# CORPL: A Routing Protocol for Cognitive Radio Enabled AMI Networks

Adnan Aijaz, *Student Member, IEEE*, Hongjia Su, and Abdol-Hamid Aghvami, *Fellow, IEEE*

*Abstract*—**It is expected that the use of cognitive radio for smart grid communication will be indispensable in near future. Recently, IETF has standardized RPL (routing protocol for low power and lossy networks), which is expected to be the standard routing protocol for majority of applications including advanced metering infrastructure (AMI) networks. Our objective in this paper is to enhance RPL for cognitive radio enabled AMI networks. Our enhanced protocol provides novel modifications to RPL in order to address the routing challenges in cognitive radio environments along with protecting the primary users as well as meeting the utility requirements of secondary network. System level performance evaluation shows the effectiveness of proposed protocol as a viable solution for practical cognitive AMI networks.**

*Index Terms*—**AMI networks, cognitive radio networks, routing, RPL, smart grid.**

## I. Introduction

THE LEGACY electric power grid, which has lasted for years, is energy inefficient, insecure, and prone to frequent transmission failures and congestion [1]. The term *smart grid* refers to the next generation of electric grid where power distribution and management is upgraded by incorporating advanced bi-directional communications, automated control and distributed computing capabilities for improved agility, efficiency, reliability and security [2]. It allows electricity providers, distributors, and consumers to maintain a real time awareness of operating requirements and capabilities. An integrated high performance, reliable, scalable, robust, and secure communication network is critical for the successful operation of smart grid in order to support different applications.

One of the key elements of the smart grid is the advanced metering infrastructure (AMI) wherein multiple smart meters (located at customer premises) communicate with a local access point (meter concentrator) which is further connected to a meter data management system (MDMS) that acts as a control center for storage, processing and management of meter data in order to be used by different applications [3]. The AMI networks can contribute in several ways in realizing the vision of smart grid. For example, through the AMI network, utility providers can manage on demand power requirements, monitor power quality, identify anomalies, and regulate electricity usage (using dynamic pricing).

Depending upon the size of a utility, the number of smart meters in a network may vary from a few hundred to several thousand. Several communication technologies such as cellular, WiMAX, power line communications (PLC), etc., are currently under consideration for AMI networks. However, there is no clear consensus by the community so far. Each of these technologies has its own pros and cons. For example, cellular networks are primarily optimized for conventional human-to-human (H2H) communication. Hence, radio resource management between H2H users and smart meters becomes challenging as both have different quality-of-service (QoS) requirements. Secondly, a large number of smart meters in a community can create traffic overload on the uplink random access channel. Thirdly, packet size for AMI type traffic can be much smaller than that of the signalling traffic resulting in low efficiency [4]. Last, but not the least, cellular coverage penetration is an important issue that needs to be considered due to the variability in smart meter locations (e.g., some meters may be installed at places such as garages, under the stairs, or may be present inside metal cages). Similar challenges exist for WiMAX based solutions. Apart from this, the security issues of WiMAX are still under investigation [5]. Moreover, utility providers are not comfortable with the fact that their data travels through a third party network; an issue which is common to both cellular and WiMAX based solutions. PLC appears to be an attractive solution due to the use of existing power grid infrastructure. However, the underlying communication medium will not be available in case of power outage which is a serious issue. Moreover, in some parts of the world (e.g., Norway) regulatory authorities have banned the use of PLC due to possible detrimental effect on military HF radio communications [6].

A practical solution is to deploy a static multi-hop wireless mesh network connecting a large number of smart meters which in turn is connected to a gateway (concentrator). This solution is particularly attractive as it scales well with the size of the AMI network. Moreover, the utility provider has complete control over the infrastructure. It should be noted that although smart meters are static, the wireless link between an arbitrary pair of smart meters is generally unstable due to fading and interference effects. Therefore, the AMI network requires proper routing functionalities for reliable and low latency delivery of data for different applications.

RPL (routing protocol for low power and lossy networks) [7] is a routing protocol that has been recently standardized by IETF and intends to support a variety of applications including

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The authors are with the Centre for Telecommunications Research, King's College London, London, WC2R 2LS, U.K. (e-mail: adnan.aijaz@kcl.ac.uk).

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building automation, healthcare, urban sensor networks, industrial monitoring, etc. RPL is currently under active investigation in the research community. Moreover, it is attracting a lot of attention for AMI mesh networks in smart grids (e.g., see [8]–[12]) and is expected to be the standard routing protocol for AMI applications.

On the other hand, cognitive radio (CR) [13], [14] is viewed as a novel approach to address the spectrum scarcity and spectrum inefficiency issue in wireless networks. In CR networks, unlicensed users (secondary users) dynamically access the frequency band/channel whenever the licensed user (primary user) is absent and need to vacate the band/channel whenever the latter is detected. There are several motivations for using CR technology for smart grid communications [15]. The multitude of connected devices will create a major challenge in terms of spectrum congestion. With dynamic spectrum access capabilities of CR, existing spectrum can be utilized more efficiently in order to avoid the potential shortage of spectrum. Moreover, operation in unlicensed bands will result in significant interference issues, ultimately degrading the network performance. Thus there is a need to explore alternate spectrum opportunities. Recently, a number of studies (e.g., see [16]–[20]) have been presented on different smart grid related platforms regarding the application of cognitive radio for smart grid communication.

Against this background, our objective in this paper is to enhance RPL for cognitive radio enabled AMI networks. To the best of our knowledge, the adaptability and application of RPL in CR enabled AMI networks has not been studied before. We enhance basic RPL with novel modifications especially tailored for CR environments. We develop an opportunistic forwarding approach to meet the utility requirements of secondary network (cognitive AMI network) along with protecting the primary users (PUs). The enhanced protocol is termed as CORPL (cognitive and opportunistic RPL). The rest of the paper is organized as follows. Section II presents an overview of RPL. In Section III we discuss the challenges for any routing protocol in CR environment. CORPL considers these challenges as design objectives. Section IV presents the CORPL framework followed by the performance evaluation in Section V. Finally the paper is concluded in Section VI.

