Interference issues in Smart Grid Home Area Network to enable Demand Response and Advanced Metering Infrastructure: survey and solutions

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Abstract

The electric power grid has served us well for the past years. However, they are not designed to meet the demand of the future needs including the ever-rising energy demand, integration of the micro generation with the grid, reliability and security. Therefore, recently, an efficient electric energy system called the Smart Grid (SG) has been proposed as the next-generation electrical power system technology that embraces advanced communications technologies and ubiquitous computing capabilities in every aspect of electricity generation, transmission, distribution and consumption. The core component of the SG is a communication networks which comprises a variety of wireless communication technologies. In this paper, we present a survey on the interference issues in the SG communication network specifically the Home Area Network (HAN) utilizing low-power based wireless technology in enabling the Demand Response (DR) and Advanced Metering Infrastructure (AMI) functionalities. We also discuss the current proposed methods in mitigating, avoiding and dealing with the interference problem. Finally, we discuss the utilization of cognitive radio based technique as a promising method in solving the interference problem and in enabling optimal communication service for Smart Grid HAN (SG-HAN).

Keywords: SMART GRID, DEMAND RESPONSE, ADVANCED METERING INFRASTRUCTURE, HOME AREA NETWORK, IEEE 802.15.4, INTERFERENCE, COGNITIVE RADIO

1. Introduction

Electricity is named as the greatest invention of the 20th century engineering achievements by the United States' National Academy of Engineering [1]. It is far more important than the invention of the great Internet. It is also a very important ingredient for the economy growth of a country [2]. It is predicted that the world's electric energy consumption will be greatly increased from years to years. According to the United States Army Corps of Engineers [3], the worldwide energy consumption is going to increase 60% by 2030 and might be triple by 2050. Furthermore, according to the United States Energy Information Administration [4], the electric energy generation is projected to be as high as 35.2 trillion kWh in 2035 which is an increase of 62.1% from year 2008 as stated in Table 1. To make it worse,

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today's digital economy and society not only need a greater electric supply, but it needs to be more reliable and high in quality [5]. In the United States (US), the demand of this digital-quality power is predicted to be increasing and will become 30% of the total US electrical load by 2020 [5]. The needs of these demands have to be fulfilled. Else, history has shown that tens to hundreds billions of dollars per year were lost due to the unreliable power supply including power outage[1], power quality issues and power disturbance problem [6], [7].

Table 1. Organisation for Economic Co-operation and Development (OECD) and non-OECD net electricity generation by energy source, 2008-2035 (trillion kilowatthours) [4]

Region	2008	2015	2020	2025	2030	2035	Average annual percent change, 2008-2035
OECD							
Liquids	0.4	0.3	0.3	0.3	0.3	0.3	-0.8
Natural gas	2.3	2.5	2.7	2.9	3.4	3.8	1.8
Coal	3.6	3.3	3.4	3.5	3.6	3.8	0.2
Nuclear	2.2	2.4	2.6	2.7	2.8	2.9	1.0
Renewables	1.8	2.3	2.7	2.9	3.1	3.2	2.2
Total OECD	**10.2**	**10.9**	**11.6**	**12.4**	**13.2**	**13.9**	**1.2**
Non-OECD							
Liquids	0.7	0.6	0.6	0.6	0.5	0.5	-1.0
Natural gas	1.8	2.4	3.0	3.5	4.1	4.6	3.4
Coal	4.1	5.2	5.6	6.7	7.9	9.1	3.0
Nuclear	0.4	0.7	1.2	1.5	1.7	2.0	6.0
Renewables	1.9	2.8	3.6	4.0	4.5	5.0	3.7
Total non-OECD	**8.9**	**11.8**	**13.9**	**16.3**	**18.8**	**21.2**	**3.3**
World							
Liquids	1.0	0.9	0.9	0.9	0.8	0.8	-0.9
Natural gas	4.2	4.9	5.6	6.5	7.5	8.4	2.6
Coal	7.7	8.5	8.9	10.2	11.5	12.9	1.9
Nuclear	2.6	3.2	3.7	4.2	4.5	4.9	2.4
Renewables	3.7	5.1	6.3	7.0	7.6	8.2	3.1
Total World	**19.1**	**22.7**	**25.5**	**28.7**	**31.9**	**35.2**	**2.3**

