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Green-RPL: An Energy-Efficient Protocol for Cognitive Radio Enabled AMI Network in Smart Grid

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ABSTRACT With the capacity of achieving spectrum efficient wireless communications, cognitive radio enabled advanced metering infrastructure (CR-AMI) networks are expected to enhance the efficiency and practicability of future smart grids. CR-AMI networks which have been recognized as a fundamental component of the smart grid ecosystem, are practically utilized as a static multi-hop wireless mesh network. This paper focuses on the development of a novel routing protocol for low power and lossy networks based routing protocol for enhancing the energy efficiency in CR-AMI networks. For meeting the requirements of green communications in smart grids, the proposed routing protocol adopts the energy efficiency over virtual distance as the core of routing mechanism such that the energy-efficient route can be achieved. Furthermore, the protocol provides protection for primary users whilst meeting the utility requirements of secondary users. System-level evaluation indicates that the proposed protocol performs better than existing routing protocols for CR-AMI networks.

INDEX TERMS Smart grid, cognitive radio, AMI, green communication, energy efficiency.

I. INTRODUCTION

There are many challenges, such as ageing infrastructure, energy inefficiency existing in the legacy electric power grids, frequent transmission congestion and even failures [1]–[3]. Therefore, smart grid, which is the next generation of electric grids enabled by ICT technologies, has the potential to address the existing problems of the legacy power grid [1]–[4]. It can upgrade the management and distribution of power, and supply improved service with efficiency, reliability and agility, by incorporating using two-way communication, distributed computing and automated control into conventional power grid. providers, distributors and consumers to obtain real-time information of operating requirements and capabilities. To guarantee successful operation of smart grid, it is critical to design an efficient and reliable communication network [5], [6].

As one key element of the smart grid, the *Advanced Metering Infrastructure* (AMI) network consists of smart meters communicating with the *Meter Data Management System* (MDMS), which serves as a control center for management, storage and processing of meter data (e.g., electric bills). The AMI network serves both electricity distributors and consumers. The former can monitor consumers' electricity usage, and record power quality. The latter can consume electricity opportunistically by exploring the real-time electricity price. Unfortunately, the spectrum inefficiency and scarcity issues bring a bottleneck to traditional AMI applications. In this regard, cognitive radio (CR) [7]–[10] provides an effective way to deal with the spectrum scarcity and inefficiency issues in wireless networks. Especially, in [9], Zhao *et al*. proposed an effective power allocation scheme for interference alignment based CR networks, with closed-form solutions derived. Therefore, CR-AMI networks draws lots of attentions [11]–[13],where smart meters (CR users) can occupy the frequency band/channel dynamically, when licensed users (primary users) are absent. A number of studies are proposed, which involve CR technologies into smart grid AMI networks, such as [14]–[23]. Furthermore, the multi-hop wireless mesh network is a practical solution for CR-AMI networks, which connects smart meters to the gateway in turns. By using dynamic spectrum access (DSA) techniques, smart meters can access licensed channels, and transmit data to the gateway. Therefore, efficient routing protocols are necessary in such networks, to ensure high capacity and reliability of data delivery. In [13], the Cognitive and Opportunistic Routing Protocol (CORPL) is proposed, in order to enhance RPL for CR-AMI networks. In CORPL, a multi-receiver scheme is proposed, and can reduce retransmissions obviously. However, the multi-receiver scheme leads to serious coordination overhead, which increases the energy consumption of data transmissions.

On the other hand, energy crisis and atmospheric pollution are public problems all over the world, wherein *Information and Communication Technology* (ICT) is responsible for 3% of energy consumption and 2% of CO_2 emission [24], [25]. Furthermore, this energy consumption is continuously increasing at a rate of 15% per year. Especially, when smart grids are massively deployed, the energy consumption of AMI networks may intensify the issue [26]. Therefore, energy efficiency may be a new issue for AMI networks, which may pose new practical issues. Therefore, improving energy efficiency is an important design consideration, and green communication should be taken into account for CR-AMI networks. To our best knowledge, the energy efficiency of AMI networks in smart grids is not efficiently covered.

With this background, this paper aims to optimize RPL-based routing in CR-AMI networks, in order to improve the energy efficiency while meeting the utility requirements for CR-AMI networks. The key contributions are stated as follows.

- For the tradeoff between primary user protection and QoS for the secondary network, we develop a unique rank computation metric which captures both protection to primary receivers and secondary network QoS within the objective function.
- We develop a unique routing cost metric based on the energy efficiency of routing in CR-AMI networks. Based on the routing cost, the energy-efficient route can be selected, such that the energy efficiency of the whole network is improved.
- The concept of *Energy Efficiency Over Virtual Distance* (EEVD) is proposed for quantifying the energy efficiency over virtual distance, such that we can quantify the virtual energy efficiency of transmission in CR-AMI networks.
- Similar with CORPL, the multi-receiver scheme during the single-hop transmission is adopted. It can reduce the probability of retransmission due to data packet receiving failure, but may lead to retransmissions of the same data packet. In this regard, we adopt a coordination scheme based on the acknowledgement (ACK), and use micro-frames for ACK information transmission, in order to reduce data retransmissions.
- The protocol proposed in this paper is termed as Green-RPL. We conduct a system-level performance evaluation of Green-RPL for CR-AMI networks, and compare key metric performances with existing routing protocols.