## II. Overview of RPL

RPL is a distance-vector and a source routing protocol. The key aspect of RPL is to maintain network state information using one or more *directed acyclic graphs* (DAGs). A DAG is a directed graph wherein all edges are oriented in such a way that no cycles exist. Each DAG created in RPL has a root node which acts as a gateway. Each node (client node) in the DAG is assigned a rank that is computed on the basis of an objective function. The rank monotonically increases in the downward direction (DAG root has the lowest rank) and represents a node's virtual position to other nodes with respect to the DAG root. A node in DAG can only be associated with other nodes having same or smaller rank compared to its own rank in order to avoid cycles. RPL does not specify any particular objective function for DAG rank computation. In order to construct a DAG, the gateway broadcasts a control message called *DAG information object* (DIO) containing relevant network information including the DAGID to identify the DAG and the rank information along with the objective function for rank computation. Any node that receives the DIO message and wants to join the DAG should add the DIO sender to its parent list, compute its own rank according to the objective function, and forwards the DIO message with the updated rank information. When a node already associated with the DAG receives another DIO message, it can discard the DIO message (according to some criteria specified by RPL), process the DIO message to maintain its position in existing DAG, or improve its position by obtaining a lower rank according to the objective function. Once the DAG is constructed, each node will be able to forward any inward traffic (destined to the gateway) by choosing its most preferred parent as the next hop node.

RPL also specifies a methodology for outward traffic (gateway to client node) through *destination advertisement object* (DAO) control message which is unicast in the upward direction. The intermediate nodes record the reverse path information and thus a complete outward path is established from the gateway to the client node.

To maintain a DAG, each node periodically generates DIO messages triggered by the *trickle timer* [21] which optimizes the message transmission frequency based on network conditions. The frequency is increased in case of inconsistent network information and decreased in case of stable network conditions. For more information on RPL, the interested reader is referred to comprehensive surveys in [22] and [23].

## III. Routing Challenges in CR Environment

A key aspect of any CR environment is spectrum sensing. Nodes periodically monitor the current channel for PU activity before using it for transmission. During this interval (sensing time), nodes are not involved in forwarding data packets and therefore, the multi-hop network is virtually disconnected at the node that is engaged in spectrum sensing. Hence, the routing algorithm should explicitly account for the spectrum sensing state of different nodes.

The secondary network operation must ensure protection for both PU transmitters and PU receivers (temporal and spatial protection). The latter is particularly important for those PU applications where the transmission is uni-directional (e.g., TV broadcast). The protection to the PU transmitter is subject to accurate detection of the PU activity. On the other hand, PU receivers are difficult to detect and can be easily affected by the transmission from neighboring CR users. Therefore, the network layer should provide explicit protection to PU receivers by avoiding regions where such users might be present [24].

The protection provided to PUs results in a performance tradeoff for the secondary network. Hence the routing protocol must optimize the operation for both primary and secondary networks depending upon the level of protection for the former and the quality-of-service (QoS) requirements of the latter.

## IV. CORPL Framework

In this section, we describe the framework of our enhanced RPL protocol for CR environments, i.e., CORPL. The objective of CORPL is to retain the DAG based approach of RPL and at the same time introduce novel modifications to allow its application in CR environments. Before describing the proposed protocol, it is important to discuss the underlying system model.

### A. System Model

We consider a static multi-hop wireless AMI network consisting of different smart meters and a gateway node (meter concentrator). We assume that the smart meters are CR enabled.[1] Each smart meter (node) is equipped with a single radio transceiver that can be tuned to any channel in the licensed spectrum. We assume $N$ stationary PU transmitters (and hence $N$ available channels) with known locations and maximum coverage ranges. The PU (transmitter) activity model for the $j$th channel is given by a two state independent and identically distributed (i.i.d.) random process such that the duration of busy and idle periods is exponentially distributed with a mean of $1/\mu_{ON}^j$ and $1/\mu_{OFF}^j$, respectively. Let $S_b^j$ denote the state that the $j$th channel is busy (PU is active) with probability $P_b^j = \mu_{OFF}^j/(\mu_{ON}^j + \mu_{OFF}^j)$, and $S_i^j$ denote the state that the $j$th channel is idle with probability $P_i^j$, such that $P_i^j + P_b^j = 1$. We assume that a node employs energy detection techniques [25] (during spectrum sensing period) for primary signal detection wherein it compares the received energy $(E)$ with a predefined threshold $(\sigma)$ to decide whether the $j$th channel is occupied or not, i.e.,

$$Sensing\ Decision = \begin{cases} S_b^j & \text{if } E \geq \sigma \\ S_i^j & \text{if } E < \sigma \end{cases} \tag{1}$$

The two principal metrics in spectrum sensing are the detection probability $(P_d)$, and the false alarm probability $(P_f)$. A higher detection probability ensures better protection to incumbents, whereas a lower false alarm probability ensures efficient utilization of the channel. As per [26], false alarm and detection probabilities for the $j$th channel can be expressed as follows.

$$P_f^j = Pr\left\{E \geq \sigma | S_i^j\right\} = \frac{1}{2} Erfc\left(\frac{1}{\sqrt{2}} \frac{\sigma - 2n_j}{\sqrt{4n_j}}\right), \tag{2}$$

$$P_d^j = Pr\left\{E \geq \sigma | S_b^j\right\} = \frac{1}{2} Erfc\left(\frac{1}{\sqrt{2}} \frac{\sigma - 2n_j(\gamma_j + 1)}{\sqrt{4n_j(2\gamma_j + 1)}}\right), \tag{3}$$

where $Erfc(\cdot)$ is the complementary error function, and $\gamma_j$ and $n_j$ denote the signal-to-noise ratio (SNR) of the primary signal and the bandwidth-time product for the $j$th channel respectively.