The conventional way of meeting the ever increasing electric energy demand is by constructing a new power generator or power plant, for instance, the newly completed *Bakun Dam* project in Sarawak, Malaysia. Besides, in Malaysia, the government is also considering utilizing the nuclear energy for the future generation of electricity to meet the demand. Even though the new power plant could support the increase in electric energy demand, but the impact of the plant especially to the environment is huge. The ecosystem is disrupted, the forest is destroyed, water and soil is polluted and the CO_2 emission is increased. The impact is not only to the ecosystem, a new power plant will also affect animals and human themselves. Lots of animals and humans especially *orang asli* are losing their habitats and home. Furthermore, the construction of the new power plant will require a several trillions dollars as shown in Table 2 [8]. In addition, the increase of the world oil and gas prices worsens the situation [4].

On the other hand, it is reported that the available electrical generator plant is underutilized most of the time [9]. Figure 1 shows that more than 93.8% of the generator capacity is only used less than 1% of the time while most of the time, the generator is underutilized. It is also reported by [10] that the peak of the energy demand depends on the time and the seasons of the day. Therefore, the installation of a new power

[1] The complete absence of voltage, whether for a fraction of a second or several hours [7]

generator plant which is used only less than one hundred hours per year could be avoided if this peak demand could be shifted to other times when the demand is lower [11].

Table 2. Cumulative investment in energy-supply infrastructure in the Reference Scenario, 2007-2030 ($ billion in year-2007 dollars) [8]

	Coal	Oil	Gas	Power	Total
OECD	**165**	**1 437**	**2 286**	**5 708**	**9 739**
North America	87	1 023	1 675	2 645	5 490
Europe	39	304	417	2 259	3 099
Pacific	39	110	195	804	1 149
Non-OECD	**521**	**4 635**	**3 044**	**7 897**	**16 187**
E. Europe/Eurasia	53	1 079	859	916	2 913
Russia	*36*	*544*	*653*	*440*	*1 674*
Asia	431	916	682	5 327	7 386
China	*323*	*515*	*234*	*3 099*	*4 186*
India	*70*	*179*	*82*	*1 455*	*1 791*
Middle East	1	997	597	509	2 107
Africa	23	868	608	447	1 949
Latin America	13	775	298	697	1 832
Inter-regional transport	42	225	122	n.a.	389
World	**728**	**6 296**	**5 452**	**13 604**	**26 315**

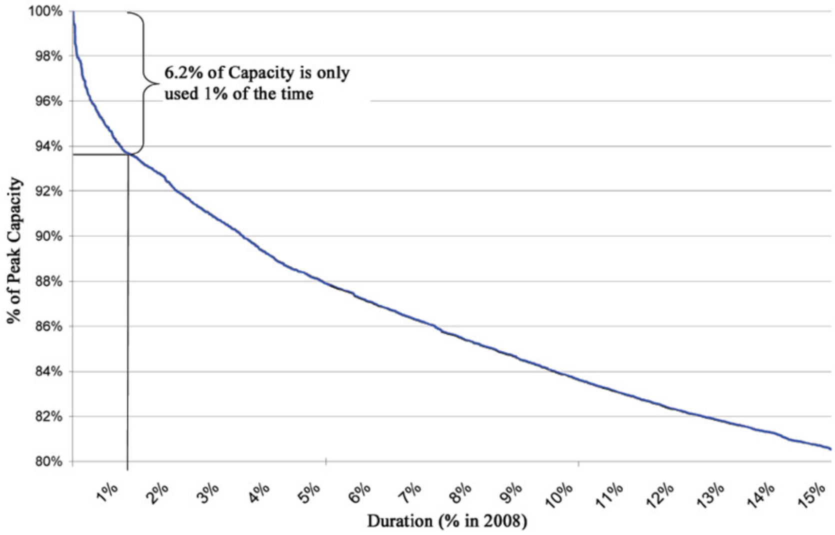

Fig. 1. Top 15% of the French Load Duration Curve, 2008 [9]

