An Energy-efficient Region-based RPL Routing Protocol for Low-Power and Lossy Networks

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***Abstract*—Routing plays an important role in the overall architecture of the Internet of Things. IETF has standardized the RPL routing protocol to provide the interoperability for Low-Power and Lossy Networks (LLNs). LLNs cover a wide scope of applications, such as building automation, industrial control, healthcare and so on. LLNs applications require reliable and energy-efficient routing support. Point-to-point (P2P) communication is a fundamental requirement of many LLNs applications. However, traditional routing protocols usually propagate throughout the whole network to discover a reliable P2P route, which requires large amount energy consumption. Again, it is challenging to achieve both reliability and energy-efficiency simultaneously, especially for LLNs. In this paper, we propose a novel energy-efficient region-based routing protocol, called ER-RPL, which achieves energy-efficient data delivery without compromising reliability. In contrast of traditional routing protocols where all nodes are required for route discovery, the proposed scheme only requires a subset of nodes to do the job, which is the key of energy saving. Our theoretical analysis and extensive simulation studies demonstrate that ER-RPL has a great performance superiority over two conventional benchmark protocols, i.e., RPL and P2P-RPL.**

***Index Terms*—Low-power and Lossy Networks (LLNs), RPL, region-based, energy-efficiency, reliability, Point-to-point (P2P) communication.**

I. Introduction

MACHINE-to-Machine (M2M) communications [1] aim to achieve ubiquitous communication among intelligent devices for application control and monitoring, which have attracted both academia and industry in recent years. Motivated by the great potential of M2M communications, many standardization activities, such as IETF, 3GPP, and IEEE have defined protocol stacks to enable M2M communications [2]. M2M devices are usually battery powered and operate in harsh environment (e.g., heat, dust, and moisture weather). The dynamic and lossy environment where a large group of highly constrained devices are interconnected by unreliable wireless links are categorized as Low-power and Lossy Networks (LLNs). Routing plays a crucial role to provide the interoperability among network components. The IETF Routing Over Low-power and Lossy network (ROLL) working group standardizes the IPv6 Routing Protocol for Low Power and Lossy Networks (RPL) [3], [4], [5], which targets highly constrained nodes and large scale networks for LLNs applications. Point-to-point (P2P) communication is a fundamental requirement of most of the LLNs applications.

LLNs applications require efficient P2P routing support. However, achieving high reliability and consuming less energy at the same time are inherently challenging. The routing paths between arbitrary M2M devices are not provided by default due to the resource constraints. Traditional routing protocols, such as Lightweight On-demand Ad hoc Distance-vector Routing (LOADng) [6] and P2P-RPL [7], disseminate route discovery messages throughout a network to find the optimal P2P routes, leading to large amount of routing overhead and energy consumption. In this paper, we propose an energy-efficient region-based routing protocol (ER-RPL), which achieves energy-efficient P2P data delivery without compromising the reliability. In contrast to traditional routing protocols, in which all nodes need to participate in the route discovery, ER-RPL only requires a subset of nodes in some regions to discovery the route. In ER-RPL, a nearly optimal route in terms of reliability can be discovered with a great energy conservation.

Our proposed ER-RPL makes use of the region information to support efficient P2P communication. For static networks, such as M2M networks and wireless sensor networks (WSNs), the area where a node resides is a piece of important information. Many LLNs applications exploit this region feature. For example, in automatic control systems, the control command can be sent to all devices in one level or a region/room of a building. In event-triggered applications, all sensors within an area can capture this event, but which sensor has collected the information may not be important. The region information can be used to efficiently discover the routing paths. Overall, the key contributions of this paper are summarized as follows:

1) We propose a novel scalable routing protocol, i.e., ER-RPL, to achieve reliable and energy-efficient data delivery for static networks. Significant reduction on control overhead is achieved, since only a portion of nodes in the network need to participate in the route discovery.
2) We propose a P2P traffic model with the consideration of routing decision for lossy networks.
3) Both theoretical analysis and simulation studies are performed to evaluate the effectiveness and flexibility of our proposed ER-RPL.
4) Two conventional routing protocols, RPL and P2P-RPL,

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2016.2593438, IEEE Internet of Things Journal

are used as the benchmarks in the simulation study. In comparison with the benchmarks, ER-RPL can achieve more reliable data delivery with significant energy conservation.

The rest of this paper is organized as follows. Section II introduces existing LLNs routing protocols and discusses the challenges of the design for efficient LLNs routing protocol. Section III presents the proposed protocol ER-RPL. Theoretical analysis are presented in Section IV. Extensive simulation and performance evaluation are conducted in Section V. Finally, this paper is concluded in Section VI.

II. Background

In recent years, LLNs applications, which cover a wide range of scenarios, including but not limited to, building automation, industrial control, urban environment and home automation [8], [9], [10], have emerged as the predominant paradigm for M2M communications. LLNs applications essentially require reliable and energy-efficient routing to support the connectivity of network utilities with tighter control and energy conservation. However, nodes operating in LLNs usually have limited battery power and communicate via dynamic and lossy wireless medium. It is inherently challenging to achieve reliability and energy-efficiency at the same time, especially for LLNs. It has been shown that traditional routing protocols face difficulties in providing an efficient routing support for LLNs [11]. For P2P communication, three main routing techniques have been proposed: proactive routing, on-demand (reactive) routing and geographic routing. In this section, we first introduce several conventional LLNs routing protocols and analysis their limitations. Then we summarize the main challenges of designing routing protocols for LLNs, and present the routing solutions that are implemented in our proposed ER-RPL.

A. Routing Protocols for Low-Power and Lossy Networks

RPL is a proactive IPv6-based distance-vector routing protocol. RPL can establish a Destination Oriented Directed Acyclic Graph (DODAG) at a high speed with the trickle algorithm [12]. According to applications' objectives, RPL uses different routing metrics to support LLNs applications. The root node serves as a transit point to bridge the DODAG with the IPv6 network. The formation of a DODAG is initiated by the root node that periodically originates DODAG Information Object (DIO). RPL is designed to optimize the routing support for multipoint-to-point (MP2P). RPL chooses the best next hop as the preferred parent to the root node given a particular objective function [13]. Although RPL can support the routing for generic traffic pattern, RPL needs to pre-establish routes and can only route along pre-established DAGs for P2P communication. The source node has to send the packet upwards until it reaches the ancestor node of the destination node. Then the common ancestor node delivers the packet downwards towards the destination node. In non-storing mode of RPL, the common ancestor has to be the root node. Hence, packets need to travel through many lossy links, resulting in long end-to-end delay. Additionally, the root becomes a bottleneck when traffic load becomes heavy.

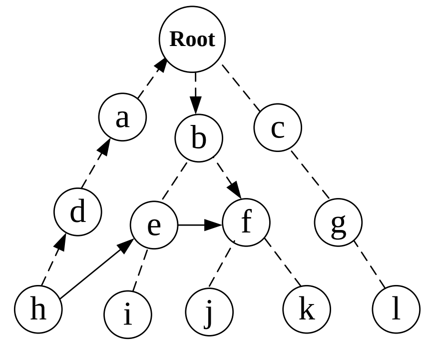

Fig. 1 Communication routes between node *h* and node *f*, provided by RPL with the dotted arrows and by P2P-RPL with solid arrows.

A reactive P2P route discovery mechanism based on RPL is defined as P2P-RPL [7], [14]. In P2P-RPL, a temporary DAG, in which the source node acts as the root node, is built to facilitate the end-to-end traffic transmission in LLNs. The lifetime of the DODAG is strictly restricted by the lifetime of the route request. A P2P Route Discovery Option (P2P-RDO), which is piggybacked in DIO, is used for the route discovery in P2P-RPL. The source node originates and disseminates route discovery messages throughout the whole network. The frequency of broadcasting route discovery messages is according to the trickle algorithm. Once the destination node receives the P2P-RDO, it replies a P2P Discovery Reply Object (P2P-DRO) to the source through the discovered route. The reverse route of P2P-DRO is used for P2P data delivery. Fig. 1 shows the communication routes for node *h* to node *f* in RPL and P2P-RPL, respectively. P2P-RPL can usually find better P2P route than RPL, but sometimes the route discovered by P2P-RPL may not be much better than the existing route in RPL. The improvement of route quality depends on the network topology, such as the distance between the source node and destination node. Moreover, the cost associated with the P2P route discovery is very costly in terms of energy consumption, especially for LLNs. Because all nodes in the network need to participate in the formation of temporary DODAGs during the route discovery, resulting in significant energy consumption for energy constrained networks.

LOADng is a reactive routing protocol derived from Ad hoc On-demand Distance Vector Routing (AODV) [15] for LLNs. The operation of LOADng makes lots of simplifications on AODV. During the route discovery stage, route request (RREQ) messages will be distributed throughout a network. If the destination node receives a RREQ message, it replies a route-reply (RREP) message through the reverse path to the source node. LOADng supports many traffic patterns, such as P2P, point-to-multipoint (P2MP), and MP2P. However, for MP2P traffic pattern, the routing overhead in LOADng is much more than that in RPL [16]. The performance comparison and detail analysis of LOADng and RPL have been conducted with different traffic patterns [17], [18]. Both P2P-RPL and LOADng disseminate route discovery messages throughout the whole network. The route discovery scheme in LOADng is similar to that in P2P-RPL, so LOADng is not addressed in the simulation study.

