A Reliable and Energy-Efficient Opportunistic Routing Protocol for Dense Lossy Networks

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***Abstract*—Power conservation and reliable data delivery are two most critical issues in the design of routing protocols for wireless networks, especially for dense lossy networks. However, traditional routing protocols, which deliver packets along predetermined routing paths with unnecessarily high transmit power, cannot cope well with dynamic and lossy wireless mediums under excessive interference. In order to prolong the lifetime of networks and improve the reliability of networks, this letter proposes a reliable and energy-efficient opportunistic routing (REOR) protocol. REOR effectively utilizes path diversity by jointly selecting optimal transmit power and optimal forwarder set, which significantly postpones the death of nodes and ensures persistent network connectivity with dynamic workload sharing approach. Extensive simulation results demonstrate that REOR achieves up to 50% reliability improvement and 30% energy conservation compared to the benchmark, i.e., the IPv6 routing protocol for low-power and lossy networks.**

***Index Terms*—Wireless communications, energy-efficient, reliable, routing protocols.**

I. INTRODUCTION

WITH the emergence of Internet of Things (IoT) [1], a paradigm shift in routing for traditional ad hoc to large convergecast networks has recently taken place. The pervasiveness of IoT essentially requires large numbers of low-power and low cost embedded devices to be efficiently and seamlessly interconnected. However, data transmission via dynamic and lossy wireless links is inherently unreliable, leading to excessive retransmissions, large amount of energy consumption and long occupation time of the shared wireless medium. Therefore, reliable and energy-efficient data delivery are of paramount importance for IoT applications [2], [3]. Conventional routing protocols select the relay that can minimize the retransmissions [4], which is an indirect approach to conserve energy. Furthermore, other factors, such as wireless link loss rates, the energy consumption during reception and idle-listening, also significantly affect the energy depletion in dense lossy networks. But not all of these factors are not taken into consideration in the designs of traditional protocols. In addition, nodes in traditional protocols generally transmit at unnecessarily high transmit power, which shortens the lifetime of nodes and introduces significant interference. Recent developments have already enabled the rapid advancement of multifunctional nodes with continuous or discrete power levels [5]. However, to the best of our knowledge, the adjustable transmission power for optimal route selection to attain energy-efficiency and reliability has not been thoroughly studied. It is a crucial task for routing protocols to achieve energy-efficiency and reliability simultaneously, especially for dense networks with severe energy constraints, e.g., Low-Power and Lossy Networks [6]. To address the aforementioned challenges, this letter proposes a distributed, reliable, and energy-efficient opportunistic routing protocol (REOR) that can simultaneously achieve high reliability and energy conservation.

Manuscript received August 25, 2016; revised October 21, 2016; accepted October 31, 2016. Date of publication November 4, 2016; date of current version February 16, 2017. The associate editor coordinating the review of this paper and approving it for publication was M. Dong.

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Digital Object Identifier 10.1109/LWC.2016.2625279

II. RELIABLE AND ENERGY-EFFICIENT OPPORTUNISTIC ROUTING PROTOCOL (REOR)

As a proactive opportunistic adaptive routing protocol, REOR is proposed to support reliable, energy-efficient, robust and scalable routing with load balancing capability. REOR can jointly select the optimal forwarder list and balance the trade-off of transmit power, aiming to attain efficient data collection with effective energy conservation. In REOR, a novel routing metric is utilized to precisely measure the end-to-end transmission cost of networks. REOR uses a top-down approach to select the optimal forwarder set, so as to minimize the energy depletion of networks, leverage path diversity and improve the robustness. In order to balance workload of networks, the priority of a node in a forwarder list is dynamically updated and calculated based on the combination of residual energy and lossy rates of wireless channels. In addition, REOR also incorporates a local loss recovery scheme to efficiently detect and retransmit lost packets, and an overhearing-based coordination scheme to avoid duplicate transmissions. The feasibility and effectiveness of REOR is demonstrated in NS-3 across a wide range of scenarios.