In order to shift this peak demand to the off-peak time, the most promising mechanism to use is the Demand Response (DR) [10], [11]. DR provides incentives including the dynamic pricing for utilities, business, industrial, and residential customers to cut the energy that they used when the energy demand is at peak[2] or when there is a problem with the power reliability [11]. DR enables user to choose when and how to use the electricity while on the other hand, it makes users to be more responsible to their electricity utilization. With DR, the balance between demand and supply of the electric energy could be achieved thus, increase the efficiency and utilization of the power grid. Failure to meet the demand would cause a great energy crisis such as what happened in California in 2001 [12], [13] and again in 2011 [14] while exceeding demand power generation is an enormous waste [14].

DR functionalities need a two-way communication system to be available on the power grid. This communication system is supported by a system called advanced metering infrastructure (AMI) [10], [11]. In addition, AMI provides real time [10] or near real time [11], [15] dynamic pricing information and the energy usage. With this information, utilities could know, predict and react to the energy demand and improve the company service quality while consumer could benefit by the dynamic pricing. Furthermore, consumer is able to monitor their energy consumption and knowing what they are paying for.

Both DR and AMI require advanced communication network [10], [11] and they are part of the future grid known as the Smart Grid (SG) [15], [16]. Smart Grid is the next-generation electrical power system that embraces advanced communications technologies and ubiquitous computing capabilities in every aspect of electricity generation, transmission, distribution and consumption. Development of Smart Grid has become a national priority and received considerable attention worldwide. In the US, the National Institute of Standards and Technology (NIST) had identified eight priority areas in SG and three of them are the DR, AMI and Network Communications. It is worth to mention here that DR is the most important SG functionalities sorted by NIST [11] and in order to enable DR and AMI, the Communication Network specifically the communication in Home Area Network (HAN) is absolutely essential. Providing a robust and reliable communication network using short range wireless technologies in HAN is very challenging due to the coexistence of various communicating devices which is available at home. Cognitive radio based communication is seen as the promising solution to this challenge.

2. Benefits of the Smart Grid Demand Response and Advanced Metering Infrastructure

The benefits of Smart Grid DR and AMI are as follows:

(1) **A multi-billion dollar saving solution in meeting the energy demand** [2], [5–7], [9], [12], [14], [16–21]**.** Smart Grid DR and AMI provide balance between demand and supply, hence solving the peak demand problem and offer a more efficient utilization of existing energy plant. Consumers also benefit from this as they could plan their energy usage and could save by purchasing electricity with lower price during off-peak time.

(2) **Environmental friendly**[2], [5], [12], [14], [16], [17], [21–25]**.** Avoid destruction of forest and the requirement of huge area for the bulk generator system construction. The avoidance of new bulk power plant also contributes to the CO_2 reduction.

[2] In dynamic pricing, during peak energy demand, the price of the electricity is more expensive compared to the off-peak time, therefore allows end user to choose whether to consume energy at other times or to continue to buy electricity with the expensive price. This is called the dynamic pricing which is one of the demand and response (DR) functionalities.

(3) **Sustainable solution to the ever increasing energy demand** [2], [4], [5], [8], [12], [14], [17], [21], [25]. The balance of power demand and supply for DR and AMI could sustain the energy demand hence creating a more sustainable and ‘green’ solution which is economically beneficial to all, including industrial investors.

(4) Smart grid is a very important, **market-driven research** topic which urgently needs attention from the government, standardization bodies, researchers and industries [25].

(5) **Increases Quality of Life and provides energy efficiency** [2], [5], [12], [14], [17], [25]**.** Variable pricing from DR and AMI functionalities will change consumer’s behavior on energy usage to be more responsible. The research outcome which is the DR/AMI system enables consumers to manage their home energy usage for better energy efficiency. DR and AMI will educate the consumers and provide them knowledge of energy usage.

