HCR-MAC: A High-capacity Receiver-based MAC Protocol for Cognitive Radio Enabled AMI Networks in Smart Grid

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Abstract

The Cognitive Radio (CR) Advanced Metering Infrastructure (AMI) network is considered as a viable solution to enhance various aspects of electric power grid and realize smart grid. However, several challenges are generated due to the harsh wireless environment in smart grid. As a result, throughput and reliability become critical issues. In this regard, we propose HCR-MAC, which is a high-capacity receiver-based MAC protocol for cognitive AMI. HCR-MAC uses a capacity-based auction mechanism and preamble sampling techniques for providing high capacity and reliability. In addition, HCR-MAC explicitly accounts for the peculiarities of a CR environment. Simulation results demonstrate the effectiveness of the proposed protocol as a viable solution for cognitive AMI networks in smart grid.

1. Introduction

The legacy electric power grid, which has been used for many years, meets some problems such as insecure, energy inefficient and frequent transmission congestion and even failure [1], [2]. The next generation of electric grid, namely, smart grid, is expected to supply improved serve with more reliability, efficiency, agility and security [3]. Smart gird is expected to have some capabilities, such as advanced bi-directional communications, automated control, distributed computing, and so on. Besides, smart grid can gathering information from equipments in different areas in realtime, and then make intelligent decisions to promote energy efficiency and security. Therefore, electricity providers, distributors, and consumers will benefit realtime awareness services, such as operating environments, requirement response, and so on.

In smart grid, Advanced Metering Infrastructure (AMI) is a key element for information gathering and processing. In AMI networks, smart meters located at customer premises are connected to the Meter Data Management System (MDMS), and MDMS serves as the control centre of storage, management and processing of consumer power-consuming information. These information can be used by different applications [3], [4]. The AMI networks are essential in smart grids, since they provide two-way communications between utilities and consumers. 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) [5], [6] provides an effective way to deal with the spectrum scarcity and inefficiency issues in wireless

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networks. Therefore, CR-AMI networks draws lots of attentions, 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 [7-9]. Therefore, a practical solution for AMI network is cognitive radio enabled multi-hop wireless mesh network, which connects a large number of smart meters. Smart meters transmit their meter data to the gateway in turn [9]. Therefore, the success of smart grid operation depends on the communication capabilities of AMI networks in harsh environmental conditions that brings out great challenges for throughput and reliability. The operation of data transmission in smart grid requires enhancements and optimizations at different layers of the protocol stack, especially at the Medium Access Control (MAC) layer. A receiver-based MAC protocol is proposed in [7], which gets a trade-off between spectral efficiency and energy efficiency and provides reliable operation in smart grid wireless environments. However, the throughput of communication is not optimized in this work.

Against this background, our objective in this paper is to enhance the receiver based-MAC on throughput capability for the AMI networks in smart grids. In this regard, we propose HCR-MAC (short for High-throughout Cognitive Receiver-Based MAC) protocol, which is a receiver-based MAC protocol for cognitive enabled AMI networks in smart grid. HCR-MAC is designed with special emphasis on throughout of cognitive AMI network operating in smart grid environments. In order to achieve high throughout, HCR-MAC uses the capacity as the key in next hop competition. Furthermore, HCR-MAC employs preamble sampling [10] approach to tackle idle listening and support sleep/wakeup modes without synchronization overheads. Especially, HCR-MAC exploits the broadcast nature of wireless medium and adopts an auction mechanism approach with multiple receivers as discussed later in detail.

The rest of the paper is organized as follows. Section II describes the framework of HCR-MAC including the system model and protocol description. In Section III, simulation performance evaluation and numerical analytical are shown. Finally, Section IV concludes the paper.

2. HCR-MAC Framework

2.1 HCR-MAC Overview

HCR-MAC is receiver-based in nature. Inherently, the receiver-based MAC is different from sender-based MAC. In sender-based MAC protocol, it is the sender that selects a receiver node from its neighbour table and includes the receiver's address in the packet header. However, in HCR-MAC, no particular nodes are defined as receivers. The sender node transmits the data packet by broadcasting such that all neighbour nodes in the communication range can receive the packets. Receivers compete in an auction process

and the winner forwards the data to the next hop towards gateway.

A sender node transmits its data without defining a particular node as a receiver. All the neighbouring nodes within communication range of the sender node receive the data packet. Based on the information received from the preamble, each individual node decides if it is eligible to participate in forwarding the data. Receivers compete in an elective process and the winner forwards the data to the next hop towards gateway/sink. In the elective process, the capacity is the key factor. In the auction, each node that contends to forward data estimates the capacity of single hop operation. Based on the estimated value of capacity, the duration before forwarding operation is determined. As a result, the receiver node with better capacity during this hop will have higher chance to forward the data packet.

