Performance evaluation of cognitive radio in advanced metering infrastructure communication

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Abstract. Smart grid is an intelligent electricity grid system. A reliable two-way communication system is required to transmit both critical and non-critical smart grid data. However, it is difficult to locate a huge chunk of dedicated spectrum for smart grid communications. Hence, cognitive radio based communication is applied. Cognitive radio allows smart grid users to access licensed spectrums opportunistically with the constraint of not causing harmful interference to licensed users. In this paper, a cognitive radio based smart grid communication framework is proposed. Smart grid framework consists of Home Area Network (HAN) and Advanced Metering Infrastructure (AMI), while AMI is made up of Neighborhood Area Network (NAN) and Wide Area Network (WAN). In this paper, the authors only report the findings for AMI communication. AMI is smart grid domain that comprises smart meters, data aggregator unit, and billing center. Meter data are collected by smart meters and transmitted to data aggregator unit by using cognitive 802.11 technique; data aggregator unit then relays the data to billing center using cognitive WiMAX and TV white space. The performance of cognitive radio in AMI communication is investigated using Network Simulator 2. Simulation results show that cognitive radio improves the latency and throughput performances of AMI. Besides, cognitive radio also improves spectrum utilization efficiency of WiMAX band from 5.92% to 9.24% and duty cycle of TV band from 6.6% to 10.77%.

1. Introduction

Smart grid is an intelligent electricity system that integrates sensors and intelligent electronic devices for automatic measuring, controlling, and monitoring. These sensors and devices measures and reports grid status frequently to ensure smart grid is in stable status. A reliable communication link is needed to transmit these smart grid data. However, there are ubiquitous smart grid components and these components are scattered in wide geographical area. It is difficult to locate a huge chunk of dedicated spectrum for smart grid communication. It is also expensive to implement wired communications in smart grid. The third option is to implement cognitive radio based communication in smart grid.

Spectrum measurements have been conducted worldwide and these occupancy results indicated that spectrum bands are poorly utilized [1]-[9]. Static-assigned licensed spectrum bands are not fully utilized while unlicensed spectrum bands are facing overcrowded issue. Cognitive radio improves spectrum utilization efficiency and mitigates the issue of spectrum scarcity by allowing unlicensed users to utilize idle licensed spectrum bands. In order to protect licensed users from potential harmful interference, unlicensed users can only access these idle spectrum when licensed users are not using these spectrum.
The benefits of using cognitive radio in smart grid communication are cost-efficient, energy-efficient, low interference level, and increases interoperability. As cognitive radio let smart grid users to access spectrum bands opportunistically, spectrum leasing is not required. Besides, one of the features of cognitive radio is transmit power control. Hence, it reduces energy consumption and keeps interference level low by computing optimal transmit power for smart grid users. Furthermore, it is expected that multiple communication techniques will be implemented in smart grid. Cognitive radio can interoperate in heterogeneous communication networks.

A cognitive radio based smart grid communication framework which consists of Home Area Network (HAN) and Advanced Metering Infrastructure (AMI) is proposed. AMI comprises communication in neighborhood area network (NAN) and wide area network (WAN). HAN supports communication between home electrical appliances and smart meter. AMI sends meter data from HAN to billing center and deals with automatic meter reading and dynamic respond. The components in AMI include smart meters, data aggregator units, and billing center. In this paper, only the performance of cognitive radio in AMI is presented.

2. Related works

Conventional communication techniques such as WiMAX, GSM, and GPRS are implemented for smart grid communications. These technologies offer long range propagation and licensed spectrum bands provide good quality channel for smart grid communication. However, they require spectrum leasing cost. Besides, channel assignment and priority are given to the licensed users of these bands. For instance, priority are given to mobile users because they are legal GSM subscribers. Depends on the service level agreement, smart grid data might or might not be assigned a good quality channel. On the other hand, wireless mesh network is implemented in smart grid. In [10], smart meter data are transmitted through RF mesh network. RF mesh networks offers the benefits of extended coverage, redundant links to cope with link failure and varying channel conditions, scalable, and low lost. However, RF mesh networks have high routing complexity. Besides, number of hops might incur huge latency in packet delivering.