(6) **Information for consumers on their power consumption and the billings** [5], [14], [17], [21]**.** Hence, consumer can plan their energy usage/consumption. With DR and AMI, consumers are provided with awareness and are able to keep track of their energy details.

3. Communication in Smart Grid Home Area Network

We envisage the SG architecture as shown in Figure 2. At the heart of the SG architecture is a communications network which consists of heterogeneous technologies including short and long-range wireless technologies. The SG communications network provides two-way connectivity between the power-generation, transmission, distribution and consumption, on one side, and the utility-provider and control center on the other side.

It is clear that advanced communications technologies will play a vital role in the success of the SG. A robust and reliable communication protocol is needed in order to enable the SG AMI and DR, more specifically, the communication in Home Area Network (HAN).

For the HAN communication network (marked in green in Figure 2), the Association of Home Appliances Manufacturers (AHAM[3]) reported in [26] that the most promising wireless technologies for SG Home Area Network (SG-HAN) are WiFi [27] (IEEE 802.11), ZigBee [28] (based on IEEE 802.15.4-2003) and HomePlug Green. It is also reported in [14], [21], [29–32] that one of the most potential technologies to use for SG-HAN is ZigBee/IEEE 802.15.4. In [33], the evaluation of wireless communication technology for SG-HAN in terms of energy efficiency is carried out. Three technologies are said to be competitive to be used in SG-HAN and evaluated in this report are ZigBee, Bluetooth and WiFi. The report concludes that, by utilizing ZigBee instead of WiFi, one can save $315 million per year for the energy cost. Furthermore, in [10], [11], NIST is acknowledging ZigBee technology as one of the candidates for the HAN communication standard.

[3] AHAM represents manufacturers of major, portable and floor care home appliances, and suppliers to the industry. AHAM’s membership includes over 150 companies throughout the world. In the United States, AHAM members employ tens of thousands of people in the United States and produce more than 95% of the household appliances shipped for sale within the United States.