The rest of the paper is organized as follows. The related work overview is presented in Section II. Section III presents The optimizing RPL-based routing framework, followed by the analytical modeling in Section IV. The performance evaluation is shown in Section V. Finally the paper is concluded in Section VI.

II. RELATED WORKS

Recently, a specially designed protocol known as RPL is proposed [27]. It has been standardized by the Internet Engineering Task Force (IETF) for a variety of applications, including the AMI network. Therefore, RPL-based routing protocol design has attracted much attention for communications in different fields. It is a distance-vector and source routing protocol, and adopts Directed Acyclic Graphs (DAGs) to structure networks. Each DAG is a directed graph where all edges are oriented without any cycles, and includes a gateway (root node) and several client nodes. Each node is assigned a rank in order to represents its virtual position to other nodes with respect to the DAG root. The rank is computed on the basis of an objective function, and monotonically increases in the downward direction (DAG root has the lowest rank). In order to avoid cycles, a node in a DAG can only transmit packets to these nodes with the same or smaller ranks. Another important procedure is forwarder selection. For different objectives, different schemes are adopted in RPL. Literatures [28] and [29] give thorough overviews of RPL, and state its advantages and potential limits communications in smart grid. Literatures [30] and [31] study modifications to meet application requirements in AMI networks for RPL. A novel DAG rank computation approach and a reverse path recording mechanism are proposed in [30], in order to enable realtime calculations for remote utility management and meter reading in smart grid.

Although RPL is well applicable to the traditional AMI network, it suffers from some limitations in CR-AMI networks. Therefore, CORPL is specially proposed in [13] to enhance routing in CR-AMI networks, where two classes of routing methods are proposed for different utility demands, Class *A* assigns a greater importance to PU receiver protection whereas in Class *B*, the end-to-end latency is the key consideration for supporting the high priority delay sensitive alarms. However, CORPL is not efficient in the energy efficiency performance. Especially, energy efficiency may be a new critical issue, when AMI networks are massively deployed for smart grids. Additionally, a receiver-based routing protocol (named as CRB-RPL)is proposed for CR-AMI networks in [32], where a receiver-based routing scheme is proposed in order to improve the reliability and end-to-end latency performance.

III. GREEN-RPL FRAMEWORK

A. SYSTEM MODEL

We consider a static multi-hop wireless AMI network. In such networks, a gateway node acts as a local access point connected to MDMS, and smart meters (nodes) transmitting their

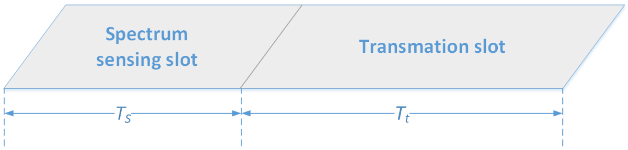

FIGURE 1. **The structure of a MAC frame in Green-RPL.**

data in turn. We assume that the smart meters are cognitive-radio-enabled. Each smart meter is equipped with a radio transceiver, and access any channel in the licensed spectrum. There are N stationary PU transmitters with known maximum coverage ranges and locations in the area of the AMI network. The PU activity can be formulated as a two state independent and identically distributed random process. For the i^{th}, the duration of busy (PU occupation) and idle periods is distributed in an exponential form with the mean of $\frac{1}{\mu^i_{ON}}$ and $\frac{1}{\mu^i_{OFF}}$, respectively. Suppose that S^i_{busy} denotes the busy state of i^{th} channel with probability $P^i_{busy} = \frac{\mu^i_{OFF}}{\mu^i_{ON}+\mu^i_{OFF}}$, and S^i_{idle} the idle state with probability P^i_{idle}. We note that $P^i_{idle} + P^i_{busy} = 1$ in ideal conditions.

We also assume that the channel status is estimated by using spectrum sensing. Smart meters employ energy detection technique [33] for primary signal detection. A predefined threshold (σ) is set to judge the state of the i^{th} channel, expressed as follows.

$$Result_{SS} = \begin{cases} S^i_{busy} & \text{if } E \geq \sigma \\ S^i_{idle} & \text{if } E < \sigma \end{cases} \tag{1}$$

There are two principle metrics in spectrum sensing, namely, detection probability (P_d) and false alarm probability (P_f). The higher detection probability brings better protection to incumbents, and the lower false alarm probability can improve the utilization of channels. The detection and false alarm probabilities for the i^{th} channel are given by

$$P^i_d = Pr\{E \geq \sigma | S^i_{busy}\} = Q\left(\frac{\sigma - 2n_i(\gamma_i + 1)}{\sqrt{4n_i(2\gamma_i + 1)}}\right), \tag{2}$$

$$P^i_f = Pr\{E \geq \sigma | S^i_{idle}\} = Q\left(\frac{\sigma - 2n_i}{\sqrt{4n_i}}\right), \tag{3}$$

where $Q(\cdot)$ denotes the complementary error function, and γ_i and n_i denote the signal-to-noise ratio (SNR) of the primary signal and the bandwidth-time product for the i^{th} channel respectively.

In addition, a feature of cognitive radio is spectrum sensing. Therefore, the MAC frame structure in cognitive radio enabled AMI networks consists of a spectrum sensing slot and a transmission slot, which is as shown in Fig. 1.