Another key aspect of HCR-MAC is using preamble sampling to improve the energy efficiency. In preamble sampling approach, each nodes use asynchronous low power listening and select the sleep/wakeup schedules independently. The nodes spend most of their time in sleep mode and wake up for a short duration, namely, clear channel assessment (CCA) every checking interval (CI) to check whether there is an ongoing transmission. To avoid missed detection, the sender node transmits a long preamble longer than CI, before the data packet, to ensure that the preamble can be detected. By tuning CI and CCA, average duty-cycles of below 1% can be achieved without any need for scheduling or synchronization.

A key aspect of any CR environment is spectrum sensing. Nodes periodically monitor the current channel for primary user (PU) activity before using it for transmission. During this interval (sensing time), nodes are not involved in forwarding data packets the network performance is degraded (e.g., in terms of end-to-end throughput, latency, and packet loss ratio). HCR-MAC utilizes a mechanism to improve overall network performance under spectrum sensing state of different nodes. Further, in HCR-MAC, nodes employ optimal transmission time subject to an interference constraint, in order to ensure protection to PUs.

2.2 System Model

The ad-hoc network of stationary nodes with CR ability is considered here. We consider J stationary PU transmitters (and hence J available channels) with known locations and maximum coverage ranges. The PU (transmitter) activity model for the jth channel is given by a two state independent and identically distributed random process, namely, busy and idle. Let S_b^j denote the state that the jth channel is busy (PU is active) and S_i^j the state that the jth channel is idle with probability. We assume that a node employs energy detection technique for primary signal detection wherein it compares the received energy (E) with a predefined threshold (σ) to decide whether the jth channel is occupied or not, expressed as follows.

$$Result_{ss} = \begin{cases} S_{busy}^i & \text{if } E \geq \sigma \\ S_{idle}^i & \text{if } E \prec \sigma \end{cases} \quad . \quad (1)$$

The MAC frame structure in a CR network consists of a spectrum sensing slot (T_s) and a transmission slot (T). For spectrum sensing, two principle 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. False alarm and detection probabilities for the jth channel can be expressed as follows.

$$P_f^j = P_r\left\{E \geq \sigma \mid S_i^j\right\} = Q\left(\frac{\sigma - 2n_j}{\sqrt{4n_j}}\right), \quad (2)$$

$$P_d^j = P_r\left\{E \geq \sigma \mid S_i^j\right\} = Q\left(\frac{\sigma - 2n_j(\gamma_j + 1)}{\sqrt{4n_j(2\gamma_j + 1)}}\right), \quad (3)$$

where Q($\cdot$) accounts for Q function, which is the complementary error function, and γ_j and n_j denote the signal-to-noise ratio (SNR) of the primary signal and the bandwidth-time product for the jth channel respectively.

2.2 System Model

In HCR-MAC, different from the sender-based mechanism (such as 1-hopMAC in literature [11]), nodes need not select a particular receiver. The sender transmits data by broadcasting. It is the receiver nodes that determine the forwarder node. The HCR-MAC protocol single hop operation along with the timeline for different nodes is shown as Fig. 1. Node S has data to send to the gateway. Firstly, it performs spectrum sensing (with duration given by T_s) to detect any PU activity. If the PU is detected to be absent, namely, S_i^j, S starts broadcasting the preamble. The preamble, which last for T_{pr}, consists of multiple micro-frames. The micro-frames contain identification information for neighbouring nodes to distinguish between PU transmission or cognitive node transmission. All the nodes within the transmission range of S will detect a few micro-frames of the preamble. Three neighbouring nodes of S (i.e., nodes A, B, and C) are eligible to forward the data towards the gateway node. They wake up and receive the data transmitted from S, when they find the preamble. If the received data packet is detected to be erroneous, it will be simply discarded. If a node (e.g., A) wants to forward the packet, it waits for a timer Δt_A and begins sensing the spectrum. When a channel is available, A broadcasts the preamble for forwarding. The first node which broadcasts the preamble is the winner and will forward the packet. The duration Δt of node y is given by

$$\Delta t_y = \omega_0 + \left(\omega_1 \gamma_{x,y}^j\right)^{-1}, \quad (4)$$

where ω_0 and ω_1 are constants.

Therefore, the receiver which can provide high capacity will perform the spectrum sensing early and have high probability for forwarding.

In addition, the sender node S retransmits the data if none of the participating nodes in the contention window transmits the preamble to supply the offer. The sender node can realize this by performing the sensing operation just before ending the contention window (T_{CW}). The duration of contention window is set according to the transmission radius of sender nodes. In case of multiple hops, the same operation continues until the data is received by the gateway.