In [11], a hybrid spectrum access in cognitive smart grid communication is proposed. Smart grid users are allowed to access both licensed and unlicensed spectrum bands opportunistically. If idle licensed bands are available, smart grid users can switch to idle licensed spectrum bands because licensed spectrum bands offer better quality of service than unlicensed spectrum bands. Several channels from both licensed and unlicensed spectrum bands are reserved as guard bands for handoff purpose. In [12], Omid Fatemieh and his team studies the feasibility of using TV white spaces for AMI communications. The proposed architecture suggests that NAN uses White-Fi and WAN uses 802.22 communication technologies. Both White-Fi and 802.22 standards transmit data by using cognitive radio in low duty cycle TV spectrum bands. White-Fi and 802.22 in different in terms of channel assignment and channel access. Omid Fatemieh and his team did not provide any justification to their framework.

3. Cognitive radio based smart grid communication framework

Figure 1 shows the proposed cognitive radio based smart grid communication framework. The framework comprises HAN, NAN, and WAN. In this paper, the performance of cognitive radio in NAN and WAN are presented.

There are three types of meter data, which are residential meter data, commercial meter data, and industrial meter data. In AMI, smart meter sends residential meter data to billing center four to six times a day. The latency is less than four hours. The interval for industrial and commercial meter data is 12 to 24 times a day and the latency is less than two hours. The packet size of these scheduled meter data is approximately 1600 to 2400 bytes. If on-demand meter data is required, smart meter sends data to data aggregator unit immediately. The packet size of on-demand data is 100 bytes and its latency is 15 seconds. AMI requires reliability of more than 98% [13].
In this proposed framework, AMI is separated into NAN and WAN. In NAN, meter data are sent from smart meters to data aggregator units. Data aggregator unit performs data compression, error checking, and data aggregation. In WAN, data aggregator unit forwards all the meter data to billing center. In this paper, WAN communication does not refer to core network that involves grid measuring, monitoring, controlling, and protection.

NAN communication is carried out using cognitive 802.11. In conventional 802.11, access points select one channel out of 11 channels from ISM spectrum bands. Wireless users that are attached to this access point will contend for this channel only for data transmission. On the other hand, cognitive users scan all six channels in ISM bands and utilize idle channels. In NAN, smart meters are equipped with cognitive radio abilities, which allow them to sense multiple channels to detect idle channel. Cognitive users access channels through CSMA/CA.

The distance between data aggregator units and billing center is relatively larger than the distance between smart meters and data aggregator units. So, a long-range communication technique is required for WAN communication. Cognitive WiMAX and TV white spaces are used for WAN communication. WiMAX has a coverage area of 4km (NLOS) and 50km (LOS). TV white spaces refer to idle channels/spectrum holes in TV bands. TV bands have excellent propagation characteristics. They can travel long distance and penetrate obstacles. WiMAX and TV white spaces are licensed spectrum bands. Hence, cognitive users must be able to detect the presence of licensed users in order to avoid causing harmful interference to licensed users. In [14], three methods are proposed to protect licensed users which are beacons, periodical spectrum sensing, and geo-location database. In this paper, geo-location database is used in WAN to protect licensed users and assign idle channels to cognitive users.

![Figure 1. Cognitive smart grid communication framework.](image)

4. Simulation
Simulation is carried out using Network Simulator 2 (NS-2). NS-2 is an open source event-driven simulator. Cognitive Radio Cognitive Network (CRCN) is patched into NS-2 to provide multi-interface multi-channel functions. Several modifications are done to support cognitive radio and multi-channel in 802.11 coding. Simulation parameters for NAN and WAN are listed in Table 1.