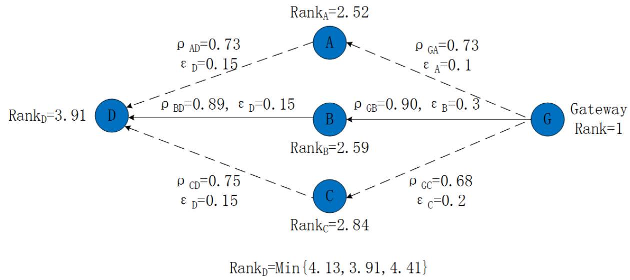

FIGURE 2. **Illustration of rank computation. The rank computation is based on protection of PU receivers and virtual energy efficiency. The node with the lowest rank is selected as the default parent node.**

B. PROTOCOL DESCRIPTION

In Green-RPL, the DAG construction follows a similar process as the classical RPL. After detecting an idle channel, the root node broadcasts a *DAG Information Object* (DIO) message to identify client node status. In order to realizing the tradeoff between protection for PU receivers and QoS of AMI network transmission, we emphasize the two aspects in the rank computation. The rank of a node (e.g., node a) is given by

$$rank_j = \min\{rank_p + k \cdot \frac{1}{\rho_{pj} \cdot (1 - \varepsilon_j)}\}, \tag{4}$$

where k denotes the adjusting constant, p denotes a node as the parent node of node j, ρ_{pj} is the link quality indicator, and denotes the probability of transmission between node j and node p, and $\varepsilon_j = \sum_{n=1}^{N} A_{nj}$ denotes the fractional coverage overlapping area of node j with all PU transmitters.

In order to protect PU communication, the route for the CR users should be selected which has pass through regions with minimum coverage overlap of PU transmitters' coverage. Moreover, the fractional area A_{nj} of node j transmission coverage under the coverage of n^{th} PU transmitter is given by (5), as shown at the bottom of this page, where r_j denotes the coverage radii of the n^{th} PU transmitter, R_n denotes the coverage radii of the n^{th} PU transmitter, and d_{nj} is the distance between the two nodes. Additionally, the rank of each node can be computed as the process shown in Fig. 2.

Furthermore, as a key element for Green-RPL, the forwarder set construction should be noted. In Green-RPL, each node must have a selected forwarder set. This set will be updated based on rank information after receiving a DIO message. The forwarder set construction procedure is in a back propagation way, and forwarding nodes should be selected from those located within the transmission range of the sender. As while as forwarding DIO messages, smart meters add individual information into the DIO option field, such as rank information.

$$A_{nj} = \frac{1}{\pi}\left\{\cos^{-1}\left(\frac{1}{2d_{nj}r_a}\right) + \frac{R_n^2}{r_j^2} \cdot \cos^{-1}\left(\frac{d_{nj}^2 + R_n^2 - r_j^2}{2d_{nj}R_n}\right) - \frac{1}{2r_j^2}\sqrt{\left[(R_n + r_j)^2 - d_{nj}^2\right](d_{nj} + r_j - R_n)(d_{nj} - r_j + R_n)}\right\} \tag{5}$$

When receiving a DIO message, smart meter node will update the neighbor status information. Based on the neighborhood information, each smart meter node constructs a forwarder set, and prioritizes these nodes. We note that the forwarder set only includes the nodes with lower ranks, and therefore, the size of the set is limited. Additionally, the corresponding entry of a node in the forwarder will be deleted, when the node does not hear from its neighbor for a pre-defined time interval. When a node receives a new DIO message, the corresponding forwarder set will be updated.

During a single hop, the sender node sends the data packet to all candidate nodes on the forwarder list. All of these nodes receive the packet, and each receiver node tries to forward the packet successively, based on the priorities. The priorities are determined by using a cost function. In Green-RPL, the cost function is based on the energy efficiency over virtual distance (EEVD) in the AMI network communication, which is given by

$$\mathcal{E}_v = \frac{E_t}{D_v}, \tag{6}$$

where D_v and E_t denote the total energy consumption for forwarding the packet and the virtual distance between the sender and the receiver, respectively.

In this research, each node estimates the EEVD based on the DIO message. The virtual distance between the sender and the receiver in the AMI network can be represented by the rank difference, which is given by

$$D_v = |Rank_a - Rank_b|. \tag{7}$$

However, E_{total} is usually evaluated under a realistic CR environment, where there exist inaccuracy and error in spectrum sensing, which may lead interference to PUs and transmission failures of secondary network users. Therefore, the probability of switching transmission to the channel i can be given by

$$P^i_{switch} = P^i_{idle}\left(1 - P^i_f\right) + P^i_{busy}\left(1 - P^i_d\right). \tag{8}$$

Moreover, the probability of transmission failure on the i^{th} channel due to the corruption in data frame is given by

$$P^i_{fail} = P^i_{switch}\left[1 - (1-p)^d\right], \tag{9}$$

where d and p denote the data frame size in bits and the bit error probability, respectively.

