# Chapter 1

# Introduction

## 1.1 Introduction to the research problem and its significance

In general, the traditional power grids are used to carry power from a few central generators to a large number of users or customers. In contrast, Smart grid (SG) uses two-way flows of electricity and information to create an automated and distributed advanced energy delivery network. SG is the next-generation of electric power system since 2005. Therefore, SG becomes one of the fast growing research topics [1-11] because this system is a promising solution for energy crisis. In [1], J. Ekanayake, et al. present the six major advantages of SG such as SG can manage demand response and demand side through the integration of SG devices and SG can provide information related to energy use and price to customers. One of the important features of SG is the integration of secure, high-speed and reliable data communication networks to manage the complex power systems intelligently and effectively. Thus, SG has harsh and complex environmental conditions, connectivity problems, dynamic topology changes, and interference and fading issues during wireless communication. It is difficult to design the information and communication technologies (ICTs) system for the overall power grid. Thus, the choice of communication infrastructure for SG is highly critical to provide reliable, secure, and efficient data delivery between SG components.

The communication infrastructure between energy generation, transmission, and distribution and consumption needs two-way communications, interoperability between advanced applications and end-to-end secure and reliable communications with sufficient bandwidth and low-latencies [2-11]. The important communication and networking technologies which may be applicable in future SG. Six important communication types [2] include wireless mesh network, such as WiMAX, cellular communication system, such as GSM, WCDMA, and CDMA-2000, wireless communications based on 802.15.4, such as ZigBee, WirelessHART, and ISA100.11a, microwave or free-space optical communications, fiber-optic communications and power line communication (PLC). The first four communication technologies are the wireless communication and the last two technologies are the wired communication. The compare the performance between wireless technologies and wired technologies for SG are considered in [3]. They can conclude that the wireless communication technologies have significant benefits more than wired technologies because the wireless communication has low installation cost, rapid deployment, mobility, and more suitable for remote end applications. In [4-5], they study the performance of the current communication technologies that are applied to SG. They found that the current communication capabilities of the existing power systems are limited to small-scale local regions and these methods implement basic functionalities for system monitoring and control which do not yet meet the demanding communication requirements for the automated and intelligent management in the next-generation electric power systems. Therefore, a key point in the success of SG technology is how to meet the complicated requirement in the communication. It demands high communication quality and energy efficiency while taking care of the system expenses and bandwidth. The bandwidth is needed to manage, store and integrate the large amounts of data that smart devices will produce. For solving these problems, Cognitive radio (CR) networks can be benefited to address the unique challenges of SG, such as multipath fading, reliability and delay requirements, different spectrum characteristics changing over location and time, noise, and harsh environmental conditions.

Many works in literature proposed shown that CR network appropriates to SG communication [12-28]. These works also present the research challenges of CR network for SG communication that can be summarized as shown below:

- Quality of Service (QoS)

CR network for SG applications have different QoS requirements including reliability, latency, and data rate. Additionally, SG is a heterogeneous network and it contains electric equipment which has dramatically different limitations, such as storage capability and computing power. Hence, it is still an open research issue to design QoS-aware communication protocols capable way.

- Interoperability

SG needs advanced communication protocols among each of its component to exchange information independent from manufacture or any type of physical device. Thus, different communication technologies and several standards will be used to proper the specific QoS requirements of SG components and applications. These communication technologies may demand operating on different spectrum bands.

- Interference

Interference avoidance scheme should be applied to the CR networks under SG environments. The spectrum management cycle can exclude this problem by providing spectrum sharing functionality.

- Dynamic Spectrum Usage

After the selection of the best available channel for the required SG application, the next step is to make the network protocols adaptive to the chosen spectrum.

Cognitive radio (CR) Network is proposed for overcome the "Spectrum crisis" problem by offering several advantages to utilize spectrum opportunistically with dynamic spectrum management techniques [29-35]. CR network has two important actors: 1) primary user (PU) and 2) secondary user (SU). PU is the owner of a licensed channel that has the priority to user the spectrum. SU is the occasional user that is responsible for sensing the licensed spectrum, identifying the unused channels in the absence of PU and a SU is called a CR user. In [29-30], an introduction of the CR technology and its network architecture are provided. They define the main functions for CR into four topics including spectrum sensing, spectrum management, spectrum mobility, and spectrum sharing. The spectrum sensing detects unused spectrum and sharing the spectrum without harmful interference with other users. The spectrum management captures the best available spectrum to meet user communication requirements. The spectrum mobility maintains seamless communication requirements during the transition to better spectrum. The spectrum sharing provides the fair spectrum scheduling method among coexisting other uses.