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Geographic routing relies on the locations of nodes (either real coordinates or virtual coordinates) instead of nodes' IP addresses to forward data packets in a greedy manner [19], [20]. A node chooses the node, which is the closest one to the destination from its neighbors, as its next hop to relay its data packets. The location/coordinate is obtained by each node or partial nodes either as a priori knowledge or through a self-configuration localization scheme. Geographic routing has the advantage of low routing overhead and scalability support, but it does not take into consideration of the lossy nature of wireless links in the selection of the next hop. Consequently, geographic routing usually cannot cope well with the lossy wireless medium to provide reliable data delivery support for LLNs. Additionally, in some geographic routing protocols, nodes have to exchange the one-hop or even two hop neighbour table periodically to maintain the coordinates [20]. It is very costly in terms of energy consumption for a resource constrained network.

B. Routing Challenges in Low-Power and Lossy Networks

Efficient support for generic traffic patterns. LLNs applications require stable routing support for generic traffic patterns, such as MP2P, P2P, and P2MP with heterogeneous node capabilities [11]. However, devices in LLNs applications have limited memory. In order to keep the routing table size to be small, the routing path between two arbitrary nodes is usually not provided by default. Thus, the route discovery is required when there is no available route between a source and destination pair.

Reliable routing in dynamic and lossy environment. It is extremely crucial and challenging to achieve reliable routing in dynamic and lossy environment. Data transmission suffers from link loss in LLNs. In addition to harsh environment, channel fading and co-channel interference add more uncertainties to data transmission in wireless channels. Retransmissions usually result from unreliable wireless channels, leading to higher energy consumptions and longer channel occupancy time. It is vital to discovery reliable routing paths for data delivery in LLNs.

Energy-efficient route discovery. In LLNs, a large number of energy constrained nodes may be potentially inaccessible due to the constraints of physical environment in realistic. Conserving power and prolonging the lifetime of the network are critical to maintain persistent network connectivity so as to attain good network performances. The expenditure of energy results from the transmission and reception of data packets and control packets. Control packets are commonly used for topology construction in proactive routing protocols and route discovery in reactive routing protocols. For nodes with severe energy constraints, the transmission and reception of control packets are very costly in terms of energy consumption. In addition, nodes in LLNs are usually battery-powered and have to run complex computational processes. Traditional routing protocols disseminate route discovery messages throughout the whole network in all directions, which incurs very much overhead. Consequently, routing overhead should be minimized so as to conserve energy in the design of routing protocols for LLNs.

Link asymmetry in real-world scenarios. Empirical studies have shown that wireless links have asymmetric nature. The main reason is that the transmitter power and receiver sensitivity are different from nodes to nodes [22]. Some other factors, such as the reflectors, absorbers, etc, also result in link asymmetry. The asymmetric nature of wireless links has significant impact on the routing protocols' performance, especially for LLNs. Protocols without considering the asymmetry of wireless links sometimes fail when it is encountered in the real deployments [23]. Therefore, the asymmetry properties of wireless channels needs to be considered in the design.

Scalability support for large scale networks. LLNs are normally large scale and require routing protocols to provide scalability support. Routing protocols for LLNs have to be scalable so as to support large and increasing number of nodes. Scalability is one of the most important criteria in the design of LLNs routing protocols [21].

To address the above challenges and limitations of existing LLNs routing protocols, our proposed ER-RPL consists of the following four major components:

1) ER-RPL is designed with the capability to support generic traffic patterns, because it takes advantage of the existing DODAG structure of RPL in addition to its efficient support for P2P route discovery.
2) ER-RPL exploits the region feature of static networks. Only a portion of nodes are required to participate in the route discovery for a source-destination node pair. In addition to the region-based route discovery, Region-to-Region (R2R) routing without route discovery is implemented as an enhancement. These designs result in a great reduction of routing overhead. In this way, reliable routing paths can be discovered in an energy-efficient manner.
3) A distributed Self-regioning algorithm is proposed for nodes to compute their region codes (RCs). Meanwhile, the region-based route discovery also works in a decentralized manner. Therefore, ER-RPL has the capability to support network scalability.
4) The asymmetric nature of wireless links are considered in the protocol design. ER-RPL is robust to different wireless channel conditions.

III. Proposed Protocol: ER-RPL

Based on the key challenges and insights described in the Section II, we propose a hybrid of proactive and reactive routing protocol, namely ER-RPL, to achieve reliable data delivery in an energy-efficient manner. In this section, we first provide the system model of ER-RPL, and then present the key stages in ER-RPL for efficient P2P route discovery and data delivery.

A. System Model

1) Preliminary: We consider that n stationary nodes are densely deployed in the area with the size of G (m^2). Nodes with mobility are out of the scope of this paper. The transmission range of nodes is R. In the network, we consider a set of nodes with location-awareness capability

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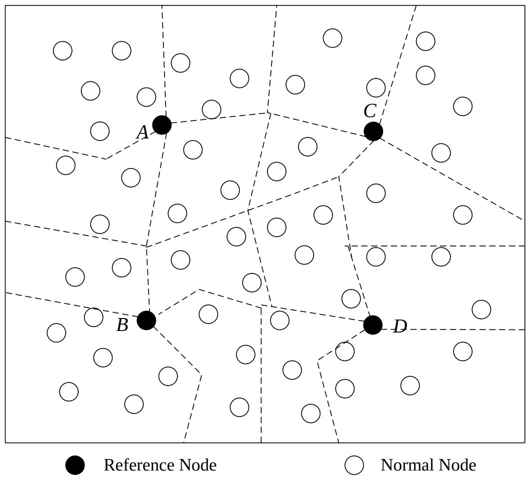

Fig. 2 An example of reference node and the regions in the network

Table I Summary of notations

Symbol	Definition
n	number of nodes
N	number of reference nodes
G	network size
Ω	The set of all RNs
ρ	network density
R	the transmission range of node and RN
λ	the number of traffic flows
I_{max}	the maximum time interval size
p_{ij}	the successful delivery probability from node i to j
E_{ij}	one hop ETX from node i to j
C_I	the *Coordinate* of RN I
h_{iI}	the hop count of arbitrary node i to RN I
$RNM(i,j)$ or RN_{ij}	the entry in the ith row and jth column of the matrix RNM
$RCM(m,n)$ or RC_{mn}	the entry in the mth row and mth column of the matrix RCM

(e.g., with GPS), which are called Reference Nodes (RNs). Fig. 2 shows an example of the RNs that are distributed in the network. Assume that N denotes the number of RNs, where $N \ll n$. The set of all RNs in the network is denoted by $\Omega = \{RN_1, RN_2, \ldots, RN_N\}$. With the help of RNs, the network area are segmented into several regions. The nodes without position knowledge are regarded as normal nodes (“nodes” in the following of this paper). The objective of protocol design is to energy-efficiently discover reliable routes for nodes without location-awareness capability so as to support reliable and energy-efficient P2P communication. Remote control applications typically require P2P communication. For example, a motion sensor (node *s*) suddenly needs to communicates with a lamp module (node *d*). Node *s* and node *d* are normal nodes in the network and do not have the location-awareness capability. The source node *s* needs to send the control command to the destination node *d* via multihop routing. In ER-RPL, a reliable route between node *s* and node *d* can be discovered in an energy-efficient manner.

Our proposed ER-RPL makes use of a small amount of location-aware RNs, but it differs from geographic routing in three fundamental ways: ER-RPL establishes the best quality route in terms of reliability in a reactive manner. 2) In ER-RPL, nodes do not have the unique geographic coordinates knowledge. The region information is only used for nodes to determine the necessity to participate in the route discovery. 3) In ER-RPL, the data delivery relays on the node's address and routing table instead of virtual or real coordinates. These features make our proposed ER-RPL essentially different from geographic routing protocols.

Our study considers two scenarios. In the first scenario, the node are nearly uniformly distributed so that the value of ρ is a constant. In the second scenario, the value of ρ is likely to change due to the irregular node deployment. Table I shows some notations to be used in this paper.

2) P2P Traffic Modelling in LLNs: Packets drop takes place in both node level and link level [22]. The link level channel contention and node level resource limitation affect communication quality. In this research study, we assume that nodes have enough buffer space, thus packets drop due to buffer overflow are negligible in this study.

Assume that the link loss is independent and identically distributed (i.i.d). The successful delivery probability from node *i* to node *j* can be denoted by p_{ij}. We assume that wireless links have bidirectional readability and can be asymmetric, which means p_{ij} may not be equal to p_{ji} for the delivery of packets. The Medium Access Control (MAC) layer has the retransmission scheme implemented to improve the reliability of transmission. The Expected Transmission count (ETX) [24] is used to measure the quality of wireless links. One hop ETX means the average number of transmissions required to successfully deliver one packet to the next hop, which is defined as $E_{ij} = 1/p_{ij}p_{ji}$, where p_{ij} is the probability of successful delivery of a data packet from node i to i, and p_{ji} in this equation refers to the probability of successful delivery of an ACK from node j to node i. Because the ACK usually has very small size, which can be recovered with the strong coding techniques. Hence, p_{ji} for ACK is approximate to one. In this study, we assume ACK does not suffer from link loss, so we can get $E_{ij} = 1/p_{ij}$. The aggregate ETX is used to select the best route for a source-destination node pair.

The traffic load from source node *i* to destination node *j* is denoted by L_{ij}, where $i \neq j$. Then the traffic load distribution matrix of the network is

$$L = \begin{bmatrix} L_{00} & \cdots & L_{0N} \\ \vdots & \ddots & \vdots \\ L_{N0} & \cdots & L_{NN} \end{bmatrix}, \quad (1)$$

where for $i \in n, L_{ii} = 0$.