On the transmitter side, we can evaluate the energy consumption based on Shannon's theorem. We assume that the minimum of requested rate is R_{min}. The capacity of the i^{th} channel need satisfy the following condition

$$C^i = p^i_{switch}B^i \log_2\left(1 + SNR^i\right) \geq R_{min}, \tag{10}$$

Therefore, if the information is transmitted on the i^{th} channel, the minimum required power for transmitting can be given by

$$\mathcal{P}^i_{min} = \frac{\left(2^{\frac{R_{min}}{p^i_{switch}B^i}} - 1\right)\delta^2}{\left|(h^i)^2\right|}, \tag{11}$$

where B^i denotes the bandwidth of the i^{th} channel, and h_i is channel coefficient, given by

$$h^i = F^i\sqrt{1/L^i}, \tag{12}$$

where F^i and L^i denote the fading coefficient of the channel and the path loss, respectively.

Therefore, the energy consumed by transmitter is given by

$$E^i_T = \mathcal{P}^i_{min} \cdot T_p, \tag{13}$$

where T_p accounts for the duration of transmitting the packet.

On the other side, the energy consumption for receiver node is mainly dependent on retransmission. Firstly, we evaluate the energy consumption in single hop. The energy consumption for a single failed successful transmission on the i^{th} channel can be given by

$$E^i_{R-fail} = P^i_{switch}\left[1 - (1-p)^m\right]T_d\mathcal{P}_R, \tag{14}$$

$$E^i_{R-succ} = P^i_{switch}(1-p)^m T_d\mathcal{P}_R, \tag{15}$$

where $\mathcal{P}_R$ and T_d denote the power drained in the receive mode and the duration of data frame, respectively.

If data transmission fails, the data will be transmitted again. The expected retransmission number can be measured in in advance and updated continuously. The energy consumption during data packet receiving successfully is given by

$$E^i_R = E^i_{R-succ} + (\mathbb{E} - 1)E^i_{R-fail}. \tag{16}$$

In addition, the energy consumption for spectrum sensing can be given by

$$E^i_{ss} = \chi^i_{ss}T_{ss}\mathcal{P}_{ss}, \tag{17}$$

where χ^i_{ss} and $\mathcal{P}_{ss}$ denote the expected number of sensing events for transmitting over the i^{th} channel and the power drained for spectrum sensing operation, respectively. Especially, χ^i_{ss} can be expressed by

$$\chi^i_{ss} = \sum_{k=0}^{\infty} k \cdot (1 - P^i_{switch})^i P^i_{switch} = \frac{1 - P^i_{switch}}{P^i_{switch}}. \tag{18}$$

The total energy drained during a single hop on i^{th} channel is estimated as follows.

$$E_t = E^i_T + E^i_R + E^i_{SS}. \tag{19}$$

In order to ensure a unique forwarder selection, Green-RPL adopts a coordination scheme based on the acknowledgement (ACK) frames. In Green-RPL, multiple receivers are selected for a single hop. Receivers try to forward the data packet in order of priority, and send ACK frames to inform lower priority receivers. However, there exists a probability of ACK receiving failure in the practical applications, due to complex

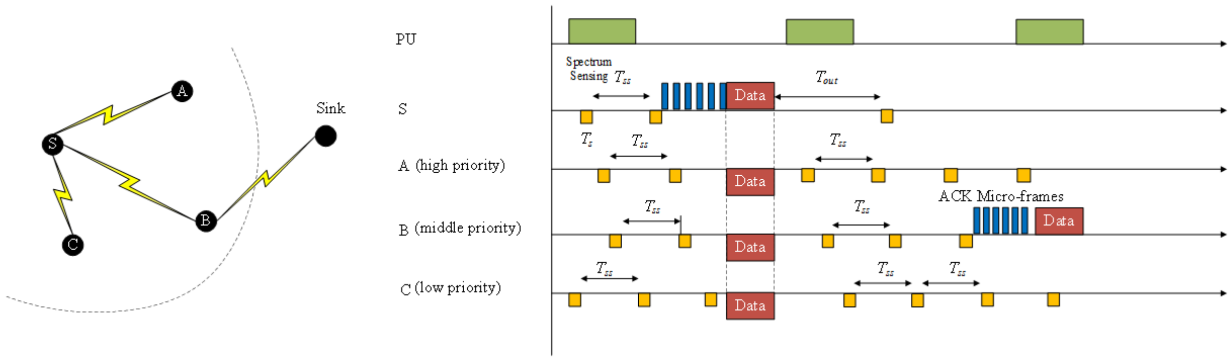

FIGURE 3. Illustration for single hop forwarding timeline in Green-RPL.

electromagnetic environments. As a result, it will lead to the *Coordination Overhead* (CO) [13], which is defined as the probability of the frame retransmission by different nodes. Therefore, we adopt a batch of micro-frames to transmit ACK information. In each micro-frame the information of packet and forwarder is included. We assume that the length of a micro-frame is T_{mf}, and the number of micro-frames in a batch is N_m, which is given by

$$N_m = \left\lfloor \frac{T_{ss}}{T_{mf}} \right\rfloor, \tag{20}$$

where T_{ss} denotes the period of spectrum sensing.

Therefore, all neighbor nodes in the transmission rage of ACK sender will receive at least one micro-frame, theoretically, such that the *CO* is reduced. If the ACK micro-frames are found by the nodes on the forwarder list and the sender, the single hop transmission is completed, and these nodes will discard the data packet. If the selected node fails to forward the micro-frames within a timeout period (no ACK is received), the next candidate in the forwarder list will try to forward the packet. If all the forwarder candidates failed to forward the packet, the sender will retransmit the packet. The EEVD-based forwarding algorithm is shown in Algorithm 1.