We assume that the AMI network comprises of two types of traffic: low priority monitoring data (that can be considered as best-effort) and high priority delay sensitive[2] information (that have an associated deadline).

[1]It should be noted that due to resource constrained nature of smart meters, there is a need of developing low cost dynamic spectrum access solutions for cognitive AMI networks. However, this is beyond the scope of this paper.

[2]A fundamental objective in smart grid is to balance the supply and demand through precise information of power load obtained via smart meters. Hence delay sensitive traffic is an integral part of AMI networks.

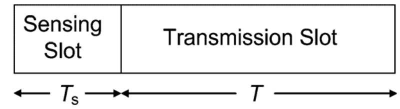



Fig. 1. MAC frame structure in CR network.

### B. CORPL Overview

To address the afore mentioned challenges, we develop an opportunistic forwarding approach [27] that consists of two key steps: selection of a forwarder set, i.e., each node in the network selects multiple next hop neighbors, and a coordination scheme to ensure that only the best receiver of each packet forwards it (unique forwarder selection). It has been shown that the opportunistic forwarding approach improves the end-to-end throughput and reliability (by exploiting the inherent characteristics of wireless channel) of the network, the latter being an important concern for lossy networks.

A key challenge in opportunistic forwarding is the selection of forwarder set. CORPL takes advantage of the existing parent structure of RPL that requires at least one backup parent besides the default parent.[3] In CORPL, each node maintains a forwarder set such that the forwarding node (next hop) is opportunistically selected. The creation of forwarder set is elaborated upon later. CORPL uses a cost function approach to dynamically prioritize the nodes in the forwarder set. Moreover, CORPL uses a simple overhearing based coordination scheme to ensure a unique forwarder selection.

CORPL takes advantage of the opportunistic forwarding approach to support high-priority delay sensitive alarms that need to arrive at the gateway before a given deadline as well as to select paths with minimum interference to PU receivers. The PU transmitter protection is ensured through optimal transmission time for the secondary network subject to an interference constraint. This will be discussed in detail later.

As nodes engaged in spectrum sensing cannot receive/forward packets, therefore, the network performance is degraded in terms of end-to-end throughput, latency, and packet loss ratio. CORPL utilizes two different techniques to improve overall network performance under spectrum sensing state of different nodes.

### C. Protocol Description

The MAC frame structure in a CR network consists of a sensing slot $(T_s)$ and a transmission slot $(T)$ as shown in Fig. 1. In periodic spectrum sensing scenarios, there is a possibility of causing harmful interference to PUs due to imperfect spectrum sensing in realistic conditions. This interference is quantified in terms of *interference ratio* (IR), defined as the expected fraction of ON duration of PU transmission interrupted by the transmission of secondary users and is given for the $j$th channel as follows [28].

$$IR_j = \left(1 - P_d^j\right) P_b^j + P_i^j \left(1 - P_f^j\right) + e^{-\mu T} \left(P_f^j - P_d^j\right), \tag{4}$$

where $\mu = \max(\mu_{ON}^j, \mu_{OFF}^j)$. We assume that the nodes in our network employ optimal transmission time that maximizes

[3]In RPL the backup parents ignore the transmission and the packet is forwarded through the default parent only.

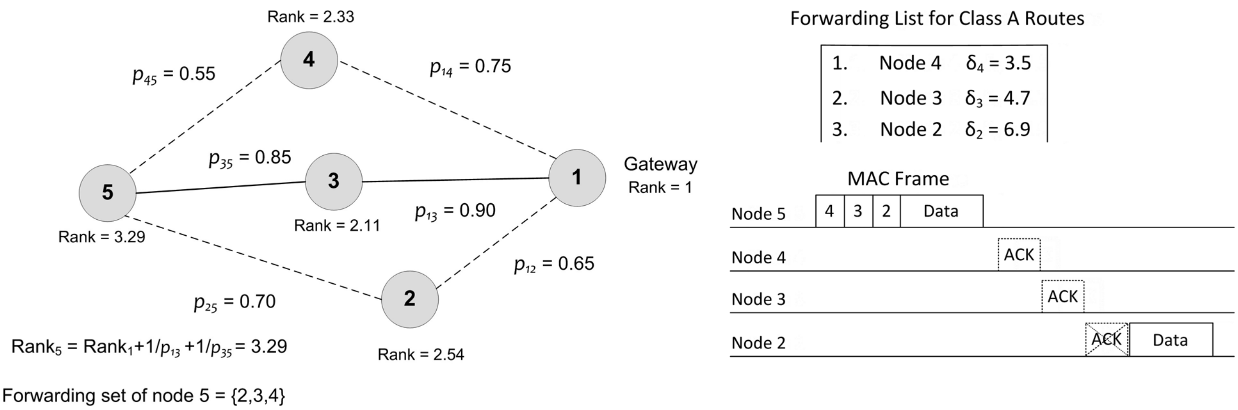



Fig. 2. Rank computation based on ETX. The default parent for node 5 is node 3 owing to a smaller rank compared to nodes 2 and 4. An example forwarder list for *Class A* routes (obtained using (8)) is also shown along with the timeline of coordination scheme. Note that a node who fails to receive the ACK will forward the frame as well.

the throughput of the secondary network subject to an interference constraint, i.e., $IR_j \le IR^j_{max}$, where $IR^j_{max}$ denotes the maximum tolerable interference ratio on the $j$th channel. This transmission time is given for the $j$th channel as follows.

$$T_j = \mu^{-1}\left[\ln P^j_i - \ln\left(P^j_i P'_d + P^j_b\left(1 - P'_d\right) - IR^j_{max}\right) + \ln\left(2P'_d - 1\right)\right], \quad (5)$$

where $P'_d$ is the detection probability threshold, defined as the detection probability at SNR level as low as $\gamma_{min}$, where $\gamma_{min}$ is specified by the regulator.