For P2P communication, a node needs to choose the next hop among its neighbouring nodes for packet forwarding. This routing decision has significant impact on the network performance. To elucidate this, let δ_{ij} be the routing choice made by node *i* to node *j*, where $j \in N(i)$ and $N(i)$ denotes node i's neighbour node set. If δ_{ij} is equal to 1, it means that node *i* chooses node *j* as its next hop. If the value of δ_{ij} is 0, it means that node i does not choose node *j* as its next hop. We use $r_{i,s}$ to denote the traffic generation rate at node *i*, and use $r_{i,d}$ to denote the arrival rate of the traffic destinated at node *i*. Assume that the traffic receiving rate of node *i* from node *j* is $f_{j,i}$, and the traffic departure rate at node *i* to node *j* is $f_{i,j}$. In this way, the P2P traffic model for node *i* can be formulated as

$$r_{i,s} + \sum_{j \in N(i)} \delta_{ji} f_{ji} - \sum_{j \in N(i)} \delta_{ij} f_{ij} p_{ij} = r_{i,d}, \qquad (2)$$

where $0 \le f_{ji} \le C_{ji}$, $\forall i, j \in n$ and $i \neq j$.

Let us define the network running time as *T*. At time t, the traffic generation rate of node *i* is $r_{i,s,t}$. The traffic arrival rate of node *i* as destination is represented by $r_{i,d,t}$. The duration of traffic flow is Δt. In this way, the traffic load of node *i* is shown in Eq. (3) and (4).

$$\int_0^T r_{i,s,t} \Delta t_i = L_{i0} + L_{i1} + ... + L_{iN} = \sum_{0 \le j \le N} L_{ij}, \qquad (3)$$

$$\int_0^T r_{i,d,t} \Delta t_i = L_{01} + L_{1i} + ... + L_{Ni} = \sum_{0 \le j \le N} L_{ji}. \qquad (4)$$

3) Energy Model: We model nodes with four basic states (transmit, receive, idle, sleep) and a transition state among them [25]. The energy consumption in transmitting and receiving states are the major components to be considered in this study. The energy consumption is modelled using the First Order Radio Model [26], which has been widely used to measure the energy dissipation for wireless sensor networks (WSNs) [27], [28]. In this model, the radio consumes E_{elec} to run the transmitter or receiver circuitry. The transmitting amplifier is ϵ_{amp}, which is used to achieve the acceptable signal-to-noise (SNR) ratio. We assume the propagation loss exponent is 2. In this way, the energy consumption for transmitting a l-bit message with a transmission range R is modelled as

$$E_{tx}(l, R) = lE_{elec} + lR^2 \epsilon_{amp}, \qquad (5)$$

The energy consumption of the receiver is modeled as

$$E_{rx}(l, d) = lE_{elec}. \qquad (6)$$

B. Overview of ER-RPL

ER-RPL inherits the mechanism from RPL to pre-establish the DODAG such that it can support the multipoint-to-point (MP2P) with the optimized topology. Additionally, ER-RPL discovers the best P2P route with the region information in a reactive manner. Both RNs and nodes are stationary in this work. In ER-RPL, each RN belongs to an area, and that area is divided into a configurable number of non overlapping regions. The region number associated with each RN can be configured with the Self-regioning algorithm. Then each node starts to estimate which region it resides in. ER-RPL requires a node to determine the necessity to participate in the route discovery based on the knowledge of the source and destination nodes' region. In this way, the route discovery is only performed among a subset of nodes in the network, leading to significant reduction of routing overhead. Basically, ER-RPL includes two main stages. *1). Network initialization stage*: Each RN computes its *Coordinates*, which is defined as the average distance per hop count. Then, each node estimates the distances to each RNs based on the RN's *Coordinates* values and their hop counts to the corresponding RN. The particular region that a node resides in the network is represented by a region code (RC). With the distributed Self-regioning algorithm, a node can compute its RC in ER-RPL. *2). Route discovery stage*: According to the RC of source node and destination node, the route discovery is only performed among a subset of nodes in the network with the region-based route discovery. Besides, the Region-to-Region (R2R) routing without route discovery is designed as an enhancement to the region-based route discovery.

C. Network Initialization Stage

A series of positioning algorithms have been proposed, which are well known as the Ad Hoc Positioning System (APS). In particular, APS includes six algorithms: DV-Distance, DV-Hop, Euclidean, DV-Bearing, DV-Coordinate, and DV-Radial [29]. Different from the work in [29], where the *Coordinates* is defined as a correction factor, our work defines the *Coordinates* as the average distance per hop of RNs. ER-RPL is designed with an enhanced DV-Hop algorithm, which uses RNs' *Coordinates* and the hop counts to RNs for the estimation of the distances between a node to the RNs. It is worthy to highlight that the number of RNs in a network is known in advance by all RN nodes. RNs play a critical role in the network initialization stage, but they do not perform any task during the reactive P2P route discovery and data delivery.

1) Coordinates of Reference Node: Each RN computes its *Coordinates* value based on its relative distances and hop counts towards other RNs in the network. Upon receiving the topology formation information initiated by the root node, each RN serves as a temporary "root" and builds up a temporary DODAG using the Minimum Hop Count [30] as the routing metric. The construction of temporary DODAG is achieved by disseminating Region Formation Objec (RFO) messages, and different regions are formed during this process. Fig. 3 shows the packet structure of a RFO message. The *DODAG_RN* is the IP address of the RN. The *Rank* shows the hop distance to that RN. The *Position* carries the geographical position of this RN. There are two stages for the exchange of RFOs, which are indicated by the *CFlag*. When the *CFlag* is set to be zero by a RN, it indicates that the current stage is the *Coordinates Computation* stage for this RN. When the *CFlag* is set to be one, it is in the *Euclidean Distance Calculation* stage. The *Coordinate* field records the *Coordinates* value of the corresponding RN. The temporary DODAG rooted at RN *I* is denoted as $DODAG\_RN_I$, where *I* is an arbitrary RN in the network area. Upon receiving RFO messages, a node first checks the *CFlag* field to determine the stage of the RN .

During the *Coordinates Computation* stage, a node joins the temporary DODAG, chooses the next hop, updates its rank, and broadcasts its status with RFO messages. Similar to

DODAG_RN	Rank	CFlag	Coordinate	Position

Fig. 3 The Packet Structure of RFO Message

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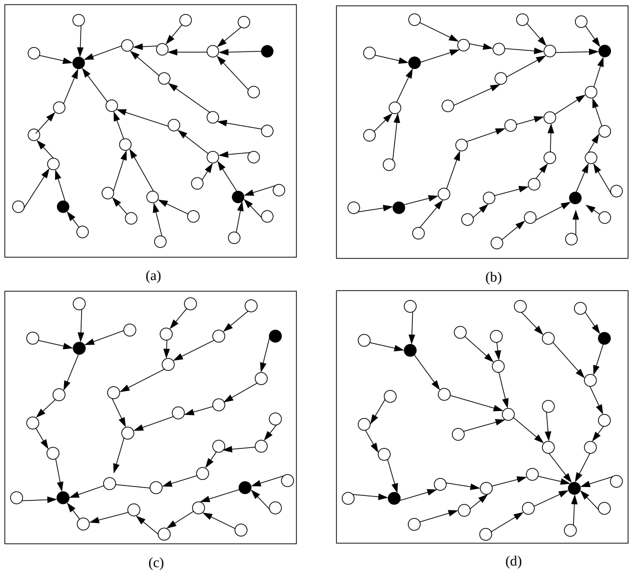

Fig. 4 Four temporary DODAGs rooted at each RN are built during network initialization stage.

the formation of DODAGs in RPL, the rank is monotonically increased based on the "preferred parent" (next hop) towards that RN. The broadcasting of RFO messages also follows the trickle algorithm. Based on the exchange of RFOs and update of rank value, each RN can collect the information of other RNs' positions and the distances between other RNs. N temporary DODAGs will be constructed with N RNs, as shown in Fig. 4. Assume that the position of RN I is (x_I, y_I). The Euclidean distance between two arbitrary RN I and RN J, is calculated using $d_{IJ} = \sqrt{(x_I - x_J)^2 + (y_I - y_J)^2}$. We use h_{IJ} to denote the hop count of RN I to RN J. When an RN joins the DODAG rooted by another RN, it records the position information as well as the hop count associated with that RN. Once an arbitrary RN I has the distance and hop count information of the other $(N-1)$ RNs, its *Coordinates* can be calculated through

$$C_I = \frac{\sum_{J\in\Omega, J\neq I} d_{IJ}}{\sum_{J\in\Omega, J\neq I} h_{IJ}}. \quad (7)$$

After a RN get its *Coordinates* value, it updates *CFlag* field as one and broadcasts RFO messages with its *Coordinates* value.

During the *Euclidean Distance Calculation* stage, a node is able to get each RN's *Coordinates* value and the hop count to that RN through joining the temporary DODAGs, the information of which is used for the Self-regioning algorithm. The *Coordinates* measurement of RN does not depend on the transmission range of nodes, the advantage of which is the simplicity. However, the accuracy depends on the isotropy property of the network deployment. The network graph of an isotropic network has a similar distribution in different directions. So the estimation of distance per hop is more accurate when nodes are deployed evenly.