Spectrum sensing is an important to play a role in CR network to efficiently and accurately detect primary user for avoiding interference to primary user [36-42]. The requirement for real-time processing indeed poses challenges on implementing spectrum sensing algorithms. Trade-off between the complexity and the effectiveness of spectrum sensing algorithms should be taken into consideration. Therefore, in this research, we will propose the new spectrum sensing schemes that has the minimum time requirement and gives the good performance.

**1.2 Literature review**

In this research, we propose the new spectrum sensing techniques in CR network for SG communication. The proposed techniques can classify into two types of channel environment. First, we present two spectrum sensing methods under AWGN channel. Second, we propose two spectrum sensing techniques under noise uncertainty and path loss effect. Therefore, in this section, we will review the relevant research papers, published in the conferences and journals, which cover spectrum sensing techniques of both environments.

In this part, we will review the literatures about CR network for SG communication [12-28]. In [12], they provide an overview at the current communication technologies for SG, and discuss the still-open research issues in this field. Furthermore, they review the CR network based SG communication for solving the resources scarcity crisis problem. In [13], they present a comprehensive review about SG characteristics and CR-based SG applications. They also discuss architectures to support CR networks in SG applications, major challenges, and open issues. Four major challenges that are considered include Quality of Service (QoS), Interoperability, Interference, and Dynamic spectrum usage. In [14], they compare SG with communication systems in general and with CR. Their simulation results confirm that CR technique is a solution for the problem of spectrum scarcity. In [15], they propose the application of CR based on the IEEE 802.22 standard in SG wide area networks (WANs). The proposed method can work as a secondary radio particularly: urban and rural. In urban area, the proposed scheme is a backup in disaster management. On the other hand, a stand-alone radio based on IEEE 802.22 can effectively provide broadband access for rural area. In [16-17], they present an unprecedented CR based communications architecture for SG, which is mainly motivated by the explosive data volume, diverse data traffic, and need for QoS support. The proposed architecture is decomposed into three subareas: cognitive home area networks (CogHANs), cognitive neighborhood area networks (CogNANs), and cognitive wide area networks (CogWANs), depending on the service ranges and potential applications. Finally, they focus on dynamic spectrum access and sharing in each subarea.

When we combine CR network and SG system together, the most of researches propose techniques for solving spectrum management functionality in CR network for improving the performance of CR network for SG communication. The spectrum management functionality can be classified into four processes: spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. In [18-20], they propose dimensionality reduction techniques such as principal component analysis (PCA), kernel PCA, and landmark maximum variance unfolding (LMVU) for spectrum sensing context on Wi-Fi signal measurements. Moreover, they provide the compressed sensing algorithms such as Bayesian compressed sensing and the compressed sensing Kalman filter for recovering the sparse smart meter transmissions. In [21], they propose parallel processing techniques based on graphics processing unit (GPU) for accelerate processing of spectrum sensing and dynamic access. In [22], they focus on the spectrum resource management in CogNANs for efficient SG services. They propose a new spectrum access paradigm called hybrid spectrum access, in which both licensed and unlicensed spectrum bands are intelligently scheduled for the transmission of SG services. Numeric results indicate that the proposed technique strategy significantly improves the network capacity in supporting the SG services, compared to the traditional fixed spectrum access strategy. In [23], they propose spectrum-aware and cognitive sensor networks to overcome spatio-temporally varying spectrum characteristics and harsh environmental conditions for wireless sensor networks (WSN)-based SG applications. Specially, potential advantages, application areas, and protocol design principles of spectrum-aware and cognitive sensor networks (SCSN) are introduced. A case study is also presented to reveal the reliable transport performance in SCSNs for different smart grid environments. The goal of A. O. Bicen, et al. is to envision potentials of SCSNs for reliable and low-cost remote monitoring solutions for smart grid.

On the other hand, the time requirement problem is the one of fundamental problems for data communication [24-28]. In [24], they consider the current communication technologies for SG. Their knowledge can conclude that the current communication techniques are not support for the real time communication of SG. Moreover, In [25], they confirm that SG requires the critical real-time systems. For CR network for SG communication, several works have studied the optimization of sensing time to tradeoff between interference avoidance and sensing efficiency [26-27], since spectrum sensing and data transmission cannot be performed at the same time. In [28], they introduce spectrum sensing and channel switching techniques of CR into SG communication. They find optimal sensing time to reduce packet loss rate and delay, under the constraint that the PU is sufficiently protected. They formulate the sensing-delay tradeoff problem and prove that it has unique optimal sensing time which yields the minimum delay. However, this paper did not compare the proposed technique with the conventional techniques. Additionally, they also consider in only CogHANs network architecture. Therefore, CR network for SG communication needs a novel spectrum sensing technique that has a minimum time requirement and gives a good performance when compare with other techniques.