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1 There are 11 channels in ISM spectrum bands. However, five channels are used for routing purpose. Hence, there are six channels left for contention and data transmission.
Table 1. Simulation parameters.

| Parameter                      | Value                                |
|--------------------------------|--------------------------------------|
| Area                           | NAN: 500m × 500m                     |
|                                | WAN: 2km × 2km                       |
| Routing protocol               | AODV                                 |
| MAC protocol                   | NAN: 802.11                           |
|                                | WAN: WiMAX, 802.22                   |
| Simulation time                | 240 seconds                          |
| Number of pairs of licensed    | 2                                     |
| users                          |                                       |
| PU CBR traffic                 | 512 bytes                            |
| SU Traffic type                | Poisson                              |
| SU Packet size                 | NAN: 1600 bytes                      |
|                                | WAN: 2400 bytes                      |

The packet sizes are set according to [13]. WiMAX MAC protocol is implemented by patching 802.16 coding. By right, a 802.22 standard should be patched to simulate cognitive radio based communication in TV white spaces. However, there is no complete 802.22 coding by the time simulation is conducted. According to [15], there are many similarities between 802.16 and 802.22 MAC protocols. Hence, 802.16 MAC protocol is used to simulate 802.22 MAC.

Primary users are set to use certain channels during simulation. For example, the first pair of primary users use Channel 0 and the second pair of primary users use Channel 1 for data transmission. Cognitive users in NAN detect idle channels through CSMA/CA and cognitive users in WAN acquire idle channels through consulting geo-location database.

5. Results

The performance metric are delivery ratio, latency, and throughput. The quality of service for AMI are (i) delivery ratio more than 98%, (ii) latency less than 2000 milliseconds, and (iii) throughput of 14 to 100 kbps.

5.1 NAN

When the number of users increases, more nodes are contending for channels. The probability of collisions is higher. Nodes that encounter collisions have to back off and wait for a random period to contend for channel again. The waiting period incurs delay. In spite of the high probability of collisions and delay, the consistent performance of NAN delivery ratio is shown in Figure 2. Both conventional 802.11 and cognitive radio (no. of channel=1) have 100% delivery ratio while cognitive radio (no. of channel =2-6) has slightly lower delivery ratio.
Figure 2. Delivery ratio for NAN.

Figure 3 shows the delay performance in NAN. When the number of channel is one, the delay of cognitive 802.11 outperforms conventional 802.11 by 3.32%. Once collision occurs, nodes cannot switch to other channel because there is only one channel in conventional 802.11. Nodes have to back off and wait for the channel to be idle again. For cognitive 802.11, there are two pairs of licensed users transmitting in the network. Sensing multiple channels and competing with two pairs of primary users cause its delay higher than the delay of conventional 802.11. In case of sudden appearance of primary users, cognitive users do not need to wait for primary users to finish data transmission and contend channels. Cognitive users can switch to other available channels.

Figure 3. Average delay for NAN.

Figure 4 shows that the throughput value for conventional and cognitive 802.11 are comparable. The throughput of cognitive 802.11 is higher by 2.32%. Throughput is proportional to delivery ratio. In both cases, all packets sent are received successfully. Plus, the simulation time is same in both cases. Thus, both cases have comparable throughput.
5.2 WAN