2) Distributed Self-regioning Strategy: With the information collected during the *Euclidean Distance Calculation* stage, a node can calculate its distance to all RNs. For an arbitrary node *i*, the Euclidean distances to each RN are denoted by $\{d_{iI}\}$, where $I \in \Omega$. The distance between node *i* to RN *I* can be obtained through

$$d_{iI} = C_I h_{iI}, \quad (8)$$

A node can determine its closest RN by comparing the distances to each RN. There are multiple regions covered by each RN. $RegionNumber_{RN}$ is used to represent the particular region under one RN. After the area of one RN is segmented into four regions, whose locations are the upper left segment, lower left segment, upper right segment, and lower right segment, the region number will be *Region* I, II, III, IV, respectively, as shown in Fig. 5. In Fig. 5(a), d_{iA} is the minimum one among the distances to four RNs $(d_{iA}, d_{iB}, d_{iC}, d_{iD})$, so node *i* is inferred to reside in the region under RN *A*, which is denoted by $i \subseteq R_A(I, II, III, IV)$. The Self-regioning algorithm using the Law of Cosines is used to identify the region that the node belongs to, and then, a RC is assigned to the node. The pseudo-code of the distributed Self-regioning algorithm is shown in Algorithm 1.

Algorithm 1: Distributed Self-regioning Algorithm.

Data: $\{d_{iI}\}$, $\{d_{IJ}\}$, where $i \in N$, RN $I, J \in K$, and $I \neq J$. RN *A*, *B*, *C*, and *D* is $RN_{i,j}$, $RN_{i+1,j}$, $RN_{i,j+1}$, and $RN_{i+1,j+1}$ element of RNM, respectively.

if $\{d_{iA}\} = min\,\{d_{iI}\}$ **then**
  $i \subseteq R_A(I, II, III, IV)$;
  if $(d_{iA} + d_{iB} > d_{AB})$ **then**
    if $(d_{iA} + d_{iC} > d_{AC})$ **then**
      return $compare\_angles(\angle iAB, \angle iAC, \angle BAC)$
    else if $\angle iAB > \angle BAC$ **then**
      return III_A
    else
      return IV_A
  else if $(d_{iA} + d_{iC} > d_{AC})$ **then**
    if $\angle iAC > \angle BAC$ **then**
      return II_A
    else
      return IV_A
  else
    return IV_A
else if $\{d_{iA}\}$=$\{d_{iB}\}$=*min*$\{d_{iI}\}$ **then**
  $i \subseteq R_A(II, IV) \bigcup R_B(I, III)$;
  if $d_{iC} < d_{iD}$ **then**
    if $\angle iAC > \angle BAC$ **then**
      return II_A
    else
      return IV_A
  else if $\angle iAC > \angle BAC$ **then**
    return I_B
  else
    return III_B
else if $\{d_{iA}\}$=$\{d_{iB}\}$=$\{d_{iC}\}$=*min*$\{d_{iI}\}$ **then**
  return IV_A $(d_{DA} > d_{DB}, d_{DA} > d_{DC})$
else
  return IV_A or III_B or II_C or I_D

Function *compare_angles*(α, β, γ)
  δ=min $\{|360 - \alpha - \beta - \gamma|, |\beta - \alpha - \gamma|, |\alpha - \beta - \gamma|, |\alpha + \beta - \gamma|\}$
  if $\delta = |360 - \alpha - \beta - \gamma|$ **then**
    return *Region* I
  else if $\delta = |\beta - \alpha - \gamma|$ **then**
    return *Region* II
  else if $\delta = |\alpha - \beta - \gamma|$ **then**
    return *Region* III
  else
    return *Region* IV

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Fig. 5 shows an example of the distributed Self-regioning algorithm with four RNs. The Law of Cosines is used to compute the values of $\angle\alpha$, $\angle\beta$, and $\angle BAC$, such as

$$\angle\alpha = \angle iAB = \arccos\frac{d_{iA}^2 + d_{AB}^2 - d_{iB}^2}{2d_{iA}d_{iB}} \quad (9)$$

$$\angle\beta = \angle iAC = \arccos\frac{d_{iA}^2 + d_{AC}^2 - d_{iC}^2}{2d_{iA}d_{iC}} \quad (10)$$

$$\angle BAC = \arccos\frac{d_{AB}^2 + d_{AC}^2 - d_{BC}^2}{2d_{AB}d_{AC}} \quad (11)$$

By comparing the value of $|360-\alpha-\beta-BAC|, |\beta-\alpha-BAC|, |\alpha-\beta-BAC|, |\alpha+\beta-BAC|$, node *i* is considered to reside in IV_A, since $|\alpha+\beta-BAC|$ is the minimum one. The region code (RC) of IV_A, refers to the lower right segment of RN *A*, will be assigned to node *i*. The RC is an important concept in ER-RPL, which is a 8-bits code. The first four bits are represented by the region number and the last four bits are represented by the RN's ID. The ID of an RN is an unique integer. For example, 0000, 0001, 0010, and 0011 can be used to represent *Region* I, II, III, and IV, respectively. If node *i* is located at *Region* IV_A and the ID of RN A is 5, which is 0101 in binary, then node *i*'s RC is 00110101, as shown in Fig. 5.

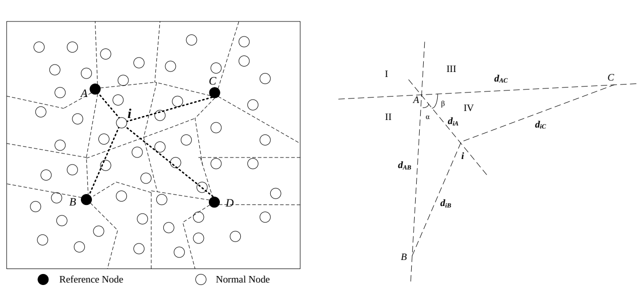
With the planned deployment of *N* RNs, a 2D tessellation with *N* cells can be formed. Each cell contains one RN. The number of RNs is a composite number, $r \times t = N$, $\forall r, t \in \mathbb{Z}_+$, where *r* is the row number and *t* is the column number of the tessellation.

Definition 1: The reference node map, $RNM = (RN_{ij})$, is defined as a $r \times t$ matrix with RNs' ID, where $0 \leq i \leq r$, $0 \leq j \leq t$.

When four regions are associated with each RN, four RCs can be generated from every element of a Reference Node Map (RNM). In this way, the Region Code Map (RCM), which consists of all RCs in the network, can be computed based on the RNM according to the *Def.* 2.

Definition 2: Based on RNM, RCM is defined as a $2r \times 2t$ matrix. $RCM = (RC_{mn})$. Each element of RNM, i.e., RN_{ij}, is used to generate four elements of RCM, which are $RC_{2i,2j}$, $RC_{2i,2j+1}$, $RC_{2i+1,2j}$, and $RC_{2i,2j+1}$.

RNM represents RNs' relative position of the cells. In the network initialization stage, nodes obtain the geographical location of each RN to build the RNM. In Fig. 5(a), the ID of RN *A*, *B*, *C*, and *D* in binary are 0101, 0110, 0111, and 1110, and then, the RNM is



(a) (b)

Fig. 5 The distributed Self-regioning algorithm: (a) Step I. (b) Step II.

$$RNM = \begin{bmatrix} 0101, 0110 \\ 0111, 1110 \end{bmatrix}, \quad (12)$$

When *Region* I, II, III, and IV are represented by 0000, 0001, 0010, and 0011, the RCM is

$$RCM = \begin{bmatrix} 00000101, 00100101, 00000111, 00100111 \\ 00010101, 00110101, 00010111, 00110111 \\ 00000110, 00100110, 00001110, 00101110 \\ 00010110, 00110110, 00011110, 00111110 \end{bmatrix}, \quad (13)$$

3) Rational of Reference Node and Region: The number of regions per RN covers may vary. In addition, there is no overlapping regions, which means one region can only belong to one RN. More regions can be created if more RNs are involved in the Self-regioning algorithm. Besides, if a node has equal distance to two or more RNs, an additional RN needs to get involved in the Self-regioning algorithm, which is covered in Algorithm 1.

Consider each region is with the same node density. After a node determines the closest RN, four regions per RN can be formed if a node uses another two RNs in the Self-regioning algorithm. And the shape of each region is approximately a rectangle. Similarly, six regions per RN can be formed if three neighbour RNs are used, and the region shape is close to a hexagon. Octagonal regions can be formed if another four neighbour RNs are used in the Self-regioning algorithm. After identifying the closest RN, if another ε neighbour RNs are involved in the Self-regioning algorithm, each RN can have 2ε regions. In this way, there are $2\varepsilon N$ regions when *N* RNs exists in the network.

Generally speaking, with more RNs involved in the Self-regioning algorithm, there are more regions. ER-RPL explores the optimal P2P route among only a subset of regions. When the network is segmented to more regions, each region has a smaller size, and then, a smaller subset of nodes participate in the route discovery on average. In this way, a greater reduction of control overhead can be achieved, when more RNs are used in the Self-regioning algorithm. The impact of region numbers on the reduction of overhead will be elaborated in Section IV.