As we want to retain the DAG structure of RPL, therefore, in CORPL the construction process follows a similar procedure as explained earlier. After detecting a vacant channel, the gateway node transmits a DIO message. We use *expected transmission count* (ETX) [29] as the default metric for rank computation, which is frequently used in lossy networks. The ETX of a link from node $a$ to node $b$ is given by $E_{ab} = 1/p_{ab}$ where $p_{ab}$ is the probability of node $b$ receiving a transmission from node $a$. The ETX of a link will be measured and updated continuously, once the link starts to carry data traffic. The rank computation method for a node joining the DAG is illustrated in Fig. 2. Due to periodic spectrum sensing by each node, the DAG convergence time (defined as the time taken by the set of nodes to obtain topological information and become part of the DAG) will increase due to higher packet loss ratio as explained earlier.

Next we describe the procedure of constructing the forwarder set for opportunistic forwarding. It should be noted that each node in CORPL has a default parent (like RPL) which has been selected based on ETX. The forwarder set is constructed in such a way that the forwarding nodes are within the transmission range of each other. During the DIO transmission, each node also reports some additional information using the Option field of the DIO message.[4] Each node updates the neighborhood information through the DIO message transmission. Based upon the neighborhood information, each node dynamically prioritizes its neighbors in order to construct the forwarder list.[5] The priorities are assigned according to a cost function. Since the construction of forwarder list incurs overhead, the forwarder set should be limited to a maximum of $M$ neighbors. When a node does not hear from its neighbor for a predefined time interval, its corresponding entry in the forwarder list is deleted. Similarly, the forwarder list is updated if a node having a better cost appears.

The cost function to prioritize the nodes in the forwarder set depends on the routing class. CORPL considers two different routing classes. The first class (*class A*) assigns a greater importance to PU receiver protection whereas in second class (*class B*), the end-to-end latency is the key consideration for supporting the high priority delay sensitive alarms. These two classes of protocols are explained as follows.

In order to reduce interference to PU receivers (which can be present anywhere in the coverage area of PU transmitters), the routes for the secondary network should be selected such that they pass through regions of minimum coverage overlap with the PU transmission coverage. A node $k$ calculates the fractional area of its transmission coverage under the coverage of $j$th PU transmitter as $C_{kj} = C'_{kj}/\pi r^2_k$, such that $C'_{kj}$ is given by (6) at the bottom of the page, where $R_j$ and $r_k$ denote the coverage

[4]One option field is limited to 7 bytes, such that 1 byte is allocated to "Option Type," 1 byte is allocated to "Option Length," and 5 bytes are allocated for "Option Data." We assume that 5 bytes are sufficient for including neighbor address along with necessary neighborhood information.

[5]The forwarder list refers to the arrangement of nodes in the forwarder set according to their respective priorities.

$$C'_{kj} = r^2_k \cos^{-1}\left(\frac{d^2_{kj} + r^2_k - R^2_j}{2d_{kj}r_k}\right) + R^2_j \cos^{-1}\left(\frac{d^2_{kj} + R^2_j - r^2_k}{2d_{kj}R_j}\right) - 0.5 \times \sqrt{\left\{(R_j + r_k)^2 - d^2_{kj}\right\}(d_{kj} + r_k - R_j)(d_{kj} - r_k + R_j)}, \quad (6)$$

radii of the $j$th PU transmitter and the $k$th node respectively, and $d_{kj}$ is the distance between the two.

For delay sensitive alarms, the node must find the next-hop that guarantees the deadline. If the deadline has elapsed, the packet will be dropped. The node assumes that the time before the deadline can be uniformly shared among the nodes in the route. The *delay budget* (DB) for the transmission is given by

$$DB = \frac{deadline(P) - t}{d(k)}, \quad (7)$$

where $deadline(P)$ is the deadline associated with the packet $P$, $t$ is the current time, and $d(k)$ is the hop distance between the $k$th node and the DAG root. When a packet is at node $k$, the delay before the packet is correctly transmitted to the next hop depends on: a) delay until a vacant channel is found $(t_1)$ and b) the average delay until the next hop correctly receives the packet $(t_2)$. While $t_1$ depends on PU activity and spectrum sensing outcome, $t_2$ is characterized by the MAC layer and can be estimated by the packet delivery ratio. The node that provides the highest margin for delay budget, i.e., $(DB \geq t_1 + t_2)$ will be given the highest priority in the forwarder list.

The nodes in the forwarder list are prioritized according to a cost function based on neighborhood information. A node $k$ calculates the cost for a node $i$ in its forwarder set as follows.

$$\delta_i = \omega_1 \cdot C_i + \omega_2 \cdot E_{ki} + \omega_3 \cdot DBM_i, \quad (8)$$

where $C_i = \sum_{j=1}^{N} C_{ij}$ is the net overlapping area of $i$th node with all PU transmitters, $E_{ki}$ is the ETX of the link between nodes $k$ and $i$, $DBM_i$ accounts for the delay budget margin provided by the $i$th node, and $\omega_1, \omega_2$, and $\omega_3$ are design parameters such that $\omega_1 + \omega_2 + \omega_3 = 1$. For *class A* routes, $\omega_1 \gg \omega_2, \omega_3$ and the node with minimum cost has the highest priority. For *class B* routes, $\omega_3 \gg \omega_1, \omega_2$ and the node with the highest cost has the highest priority. The cost function also includes a weightage for ETX which is a link quality indicator. It has been shown that the cooperative gain of opportunistic forwarding becomes less significant when the inter-forwarder link success probabilities are low [29]. Thus, it is important to consider the effect of ETX in selecting the forwarding nodes.

CORPL requires some modifications at the MAC layer as well. In CORPL setup, the MAC layer adds the addresses of the nodes in forwarder list to the MAC header of the frame. The receiving nodes (nodes in the forwarder set) extract the address information (added on top of the standard header) by decoding MAC header. A node obtains the priority information by checking the location of its address in the MAC header (e.g., if its address is in the first address location of the header, it has the highest priority in the forwarder list).