A. System Model

Consider that N stationary nodes with limited energy are dispersed in an area, the network can be described as a non-cyclic graph, denoted by $G = (N, E, W)$, where E represents the set of edges in the network and W is the upper bound of a node's outdegree. We conduct a mapping for every node to a positive, real-valued energy cost for routing as $c_e : N \to \mathbb{R}^+$. Furthermore, a mapping for each link to a link cost, which is $c_l : E \to \mathbb{R}^+$ is also performed. In this way, the network becomes a weighted graph. The cost from node u to node v through a set of edges in E is denoted as $c(u, v)$. In REOR, a set of forwarding nodes are used to relay packets to the destination node, and this node set is called cluster-parent-set (CPS). The CPS of node u is denoted by $CPS(u)$, and $c(u, CPS(u))$ is used to denote the cost for node u to successfully deliver one packet through

$CPS(u)$ to the destination node, denoted as d. In REOR, a node chooses the most cost-efficient set of forwarding nodes as its optimal CPS, denoted as $CPS_o(u)$ for node u. The way to select the optimal CPS for node u is to select the $CPS(u)$ that gives the minimum cost to node u, which is $c(u, CPS_o(u)) = min\{c(u, d)\}$. The value of $c(u, CPS(u))$ can be obtained by the submission of two components: the cost that node u takes to successfully deliver the packet to its $CPS(u)$, and the cost that the recipient of the packet takes to successfully deliver the packet to the destination through its own CPS, i.e., $c(u, CPS(u)) = c(u, v) + c(v, CPS(v))$, where $v \in CPS(u)$. In this letter, we consider that nodes are capable of adjusting their transmitting power to a certain number of discrete values. The transmission range of a node is determined by the level of its transmit power, the relationship of which will be introduced later. The number of adjustable levels of transmission power/ranges is considered to be M, where $M \geq 1$, and the available transmission ranges is denoted by $(R_1, R_2, \ldots, R_M)$, where $(R_1 < R_2 < \cdots < R_M)$. The optimal transmit power level of node u is denoted as R_{o_u}.

B. Routing Metric

In order to precisely measure the transmission cost, we propose a novel routing metric, which considers energy cost and lossy nature of wireless channels. The accumulated end-to-end transmission cost of a node is composed of its one hop opportunistic routing cost and the remaining cost of its optimal CPS to deliver the packet to the destination associated with its optimal CPS. The First Order Radio Model [7], which is commonly used to calculate the energy consumption in wireless sensor networks, is applied in this letter. In this model, the radio takes E_{elec} to run its circuitry of the transmitter or the receiver. The transmitting amplifier is used to achieve an acceptable signal-to-noise (SNR) ratio, which is denoted by ϵ_{amp}. In this letter, the propagation loss exponent is considered to be 2. The energy consumed to transmit a k-bit message with a transmission range r at the transmitter, and receiver side is modeled as $E_{tx}(k, r) = E_{elec}k + \epsilon_{amp}r^2$ and $E_{rx}(k) = E_{elec}k$, respectively. The energy depletion for overhearing k bits of packets is denoted by $E_{oh}(k) = \alpha E_{elec}k = \alpha E_{rx}(k)$.

We denote node i's one-hop neighbor number as N_i, and the size of its forwarder set (its CPS) as n_i. The energy consumption for node i's one transmission of a k-bit message with a transmission range r is denoted by $E_i(k, r)$, which includes three components, namely the energy consumed in transmitting, receiving, and overhearing. It is observed that overhearing contributes a significant portion of the total energy cost in dense networks, due to large number of overhearing recipients. This letter considers that the overhearing nodes receive the full length packets, where α becomes 1. Thus

$$\begin{aligned} E_i(k, r) &= E_{tx}(k, r) + n_i E_{rx}(k) + (N_i - n_i) E_{oh}(k) \\ &= E_{tx}(k, r) + N_i E_{rx}(k). \end{aligned} \tag{1}$$

The probability of a successful transmission between node i with node j is denoted by p_{ij}. The wireless link qualities can be measured via various methods, such as packet sequence numbers and packet retransmission counts [8]. The joint ETX is the average number of transmissions that a node takes for its forwarders to successfully receive at least one data packet. The joint ETX of node i is defined as

$$ETX_{CPS(i)} = \frac{1}{p_{i,CPS(i)}} = \frac{1}{1 - \prod_{j \in CPS(i)} (1 - p_{ij})}. \tag{2}$$

Node i can estimate the wireless link qualities to all its one-hop neighbors. The number of actual recipients for each transmission is a random variable. However, we can calculate the average number of recipients for each sender based on the link qualities and neighbor numbers in lossy networks. Thus, we define an average degree of link loss for each node, which is denoted by β_i for node i. It is the probability that node i's transmission can, on average, be successfully received by a neighbor node, and is defined as

$$\beta_i = \frac{\sum_{j \in N_i} p_{ij}}{N_i}. \tag{3}$$

In this way, $\beta_i N_i$ neighbor nodes successfully receive the transmission of node i on average. So $E_i(k, r)$ is updated as

$$E_i(k, r) = E_{tx}(k, r) + \beta_i N_i E_{rx}(k). \tag{4}$$

We define the Anycast Energy Cost (AEC) as the transmission cost to the network for one packet successful reception by at least one node among its CPS. Thus, the AEC of node i for transmitting a k-bit packet with the transmission range r is

$$AEC_{i,CPS(i)} = \frac{E_i(k, r)}{1 - \prod_{j \in CPS(i)} (1 - p_{i,j})}. \tag{5}$$