D. Reactive P2P Route Discovery

This section presents the routing design of our proposed ER-RPL, which comprises of three major components for the reliable and energy-efficient data delivery. Firstly, during the region-based route discovery, a submatrix of the region code map (RCM) is computed based on the source node's region code (SRC) and the destination node's region code (DRC). Upon receiving a route request, a node determines whether or not it should join this route discovery process by checking its RC's existence in that submatrix of the RCM. Then a temporary DODAG is formed among only a portion of nodes in the network. Secondly, the Region-to-Region (R2R) routing without route discovery is designed as an enhancement for efficient P2P communication. The R2R route makes use of the available route between two regions. R2R routes are enabled during a route discovery that is performed previously. Besides, the route adjustment on-the-fly is implemented to

Type	Start Point Address	End Point Address	Sequence Num	Lifetime
Source Region Code	Destination Region Code	Accumulated ETX	Hop	

Fig. 6 Packet structure of MRO.

further shorten the R2R routes. Thirdly, the dead zone problem refers to that nodes in some regions cannot provide the connectivity to their neighbour regions, due to the limited transmission range and sparse node deployment. An Adaptive Region Selection (ARS) is design in ER-RPL to solve the dead zone problem.

1) Region-based P2P Route Discovery: Given a source-destination node pair, a submatrix of RCM, namely IRCM, can be generated, which composes a subset of RCs in the network. The IRCM is used to for a node to determine the necessity to join the route discovery. In particular, if a node's RC is the element of IRCM, it should participate the route discovery for the source-destination node pair. With IRCM, a subset of regions are selected in ER-RPL for route discovery. The size of that selected area is denoted by g, where $g \leq G$. The regions of the source and destination nodes are located in the diagonal of the selected area. ER-RPL chooses the shortest (most reliable) routing path to deliver data for the source-destination pair. Assume that RC_{m_s,n_s} and RC_{m_d,n_d} denote the SRC and DRC in a RCM, respectively. Then the IRCM is a $(|m_s - m_d| + 1) \times (|n_s - n_d| + 1)$ matrix, and the $IRCM(u, v)$ has equal entry to $RCM(u + min(m_s, m_d), v + min(n_s, n_d))$, where $0 \leq u \leq (|m_s - m_d| + 1)$, $0 \leq v \leq (|n_s - n_d| + 1)$.

With the *RCM* in Eq. (13). Assume the SRC is 00110101 and the DRC is 00011110, the *IRCM* is

$$IRCM = \begin{bmatrix} 00110101, 00010111 \\ 00100110, 00001110 \\ 00110110, 00011110 \end{bmatrix}. \quad (14)$$

The Message Request Object (MRO) is designed as the control message in ER-RPL, the packet structure of which is shown in Fig. 6. The *Start Point Address* and *End Point Address* record the source and destination IP addresses, respectively. The *Lifetime* indicates how long the temporary DODAG exists. The lifetime cannot be extended or shortened unless the source node receives a hint from the upper layer, . The end-to-end cost in terms of ETX is recorded in the *Accumulated ETX* field. The hop count towards the destination is stored in the field of *Hop*. Different types of MRO messages are distinguished through the field of *type*. There are four types of MRO, i.e., MRO(0), MRO(1), MRO(2), and MRO(4).

For a P2P route request, the source node sends MRO(0) through the existing DAG (via the root) to the destination node. MRO(0) records the accumulated cost and hop count along this path. Upon receiving MRO(0), the destination node can decide whether to use this existing route or explore a better route based on the route constraints[1]. If the existing route's cost is within the route constraints, MRO(1) is sent from the destination node to the source node. Otherwise, this route is considered as unsatisfactory, and then the destination node checks whether the routes between the source node's region and the destination node's region are available or not. If the R2R route has been enabled, there exists a route from the destination node to the source node through an intermediate node. In this case, the source node sends MRO(2) to the intermediate node through the best quality path. That intermediate node has the routing path to any node in the source node's region, and it forwards the MRO(2) to the source node through the optimal routing path. Once the source node receives the MRO(2), it sends data packets through the reverse route of the MRO(2). However, if the existing route is unsatisfactory and there is no R2R route available, the destination node initiate the region-based route discovery, in which temporary DODAG construction as the root with MRO(3). Specifically, the SRC and the DRC are piggybacked in MRO(3).

Once a node receives MRO(3) from its neighbour nodes, it first computes the IRCM based on the SRC and DRC, and then, it checks whether or not its RC exists in the IRCM. If it is so, the node will join the route discovery with the following steps: 1) it temporarily records the sender's ID with its end-to-end cost and hop count corresponding to the destination node in its local table. 2) it chooses the neighbour node that gives the minimum accumulated cost to the destination as its preferred parent. 3) it computes its cost towards the destination, updates its hop count and broadcasts MRO(3) to its neighbours. In this way, nodes always select the best quality path towards the destination, such that a temporary DODAG is constructed. In ER-RPL, nodes in the regions of IRCM choose the best route to the destination given a particular routing metric. Once the source node receives the route discovery message, it sends data packets to the destination node through the optimal route discovered by the DODAG construction.

Assume that *M* denotes the total number of regions, which is equivalent to $(2r \times 2t)$, and *K* denotes the number of the subset of regions that involve in the route discovery, which is equivalent to $(|m_s - m_d| + 1) \times (|n_s - n_d| + 1)$. The complexity of our proposed protocol is $\mathcal{O}(M + M + K)$, where $K < M$. As *N* is very small $(N \ll n)$, the complexity of our algorithm is low, so that our proposed algorithm is comparable with the existing protocols, such as RPL and P2P-RPL.

2) Region-to-Region Routing without route discovery: During the region-based route discovery process, the best quality path towards the destination node is selected by each node in the regions of the IRCM. Meanwhile, nodes in the same region with the source or destination node, send their routing information (hop-by-hop or source routing) to the destination node. In this way, the downwards routes from the temporary root (destination node in this routing pair) to all nodes in the source node's region and destination node's region can be supported by the destination node. The DODAG root, which is the destination node in this P2P pair, is used as an intermediary to support the communication between the source node's region to the destination node's region. Besides, in order to enable the R2R routing, every node keeps a R2R table, each row of which stores one node id, two RCs and the lifetime for this row. In order to keep the R2R table small, only nodes with SRC or DRC create the entry for this source-destination pair. Upon receiving the MRO(3) that carries the SRC and

[1]The work in [31] describes how to measure the P2P routing metrics in detail.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2016.2593438, IEEE Internet of Things Journal

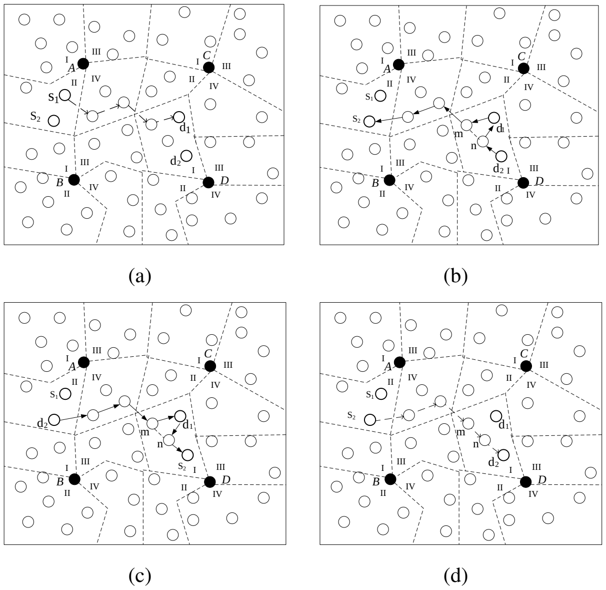


Fig. 7 Region-to-Region routing without route discovery. The solid arrow is used to indicate the route which MRO(2) travels along. The dash arrow indicate the route for data delivery. (a) The routing between *Region* II_A and *Region* I_D is enabled. (b) R2R routing is used for s_2 and d_2. (c) The intermediate node, d_1, can locates either in s_2's region or d_2's region. (d)R2R routing with Route Adjustment on-the-fly.

DRC, a node stores the SRC and DRC pair corresponding to the destination node (temporary root) in its R2R table. Upon receiving a P2P routing request, the destination node first examines its R2R routing table before it initiates the route discovery. If the route to source node's region is indicated as available, the destination node will send a reply MRO(2) via the corresponding DODAG root to the source node.

Fig. 7 illustrates an example for R2R routing in ER-RPL. As shown in Fig. 7(a), the routes between nodes in *Region* II_A and *Region* I_D are enabled during the route discovery from destination node d_1 to source node s_1. All nodes in *Region* II_A and *Region* I_D update their route information to node d_1 and store the information of (d_1, I_D, II_A) with its lifetime in its R2R table. Node d_1 temporarily records the routes to all nodes in *Region* IV_A and *Region* I_D. When there is another source-destination node pair, i.e., $s_2 - d_2$ in Fig. 7(b), the destination node d_2 checks its R2R table, in which the entry (d_1, I_D, II_A) indicates that there is an existing route to nodes in *Region* I_D via the intermediary node d_1. Instead of route discovery, the destination node d_2 replies with MRO(2) to the node d_1. With the routing information to s_2, d_1 forwards MRO(2) to node s_2. Once node s_2 receives the MRO(2), the reverse route of MRO(2) will be used for data delivery.

The R2R routing without route discovery can generally be applied no matter the intermediate node is located in the source or destination node's region. The example can be found in Fig. 7(b) and 7(c). In both cases, the entry for the source node region in R2R is (d_1, I_D, II_A), and node d_1 acts as the intermediate node. Although the routing paths from the source and destination node to the intermediate node are the best quality paths, the R2R route may not be the optimal one due to the existence of the intermediary. There are some extra hops in R2R routing, but it is less significant when the route tends to be long between the source region and the destination region. In a network, the number of nodes in each region become lesser when there are more numbers of regions. In this way, the sub-optimal route will be closer to the optimal route and the R2R table size becomes smaller.