In CORPL, the default parent has the highest priority for best-effort traffic. However, for *class A* and *class B* routes, the default parent is also considered in the forwarding set. If a better node (with lower or higher cost for *class A* or *class B* respectively) is available, a special flag is set in the header (See 6LoWPAN packet header) of forwarding packet which indicates that the packet is not intended for the default parent. In this case the default parent follows a similar procedure as described earlier for any other receiving node.

In order to ensure a unique forwarder selection, CORPL employs a simple overhearing-based coordination scheme based on the acknowledgement (ACK) frames. This is illustrated in Fig. 2. If the special flag is not set, the default parent forwards the data to the next hop and generates an ACK. This ACK is captured by the nodes in the forwarder set (recall that the nodes forming the forwarder set are within transmission range of each other). If the default parent fails to forward the frame within a timeout period (no ACK is received), the node with the next highest priority forwards it. In case of *class A* or *class B* routes, the highest priority node forwards the data by default and in case it fails to forward, the second highest priority node forwards it with the same technique. It should be noted that this approach has an associated probability of erroneous forwarding of same frame by multiple forwarding nodes. Thus, we define *coordination overhead* as the probability of a node in the forwarder set retransmitting a frame when any other node has already forwarded it to next hop. The coordination overhead $(O_c)$ for a node $a$ whose parent set is indicated by $\mathcal{P}_s^a$ can be calculated as follows.

$$O_c^a = \sum_{b=1}^{|\mathcal{P}_s^a|} p_{ab} \cdot EC_{bg} \cdot \prod_{r=1}^{b-1} (1 - p_{ar}), \quad (9)$$

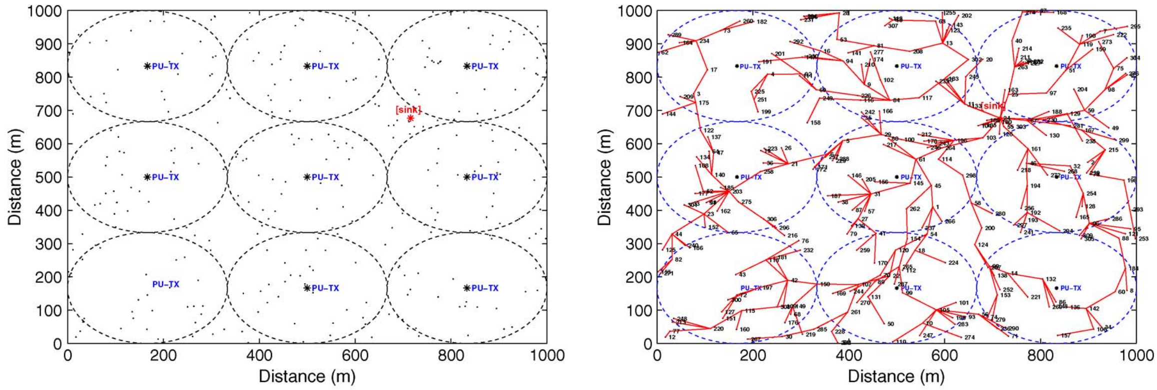
where $EC_{bg}$ is the path cost from node $b$ to gateway node. As the rank computation is based on ETX, therefore for calculating $O_c$, we assume the path cost in terms of ETX.

The total path cost to reach the gateway node from a node $b$ with a parent set $\mathcal{P}_s^b$ depends on the cost of opportunistic forwarding to its parent set and the remaining path cost of node $b'$s parent set [30], which is given by

$$EC_{bg} = \frac{1 + \left\{ X_1 p_{b1} + \sum_{j=2}^{|\mathcal{P}_s^b|} X_{bj} p_{bj} \cdot \prod_{n=1}^{j-1} (1 - p_{bn}) \right\}}{1 - \prod_{j \in \mathcal{P}_s^b} (1 - p_{bj})}, \quad (10)$$

where it is assumed that the nodes in $\mathcal{P}_s^b$ are sorted by their cost (in terms of ETX) to the gateway node, i.e., $X_1 < X_2 < \cdots < X_{|\mathcal{P}_s^b|}$. Note that the second term in the numerator accounts for the probability of a data packet being received by a particular node in $\mathcal{P}_s^b$ and not being received by any node with a lower cost to reach the gateway node, whereas the denominator accounts for the probability that at least one node in $\mathcal{P}_s^b$ has received the packet.

CORPL employs two different techniques for mitigating the performance degradation due to spectrum sensing. The first technique improves the performance through gathering sensing schedule information of the neighboring nodes. During DIO message transmission, each node also appends the following information: a) time left before the node starts the next round of spectrum sensing, b) interval between two successive spectrum sensing events, and c) timestamp. A receiving node maintains this information along with the forwarder list. Therefore, a node knows when its neighboring nodes will undertake spectrum sensing and for how long. This is particularly important for delay sensitive traffic. Nodes which are unable to forward packets due to spectrum sensing, and hence provide a lower




(a) (b)

Fig. 3. Simulated network topology. The circles represent the coverage area of PU transmitters. In order to have realistic number of secondary nodes, the density is kept low (node density $= 3 \times 10^{-4}$ nodes per unit area in this case). Nodes are connected in the form of a DAG where numbers represent node IDs. (a) PU transmitters and Poisson distributed secondary nodes. (b) DAG construction.