In this research, we will propose a new spectrum sensing that has a minimum time requirement and gives the good performance. Hence, in this part, we will review the literatures about the spectrum sensing in CR network.

Three parameters are defined to evaluate the efficiency of spectrum sensing — accuracy of detection, computational complexity, and sensing time. The accuracy of detection is defined by the rate of correct detection of PUs when such users are actually present and occupying the spectrums concerned. This is a prime concern of spectrum sensing because a PU must not be affected by an SU. On the other hand, detecting the presence of a PU when in fact the PU is absent, otherwise known as false detection, has to be minimized to fully utilize spectrum bands. The accuracy of detection is usually shown in terms of a statistic; that is, in terms of a probability, which is often referred to as the probability of detection ($P_d$). Likewise, false detection is sometimes referred to as the probability of false alarm ($P_{fa}$). In terms of the probability of detection, the higher the probability, the less likely it is that a PU will experience interference.

The second quality of service (QoS) parameter, computational complexity, is described by the computational burden. The complexity of a spectrum sensing technique affects both the amount of energy consumed by the technique during sensing and the latency of the technique. The higher the complexity, the higher the amount of energy consumed and the higher the latency, neither of which is desired. It generally comes at a cost when the spectrum sensing technique needs to improve its accuracy of detection.

The third QoS is sensing time, which is highly related to computational complexity. It should be noted that the computational complexity of a spectrum sensing technique can also be described by sensing time, since this is increased when the computational burden is increased. From the perspective of sensing time, the more channels an SU monitors, the more opportunities they will have of accessing a licensed band. In addition, an increase in sensing time will result in a decrease in an SU’s throughput. It is stated in the IEEE 802.22 standard [43] that an SU needs to perform spectrum sensing within 2 s of a set sensing period with a false alarm probability of less than 0.1 and a detection probability higher than 0.9.

Generally, spectrum sensing techniques [44-58] can be classified into the following two groups: blind techniques and techniques based on prior knowledge of a signal. Blind techniques — energy detection (ED) [43-49], maximum eigenvalue detection (MED) [50], covariance absolute value (CAV) [50-52], and maximum to minimum eigenvalue (MME) detection [53-56] — determine the presence of PUs by measuring the energy or correlation of a received signal. Knowledge-based spectrum sensing techniques — matched filter detection (MFD) [43-47], cyclostationary detection (CFD) and leading eigenvector detection (LED) [58] — require information on the patterns of signals from PUs to analyze observed signals. In general, knowledge-based techniques perform with higher accuracy than blind techniques. However, their computational burden and sensitivity to prior information are also higher than blind techniques such as MFD has to know an exactly waveform pattern of primary user signal while CFD needs to know cyclic frequency of primary signal. Furthermore, the performance of knowledge-based techniques are dependent upon on databases of patterns of PU signals; the pattern of a wireless microphone (WM) signal changes from one pattern to another in reality, even though it operates at the same frequency. The IEEE 802.22 standard categorized WM signals into three patterns — silent, soft speaker, and loud speaker [59]. If a new pattern belonging to a WM signal, one not yet in the database, is observed, then the accuracy of the knowledge-based techniques performances will drop. To keep track of all the possible patterns, large-sized databases are required, which in turn, would require the use of large memory spaces. It is factors such as these that will eventually result in a high computational time.

ED [60-63] is the most widely utilized because it consumes the shortest sensing time with the least complexity. However, the accuracy of detection of ED is unreliable under bad condition of communication channel or at low signal to noise ratio (SNR) condition. In [64-65], the performance of ED is improved by using an adaptive threshold. In general, the threshold of ED is set by fixing target performance metrics. There are 2 ways to set a threshold for ED. The first way is done by fixing target probability of false alarm which is called “constant false alarm rate (CFAR)”. The other way is done by fixing target probability of detection which is called “constant detection rate (CDR)”. An adaptive threshold energy detection (ATED) changes its decision threshold depending on the condition of communication channel. The system threshold switches between the threshold of CFAR and CDR. Although the detection performance of ED is improved, the false alarm detection rate does not achieve the target performance stated by IEEE 802.22 standard which the spectrum sensing technique has to perform spectrum sensing with probability of false detection less than 0.1.