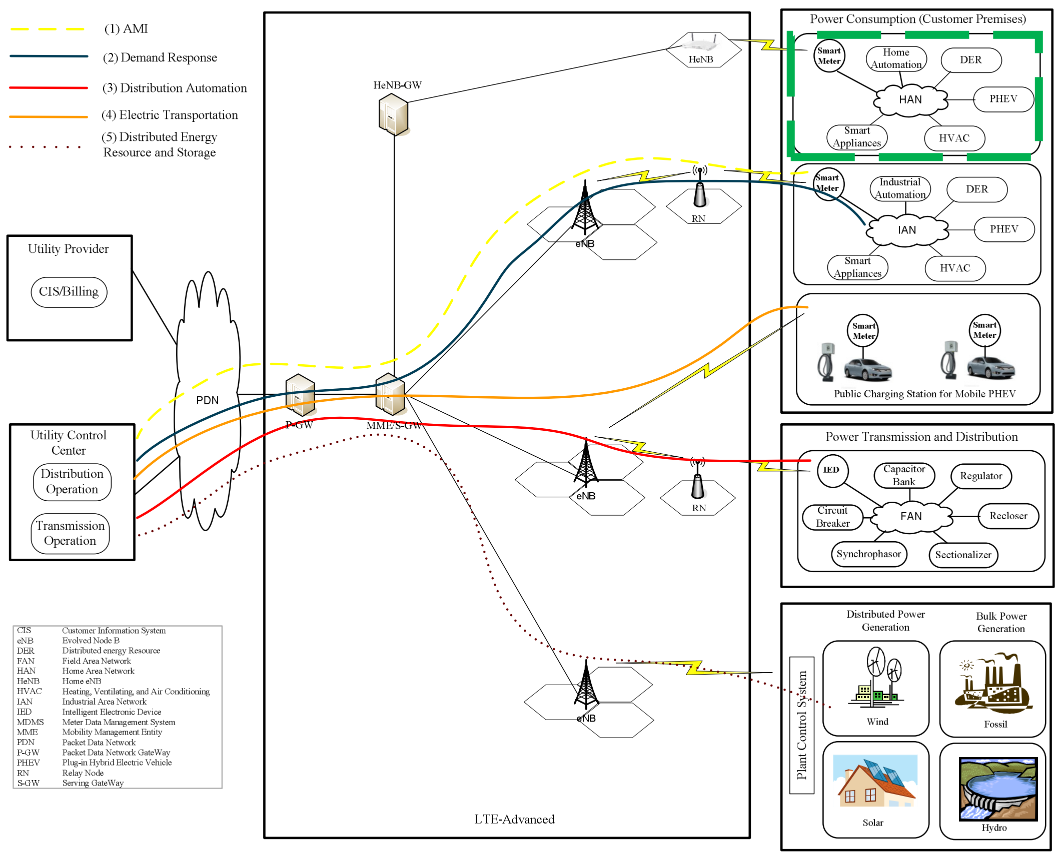

Fig. 2. Smart Grid Communications Architecture

ZigBee is based on the low-power personal area network standard, the IEEE 802.15.4-2003[4] [34]. The global allowable operational band for this standard is the unlicensed 2.4 GHz ISM band. Operating on this band is extremely attractive not only because of the device can operate in the wireless medium without license, but also, the device is compatible to work in any countries in the world. On the other hand, it is very challenging to operate in this band especially for low power radio such as ZigBee/IEEE 802.15.4. The competition in this band is very high. The technologies that operate in this 2.4 GHz band include WiFi (IEEE802.11b/g/n), Bluetooth, microwave oven, pace maker, Cordless Phones, Home Monitoring Cameras, Wireless headsets, mouse and keyboard and Motorola Canopy systems [35].

[4] ZigBee MAC and PHY are based on IEEE802.15.4-2003. ZigBee is compatible only with the original IEEE802.15.4 but not with the addendums of this standard.

3.1. Interference Issues in SG-HAN

Generally speaking, there is no primary user (PU) and secondary user (SU) in the 2.4 GHz band. All wireless technologies can operate without priority. However, the reality is, WiFi and some other wireless devices including the industrial scientific and medical equipment and vehicle tracking equipment are in fact the tertiary users of this band [36]. Furthermore, the coexistence issue becomes more significant when the low-power wireless technology (IEEE 802.15.4 based radio) devices are used for the SG-HAN compared to when they operate in the forest or remote areas. As such, in a home area, besides the SG-HAN network, there is a high possibility that other wireless networks such as WiFi, microwave oven and cordless phones which operate in the same band, time and space also exist.

To date, the IEEE 802.15.4 radio including the ZigBee has no effective and efficient coexistence mechanisms [26]. IEEE 802.15.4 based radio employs the Direct Sequence Spread Spectrum (DSSS[5]) to coexist. However, IEEE 802.15.4 radio suffers from interference issues caused by WiFi due to higher transmission power of this standard compares to IEEE 802.15.4. WiFi transmitter [37] is able to transmit with power up to 100 mW in Europe and 1W in US [38] which is hundred and thousand times higher than IEEE 802.15.4 [39], [40] respectively. This difference is able to overwhelm the interference resistance capabilities of DSSS and simply can create high noise level and even become jammers to IEEE 802.15.4 based radio including ZigBee. Furthermore, a WiFi channel completely covers multiple of IEEE 802.15.4 channels, so spreading the signal over the whole IEEE 802.15.4 channel does not effectively mitigate interference from the signal transmitted by the collocated WiFi radio. Figure 3 depicts the channel distributions for IEEE 802.11b/g/n and IEEE 802.15.4 in the 2.4 GHz band.