**Algorithm 1:** Opportunistic Forwarding in CORPL

$\mathcal{K}^n = \{k_1, k_2, \cdots, k_M\} \longrightarrow$ forwarder set of node $n$
$k^{'} \in \mathcal{K}^n \longrightarrow$ default parent of node $n$
$\mathcal{Q}^n_{class\ A} = \{\cdot\}_{1\times M}$, $\mathcal{Q}^n_{class\ B} = \{\cdot\}_{1\times M}$
**for** $i = 1 : \mid \mathcal{K}^n \mid$ **do**
  **if** *class A* **then**
    calculate $\delta_i \mid \omega_1 \gg \omega_2, \omega_3$ as per (8)
    $\mathcal{Q}^n_{class\ A}(i) \leftarrow \delta_i$;
    **else if** *class B* **then**
      calculate $\delta_i \mid \omega_3 \gg \omega_1, \omega_2$ as per (8)
      $\mathcal{Q}^n_{class\ B}(i) \leftarrow \delta_i$;
    **end**
  **end**
**end**
sort $\mathcal{Q}^n_{class\ A}$ and $\mathcal{Q}^n_{class\ B}$ in ascending order
(Forwarding Rules)
**if** *incoming packet belongs to class A* **then**
  highest priority next hop = $k^* \in \mathcal{K}^n$ with cost = $\mathcal{Q}^n_{class\ A}(1)$
  **else if** *incoming packet belongs to class B* **then**
    highest priority next hop = $k^* \in \mathcal{K}^n$ with cost = $\mathcal{Q}^n_{class\ \mathbf{A}}(M)$
  **end**
  **else**
    highest priority next hop = $k^{'} \in \mathcal{K}^n$
  **end**
**end**

delay budget margin can be avoided by assigning a lower priority in the forwarder list.

The second technique improves performance by decreasing the spectrum sensing time. Reduction of sensing time is possible when a node is situated in region of low PU activity, and hence the number of channel changes that occur over time is small [31]. Initially the sensing time is set to maximum value, i.e., $T_s = T_s^{max}$ for a fixed missed detection probability ($P_m = 1 - P_d$). The sensing time is decreased over time (by tracking the PU activity and establishing the fact that the node is located in region of low PU activity) according to the following relation: $T_s^{new} = T_s - \varphi \cdot \Delta_s$, where $\Delta_s$ is the step size, given by $\Delta_s = 0.5 \times T_s$ and $\varphi$ is a constant which is obtained from the gradient of sensing time versus the missed detection probability curve (see [31] for more details). When successive missed detection events occur, the node increases the sensing time with similar step size.

TABLE I
Simulation Configuration Parameters

| Parameter | Value |
|---|---|
| Path loss model | $128.1 + 37.6\log_{10}(r)$, $r$ in km, carrier freq = 2 GHz |
| Standard deviation of shadowing | 8 dB |
| Detection probability threshold ($P_d^{'}$) | 0.9 |
| Probability of false alarm ($P_f$) | 0.1 |
| Channel bandwidth | 200 KHz |
| PU received SNR ($\gamma$) | $-15$ dB |
| Busy state parameter of PU ($\mu_{ON}$) | 2 |
| Idle state parameter of PU ($\mu_{OFF}$) | 3 |
| Maximum Interference Ratio ($IR_{max}$) | 0.25 |
| Size of forwarder set ($M$) | 5 |
| Size of DIO message including options | 28 bytes |

It should be noted that traffic in AMI networks is mostly inward (from nodes to gateway), therefore CORPL primarily focuses on inward traffic. The outward traffic, which is rare, follows the standard reverse path recording methodology [22] using DAO messages as described in the RPL standard.

## V. Performance Evaluation

In this section, we evaluate the performance of CORPL under different scenarios. We implement CORPL in MATLAB with the topology as shown in Fig. 3. Other simulation parameters are given in Table I. We consider a square region of side 1000 meters that is occupied by 9 PU transmitters. The secondary users are assumed to be Poisson distributed in the whole region with a mean density as shown. We consider a frequency selective Rayleigh fading channel between any two nodes, where the channel gain accounts for small scale Rayleigh fading, large scale path loss and shadowing. For performance comparison, we also implement RPL in CR environments.

First we investigate the impact of spectrum sensing on the overall performance. Fig. 4 shows the average DAG convergence time against the spectrum sensing time. The results are

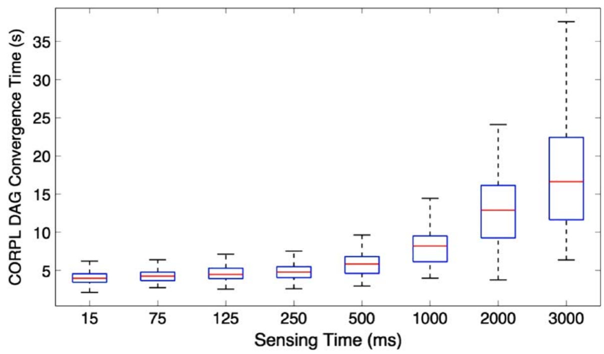
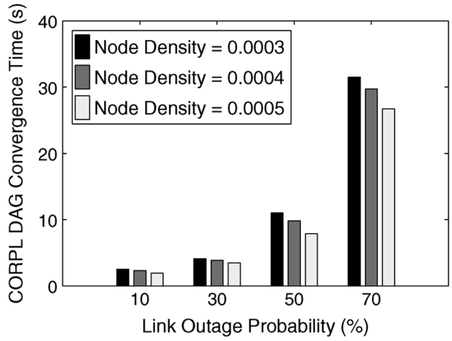
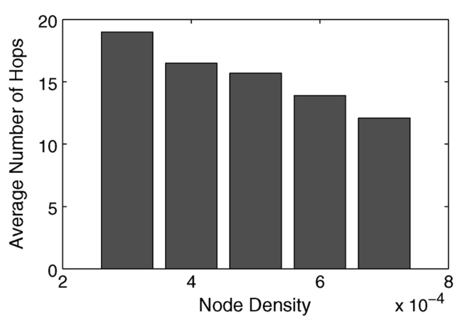



Fig. 4. Spectrum sensing time against the average DAG convergence time over 100 iterations (node $\text{density} = 3 \times 10^{-4}$ nodes per unit area).




(a)




(b)

Fig. 5. (a) DAG convergence time against LOP. (b) Average no. of hops towards gateway for different node densities.