Route Adjustment On-the-fly: We propose a route adjustment "on-the-fly" scheme to shorten R2R routes and alleviate the effect of sub-optimal routes. When a node receives or overhears a MRO(2), it always chooses the one that provides a smaller hop count as the next hop. Without using additional control messages, this scheme allows a node to flexibly choose its preceding nodes to attain the goal.

In Fig. 7(b), node *m* overhears the MRO(2) from node *n*, whose hop count to d_2 is one. After node *m* receiving MRO(2) from node d_1, whose hop count to d_2 is two, and then node *m* chooses node *n* as the next hop, such that its hop count to d_2 is two. Comparing the hop count in Fig. 7(b) with Fig. 7(d), the hop count is effectively reduced with this scheme.

3) Adaptive Region Selection for the Dead Zone Problem: In the previous section, we assume that the density of nodes in each region is approximately a constant. However, due to the irregular node deployment, the node density may vary from region to region. Let ρ_A denote the node density of *Region* A. It is known that a sufficient density is a critical requirement to ensure almost surely (a.a.s.) network connectedness [32]. Let us consider *n* nodes placed uniformly and independently in a 2D network area. For the sake of simplicity, the region shape is square with a size of $L_I \times L_I$. Each region is considered to be divided into square size cells. The cell has an edge of $\sqrt{2}R/2$. For region I, the node density required for a.a.s. connectedness is defined in the following theorem:

Theorem 1: $\rho_I \geq \frac{\alpha ln L_I}{r^2}$, for some $\alpha > 0$, $lim_{L_I \to \infty} P_{conn}(L_I) = 1, P_{conn}(L_I)$ denotes the probability that *Region* I is connected.

This theorem provides the necessary conditions to ensure asymptotically a.a.s. region connectivity. A similar theorem is proved in [27]. So the proof is omitted here. Although this theorem theoretically provides the required density for the network connectedness, an effective routing solution to check the connectedness is also needed in practice.

As we know, the region connectivity is impaired if the network density is too low. When some regions are with sparse

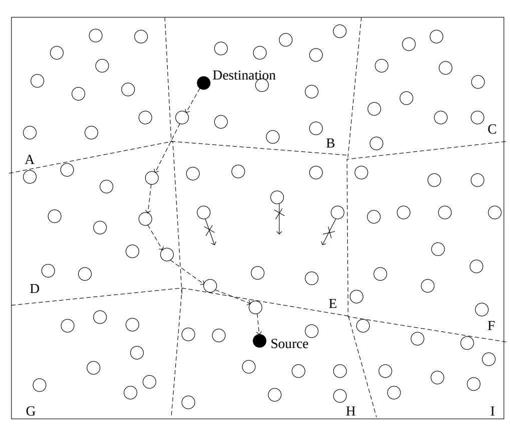


Fig. 8 Illustration of Dead Zone Problem.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2016.2593438, IEEE Internet of Things Journal

node distribution, these regions may not able to provide the connectivity for their neighbor regions. The dead zone problem arises when the P2P route is discovered among such regions. In Fig. 8, when the destination node needs to discover a route to the source node, nodes in *Region* B, E, and H will participate in the route discovery process. Due to the limited transmission range and sparse node deployment, nodes in *Region* E are not able to establish a route for *Region* B and *Region* H. Therefore, *Region* E is considered as a dead zone for *Region* B and *Region* H. However, the routing path can be successfully provided, if nodes in *Region* D join the route discovery process.

We propose an Adaptive Region Selection (ARS) scheme to provide an efficient solution for the dead zone problem. During the network initialization stage, nodes update their RCs and one hop neighbor information through their preferred parent nodes to the root node, so that the root node has a global knowledge of the network topology. A similar approach is defined in RPL [3], where the Destination Advertisement Object (DAO) is used to propagate upwards along the DAG to the root node, so that downwards routes from the root node can be supported in RPL. The root node usually has a strong computation capability and large memory space, which can store RNs' *Coordinates*, nodes' RCs and their one hop neighbour list. Upon receiving MRO(0) for a P2P routing request, the root node computes the IRCM and performs a neighbor list checking, so that it can determine whether the source node and destination node are reachable within the regions of IRCM. If the root node detects that those regions cannot provide the connectivity, it will use a flag to indicate the dead zone problem in MRO(0). Upon receiving the MRO(0) with the dead zone indication, the destination node will piggyback this information in the route discovery message (MRO(3)). Instead of IRCM, the Expanded IRCM (EIRCM) is used in this case.

Definition 3: Assume that SRC and DRC are the RC_{m_s,n_s} element and the RC_{m_d,n_d} element in the RCM, respectively, where the RCM is an $2r \times 2t$ matrix. The EIRCM is defined as a $(m_{dd} - m_{ss} + 1) \times (n_{dd} - n_{ss} + 1)$ submatrix of RCM, where m_{ss}, n_{ss}, m_{dd}, and n_{dd} can be computed according to Eq. (15). $EIRCM(u, v)$ has entry equal to $RCM(m, n)$, where $m = u + m_{ss}$, and $n = v + n_{ss}$.

$$\begin{aligned} m_{ss} &= \begin{cases} min(m_s, m_d) - 1, & \text{if } min(m_s, m_d) \neq 0 \\ 0, & \text{otherwise,} \end{cases} \\ n_{ss} &= \begin{cases} min(n_s, n_d) - 1, & \text{if } min(n_s, n_d) \neq 0 \\ 0, & \text{otherwise,} \end{cases} \\ m_{dd} &= \begin{cases} max(m_s, m_d) + 1, & \text{if } max(m_s, m_d) \neq m \\ m, & \text{otherwise,} \end{cases} \\ n_{dd} &= \begin{cases} max(n_s, n_d) + 1, & \text{if } max(n_s, n_d) \neq n \\ n, & \text{otherwise.} \end{cases} \end{aligned} \tag{15}$$

During the region-based route discovery process with ARS, a node computes EIRCM instead of IRCM after receiving MRO(3) with the dead zone problem indication. If a node's RC is an element in the EIRCM, the node joins this temporary DODAG for the P2P route discovery. In this way, more regions are involved in the route discovery process so that the chance to successfully discover a good route for the source-destination node pair is greatly increased.

IV. Model Validation

The trickle algorithm is used in RPL, P2P-RPL and ER-RPL to achieve both rapid propagation and low maintenance overhead. Three key parameters are used to define the interval of broadcasting control messages [12]; the minimum time interval size I_{min}, the maximum time interval size I_{max}, and the redundancy counter *c*. The current communication interval is denoted as *I*. When a node starts a trickle timer, it resets *c* to 0 and the control messages update time, which is denoted by *t*, to a random value between $I/2$ to I. Whenever a node hears a transmission that is "consistent" [2], it increments the counter *c*. The trickle algorithm doubles the current communication interval, *I*, once the interval *I* expires. The "inconsistent" messages cause trickle timer to reset. Until the interval length is greater than I_{max}, I is set to be I_{max}. When the interval *I* reaches I_{max}, the transmission rate of control messages, f_c, follows

$$f_c \approx \frac{1}{I_{min} 2^{I_{max}}}. \tag{16}$$

Assume that the number of traffic flows is denoted by λ. In P2P-RPL, all nodes participate in the route discovery. When λ traffic flows require the route discovery, where $\lambda < n(n-1)/2$, the control overhead of P2P-RPL for time *t* is

$$O_{p2p-rpl} = n\lambda f_c t = \frac{n\lambda t}{I_{min} 2^{I_{max}}}. \tag{17}$$

The route discovery may not be necessary under certain circumstances. For example, nodes can have direct communication to their one-hop neighbours. By assuming that nodes' one-hop neighbours number is $\pi R^2 \rho$, the ratio of one-hop data delivery is

$$\varphi_{nb} \approx \frac{C_n^1 (\pi R^2 \rho - 1)}{n^2} = \frac{\pi R^2 \rho - 1}{n}. \tag{18}$$

Nodes' routing tables usually contain some valid routes. The ratio of the number of valid routes to the number of nodes in the network is denoted as φ_{rt}. The value of φ_{rt} is affected by many factors, such as the routing table size, traffic flows, and the routing lifetime. The number of one-hop neighbours can be approximately considered as the number of valid routing entries due to the limited memory space of nodes. With the i.i.d. selection of source and destination nodes, the control overhead of P2P-RPL for λ traffic flows during time *t* is

$$O_{p2p-rpl} \approx \frac{(1 - \varphi_{rt}) n\lambda t}{I_{min} 2^{I_{max}}} \approx \frac{(1 - \varphi_{nb}) n\lambda t}{I_{min} 2^{I_{max}}}. \tag{19}$$

In ER-RPL, only a subset of nodes participate in the route discovery. For simplicity, we consider a dense network, in which the node density, ρ, of each region is the same. We also assume the route discovery is needed to support the

[2] A control message (DIO, P2P-DRO, and MRO(3) in RPL, P2P-RPL, and ER-RPL, respectively) from a sender with a lesser DODAG rank that does not cause any changes to the recipient's parent set, preferred parent, or rank is considered consistent. Otherwise, the control message is inconsistent.

