, in this section, we use a simple linear link lossy model based on the distance between transmitter and receiver. In these simulations, a link with a distance of 0m has 0% probability of additional packet loss, and a link with distance of 50m has 50% probability of additional loss, which is same as the setting in [25]. The PRRs derived from the distance between transmitter and receiver with this modified channel model are shown in Fig. 13.

Fig. 14(a) shows the end-to-end packet delivery ratio as the node density increases. Compared with the results using the channel model without increased packet losses shown in Fig. 8(a), the packet delivery ratio for all protocols decreases. From this figure, we can see that AODV-R3E even outperforms GOR with increased packet losses and shows the highest average packet delivery ratio among these protocols. It indicates that finding a reliable guide path is very important if the wireless links are highly unreliable. We also observe that generally, as the node density increases, the packet delivery ratio for both AODV-R3E and GOR also increases. While the AODV-ETX only provides less than 50% delivery ratio, REPF shows less than 10% delivery ratio.



(a) Packet delivery ratio (b) End-to-end delay (c) Data transmission cost (d) Control message cost

Fig. 14. Performance comparison with increased packet losses, only the successful end-to-end transmissions are counted

Fig. 14(b) plots the end-to-end delay among the four compared schemes. For the same reason discussed earlier, AODV-R3E has a little larger delay than GOR. When comparing with the results shown in Fig. 8(b), the delivery delays of both AODV-R3E and GOR increase due to the poor link qualities.

Fig. 14(c) and Fig. 14(d) show the data transmission cost and control message cost, respectively, under the modified channel model. It is interesting that, for AODV-R3E and GOR, the performance on these two metrics does not change much compared with the results in Fig. 8(c) and 8(d). The reason is that, these results only count the successful end-to-end transmissions, and there is no retransmission in AODV-R3E and GOR. Thus, the end-to-end hop-count does not increase for those successful transmissions. However, in the modified channel model with increased packet losses, the end-to-end delivery delay increases since the one-hop medium time is increased. This is because, from Eq. 4, the one-hop medium time increases as the link qualities become poor.

F. Performance Summary

In the previous sections, we see that AODV-R3E without utilizing the location information achieves a comparable performance to GOR. Compared with REPF, it significantly improves the packet delivery ratio, and compared with AODV-ETX, it provides much lower data transmission cost and control message cost. Remarkably, in the modified channel model with increased packet losses, AODV-R3E even performs better than GOR, since it forwards data packets along the path which provides more cooperative forwarding opportunities.

V. RELATED WORK

Opportunistic routing to combat fading channels in wireless networks has been an active research area. A number of opportunistic routing protocols have been proposed for this purpose [15], [16]. ExOR [11] is a representative opportunistic routing protocol. However, ExOR, as well as SOAR [29], requires every node to measure and maintain the global topology of the network. In GeRaF (Geographic Random Forwarding) [24], 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 [30], the authors proposed a contention-based geographic routing protocol which incorporates the cooperative relaying and leapfrogging. RRP [22] 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) [31], 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 recent years, IWSNs have been designed and developed for many industrial applications, e.g., industrial process monitoring and control, environment and equipment monitoring, and distributed control systems, etc [32]–[35]. They are expected to take the place of conventional industrial wired communication systems [1], [2], [36], making it possible to wirelessly monitor and control the environment in real time. Although there exists a large research effort in the area of WSNs, many research issues have not been well addressed such that WSNs can be adopted properly for industrial automation. In [37], Akerberg et al. discuss major requirements for typical WSN applications in process automation and outline the research direction for IWSNs. EARQ [38] presents a routing protocol for IWSNs to achieve real-time, energy efficient and reliable delivery of a packet. [39] and [40] propose techniques for providing quality-of-service (QoS) support regarding to timeliness and reliability in IWSNs.

In industrial environments, wireless links are normally highly dynamic due to many factors such as RF interference, harsh environments and vibrations. Providing reliable and efficient communication in IWSNs is a challenging problem [41]. Recently, WirelessHART [42] and ISA 100.11a [43] have been proposed specifically for reliable and real-time wireless communication in industrial environments. Yang et al. [44] propose a CCA-Embedded TDMA scheme to improve the transmission efficiency of WirelessHART MAC. The authors in [45], [46] evaluate the potentials of flooding as a data dissemination technique in IWSNs. Quang et al. [47] propose a gradient-based routing with two-hop information for IWSNs to enhance the real-time performance. In this work, we address the reliable routing problem in WSNs/IWSNs by applying the opportunistic routing paradigm to reactive routing protocols, and jointly optimizing the route discovery and cooperative forwarding.

VI. CONCLUSION

In this work, we presented R3E, which can augment most existing reactive routing protocols in WSNs/IWSNs 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. Without utilizing the location information, data packets can still be greedily progressed toward the destination along the virtual path. Therefore, R3E provides very close routing performance to the geographic opportunistic routing protocol. We extended AODV with R3E to demonstrate its effectiveness and feasibility. Simulation results showed that, as compared to other protocols, AODV-R3E can effectively improve robustness, end-to-end energy efficiency and latency.

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