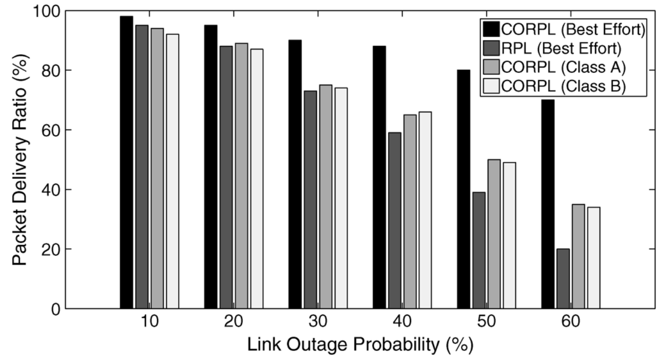



Fig. 6. PDR performance comparison for different protocols (node $\text{density} = 3 \times 10^{-4}$ nodes per unit area).

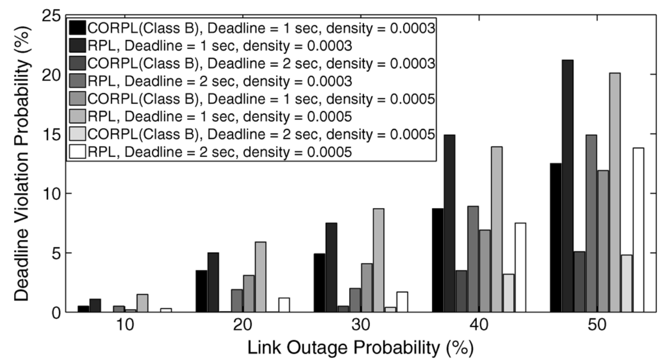



Fig. 7. Deadline violation probability for different scenarios (averaged over 10 000 packets from different nodes; the order of legend applies left to right).

averaged over 100 iterations and represented in the form of a box plot. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentile, and the whiskers extend to the most extreme data points not considered as outliers. The link outage probability (LOP) is set to 20%. We note that the DAG convergence time increases as sensing time increases due to the fact that DIO messages are dropped with higher probability (nodes spend more time in spectrum sensing state). Therefore, a large number of DIO message retransmissions contribute to a higher DAG convergence time.

Similarly, the DAG convergence time increases as the LOP increases due to higher link layer retransmissions as shown in Fig. 5(a). Note that the DAG convergence time reduces as the node density increases. This is because a higher density results in faster dissemination of network information owing to more nodes in the coverage range. Moreover, the probability of a node associating with a lower ranked parent increases which ultimately improves the DAG convergence time by reducing the number of hops towards the gateway as shown in Fig. 5(b).

Next, we evaluate the performance in terms of *packet delivery ratio* (PDR) which is defined as the ratio of number of packets received to the total number of packets sent. PDR captures the fraction of packets sent by different nodes that are actually delivered to the gateway. We generate 10 000 packets ($\text{packet size} = 100$ bytes) from different nodes and calculate the average PDR for different scenarios as shown in Fig. 6. It is evident from the results that CORPL outperforms RPL, where traffic is forwarded through the default parent only. The performance gain is significant under poor channel conditions (high LOP). CORPL utilizes the diversity of routes and hence improves the PDR by reducing retransmissions. For best-effort traffic in CORPL, ETX is the only factor in ranking the nodes in the forwarder set. Hence, the PDR for best-effort traffic is higher than *class A* and *class B* routes which assign a relatively less weightage to ETX.

We also evaluate the class specific performance of CORPL. The results in Fig. 7 evaluate the *deadline violation probability* (DVP) for delay sensitive alarms under different scenarios. The DVP increases as the LOP increases due to higher link layer retransmissions that decrease the remaining lifetime of a packet at the intermediate nodes and therefore, the packet is dropped before reaching the gateway. CORPL (*class B*) provides enhanced performance compared to RPL as the next hop is opportunistically selected in the former by assigning higher priority to nodes providing higher delay budget margin. This is unlike RPL where the default parent may not always provide enough delay budget margin. Moreover, a higher node density reduces the DVP by reducing the number of hops towards gateway as shown in Fig. 5(b).

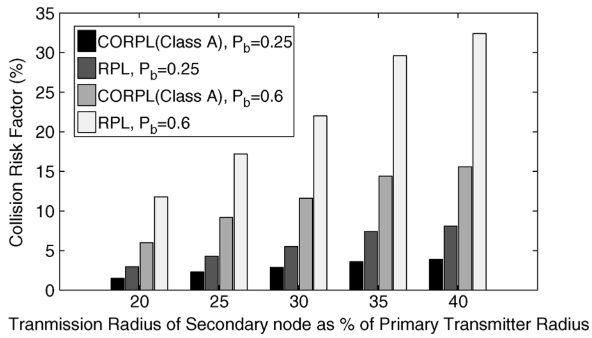



Fig. 8. Collision risk factor against secondary nodes transmission radii (results are averaged over 10 000 packets from different nodes, node $\text{density} = 3 \times 10^{-4}$ nodes per unit area).

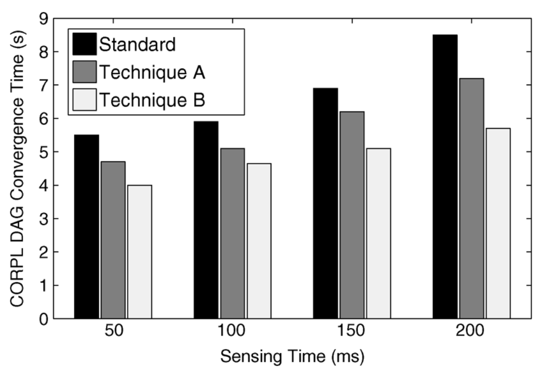



Fig. 9. DAG convergence time for different performance enhancement techniques ($\text{LOP} = 20\%$, results are averaged over 100 iterations, node $\text{density} = 3 \times 10^{-4}$ nodes per unit).