In this paper, we propose double constraints adaptive energy detection (DCAED), a novel adaptive scheme that adapts the threshold controlled by 2 target detection performance including probability detection and probability of false alarm. Since there is no directly way to set the threshold by fixing 2 target performance metrics. There is a parameter that can be set by fixing 2 target performance metrics. This parameter known as “critical sample ($\mathrm{N_c}$)”. DCAED exploits a relation between critical sample and two target performance metrics to set an adaptive factor. The adaptive factor is used to change the threshold of DCAED. The simulation results prove that DCAED gives good detection performance in both performance metrics even at low SNRs. In addition, an average sensing time of DCAED also achieves the requirement of IEEE 802.22 standard which is lower than 2 seconds.

On the other hand, we known that the knowledge-based techniques perform with higher accuracy than blind techniques. Therefore, we propose fast spectrum sensing with coordinate system (FSC) that is a knowledge-based technique, whereby the information of a PU is a prerequisite. The main difference from MFD, CFD and LED is that only significant features of original signals are used to construct a coordinate system. While these features reveal the intrinsic patterns of a PU, their dimension is much smaller than the original signal. To construct the new coordinate system, a feature-extraction process and feature-selection processes of a principal component analysis (PCA) [66-67] algorithm are adopted. To determine the existence of a PU, the FSC algorithm measures the percentage (weight) of correspondence between the received signal and a coordinate system. The magnitude of this weight will rise when a PU exists. Alternatively, it will fall when a PU does not exist. The FSC algorithm consumes little memory, requires little computational burden, and has a short sensing time.

The two proposed techniques that are previously descripted are considered in only additive white Gaussian noise (AWGN) channel. However, there are many factors that degrade the performance of the spectrum sensing technique [56] such as low signal-to-noise ratio (SNR) condition, environment of noise uncertainty, fading and shadowing. Therefore, in this paper, we focus on two main factors, including low SNR condition and environment of noise uncertainty. Low SNR condition refers to the condition that power of noise is much more than power of real signal. This condition effects to the decision making of the existence of primary user and may cause harmful interference to primary user. On the contrary, an environment as noise uncertainty always presents in practical. The uncertainty of noise power is caused by transmission of other users. When the uncertainty of noise occurs, there will be a difference in an estimated noise power and real noise power that cause the performance of spectrum sensing technique significantly degrades.

The third proposed technique that considers the noise uncertainty is two-stage spectrum sensing. Since no single-stage spectrum sensing technique is perfect enough to be implemented in CR device, two-stage spectrum sensing technique is proposed. The two-stage spectrum sensing technique improves the performance of conventional spectrum sensing techniques by exploiting individual advantages of conventional spectrum sensing techniques. The framework of the two-stage spectrum sensing technique can be separated into 2 stages including coarse sensing stage (or first stage) and fine sensing stage (or second stage). For a given channel, the existence of primary user is firstly determined by the coarse sensing stage, if the decision value of the first stage is greater than the threshold of the first stage then the spectrum band is declared to be existed. If the decision value of the first stage is lower than the threshold of the first stage, the second stage is activated.

There are two existing two-stage spectrum sensing techniques including energy detection (ED) to cyclostationary detector (CS) two-stage spectrum sensing technique [68-69] and energy detection (ED) to maximum eigenvalue detection (MED) two-stage spectrum sensing technique [70-72]. Mostly, ED [50] is utilized as a first stage of two-stage spectrum sensing technique because it uses less sensing time than the other techniques. For the second stage, there are two types of conventional spectrum sensing techniques that were proposed for this stage such as CS and MED [51, 73]. CS technique offers a reliable performance of detection at low SNRs. However, the CS technique is cannot be used when the cyclic frequency of primary signal is unknown. On the other hand, under the combination of ED and

MED algorithms, the two-stage spectrum sensing technique offers reliable detection at low SNRs and uses short sensing time at high SNRs. The second stage of ED to MED two-stage spectrum sensing technique offers a reliable detection when the noise power is exactly known. However, an environment as noise power uncertainty always presents in practical which makes the detection performance of MED technique significantly degrades.

