# Design and Performance Evaluation of Cognitive Radio for Real-Time Communication in Smart Grid

**Vasudev Dehalwar**

**Submitted in fulfilment of the requirements for the degree of Doctor of Philosophy**

VICTORIA UNIVERSITY
MELBOURNE AUSTRALIA

College of Engineering and Science
Victoria University

PO Box 14428
Melbourne
Victoria, Australia, 8001
2017

असतो मा साद गमय,

तमसो मा ज्योतिर् गमय,

मृत्योर मा अमृतम् गमय

**Lead us from ignorance to truth,**

**Lead us from darkness to light,**

**Lead us from death to deathlessness.**

# Table of Contents

# ABSTRACT

The electric power grid has been developed over the last century which lacks bi-directional flow of data. The advancement in Information and Communication Technology (ICT) has motivated to convert the existing grid into the Smart Grid. The Sensors, Intelligent Electronic Devices (IEDs), Phasor Measurement Unit (PMU), etc. are the backbone of Smart Grid network. The billions of installed components in Smart Grid will generate high volumes of operation and control data. Transferring this high-volume data in the Smart Grid network is a big challenge! The present communication technology has limitations in delivering the Big Data of Smart Grid to control center in real-time.

This research explores the possibility of using IEEE802.22 international standard for communication of Big Data. IEEE802.22 uses Cognitive Radio for communication that allows opportunistic use of unused TV white space by Secondary User if that spectrum is not being used by Primary User. This study reflects on following the points:

(i) The prospects of Integrating IEC61850 with IEEE802.22;

(ii) Probability of sensing Primary User's spectrum efficiently in real-time for optimum use of spectrum in Cognitive Radio; and

(iii) Verifying the feasibility of Cognitive Radio to meet the timing constraints (latency) of data transmission for power protection.

IEC61850 can be integrated with IEEE802.22 to provide seamless communication. Manufacturing Message Specification (MMS) protocol of IEC61850 can be used for teleprotection at the substation. The MMS is a protocol that supports transfer of real-time process data and supervisory control information between networked devices and control center. IEEE802.22 can effectively support flexible, reliable, secure communication over diverse topography.

The spectrum sensing is essential for interference free data communication. The spectrum sensing techniques explored for detecting Primary User are energy detection and cyclostationary feature detection. It has been found that cyclostationary spectrum sensing has the property to separate random noise from cyclostationary signals, so it is more capable of sensing primary user signals from the mixer of received signals.

This research also explored the suitability of using Cognitive Radio for real-time communication. Various network simulators are examined to build Cognitive Radio scenarios based on topologies. The study considered Cognitive Radio Cognitive Network (CRCN) based on Network Simulator 2 (NS-2) and Cognitive Radio Extension (CRE-NS3) based on NS-3 and they are a good choice for simulating Cognitive Radio environment. The performance parameters studied are throughput, latency, packet delivery ratio, etc. for different protocols and topologies. The study found that Cognitive Radio communication meets the latency requirements of Smart Grid to a larger extent.

***Index Terms**: Smart Grid, Cognitive Radio, Machine to Machine communication (M2M), Spectrum Sensing, Advance Metering Infrastructure (AMI), Teleprotection, IEEE802.22, Wireless Regional Area Network (WRAN), Big Data, Field Area Network (FAN), IEC61850, Load Forecasting, NS-2, NS-3.*

# Declaration of Authenticity

I, Vasudev Dehalwar, declare that the PhD thesis entitled *“Design and Performance Evaluation of Cognitive Radio for Real-Time Communication in Smart Grid”* is no more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

Signature　　　　　　　　　　Date: 9/06/2017

[redacted]

(Vasudev Dehalwar)

# Acknowledgements

I would like to express my sincere gratitude to my supervisors Professor Akhtar Kalam and Adjunct Professor Aladin Zayegh for their constant motivation, support and words of wisdom. They are my primary source of inspiration and guidance throughout my entire research at Victoria University. Their valuable comments and suggestions pave the way to the successful completion of my PhD program.