We evaluate the level of protection for PU receivers in terms of *collision risk factor* (CRF), which is defined as the ratio of colliding transmissions to the total number of secondary node transmissions at the PU receivers. Hence CRF depends on PU transmitter activity and coverage overlap between secondary nodes and PU transmitters. As seen by the results in Fig. 8, CORPL (*class A*) reduces the chances of collision to PU receivers by up to 50% under both low and high PU transmitter activity. Note that the CRF increases with increased PU activity and secondary node transmission range due to higher probability of collision with PU receivers.

CORPL employs two different techniques for mitigating the performance degradation due to spectrum sensing, which have been evaluated in Fig. 9 by calculating the average DAG convergence time. *Techniques A* and *B* respectively refer to gathering sensing schedule information and reducing sensing time under low PU activity, whereas in standard method no enhancement technique is employed. Both techniques improve the DAG convergence time. However, the highest improvement is achieved through *technique B* where the sensing time is reduced over time by tracking the PU activity in the form of a moving window. The abscissa in Fig. 9 refers to $T_s^{max}$ for *technique B*, using which the step size is calculated as described earlier. Both techniques will also enhance the DAG maintenance phase by reducing the number of packets dropped due to periodic spectrum sensing state.

Lastly, we evaluate the coordination overhead $(O_c)$ of CORPL. In simulations, it is estimated as the ratio of the number of duplicate packets to the total number of packets

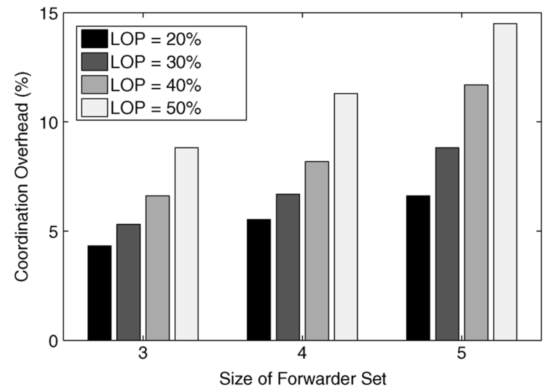



Fig. 10. Coordination overhead for CORPL (best-effort traffic) against link outage probability (averaged over 10 000 packets from different nodes, node $\text{density} = 3 \times 10^{-4}$ nodes per unit).

received at the gateway node. The results in Fig. 10 show the trend of $O_c$ against the size of forwarder set $(M)$ for different values of LOP. We note that $O_c$ increases as LOP increases due to the fact that the probability of a node (in the forwarding set) not capturing an ACK increases, which results in duplicate packet forwarding. With a similar reasoning, $O_c$ increases as the size of the forwarder set increases.

## VI. Concluding Remarks

RPL is emerging as the *de facto* routing protocol for many applications including AMI networks. A fundamental challenge in AMI networks is the reliable and low latency data delivery for different application in order to realize the vision of smart grid. Considering the promising future of cognitive smart grid networks, we propose CORPL; which is an enhanced RPL based routing protocol for cognitive radio enabled AMI networks. CORPL utilizes an opportunistic forwarding approach that not only ensures protection to PUs but also fulfils the utility requirements of the secondary network. Results show that CORPL improves the reliability of the network while reducing harmful interference to PUs by up to 50% as well as reducing the deadline violation probability for delay sensitive traffic. Hence, CORPL provides a viable solution for practical cognitive AMI networks. The future work will focus on analysis of CORPL under the dynamics of power systems.

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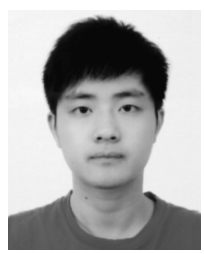
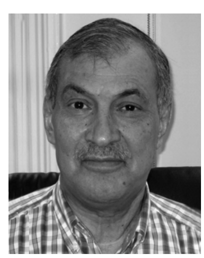
**Adnan Aijaz** (S'12) received his B.E. degree in electrical (telecom) engineering from National University of Sciences and Technology (NUST), Pakistan, in 2008. After his graduation he worked in the cellular industry for 2.5 years in the areas of network performance management, optimization, and quality assurance. In September 2010, he joined King's College London (KCL), where he received his M.Sc degree (with distinction) in mobile and personal communications. Since October 2011, he has been with the Centre for Telecommunications Research, KCL, where he is studying towards a Ph.D. His research interests include M2M communication, smart grids, cognitive radio networks, green communication, and molecular communication.



**Hongjia Su** received his B.Eng degree in electronics, telecommunications, and internet engineering from University of Bradford, U.K., in 2011 and his M.Sc degree in telecommunications and internet technology from King's College London, U.K., in 2013. He now works as a research engineer at Communications Technology Laboratory of Huawei Technologies, Shanghai, China. His current research focuses on IEEE 802.11ax.



**Abdol-Hamid Aghvami** (M'89–SM'91–F'05) is a Professor of Telecommunications Engineering at King's College London. He has published over 500 technical papers and given invited talks and courses world wide on various aspects of Personal and Mobile Radio Communications. He was Visiting Professor at NTT Radio Communication Systems Laboratories in 1990, Senior Research Fellow at BT Laboratories in 1998–1999, and was an Executive Advisor to Wireless Facilities Inc., USA, in 1996–2002. He was a member of the Board of Governors of the IEEE Communications Society in 2001–2003, was a Distinguished Lecturer of the IEEE Communications Society in 2004–2007, and has been member, Chairman, and Vice-Chairman of the technical programme and organising committees of a large number of international conferences. He is also the founder of International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC); a major yearly conference attracting nearly 1000 attendees.

Prof. Aghvami was awarded the IEEE Technical Committee on Personal Communications (TCPC) Recognition Award in 2005 for his outstanding technical contributions to the communications field, and for his service to the scientific and engineering communities. Prof. Aghvami is a Fellow of the Royal Academy of Engineering, Fellow of the IET, Fellow of the IEEE, and in 2009 was awarded a Fellowship of the Wireless World Research Forum in recognition of his personal contributions to the wireless world.