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communication between two arbitrary nodes in the network. For a network containing k^2 regions, the ratio of nodes that participate in route discovery and consume overhead to total nodes is denoted as $\varphi(k,\rho,n)$, where $0 < \varphi(k,\rho,n) \leq 1$. For a $k \times k$ RCM, the SRC is $RCM(m,n)$, and the DRC is $RCM(a,b)$, where $a \in [0,k-1], b \in [0,k-1]$. Then IRCM is a $(|m-a|+1) \times (|n-b|+1)$ matrix. In this case, the value of $\varphi(k,\rho,n)$ is $(|m-a|+1)(|n-b|+1)/k^2$. When the source node and destination node are i.i.d., $\varphi(k,\rho,n)$ will no longer depend on ρ and n as the number of traffic flows λ tends to be ∞, which is represented by $\varphi(k)$. In this case, we can have

$$\varphi(k) \approx \frac{\sum_{a=0}^{k-1}\sum_{b=0}^{k-1}\sum_{m=0}^{k-1}\sum_{n=0}^{k-1}(|m-a|+1)(|n-b|+1)}{k^6}. \quad (20)$$

Similarly, it is not always necessary to discover routes for the one-hop neighbours and node with valid routes in the routing table. The expectation value of $\varphi(k,\rho,n)$ is $\varphi(k)$, which does not consider the valid routing entries in the routing table. So we can get

$$\varphi(k,\rho,n) \approx \varphi(k) + \varphi_{rt} \approx \varphi(k) + \varphi_{nb}. \quad (21)$$

So theoretically, the control overhead for ER-RPL based on the previous conditions is

$$O_{er-rpl} \approx \frac{\varphi(k,\rho,n)n\lambda t}{I_{min}2^{I_{max}}}. \quad (22)$$

V. Network Simulation

A. Experimental Setup

In this study, RPL, P2P-RPL and ER-RPL are implemented from scratch on Network Simulator 3 (NS3) [33]. The error erasure channel is used to model the lossy environment. Each wireless link is assigned with a random probability p_{ij}, where $0.3 \leq p_{ij} \leq 0.8$. Many research studies have provided solutions to measure the wireless link quality [34], [35], which is out of the scope of this paper. We assume that the link layer will handle this issue. Four RNs are used in this study. Each RN has four regions with the distributed Self-regioning algorithm. Both symmetric links ($p_{ij} = p_{ji}$) and asymmetric links ($p_{ij} \neq p_{ji}$) are considered, which are denoted by *s* and *as* in the performance analysis section, respectively. For instance, for a particular protocol, ER-RPL$_{s}$ and ER-RPL$_{as}$ denote the routing performance with symmetric and asymmetric links, respectively. RPL is in non-storing mode. Our simulation studies are conducted with the IEEE 802.11. It is worth to highlight that IEEE 802.11 is usually not considered as the best candidate for LLNs, while IEEE 802.15.4 [4] is viewed as the optimal choice for LLNs. But the routing protocols' general behavior, such as path-length, packet delivery, control overhead, etc, can be concluded from the simulation study with IEEE 802.11 [16], especially for networks with a low data rate. A detail performance comparison of IEEE 802.11 and IEEE 802.15.4 can be found in the work of [36].

We focus on the P2P routing performances in two scenarios. In Scenario I, the maximum time interval I_{max} are varied from 5 to 8 and traffic flows are set to 30. In Scenario II, the number of P2P traffic flows are varied from 10 to 40, and I_{max} is set to 8. In both scenarios, two types of node deployment strategies are studied. Without loss of generality, 100 nodes are randomly deployed in a $180m \times 180m$ network area with the random planar deployment strategy, and we also study the 10×10 grid deployment with some randomness for the constant node density scenario. The node's position is $(20b \pm \Delta x, 20r \pm \Delta y)$, where $-5 \leq \Delta x \leq 5, -5 \leq \Delta y \leq 5$. Assume that the node ID is U, the value of b and r are obtained through $U = 10b + r$, where b, r is $\mathbb{N}$, and $r < 10$. In this simulation study, the source and destination node pair is randomly selected for each traffic flow. Each traffic flow lasts for 90 seconds and then another P2P flow starts. In this way, the number of concurrent traffic flows are kept the same but there are different source and destination routing pairs generated during the simulation. Other parameters are displayed in Table II. The simulation time is 1000s. A different random topology is generated in each run and each data of the results is the average value from ten runs.

Table II Parameter setting for our simulation.

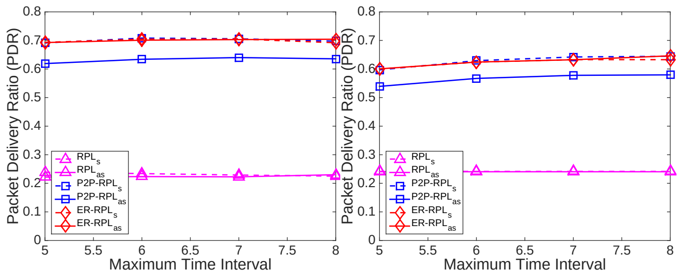
Parameter	Value
Number of nodes	100
Number of reference nodes	4
Retransmission limit	5
Communication range	35m
Packet size	512 bytes
Traffic rate	4 pkt/s, CBR flow
Routing metric	ETX
Transmitter electronics (E_{elec})	50nJ/bit
Transmit amplifier (ϵ_{amp})	100pJ/bit/m^2
The Minimum time interval size (I_{min})	50ms
Redundancy constant (c)	∞

B. Performance Metrics

The following metrics are adopted to evaluate the performance of the proposed protocol and the benchmarks.

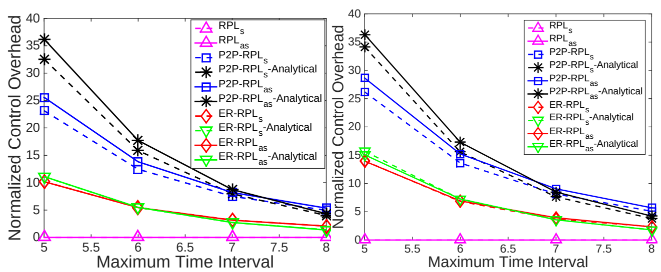
1) *Packet delivery ratio* refers to the ratio of the number of packets successfully delivered to destination nodes to the number of packets generated by source nodes. This metric illustrates the routing reliability.
2) *Normalized routing control overhead* refers to the ratio of the number of control messages to the number of data successfully delivered to the destination nodes.
3) *Energy consumption per data successfully delivered* is the ratio of the total energy consumption to the number of data packets that are successfully delivered to the destination nodes. The total energy consumption of the network includes the energy spent for all phases of the network during the simulation.
4) *Average hop count* refers to the average number of hops for the discovered route between the source nodes and the destination nodes.
5) *Average end-to-end delay* includes all possible delay during data transmission due to transmission time, retransmission caused by collision and queuing time.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/JIOT.2016.2593438, IEEE Internet of Things Journal



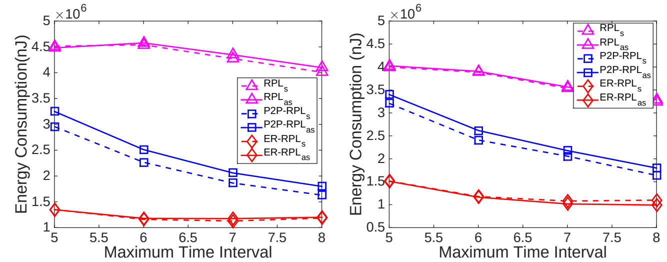
(a) (b)

Fig. 9 Scenario I: The PDR comparison. (a) grid with randomness deployment (ρ is a constant). (b) random planar deployment (ρ is not a constant).



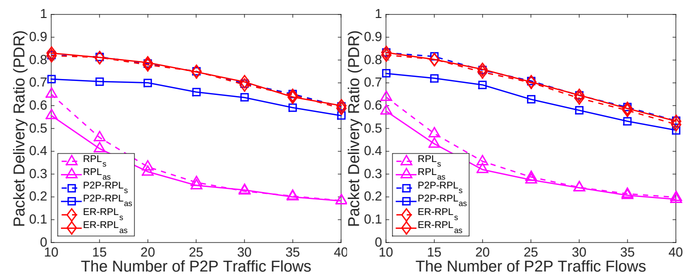
(a) (b)

Fig. 10 Scenario I: Control overhead comparison of simulation vs theoretical results. (a) grid with randomness deployment (ρ is a constant). (b) random planar deployment (ρ is not a constant).



(a) (b)

Fig. 11 Scenario I: Energy consumption per successful data delivery comparison. (a) grid with randomness deployment (ρ is a constant). (b) random planar deployment (ρ is not a constant).



(a) (b)

Fig. 12 Scenario II: The PDR comparison. (a) grid with randomness deployment (ρ is a constant). (b) random planar deployment (ρ is not a constant).

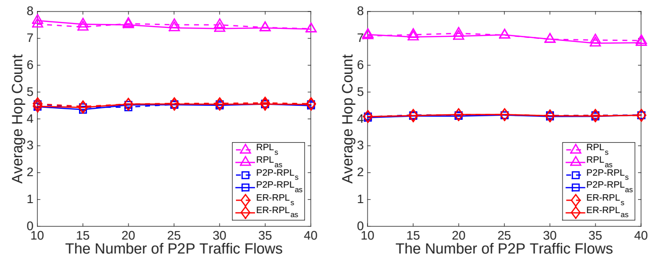
C. Performance Evaluation

As shown in Fig. 9, ER-RPL improves the packet delivery ratio (PDR) by 150% compared to RPL. ER-RPL$_s$ achieves a very close performance to P2P-RPL with symmetric links (P2P-RPL$_s$), which is the optimal value with symmetric links. It shows that although only partial nodes are involved in the P2P route discovery process, ER-RPL can still choose the nearly optimal route to provide reliable routing, which is one of our goals in this work. With the region-based route discovery, ER-RPL$_{as}$ can maintain the performance and outperform P2P-RPL with asymmetric links (P2P-RPL$_{as}$) by around 10%. In P2P-RPL, the P2P route is discovered throughout the whole network. Therefore, the optimal route from the destination node to the source node is selected by P2P-RPL. The PDR degrades in P2P-RPL if the wireless link becomes asymmetric. Because in P2P-RPL, the temporary DODAG is rooted at the source node, so that the route for data delivery may not be the optimal one from the source to the destination under asymmetric links. Different from P2P-RPL, whose temporary DODAG is rooted at the source node, ER-RPL forms the temporary DODAG at the destination node, so the best route from the source to destination is always used.