Fig. 3 show an illustrated of forwarding in Green-RPL, and indicates the timeline of a single hop. The sender node S sends the data packet to the selected receivers A, B and C. For forwarding, node A has the highest priority, node B has the middle priority, and node C has the lowest priority. Therefore, node A tries to forward the data packet, but fails within duration T_{out}. Afterwards, node B tries and finds the available channel for forwarding. Therefore, node B sends the ACK micro-frames to the sender S and other receivers, such as C. Node B transmits the data packet, and completes the single hop transmission.

IV. ANALYTICAL MODELING

A. ENERGY CONSUMPTION

we evaluate the model of retransmission for Green-RPL firstly. In case of a failed transmission, the sender node will retransmit data packets. It can be assumed that the total number of failed transmissions until a successful transmission can be denoted by a random variable. The probability of a

Algorithm 1 EEVD-Based Forwarding Algorithm in Green-RPL

$\mathcal{K}^j = \{k_1, k_2, \cdots, k_K\} \rightarrow$ forwarder set of the j^{th} node
$\mathcal{Q}^j = \{\cdot\}_{1\times K} \rightarrow$ the priority queue of the j^{th} node
for $k = 1 : K$ **do**
  calculate the $\mathcal{E}_v^k$ according to (6)
  $\mathcal{Q}^j(k) \leftarrow \mathcal{E}_v^k$
end
sort the $\mathcal{Q}^j$ in ascending order
the sender is set as the last member in forwarding list
default forwarder $\leftarrow$ the node with $\mathcal{Q}^j(1)$
node j sends the packet to all nodes in $\mathcal{Q}^j$
for $k = 1 : K + 1$ **do**
  if *no ACK frames are received in a timeout period* **then**
    the node with $\mathcal{Q}^j(k+1)$ tries to forward the packet
  end
end

successful transmission after v failed transmissions can be given by

Retransmission is an important factor for energy consumption and delay. Thus, we build the retransmission number model for Green-RPL firstly. In case of a failed transmission, the sender node will retransmit data packets. It can be assumed that the number of failed transmissions until a successful transmission can be denoted by a random variable. Moreover, the probability of a success transmission following v failed transmissions is expressed as follows

$$P_{re}(v) = (1 - (P^i_{fail})^K)(P^i_{fail})^{K\cdot v}. \tag{21}$$

where K denotes the size of forwarder set.

The expected retransmission number before a successful transmission is given by

$$\chi_{re} = \sum_{v=0}^{V_{max}} v \cdot P_{re}(v) = \sum_{v=0}^{V_{max}} v \cdot (1 - (P^i_{fail})^K)(P^i_{fail})^{K\cdot v}, \tag{22}$$

where V_{max} represents the maximum number of retransmissions.

For the transmitter, the energy consumption during the transmission on the i^{th} channel can be estimated as follows.

$$E_{AT-succ} = (\chi_{re} + 1)(E^i_{ss} + E^i_T). \tag{23}$$

On the receiver side, the energy consumption for a single failed transmission and a single successful transmission on i^{th}channel are given by (14) and (15), respectively. But, in each hop, there may be N eligible receivers to forward data packets. Thus, the energy consumption during a successful transmission in the case that k nodes ($k \leq N$) receive data successfully can be expressed as follows.

$$E^i_{AR-succ} = \frac{\sum_{k=1}^{K} \binom{K}{k} \left[(K-k)E^i_{R-fail} + KE^i_{R-succ}\right]}{\sum_{k=1}^{K} \binom{K}{k}}. \tag{24}$$

Similarly, the energy consumption during a failure transmission, where all receivers do not receive the data successfully, can be expressed as follows.

$$E^i_{AR-fail} = K \cdot E^i_{R-fail}. \tag{25}$$

The average energy drained in the data transmission over i^{th} channel during a single hop is given by

$$E^i_{total-A} = E_{AT-succ} + \chi_{re}E^i_{AR-fail} + E^i_{AR-succ}. \tag{26}$$

B. DELAY

Based on the model of retransmission number, the end-to-end delay during packet transmission in Green-RPL is given by

$$D = \sum_{h=1}^{H} \chi^h \cdot (T_{pr} + T_d + T_{CW}) + \Delta t^h_i + \chi^h_{ss} \cdot T_s + (\chi^h_{ss} - 1) \cdot T_C, \tag{27}$$

where H is the number of hops, χ^h is the number of retransmission in the h^{th} hop, Δt^h_i is the duration before spectrum sensing for forwarding in the h^{th} hop, and χ^h_{ss} is the spectrum sensing event number in the h^{th} hop.