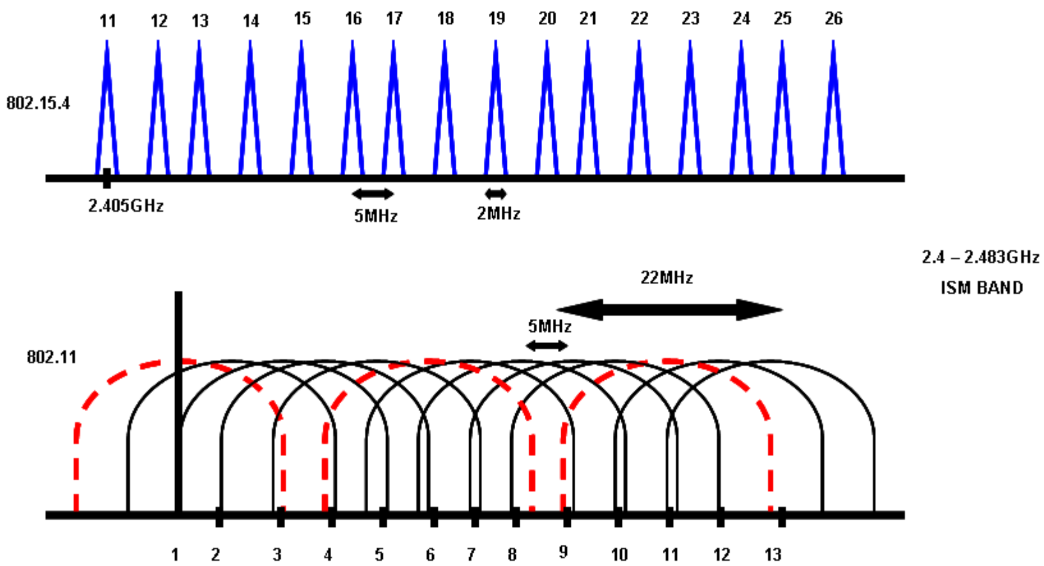

Fig. 3. Overlapping Channels in IEEE 802.15.4 and WiFi [41]

[5] IEEE802.11b is using DSSS, IEEE802.11g is using DSSS and OFDM and IEEE802.11n is using only OFDM.

Besides DSSS, there is also a suggestion of utilizing the non-overlapping WiFi-IEEE 802.15.4 channels to avoid the interference from WiFi which are channels 15 and 20 [42]. These channels are in between the often-used WiFi channels 1, 6 and 11. However, this is only true if the WiFi network is well planned. In the case of HAN, as what usually occurs, the end-user randomly selects the channel for Wi-Fi which falls on the supposedly non-overlap region with IEEE 802.15.4. Basically, the channel is randomly selected and this made the assumption of non-overlapped WiFi-IEEE 802.15.4 channels not true.

In the case of CSMA, acknowledged transmission and retry are proposed to mitigate the interference effect. However, the high numbers of back-off and retransmission will consume more energy and cause delays. It is better to sense for idle channel rather than trying to mitigate the interference using CSMA, acknowledgement and retransmission method. Hence, Cognitive Radio (CR) based method is seen as the enabling technology to monitor the channel condition for optimum and efficient communication.

In ZigBee, a method called frequency agility is proposed to address this interference issue [42], [43]. However, ZigBee protocol is only able to use three channels which are channel 15, 20 and 25 for its frequency agility. This channel is the non-overlapping WiFi- IEEE 802.15.4 channels. Therefore, the same issue as addressed above will arise. Furthermore, the details of this method is not published clearly anywhere even in the alliance white papers [44]. Again, the spectrum awareness and dynamic spectrum access feature of CR is seen to be promising solution in addressing this problem.