I would also like to acknowledge the help rendered by my friend and mentor Professor Mohan Lal Kolhe from the University of Agder, Kristiansand, Norway for the help and suggestions starting from the process of University selection, application for the scholarship and selection of the research topic. I also thank him for his constant support in my lean and mean time of my career.

I would also like to express my sincere thanks to team and management of Australia India Institute, Melbourne University for selecting me for the prestigious "Victoria India Doctoral Scholarship-2013". The staff of Australia India Institute has been very cooperative in providing me and my research group unflinching support throughout my stay here in Melbourne.

I would also like to acknowledge the help and support extended by the management and staff of Victoria University by waiving my tuition fee as a policy of "Victoria India Doctoral Scholarship -2013". I feel blessed by joining the company of erudite and learned faculty, staff and students of this vibrant University with the best infrastructure in a top-class research environment.

I would also like to thank my alma mater and my parent organisation Maulana Azad National Institute of Technology, India for sponsoring me and giving me an opportunity to do research in cutting-edge technology in world class environment.

No task is successful without the support of the family. I would like to sincerely appreciate the efforts of my wife Geeta Chhawaniya and children Dakshita and Bhaavani to understand the seriousness and magnitude of the PhD program. Thanks also for giving me unconditional love and affection in this entire duration and keeping the aura of liveliness, warmth and kinship at home.

I am also grateful to my parents for their upbringing and helping me to rise in my career. Their humility is one of the greatest strength for me. I would also like to thank my brothers, sisters and the whole family for standing by my side in this great endeavour. I could not imagine my success without unflinching support of my family members.

I am also indebted to my friends and colleagues who motivated and encouraged me on this great journey. I shall be ever thankful to Dr Kannan Jegathala Krishnan who was my initial contact in Australia. He helped me in many crucial situations and guided me in understanding and decoding life in Melbourne. I shall also be thankful to my other friends Salman Khan, Dr. Sajad Amjadi, Abdulrahman Hadbah, Nitesh, Taky Chan, Amin and others with whom I have discussed many academic and non-academic issues.

I would also like to thank the extremely helpful online communities of developers for providing me useful suggestions during my projects. In addition, I would like to extend my gratitude towards all those people who have directly or indirectly helped me in accomplishing my goal.

Last but not the least, I would like to pay my obeisance to the almighty God for giving me health, wisdom and courage to chalk out my path in this winding world.

# List of Figures

# List of Tables

# Abbreviations

| | |
|---|---|
| AAA | Authentication, Authorization, and Accounting |
| ACSI | Abstract Communication Service Interface |
| AMI | Advanced Metering Infrastructure |
| ANN | Artificial Neural Network |
| BAN | Building Area Networks |
| BS | Base Stations |
| BWRC | Berkeley Wireless Research Centre |
| CBP | Co- Existence Beacon Protocol |
| CBS | Cognitive Base Station |
| CI | Computational Intelligence |
| CIS | Consumer Information System |
| COP | Coincident Peak Pricing |
| CPE | Customer Premise Equipment |
| CPP | Critical Peak Pricing |
| CPS | Cyber-Physical System |
| CRCN | Cognitive Radio Cognitive Network |
| CRE-NS3 | Cognitive Radio Extension for NS-3 |
| CT | Current Transformer |
| DC | Data Concentrator |
| DFT | Discrete Fourier Transformation |
| DoS | Denial-of-Service |
| DS | Downstream Subframe |
| DSM | Demand Side Management |
| EIPR | Effective Isotropic Radiated Power |
| EMS | Energy Management Systems |
| EST | Effective Secondary User Throughput |
| FAN | Field Area Networks |
| FDIR | Fault Detection, Isolation and Restoration |
| FDR | Frequency Disturbance Recorders |
| GIS | Geographic Information System |
| GOOSE | Generic Object Oriented Substation Event |
| GSSE | Generic Substation Status Event |
| HAN | Home Area Network |
| HEMS | Home Energy Management Systems |
| IAN | Industrial Area Networks |
| ICT | Information and Communication Technology |
| IEC | International Electrotechnical Commission |
| IED | Intelligent Electronic Device |
| IoT | Internet of Things |
| LOS | Line of Sight |
| LRU | Least Recently Used |
| M2M | Machine to Machine Communication |