C. COORDINATION OVERHEAD

In application, there exists an associated probability of ACK receiving failure, which may lead to repetitive forwarding for the same frame. Hence, the coordination overhead in the h^{th} hop is given by (28), as shown at the bottom of this page, where ρ_a and ρ_k denote the probability of successful forwarding for the a^{th} node on the forwarder list, and the probability of successful forwarding for the k^{th} node on the forwarder list, respectively; ρ^b_k denotes the probability of

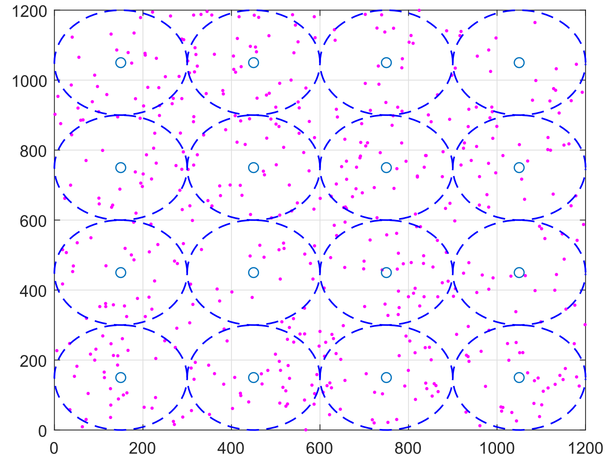

FIGURE 4. The topology of networks in simulations. A circle denotes the transmission range of a PU transmitter (the network density is 4 × 10^{-4}).

successful transmission between the b^{th} and k^{th} nodes on the forwarder list.

Therefore, the end-to-end CO for the route is estimated as follows.

$$CO = \prod_{h=1}^{H} (1 + CO_h). \tag{29}$$

D. RELIABILITY

In literatures, *Packet Delivery Ratio* (PDR) is adopted commonly for the reliability evaluation of routing. Thus, we use PDR in the reliability performance evaluation of Green-RPL. PDR of a transmission can be estimated by the ratio of the received packets to the total packets. Concretely, the end-to-end PDR for packet transmission in Green-RPL routing is calculated as follows.

$$R = \prod_{h=1}^{H} \left(1 - (P^{C_h}_{fail})^{KV_{max}}\right), \tag{30}$$

where C_h denotes the selected channel over h^{th} hop.

V. PERFORMANCE EVALUATION

In this section, the performance of Green-RPL is evaluated under different scenarios. The Green-RPL is implemented with the topology shown in Fig. 4. We consider 16 PU transmitters distributed in a square region of sides 1200 meters. We assume the spatial topology of secondary users is modeled using Poisson distribution in the whole region with a mean density. Channel between any two nodes is assumed to be a

$$CO_h = \sum_{k=2}^{K} \left\{ \left(1 - \rho_{s(k-1)}\right) \rho_{sk} \left(1 - \prod_{i=1}^{N} \left(1 - p^i_{switch}\right)\right) \left[1 - \prod_{a=k+1}^{K} \left[1 - (1 - \rho_{ka})^{N_m}\right]\right] \right\} + \rho_{s1} \left(1 - \prod_{i=1}^{N} \left(1 - p^i_{switch}\right)\right) \left[1 - \prod_{a=2}^{K} \left[1 - (1 - \rho_{1a})^{N_m}\right]\right] \tag{28}$$

TABLE 1. Parameters of simulation configuration.

Parameter	Value
Path loss model	$128.1 + 37.6\log_{10}(r)$, r in km
Standard deviation of shadowing	8 dB
Detection probability threshold(P_d)	0.9
Probability of false alarm (P_f)	0.1
Channel bandwidth	200kHz
PU received SNR(γ)	-15dB
Busy state parameter of PU (μ_{ON})	[1, 9]
Idle state parameter of PU (μ_{OFF})	3
Maximum interference ratio (IR_{max})	0.25
Size of forwarder set (M)	5
Size of DIO message including options	28 bytes

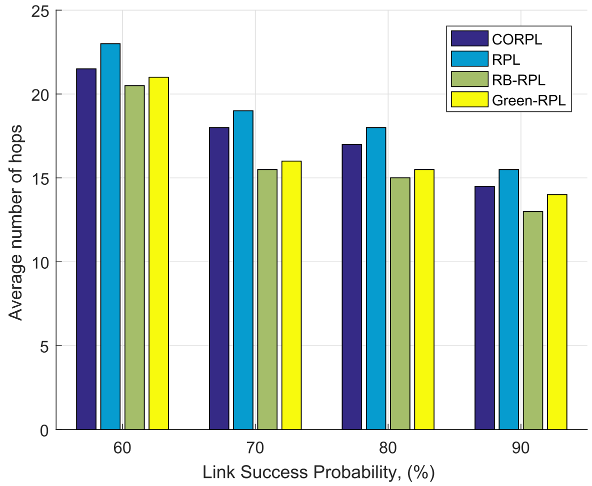

FIGURE 5. **Average number of Hops against CR network density.**

frequency selective Rayleigh fading, where the channel gain leads to small scale Rayleigh fading, large scale path loss and shadowing. We evaluate the performances of the proposed protocol compared with CORPL, RB-RPL and RPL in the same simulation configuration. In TABLE I, other simulation parameters are given.

Firstly, we evaluate the average number of hops against the smart meter density. As a crucial factor of end-to-end delay increasing, the number of hops associates with the node density in CR network. As is shown in Fig.5, the number of hops decreases with the node density increasing. In the comparison with CORPL, CRB-RPL and RPL, Green-RPL needs less hops for the packet transmission. It is because Green-RPL improve the energy efficiency of routing by deceasing the energy consumption and increasing virtual transmission distance during each hop. As a result, Green-RPL has larger average virtual distance for a single hop, and needs less hops.