3.2. Reviews on Current Proposed Solutions for the Interference Issues

The impact of coexistence to IEEE 802.15.4 based radio in the ISM 2.4-GHz band is being evaluated analytically and experimentally through mathematical model, simulation, and measurement. In [45], an experimental measurement is done using TelosB[6] [46] mote to measure the impact of the nearby WiFi access point to the packet delivery ratio (PDR) of the mote. A clear WiFi effect on TelosB mote can be seen from the result published as the PDR of the mode is significantly decreased especially at the centre frequency of the WiFi access point. In [47], the effect of WiFi to the body area network (BAN) which is using Tmote Sky[7] as the testbed is experimentally evaluated. The result shows that the impact is more significant when the sensor node is transmitting at a lower power level. The paper concludes that, the problem could be reduced by using a maximum transmitting power from the sensor node. However, this solution is not efficient especially in BAN scenario as higher power transmission is going to raise a great concern from the health perspective. This is also not efficient to be used in the Smart Grid HAN as the node power will drain out quicker and also, transmitting at maximum power actually is not going to eliminate or mitigate the interference effect effectively.

Besides research in academic, industries and standardization bodies are also looking at this interference problem seriously. A number of the IEEE 802.15.4 radio chip manufacturers are laying down guidelines for their products to operate in order to address this issue. For instance, Jennic Limited [48] published an application note on the coexistence of IEEE 802.15.4 in the ISM 2.4GHz band. They conclude that the effect of WiFi signal to the IEEE802.15.4 cannot be ignored and they recommended two solutions: 1) the channel used by sensor node has to be carefully selected and 2) sensor nodes need to be placed at a sufficient separation distance from the WiFi access point. However, these proposed

[6] TelosB is one of the Crossbow WSN mote products which utilizing the CC2420 Chipcon IEEE802.15.4 chip from Taxes Instrument as its radio.

[7] Tmote Sky is utilizing the CC2420 Chipcon IEEE802.15.4 chip from Taxes Instrument as its radio.

solutions are not practical, effective and efficient in many cases. For the first solution, in SG-HAN scenario, the end-user does not have technical knowledge on selecting a proper channel for their HAN network to operate. Even if they have a technical background to change the channel used, it is difficult to determine and select the best channel to use as this requires measurement tools to measure the specific HAN wireless condition in time, space and frequency. Furthermore, the channel condition might vary with the time due to the changing of surrounding environment condition including a new access point deployment by neighbors. In addition, the channel chosen should not be overlapped with the neighboring HAN network as this will also potentially cause a collision, delay and energy overhead. The desired solution is that the node can autonomously select the best channel in the band for its operation. This can be achieved by utilizing cognitive radio technique. Jennic's second proposed guideline is also not a promising solution. In the SG-HAN scenario, some of the smart home appliances might be placed next to each other or near the home access point accidentally. It is inconvenient to follow the rule of ensuring the distance between the home smart appliances and WiFi access point thus, this is not a practical solution. Besides WiFi, [48] also addressed the effect of Bluetooth on IEEE 802.15.4 based radio performance and they recommend that, a separation distance of 2 m is needed for the radio to achieve satisfactory performance. Besides Jennic, other ZigBee Alliance members [37], [49] also published documents acknowledging this issue.

Furthermore, the IEEE 802.15.4 TG4e [50] is also taking the interference problem as one of their considerations in producing addendum from the IEEE802.15.4-2006 for the standard to be used in the industries. One of the TG4e final documents [51] concludes that the packet lost rate over time highly depends on the channel condition. The channel which interferes with the WiFi operation is clearly seen to be affected as compared to the interference-free channel. Adaptive frequency diversity (AFD) [52] is proposed by this task group in order to cope with this interference problem and this technology is then adapted to be used in the wireless HART [53].

4. Cognitive Radio based communication for Smart Grid Home Area Network

In the recent years, a new and novel method has been proposed in addressing this problem which is by using the cognitive radio based technique. Cognitive radio [54] is defined as an intelligent wireless communication system that is aware and learns from its surrounding environment and adapts its internal state and operation by making corresponding changes in certain operating parameters including the frequency used, transmission power, modulation and coding in order to achieve highly reliable communication whenever and wherever needed [55].