The energy cost of the network for a CPS to deliver a packet to its destination is defined as the Remaining Energy Cost (REC). Meanwhile, we denote the end-to-end transmission cost for a node i through its optimal CPS as $EC_{i,CPS_o(i)}$, the simplified version of which is EC_i. It is assumed that the nodes in a CPS are sorted according to their end-to-end energy cost, in which $(EC_1 \leq EC_2 \leq \cdots \leq EC_{|CPS(i)|})$. The REC of node i's CPS can be calculated as

$$REC_{i,CPS(i)} = \frac{EC_1 p_{i1} + \sum_{i=2}^{|CPS(i)|} EC_j p_{ij} \prod_{k=1}^{j-1} (1 - p_{i,k})}{1 - \prod_{j \in CPS(i)} (1 - p_{i,j})}. \tag{6}$$

The accumulated end-to-end transmission cost of a node is composed of its AEC and the REC associated with its optimal CPS. Hence, the end-to-end transmission cost for an arbitrary node i through its CPS can be computed through

$$EC_{i,CPS(i)} = min(AEC_{CPS(i)} + REC_{i,CPS(i)}). \tag{7}$$

C. The Selection of the Optimal CPS

The number of one-hop neighbors usually increases as the transmission range increases, which is a result of increased power levels and vice versa. The relative distance between two arbitrary nodes can be estimated by the Received Signal Strength Indicator (RSSI), thus a node can obtain different neighbor lists corresponding to different transmission ranges, as shown in Fig. 1. The set $\{nb_{i_r}\}$ denotes the neighbor list for node i with transmission range r. During the network initialization stage, each node selects an optimal CPS in conjunction with a power-level refinement, aiming at minimizing the end-to-end energy cost. In this design, only nodes with inter-link qualities above 0.5 can be selected as one candidate forwarder set, considering that coordination errors lead to duplicated packets. As shown in Fig. 2, wireless link loss rates among r_1, r_2, and r_3 should be less than 0.5 so they can be selected as one CPS. We use Ω to denote the set of nodes that can be used for the selection of the optimal CPS. Then, the different possible combinations of nodes, the size of which is varied from 1 to W, are chosen from Ω to compute the energy cost for node i through that set. The list of helpers of node i is denoted as $\{nb_{i_h}\}$. For instance, the children nodes of node i are belong to the $\{nb_{i_h}\}$, as shown in Fig. 1. While computing a CPS set, a node cannot choose any node from its list of helpers to avoid the routing loop. Except for nodes in $\{nb_{i_h}\}$, node i considers all nodes within

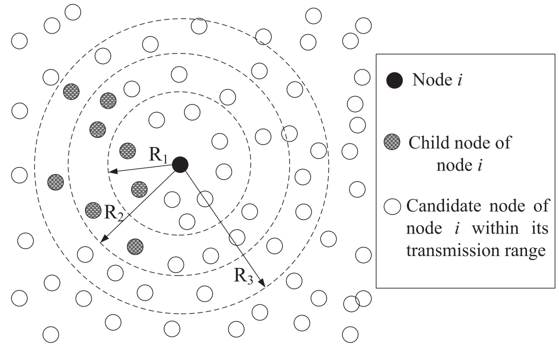

Fig. 1. Illustration of the adjustable transmission range.

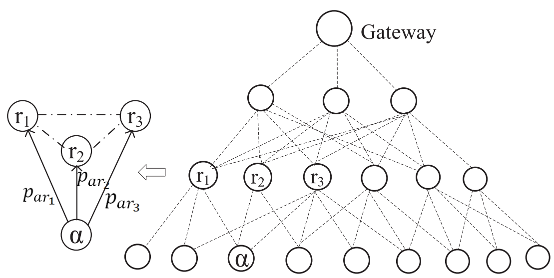

Fig. 2. Network formation with opportunistic routing.