The capacity can be evaluated based on Shannon's theorem. Let P_{sw}^j denote the probability of switching transmission to the jth cognitive channel for a node (e.g., node i), which is given by

$$P_{sw}^j = P_b^j\left(1 - P_d^j\right) + P_i^j\left(1 - P_f^j\right), \quad (5)$$

We assume that the maximum allowed power for transmission over the jth channel is P_{sw}^j. Then, the maximum capacity of channel j is given by

$$C_{x,y}^i = W_{x,y}^i \log_2\left(1 + \frac{P_{max}^j |h_{x,y}^j|^2}{\delta^2}\right), \quad (6)$$

where $W_{x,y}^i$ denotes the potential bandwidth of the jth channel for transmission between CR users x and y; δ^2 and $h_{x,y}^j$ denote the power of noise and the channel coefficient, respectively.

The potential bandwidth actually provides the usable bandwidth since CR users access a channel with certain probability given by (5). Then, $W_{x,y}^j$ can be obtained as follows.
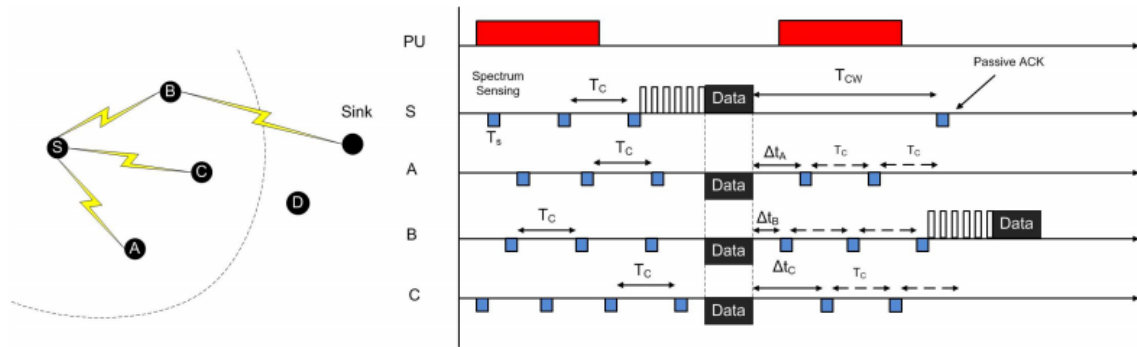
Figure 1. Timeline of HCR-MAC protocol with an illustrated scenario of sender and receiver nodes

$$W_{x,y}^{j} = P_{sw}^{j} B_{j} \ , \ (7)$$

where B_{j} is the bandwidth of the jth channel.

In addition, the sender node S retransmits the data if none of the participating nodes in the contention window transmits the preamble for forwarding. The sender node can realize this by performing the sensing operation just before ending the contention window (T_{CW}).

3 Performance Evaluation

In this section, we evaluate the single hop performance of HCR-MAC. The Green-RPL is implemented with the topology shown in Fig. 2. A square region of side 1200 meters is considered that is occupied by 16 PU transmitters. The secondary users are assumed to be Poisson distributed in the whole region with a mean density. Without loss of generality, we assume that RPL is operating at the Network layer. The transmission radius of each node is set to 40 meters. In TABLE I, other simulation parameters are given. In addition, we implement a sender-based MAC protocol (1-hopMAC [11]) in CR environments (CSB-MAC) and a receiver-based MAC protocol (CRB-MAC in [7]) for comparison.

First, we evaluate the average capacity against the maximum transmitting power allowed in each channel. The analytical and simulation results are given in Fig. 3. It is assumed that the maximum transmitting power allowed in each channel is fixed, which ranges between 20 dBm and 30 dBm, and the maximum power constraint of each cognitive radio sensor node is 30 dBm. The average capacity increases as the maximum allowed transmitting power increases. However, the average capacity reaches the saturation point when the total transmission power reaches the maximum power constraint.
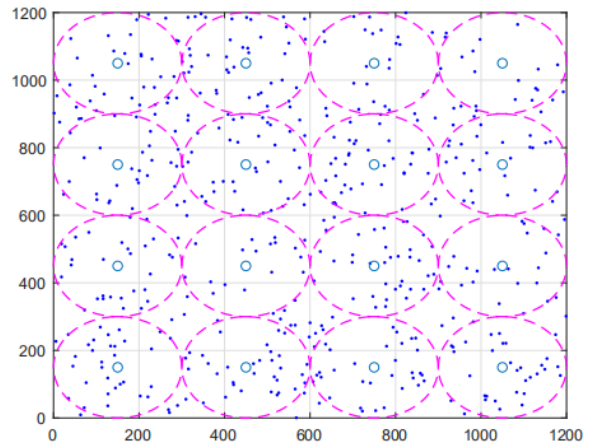

Figure 2. Sample simulated topology with Poisson distributed nodes (density = 0.3 nodes per unit area). The filled squares and dotted circles represent the location and coverage area of PU transmitters respectively.