In this paper, we propose two novel schemes of two-stage spectrum sensing technique for CR, i.e., ED to CAV (covariance absolute value detection) two stage spectrum sensing technique and ED to MME (maximum-minimum eigenvalue detection) two stage spectrum sensing technique. ED is used as the first stage of the proposed algorithms because it performs spectrum sensing within short sensing time and gives reliable detection at high SNR environment. In the second stage, we exploit two difference type of blind detection techniques, including CAV [52-54, 74] and MME [55]. The merit of blind detection technique is that it is robust to the uncertainty of noise power. Under the combination of ED and blind detection techniques, our algorithms offer better detection performance than the existing two-stage spectrum sensing techniques. The simulation results proved that ED to CAV two stage spectrum sensing technique gives the best performance among the others. The performance of spectrum sensing techniques are evaluated through three standard patterns of wireless microphone signal, including, including silent, soft speaker and loud speaker, based on IEEE802.22 document [59]. In our simulation, the patterns of received signal changes randomly.

Finally, we propose modified FSC that re-derives some parameters of FSC algorithm in order to perform spectrum sensing under path loss effect and noise uncertainty since a conventional FSC did not take these factors into the account therefore it is not appropriate to perform spectrum sensing under path loss effect and noise uncertainty. This is due to the fact that the FSC threshold is very sensitive to the strength of signal's power since it performs spectrum sensing under a framework of pattern recognition. Therefore, the FSC threshold is needed to re-derived and vary on the changing in the strength of path loss. In simulation results, we evaluate the performance of MFD, LED and MFSC under path loss effect and take a noise uncertainty into the account in order to make the environment of the communication channel nearly to the practical communication system. From the evaluation, we found that MFD still gives the highest $P_{\mathrm{d}}$ when noise uncertainty does not exist. On the other hand, the effect of noise uncertainty does not cause any degradation to the detection performance of LED, while the detection performance of MFD degrades significantly. MFSC algorithm is the most achievable of spectrum sensing requirement when it gives high detection performance while consumes the least average sensing time under noise uncertainty with path loss effect.

### 1.3 Objectives

This project proposes the novel spectrum sensing techniques in CR network for SG communication. The proposed techniques have a minimum time requirement and give a better performance than the conventional spectrum sensing methods. Moreover, we consider two channel environments including AWGN channel and the channel that consider the noise uncertainty and path loss effect.

### 1.4 Methodology

1. Literature review of the spectrum sensing algorithms of cognitive radio (CR) networks: Study research papers relevant to the research works of the research.

    1.1 Study research papers relevant to spectrum sensing algorithms.

    1.2 Study research papers concerning with improving the spectrum sensing algorithms.

    1.3 Study research papers regarding the time requirement of the spectrum sensing algorithms.

2. Simulation software implementation of the spectrum sensing algorithms

    2.1 Consider and compare the time requirement of each of spectrum sensing techniques from literature reviews.

    2.2 Provide time delay mathematical model of the spectrum sensing algorithm for CR network.

    2.2 Develop the time reduction of the spectrum sensing algorithm for CR network.

3. Simulation software implementation of the proposed technique

    3.1 Develop the proposed technique for the spectrum sensing algorithm simulation program.

    3.2 Test the time requirement of the proposed spectrum sensing algorithm for CR network.

4. Project summary

    4.1 Summarize the major finding as we found in step 3 and conclude the performance of the proposed time reduction in all concerned aspects.

4.2 Check whether the conclusions meet all the objectives of the research work of the research.

4.3 Write the research report.

## 1.5 Scope of research

The research problem is the time reduction of CR network for SG communication. The scope of these researches is as follows:

- Study the performance and the limitation of spectrum sensing in the CR network.
- Study the factors that degrade the performance of the spectrum sensing technique.
- Simulate and compare the time requirement communication of the conventional spectrum sensing techniques in the CR network.
- Propose the new spectrum sensing techniques that has lower time requirement and good performance in the CR network.
- Simulate and compare the time requirement communication of the proposed technique in the CR network.

## 1.6 Schedule for the entire project and expected outputs

### 1st year of the project

Months 1-3 Literature review of Spectrum sensing algorithm of Cognitive radio networks.

Months 4-6 Improved observation model for spectrum sensing algorithm.

Months 7-10 Simulation software implementation of improved observation model.

Months 11-12 Literature review of communication protocol for smart grid.

### 2nd year of the project

Months 13-15 Improved observation model for spectrum sensing algorithm that can be used under noise uncertainty and path loss effect.

Months 16-18 Simulation software implementation of improved observation model.

Months 19-21 Evaluation of developed model and algorithm and write the journal.

Months 22-24 Project summary.