Fig. 10 shows that the routing control overhead for route discovery decreases with the increment of the maximum time interval size (I_{max}). ER-RPL achieves average 60% less control overhead compared to P2P-RPL. The control overhead of P2P-RPL$_{as}$ is larger than P2P-RPL$_s$ due to fewer packets received by the destinations. RPL uses the pre-established route for the delivery of data packets, so the route discovery is not required and we consider that no additional control messages occur in this case. Fig. 10 also depicts the theoretical results with Eq. (19) and (22). With a short maximum time interval, the network reaches the convergence stage quickly. So the effect of high frequency during the network initialization stage is negligible. Meanwhile, due to the valid routing entries, the overhead is slightly lower in the simulation than the theoretical results, which regards the number of one-hop neighbours as the number of valid routes. However, with the increment of I_{max}, it takes more time for the network to converge, thus it occurs higher overhead.

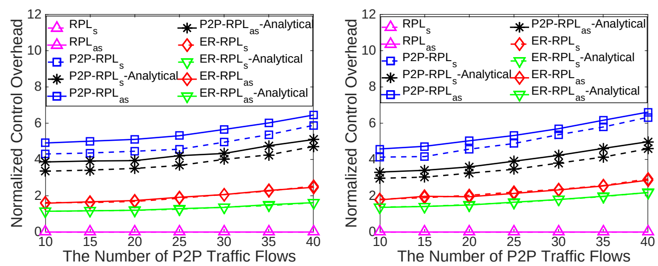
Fig. 11 depicts the energy consumption decreases with the decreasing frequency of control messages. ER-RPL achieves around 66% and 60% energy conservation compared to RPL on average, as shown in Fig. 11(a) and Fig. 11(b), respectively, because the longer routes in RPL consume more energy. The impact of the frequency of control message is more significant on P2P-RPL than ER-RPL. P2P-RPL disseminates control messages throughout the network, and the large amount of control messages constitute a significant portion of the total energy cost. So the variation of the frequency of control messages leads to a obvious difference on the energy consumption performance in P2P-RPL. With a great reduction of the control overhead, ER-RPL achieves a significant energy conservation compared to P2P-RPL. The energy consumption of ER-RPL only changes slightly with a variation of the frequency of control messages. Apart from the frequency of the control messages, other factors also affect the energy performance, e.g., the size of data packets and control messages.

Fig. 12 shows the PDR performance drops as the traffic flow increases. In RPL, the root becomes the bottleneck of the network when the traffic is heavy, resulting in a serious



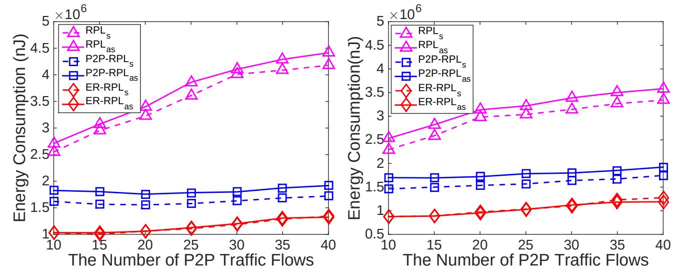
(a) (b)

Fig. 13 Scenario II: Hop count comparison.. (a) grid with randomness deployment (ρ is a constant). (b) random planar deployment (ρ is not a constant).



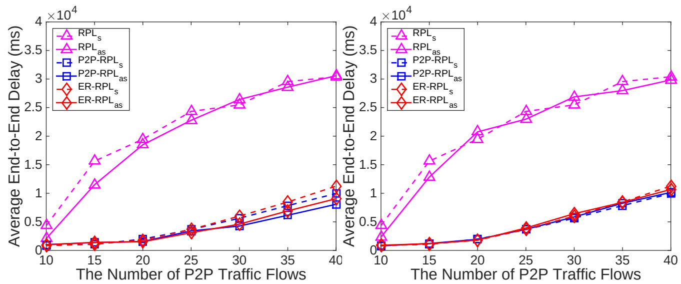
(a) (b)

Fig. 14 Scenario II: Control overhead comparison of simulation vs theoretical results. (a) grid with randomness deployment (ρ is a constant). (b) random planar deployment (ρ is not a constant).



(a) (b)

Fig. 15 Scenario II: Energy consumption per successful data delivery. (a) grid with randomness deployment (ρ is a constant). (b) random planar deployment (ρ is not a constant).



(a) (b)

Fig. 16 Scenario II: End-to-End delay comparison. (a) grid with randomness deployment (ρ is a constant). (b) random planar deployment (ρ is not a constant).

performance drop. The dead zone problem may take place in the random planner deployment. But ER-RPL still achieves a nearly optimal value, as represented by the PDR performance of $P2P\text{-}RPL_s$. It shows that the proposed ARS is an efficient solution for the dead zone problem.

Fig. 13 depicts that the average hop count of P2P routes selected by ER-RPL is very close to P2P-RPL, which is 40% less than that of RPL. In RPL, data packets are delivered through the pre-established route via the root, thus it needs to travel through longer route compared with ER-RPL and P2P-RPL. The average hop count is slightly more in Fig. 13(a) compared to Fig. 13(b). Because the node density of the grid with randomness deployment is lower than that of the random planar deployment in this study.

Fig. 14 depicts that routing overhead increases as the traffic flows increase. In Fig. 14(a), ER-RPL achieves about 59%, 66% less control overhead than P2P-RPL with symmetric and asymmetric links, respectively. In Fig. 14(b), $ER\text{-}RPL_s$ and $ER\text{-}RPL_{as}$ achieve about average 55%, 58% less overhead compared with $P2P\text{-}RPL_s$ and $P2P\text{-}RPL_{as}$, respectively. This is because more regions join the route discovery with the ARS to solve the dead zone problem in random planar networks. Results from the simulation study are close to that from the theoretical analysis. The subtle difference is due to some factors which are considered in the simulation model but are not considered in the analytical model (Eq. (19) and (22)), such as the randomness of control frequency in the initialization stage, the lifetime of routes, the routing table, etc. The design of R2R routing can further reduce the amount of routing overhead in ER-RPL, which is shown by the smaller gap between the theoretical and simulation results than P2P-RPL.

Fig. 15 shows that the energy consumption increases with the increase of P2P traffic flows. ER-RPL achieves a great energy conservation compared with RPL and P2P-RPL. In RPL, all traffic flows are delivered through the root node. The area near the root easily becomes congested with high traffic, and a large number of packets get dropped. So the increase of P2P traffic flows has a more significant impact on RPL than ER-RPL and P2P-RPL. ER-RPL and P2P-RPL shows a more robust energy performance with the increase of network traffic flows. In addition, ER-RPL has a similar performance in terms of energy consumption with symmetric and asymmetric links, while $P2P\text{-}RPL_{as}$ consumes more energy than $P2P\text{-}RPL_s$, because less number of dara packets are successfully delivered in P2P-RPL when the link is asymmetric .

Fig. 16 depicts that the end-to-end delay increases as the traffic flow increases. Compared with ER-RPLand P2P-RPL, RPL suffers from a longer delay due to the longer route used for the delivery of data packets. Additionally, the increasing traffic load has a significant impact on the delay in RPL, due to the bottleneck (i.e., the root node) in the network.

VI. Conclusion

This paper has proposed ER-RPL, which is a distributed energy-efficient region-based routing protocol. ER-RPL is a hybrid of proactive and reactive routing protocol, and it makes use of the region information of networks. ER-RPL can support generic traffic patterns and simultaneously achieve reliability and energy-efficiency. Both theoretical and experimental analysis have been provided to validate the flexibility and effectiveness of ER-RPL. ER-RPL can select nearly optimal routes in terms of reliability with great energy conservation. In addition, extensive simulation results also demonstrate that ER-RPL can achieve a great reduction of routing overhead, and it is robust to the wireless channel conditions. As this paper focuses on static networks, we plan to extend our work to mobile networks in our future work.

Acknowledgment

This research is funded by the Republic of Singapore's National Research Foundation (NRF) through a grant to the Berkeley Education Alliance for Research in Singapore (BEARS) for the Singapore-Berkeley Building Efficiency and Sustainability in the Tropics (SinBerBEST) Program. BEARS has been established by the University of California, Berkeley as a center for intellectual excellence in research and education in Singapore. In addition, this work is also partially supported by the Early Career Scheme (Project No. 25200714) established under the University Grant Committee of the Hong Kong Special Administrative Region, China; the National Natural Science Foundation of China (Project No. 61401384); and The Hong Kong Polytechnic University (Projects 4-ZZCZ, 4-ZZDF, 4-ZZEF, G-YBK6, and G-YN17).

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