The vital objective of the cognitive radio is to achieve the best communication properties through cognitive capability and reconfigurability [56]. In other words, cognitive radio also embodies awareness, intelligence, learning, adaptivity, reliability and efficiency. Cognitive cycle consists of three major steps as follows [57][58]:

- Sensing of RF stimuli which involves the detection of spectrum holes to facilitate the estimation of channel state information and prediction of channel capacity for use by the transmitter.
- Cognition/spectrum management which controls opportunistic spectrum access and capturing the best available spectrum to meet user communication requirements. Cognitive radios should decide on the best communication parameters to meet the Quality of Service (QoS) requirements
- Actions to be taken can be in terms of re-configurable communication parameters such as transmission power, transmission rate, routing, modulation and coding.

Those three tasks form a cognitive cycle as shown in Figure 4.

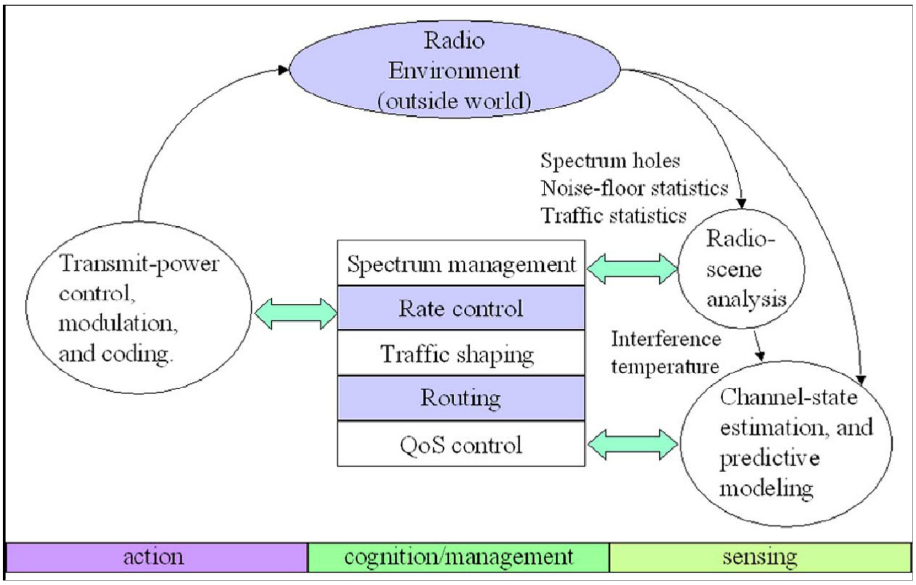

Fig. 4. Basic cognitive cycle [58]

Applying cognitive radio approach to the wireless communication network in SG-HAN will give several advantages including solving the interference problem. Cognitive radio based network provides self-awareness, self-organizing, self-configuring and self-healing [59]. In addition, cognition provides intelligence, learning capabilities, adaptability, reliability and efficiency to the network. Cognitive radio based SG-HAN wireless network will be capable of making proactive decisions based on these abilities and may help to achieve end-to-end goals of the network, even in the presence of multiple constraints and optimization objectives [59].

5. Conclusion

Smart Grid (SG) technology is becoming a very important research field in realizing efficient energy management system. Obviously, this market-driven technology needs urgent attention from the government, standardization bodies, academia and industries to meet the rising energy demand. DR and AMI are the priority functionalities of the SG that provide many advantages including a sustainable electric energy supply, better energy management both for consumers and utilities. They provide a solution that can save billions of dollars in energy bills. Both DR and AMI require a robust and reliable communication support for reliable collection, delivery and control of power consumption information. In this paper, we have shown that the low-power ZigBee/802.15.4 based protocol is one of the most promising technologies for HAN communication network. However, operating in the overcrowded 2.4-GHz license-free ISM frequency band, occupied by other radio systems such as Bluetooth and WiFi, poses challenges in terms of coexistence and interference issues for this low-power technology. We have also highlighted that the current interference mitigation and avoidance methods cannot fully solving the problem. Hence, cognitive Radio based technique is seen as the promising solution to this issue. CR provides context awareness and intelligence to the radio to reconfigure itself thus, enabling optimal communication service for Smart Grid HAN (SG-HAN).

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