Table 1. This is a legend. Caption to go above table

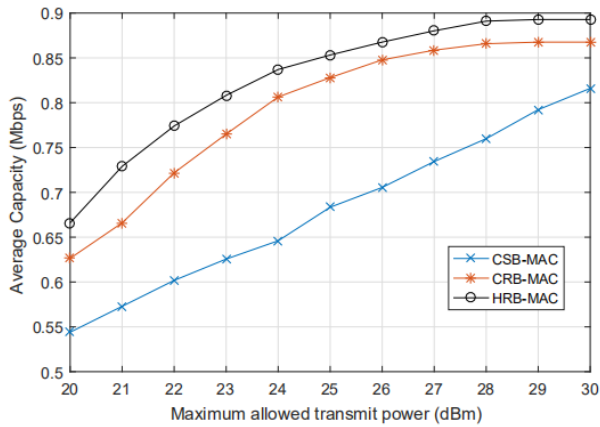| Parameter	Value
Path loss model	128.1 +37.6log10(r), r in km
Standard deviation of shadowing	8 dB
Detection probability threshold(P_d)	0.9
Probability of false alarm (P_f)	0.1
Channel bandwidth	200kHz
PU received SNR(γ)	-15dB
Busy state parameter of PU	[1, 9]
Idle state parameter of PU (μ_{OFF})	3
Maximum interference ratio (IR_{max})	0.25

Figure 3. Average capacity against bit error rate

Next, we evaluate the reliability performance. The reliability in terms of PDR against bit error rate is shown in Fig. 4. HRB-MAC and CRB-MAC have better performances of reliability. This is because that more receivers are participating in the data forwarding process, due to the receiver-based mechanism. Therefore, we can draw the conclusion that HRB-MAC shows the resiliency to channel quality variations and provides high reliability.
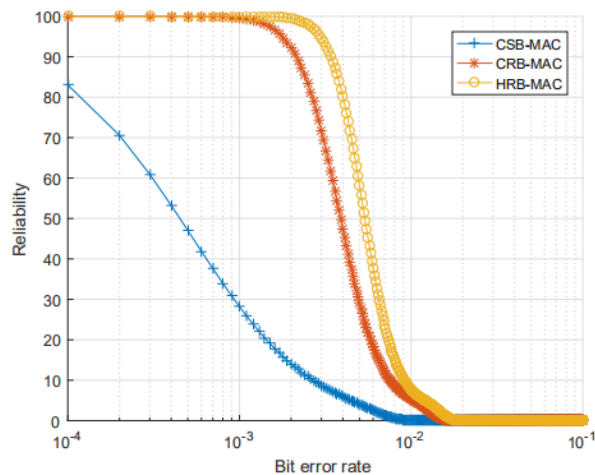

Figure 4. Reliability performance against BER, in terms of PDR

Last, but not the least, we discuss the delay performance in Fig. 5. Since delay is dependent on the number of retransmissions, HCR-MAC outperforms CSB-MAC and CRB-MAC in terms of delay performance owing to fewer

retransmissions. The delay reduces as the number of receivers increase because of higher probability of successful transmission. Moreover, the delay performance reaches a saturation point as the maximum number of retransmissions is reached. Note that a high PU activity, with same number of receivers, further increases the delay due to more spectrum sensing events to find a vacant channel.
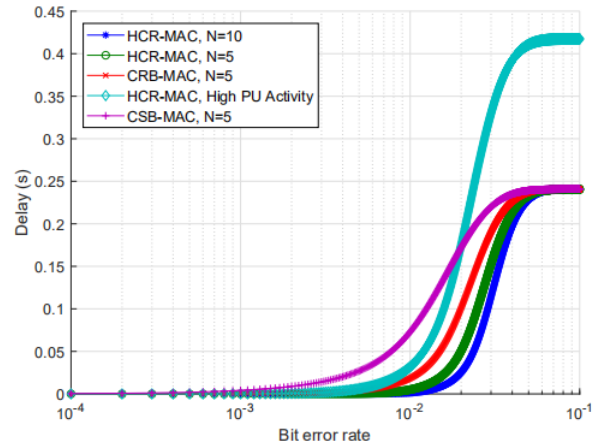

Figure 5. Delay performance against BER

4 Concluding Remarks

In this paper, we have proposed HCR-MAC, which is a receiver-based MAC protocol for cognitive AMI networks in smart grids. HCR-MAC employs a capacity-based auction mechanism for forwarding competition, such that the receiver with the best capacity will forward the data packet. Furthermore, the preamble sampling is adopted to cater for high energy efficiency and reliability requirements of application in smart grid. System level simulation results demonstrate that in lossy wireless environments HCR-MAC generates less retransmissions, and therefore, enhances the throughout and delay performance. Moreover, high reliability can be provided by increasing the number of receivers due to the receiver-based nature. Hence, HCR-MAC provides a viable solution for cognitive AMI networks in realizing the vision of smart grid.

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