| | |
|---|---|
| MAE | Mean Average Error |
| MAPE | Mean Average Percent Error |
| MDMS | Meter Data Management System |
| MMS | Manufacturing Message Specification |
| MU | Merging Unit |
| NAN | Neighbourhood Area Network |
| NCMS | Network Control and Management Systems |
| NIST | National Institute of Standards and Technology |
| NLOS | Non-Line of Sight |
| NS-2 | Network Simulator 2 |
| NS-3 | Network Simulator 3 |
| OFDMA | Orthogonal Frequency Division Multiple Access |
| PBS | Primary Base Station |
| PLC | Power Line Communications |
| PMU | Phasor Measurement Unit |
| PU | Primary User |
| PUI | Primary User Interference |
| QoS | Quality of Service |
| RF | Radio Frequency |
| ROC | Receiver Operating Characteristic |
| SC | Spectral Coherence |
| SCADA | Supervisory Control and Data Acquisition |
| SCD | Spectrum Correlation Density Function |
| SCL | Substation Configuration Language |
| SM | Spectrum Manager |
| SNR | Signal-to-Noise Ratio |
| SSA | Spectrum Sensing Automaton |
| SSF | Spectrum Sensing Function |
| SU | Secondary User |
| SUN | Smart Utility Network |
| SV | Sampled Values |
| SVM | Support Vector Machine |
| ToU | Time of Use |
| TVWS | TV White Space |
| US | Upstream Subframe |
| VT | Voltage Transformer |
| WAN | Wide Area Network |
| WRAN | Wireless Regional Area Network |
| XML | Extensible Markup Language |

# List of Publications

**Journal Publications**

1. Vasudev Dehalwar, Akhtar Kalam, Mohan Lal Kolhe, Aladin Zayegh, Anil Kumar Dubey, “Integration of IEC 61850 MMS and IEEE 802.22 for Smart Grid Communication”, accepted for publication in Lecture Notes on Data Engineering and Communications Technologies.

**Conference Publications**

2. Vasudev Dehalwar, Akhtar Kalam, Mohan Lal Kolhe, Aladin Zayegh, “Review of Machine to Machine Communication in Smart Grid” IEEE International Conference on Smart Grid and Clean Energy Technologies 2016, October 2016, Chengdu, China.
3. Vasudev Dehalwar, Akhtar Kalam, Mohan Lal Kolhe, Aladin Zayegh, “Electricity Load Forecasting for Urban Area using Weather Forecast Information”, IEEE 2016 International Conference on Power and Renewable Energy, October 2016, Shanghai, China.
4. Vasudev Dehalwar, Akhtar Kalam, Mohan Lal Kolhe, Aladin Zayegh, “Compliance of IEEE 802.22 WRAN for Field Area Network in Smart Grid”, IEEE Power & Energy Society (PES) Conference on Power Systems Technology (POWERCON-16), September 2016, Wollongong, NSW, Australia.
5. Vasudev Dehalwar, Akhtar Kalam, Mohan Lal Kolhe, Aladin Zayegh, “Review of IEEE 802.22 and IEC 61850 for Real-Time Communication in Smart Grid”, IEEE International Conference on Computing and Network Communications (CoCoNet'15), 16 December, 2015, Trivandrum, India.
6. Vasudev Dehalwar, Akhtar Kalam, Aladin Zayegh, “Infrastructure for real-time communication in smart grid”, IEEE Smart Grid Conference (SASG), December 2014, Riyadh Saudi Arabia.
7. Vasudev Dehalwar, Akhtar Kalam, “Machine to Machine Communication using Cognitive Radio in Smart Grid- A Review”, International Conference on Renewal Energy Utilization (ICREU-2014), January 2014, Coimbatore, India.