Algorithm 1 The Distributed Optimal CPS Selection With the Transmit Power Refinement Algorithm

procedure THE SELECTION OF AN OPTIMAL CPS AND TRANSMIT POWER LEVEL FOR NODE i
  Assume Ω and Φ denotes two sets of nodes and are initialized to empty. Initialize C_{min} to 999
  for $r \to R_1$ to R_M **do**
    for Any node $j \in \{nb_{i_r}\}$ and $j \notin \{nb_{i_h}\}$ **do**
      $\Omega \leftarrow \Omega \cup j$
    for $w \to 1$ to W **do**
      if $w = 1$ **then**
        for each $j \in \Omega$ **do** $EC_{i,j} \leftarrow$ call Eq. (5) and (6)
          if $C_{min} > EC_{i,j}$ **then**
            $C_{min} \leftarrow EC_{i,j}$
            $R_{o_i} \leftarrow r$
            $CPS_o(i) \leftarrow \{j\}$
      else
        for $\Phi \leftarrow$ any w number of nodes $\in \Omega$ **do**
          if $p_{u,v} \geq 0.5$, where $u, v \in \Phi$ **then**
            $EC_{i,\Phi} \leftarrow$ call Eq. (5) and (6)
            if $C_{min} > EC_{i,\Phi}$ **then**
              $C_{min} \leftarrow EC_{i,\Phi}$
              $R_{o_i} \leftarrow r$
              $CPS_o(i) \leftarrow \Phi$
  $EC_{i,CPS_o(i)} \leftarrow C_{min}$

its transmission range as its candidate neighbor node set. The combinations of nodes that have minimum cost towards the gateway are selected as its optimal CPS. Specifically, REOR selects the optimal CPS with each transmission range, then it compares the energy costs with each optimal CPS. The CPS that provides the minimum energy cost is selected as the optimal CPS, and the corresponding transmission range is selected as to be the optimal transmission range. In this way, the network topology can reach the stage of convergence. The pseudo-code of the distributed optimal CPS selection with the transmit power refinement algorithm is shown in Algorithm 1.

TABLE I
PARAMETER SETTING FOR OUR SIMULATION

Parameter	Value
Traffic duration	200s
Packet size	512 bytes
Traffic rate	1 pkt/s CBR flow
Initial energy	5000000000 nJ
Transmitter electronics (E_{elec})	50nJ/bit
Transmit amplifier (ϵ_{amp})	100pJ/bit/m^2
The minimum time interval size (I_{min})	50ms

D. Coordination of CPS for Packet Forwarding

In REOR, the actual forwarder to deliver data packets in one CPS is selected opportunistically based on the actual transmission result. To support reliable data delivery without redundant transmission, REOR uses an overhearing-based coordination scheme. Specifically, a timer-based ACK is used to coordinate the transmission among one CPS. Upon receiving data packets, nodes in a CPS schedule their ACK transmission following the priority list upon receiving a data packet. The priority of nodes in a CPS for forwarding data is based on a combination of residual energy and the lossy condition of wireless channels for workload sharing. In addition, a node's priority in a CPS is dynamically updated for balancing the workloads of the network. Re_j is used to denote the residual energy of node j. In REOR, the priority of a node in one CPS is assigned according to the value of Re_j/EC_j, where $j \in CPS(i)$.

III. RESULTS AND DISCUSSION

In this letter, the IPv6 Routing Protocol for Low-Power and Lossy Network (RPL) [9], which is standardized by IETF as a routing protocol for LLNs, is used as a benchmark. Both RPL and REOR are implemented in NS-3. Binary erasure channel is used to model the lossy wireless medium. The maximum number of nodes in a CPS are set to be 3 ($W = 3$), considering the computational complexity. The simulation studies use the IEEE 802.11, which is commonly used to evaluate the performance of LLNs protocols [10]. Other parameters are shown in Table I. For REOR, the adjustable transmission range is set to be 30m, 35m, 40m, and 45m. To select the optimal transmission range for RPL, we have conduced simulation studies and compared the performance of RPL with different transmission ranges in terms of energy-efficiency and reliability. RPL uses 45m as the optimal transmission range, because it achieves the highest packet delivery ratio (PDR) and the smallest energy consumption among all transmission ranges. This letter investigates network performances with different link loss rates. 180 nodes are uniformly distributed on 240m × 240m area. The root is placed in the center. Each scenario is simulated for 10 runs, each of which is 1500s.