Next, we evaluate the performance of energy efficiency for Green-RPL. In Fig. 6, the energy consumption during a single hop against the bit error rate (BER) is shown. In low BER conditions, all protocols have good energy efficiency performances. The reason is that there are few retransmissions in a low BER condition. As BER increases, energy consumptions increase. In the intermediate stage, RB-RPL

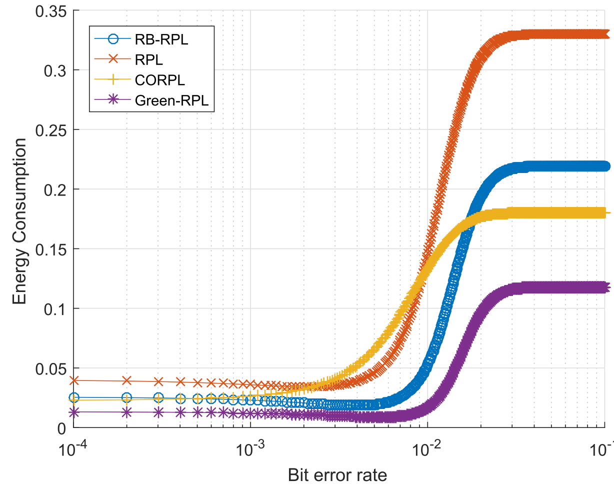

FIGURE 6. **Single hop energy drained (Joule) against bit error rate (the network density is 4×10^{-4} nodes per unit).**

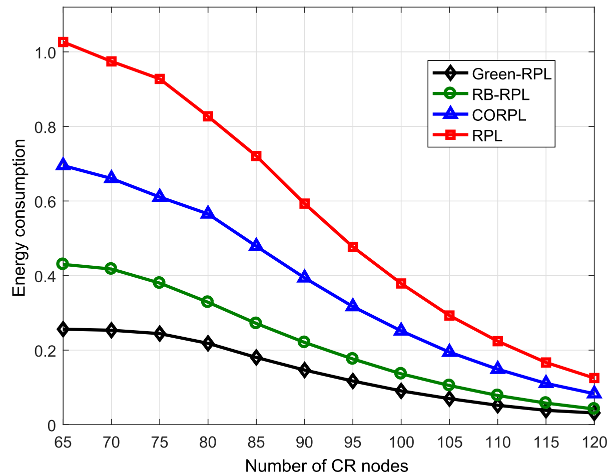

FIGURE 7. **Single hop energy drained (Joule) against node density.**

has a good energy efficiency performance, which remains stable, when those of CORPL and RPL increase rapidly. We can see that Green-RPL overmatchs other protocols in all BER conditions on the energy efficiency performance.

We also evaluate the performance of energy drained during a single hop against CR network density. Fig. 7 indicates that energy drained during a single hop decreases as node density increase. Green-RPL outperforms other protocols in all node density conditions, especially in a low network density condition. The energy consumption of Green-RPL is obviously less than those of CORPL, RB-RPL and RPL. However, in high CR network density conditions, the advantage of Green-RPL decreases, and protocols have near energy consumption performances. It is mainly because that there are more receivers in a high network density condition, and the total energy consumption for data receiving increases acutely.

We evaluate the end-to-end delay performance against *Link Successful Probability* (LSP). As shown in Fig. 8, the average end-to-end delay is reduced, when LSP increases. The CORPL class (B) and RB-RPL are specially designed for

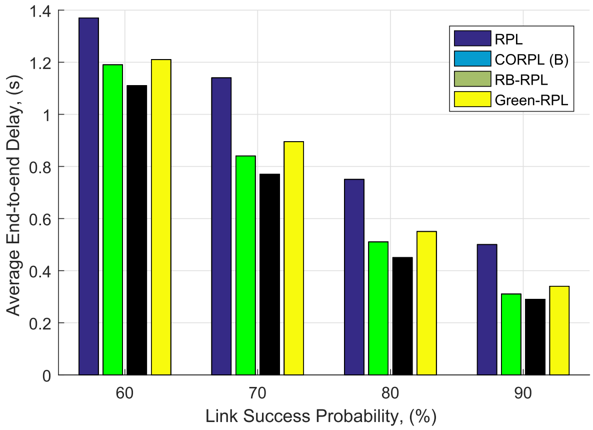

FIGURE 8. **Average end-to-end delay against different LSP, the average channel busyness probability $p_b = 0.4$.**

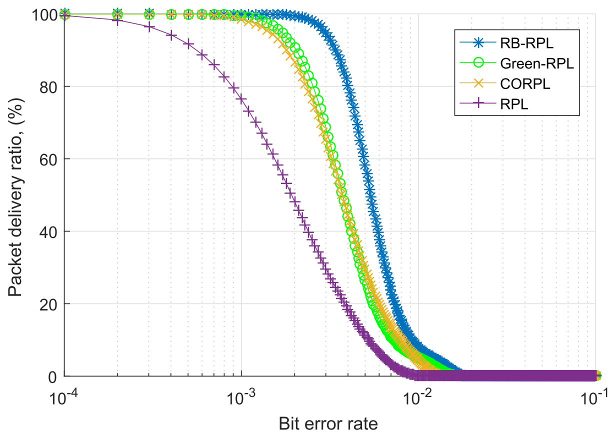

FIGURE 9. **Reliability performance evaluation for different protocols in terms of PDR.**

delay sensitive packet transmission. Hence, these two have better performances than other protocols. The end-to-end delay of Green-RPL is higher then those of CORPL and RB-RPL, but lower than that of RPL. Usually, the requirement for latency in AMI networks is low. Therefore, the end-to-end delay performance of Green-RPL is acceptable.