Figure 5 to 7 show the performance of WAN when using WiMAX band and TV white spaces opportunistically. Different from ISM bands, WiMAX and TV white spaces are licensed spectrum bands. If smart grid users wish to access WiMAX and TV bands legally, they have to pay for spectrum leasing. Although they are licensed users (since they pay for spectrum leasing), they still have to obey the policy of tele-operators in accessing spectrum. In this paper, the policy issue is not in the scope of work. Hence, instead of comparing the performance of non-cognitive radio and cognitive radio in WiMAX and TV bands, simulation is run to compare the performance of cognitive radio in WiMAX and TV white spaces. Figure 5 shows that the delivery ratio of cognitive radio in both WiMAX and TV white spaces is good. Although there is a slight drop of delivery ratio when number of nodes equals three, this packet drop is due to end of simulation time. The packet is generated near the end of simulation. When simulation times up, the packet is simply dropped.
Figure 6 shows that cognitive WiMAX offers lower delay than cognitive TV white space. The difference of delay is 36.83%. Cognitive WiMAX allows users to access channels faster. This is because TV bands can propagate long distance. However, long distance propagation causes its round trip time higher. Despite the delay of TV bands is higher, the advantage of using TV white spaces is that TV frequency band can cover wider coverage area compared to WiMAX band. In other words, one 802.22 base station can support more cognitive users. Therefore, in a fix coverage area, less number of 802.22 base stations is required compare with the number of WiMAX base station.

In random access MAC, delay increases with the number of users. This is because nodes contends channels through CSMA/CA. However, the MAC protocol of 802.16 (WiMAX) and 802.22 (TVWS) is time-slotted. Users are allocated timeslot for data transmission. TDMA performs better than CSMA/CA when number of user is high. When there is less users (i.e. no. of nodes < 4), there are many timeslots that are not assigned to any users. Users cannot use unassigned channel and have to wait for their timeslot. These unused timeslot become wasted. The number of user increases until a certain point where all timeslots are assigned to users (i.e. no, of nodes >= 4). When there are four or more than four users, all timeslots are assigned to users. There will be no wasted timeslot. More packets can be sent and therefore the average delay is lower. Hence, average delay for all nodes become smaller when there more than four users in the system.

![Figure 6. Average delay in WAN.](image)

Figure 7 shows that the throughput performance for cognitive WiMAX and cognitive TV white space. The throughput of cognitive WiMAX is higher by 55.33%. This is because cognitive WiMAX has higher capacity than cognitive TV white space. WiMAX is a high frequency communication spectrum bands that provide high speed capacity for subscribers while TV spectrum bands are low frequency bands with low capacity data transmission.
6. Spectrum Utilization Efficiency

As mentioned in Introduction, cognitive radio is able to improve spectrum utilization efficiency of spectrum bands. Hence, the new duty cycles of WiMAX band and TV band are calculated to investigate the percentage of improvement in duty cycle. Table 2 shows that allowing smart grid users to use spectrum band opportunistically greatly improve the spectrum utilization efficiency. On the left column of the table is the duty cycles of each spectrum band as reported in [9]. On the right column of the table, the duty cycle is calculated by measuring the total active time nodes sending data by using that particular spectrum and divides by total simulation by allowing smart grid users to use spectrum band opportunistically. It is observed that the duty cycles of each spectrum band have been improved.

Table 2. Spectrum utilization efficiency.

| Spectrum band | Spectrum utilization efficiency | Improvement |
|---------------|---------------------------------|-------------|
|               | Non-cognitive radio | Cognitive radio |          |
| WiMAX band    | 5.92%               | 9.24%        | 3.32%     |
| TV band       | 6.6%                 | 10.77%       | 4.17%     |

7. Conclusion

The simulation results clearly show that cognitive radio outperforms non-cognitive radio. In NAN, cognitive radio outperforms non-cognitive radio by 3.32% and 2.32% in latency and throughput, respectively. In WAN, the performance of using cognitive radio in WiMAX and TVWS is promising. Both spectrum bands can offer high channel quality, low latency, and high throughput for WAN communication. The latency in NAN and WAN are kept well below the maximum latency of AMI requirement, which is 2000 milliseconds. This is due to the ability of sensing multiple channels and utilizing idle channels opportunistically decrease the probability of collision in random access, which in turn reduces the queuing delay of each packet. Besides, cognitive radio also improves spectrum utilization efficiency. Future work include a setting up a test-bed to test the practicability of cognitive radio based smart grid communication in real life.
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