Fig. 3 shows REOR consistently outperforms RPL in terms of packet delivery ratio (PDR). Furthermore, by effectively exploiting the path diversity with CPS, REOR achieves significant improvement in reliability compared to RPL. It is shown that the improvement increases as the mean of link success rate increases. In addition, REOR achieves up to 50% improvements compared to RPL after the simulation run of 1000 seconds. Compared to the result at 1000 seconds with the 700 seconds, the improvement is more significant as the simulation runs for longer period. In REOR, the lifetime of the nodes is effectively prolonged due to the dynamic workload balancing approach. Fig. 4 shows that energy consumption of the network increases slightly as the link success rate increases due to increased numbers of successfully delivered packets

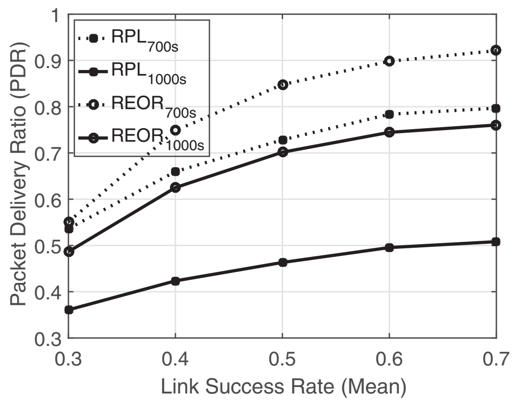

Fig. 3. Performance on the reliability of the network.

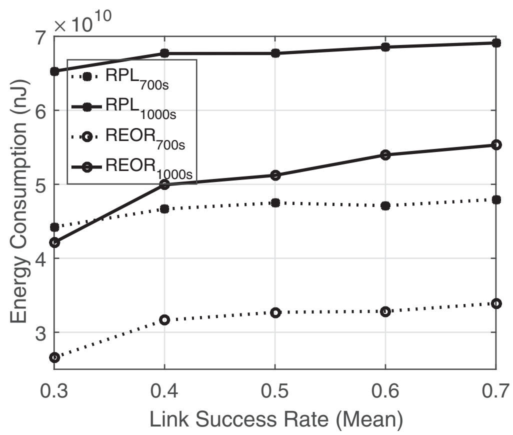

Fig. 4. Performance on energy consumption.

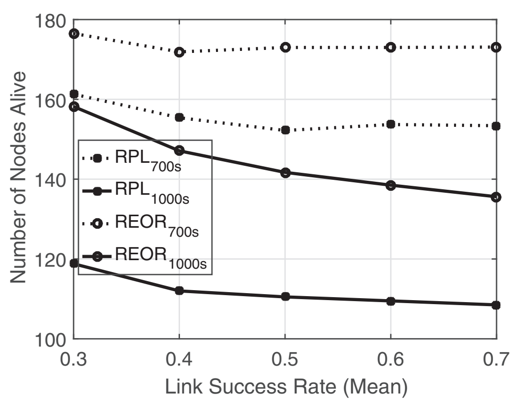

Fig. 5. Performance on alive nodes.

with better link success rates. Compared to RPL, REOR conserves 30% and 20% energy at simulation time 700 seconds and 1000 seconds, respectively. The gain of energy conservation decreases as the simulation runs for longer time. This is due to more data packets are delivered with REOR, which consumes energy and causes more nodes to die when simulations are run for longer time. Fig. 5 shows that the REOR significantly postpones the death of nodes. With a higher link success rate, more packets can be delivered to the destination, so that more nodes need to participate in packets forwarding, resulting in higher energy consumption. Therefore, the number of dead nodes with high link success rate is slightly more than that with low link success rate. Fig. 6 shows the time at which different percentages of nodes become dead with 30

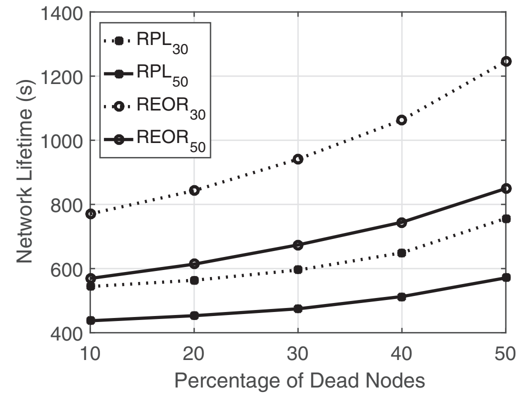

Fig. 6. Performance on network lifetime.

and 50 traffic flows, and in this case, the mean of the link loss rate is 0.6. It shows that REOR significantly delays the death of nodes, and it can maintain better network connectivity compared to RPL.

IV. Conclusion

In this letter, we have developed REOR, a scalable, reliable and energy-efficient opportunistic routing protocol. REOR jointly selects the optimal transmit power and the optimal cluster-parent-set (CPS), while incorporating an adaptive workload sharing approach. REOR can effectively achieve high reliability and fairness of networks, provide robust network connectivity and prolong the lifetime of networks. Extensive simulation studies have demonstrated that REOR can simultaneously achieve better reliability and energy efficiency compared to benchmarks across a wide range of scenarios.

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