We evaluate the reliability performance of the data transmission network in terms of *Packet Delivery Ratio* (PDR). In the evaluation, 100,000 packets are generated by random sender. We do the statistics on the number of packets received by the gateway. Fig. 9 indicates that RB-RPL has the best performance of PDR in the comparison. In low BER conditions, Green-RPL outperforms RPL and CORPL. The performance gain is reduced as BER increases.

Then, we evaluate the *Coordination Overhead* (CO) performance of the Green-RPL. CO is defined as the fraction of packet replica number received by the root node to the number of total packets received by the root node. As Fig. 10 shown, the CO of transmission increases when the link successful probability increases. This is because the probability of ACK capturing failure increases as the LSP decreases. When a node on the forwarding list do not capture ACK frames from the previous forwarder in the priority queue

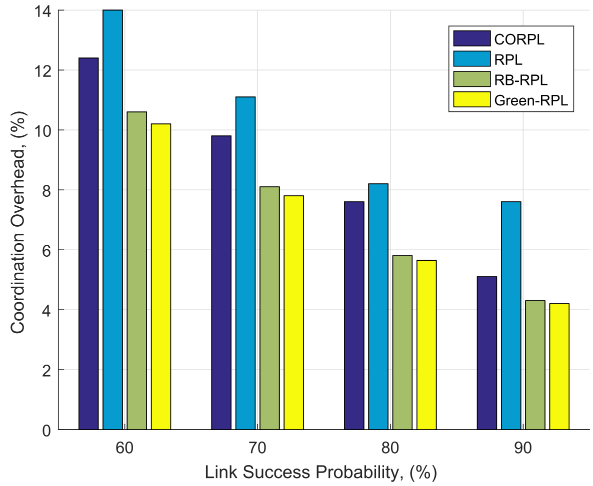

FIGURE 10. **CO performance against LSP (100, 000 packets are transmitted).**

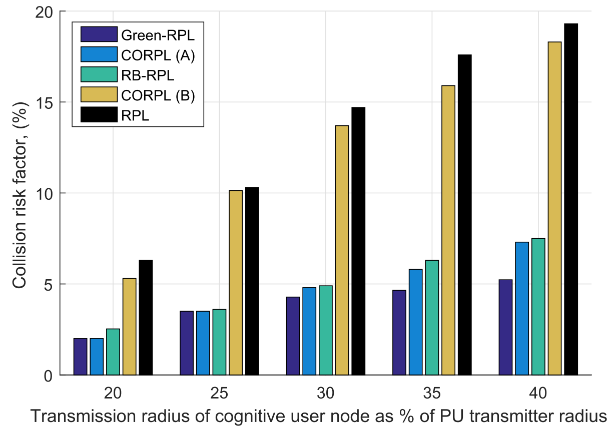

FIGURE 11. **Protection for PU receivers against cognitive user nodes transmission range (100, 000 packets are transmitted).**

in a fixed period, it will predicate the previous forwarder fails in forwarding, and tries to forward the packet, which will lead to the coordination overhead. In this comparison, Green-RPL has a good performance, because micro-frames are used for ACK information transmission.

At last, we evaluate the performance of PU receiver protection, in terms of *Collision Risk Factor* (CRF). CRF can be estimated by the fraction of transmission collision number to the total number of smart metering transmissions. As Fig. 11 indicated, Green-RPL can reduce the risks of PU transmission collision, compared with CORPL (class *A* and *B*), RPL and RB-RPL. This is because Green-RPL considers the protections to PU receivers as a fundamental object and important factor in node rank computation. Additionally, CRF is dependant on the activity frequency of PUs and coverage overlap of smart meter node transmission range and that of PU transmitter. As Fig. 11 shown, CRF increases when transmission range of nodes in the CR-AMI network, and the frequency of PU activity increases.

VI. CONCLUSION

This paper has considered the challenge of energy efficiency in CR-AMI networks, in order to reduce the energy consumption of smart grid. We propose a new RPL-based routing protocol, which is named as Green-RPL. In Green-RPL, the energy efficiency over virtual distance (EEVD) is considered as the key factor of routing. During a single hop, multiple neighbor nodes are selected to structure a forwarder set. The EEVD of each forwarder is estimated and adopted as the basis of forwarding priority. Therefore, the candidate with higher energy efficiency has a larger chance for forwarding, such that the energy-efficient route can be selected. Furthermore, it fulfills the QoS requirements of communications in smart grids, and considers protection to PUs as well. In addition, micro-frames are adopted to transmit ACK information, such that the CO is reduced. Performance evaluation shows that Green-RPL can improve the energy efficiency of the CR-AMI networks significantly, without resulting in obvious damage to other performances. Therefore, Green-RPL provides a potential solution for communications in smart grids.

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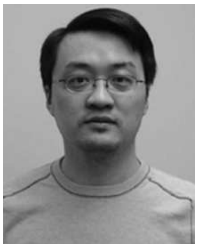

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