# CHAPTER 1

# INTRODUCTION TO SMART GRID AND COGNITVE RADIO

## 1.1. Introduction

The electric power grid has been developed over the last century with incremental growth over a period of time. Due to aging and advancement in technology the power grid need to be transform to cater the demanding requirements of modern grid. The grid in its present form lacks bi-directional information flow, visibility, automation, situational awareness, etc. which is essential for the modern grid [1]. The grid will become more reliable, secure and efficient with the integration of modern communications technologies, power electronics, sensing technology, control, computational intelligence, data management, etc. The aforementioned technologies will make the present grid into the Smart Grid [2]. Data acquisition and data analytics are important factors of modern grid which can be materialised with the new development.

The goal of Smart Grid is to provide a cost-effective supply of electricity to the consumer with more reliability and dynamism. It provides flexibility and adaptability in decision-making by consumers based on feedback received from the grid. The Intelligent Electronic Devices (IEDs) and networked components of the grid will provide feedback in real-time. The Smart Grid will also help in maintaining the power quality across all sections of the grid using Phasor Measurement Unit (PMU) and minimise the transmission and distribution losses. It will reduce faults, failures and blackout in the system thus improve the performance and efficiency of the grid [3].

Traditionally, fossil fuel accounts for 65% of world's energy generation [4]. These fossil fuels release greenhouse gases into the atmosphere in the process of power generation. These greenhouse gases cause harmful effect to the environment. The renewable energy sources (termed as green fuel) such as Solar, Wind, Tidal, etc. are an alternative sources of electricity generation, which is environmental friendly [5]. The renewal energy is an intermittent energy whose output cannot be guaranteed as it depends on many factors such as weather condition, wind condition, solar insolation, etc. Renewable Energy Sources is supposed to be integrated with the existing electrical grid for transmission and distribution. Dependency on renewal energy is very risky due to fluctuation in electricity generation which has the potential to grid failure if it is not managed properly.

The Information and Communication Technology (ICT) has been the main contributor in development of Smart Grid. There are millions/billions of network components and IEDs installed in the entire Smart Grid which will generate high volumes of operation and control data. Often the data will be a routine type of monitoring data that will be generated periodically but sometime the data may be critical. The critical data must be delivered to the control center in real-time for smart decision making [6]. The present communication infrastructure is inadequate to transfer high volume data to control center in real-time. **The goal of this research is to analyse the feasibility of sending data reliably and securely to the control center in real-time.**

The Sensors, IEDs, PMUs, etc. are the part of network backbone that are essential for data delivery. The wired and wireless communications technologies can be used interchangeably for the machine to machine communication (M2M)/Internet of Things (IoT). Wireless communication has some advantages over wired technologies in terms of cost of installation and commissioning, but it data suffers from the perspective of security, reliability, data integrity and timely delivery. Conversely, wired communication is a reliable, secure and dependable communication, but installation and commissioning of the wired network is costly and time consuming. From financial point of view the wireless communication is most suitable for the last mile connection (from micro-grid to customer premises) and wired communication is most suitable for long-haul connection. The wireless communication technologies that can be used are IEEE 802.11-Wi-Fi, ultra wideband, IEEE 802.15.4-ZigBee, IEEE802.22-Wireless Regional Area Network (WRAN), etc. [1, 6, 7].

The radio spectrum has become an important resource in wireless communication and its demand is increasing. The studies conducted by Berkeley Wireless Research Center (BWRC), USA at downtown Berkeley shows the power spectral density (PSD) and bandwidth utilisation between 15% to 85% over a period as depicted in Figure 1.1 [8, 9]. The Federal Communications Commission, USA has proposed to use unutilised spectrum called ‘white spaces’ in advancing Cognitive Radio technology for opportunistic spectrum sharing.

The new wireless technology called Cognitive Radio technology has the potential to overcome the spectrum scarcity and provide reliable wireless communication. Cognitive Radio provides opportunistic use of unused frequency bands by secondary users (SUs) if that frequency band is not being used by primary users (PUs). The PU refers to the licensed users who have legacy rights on the specific spectrum at a given time and space. SU refers to the users that exploit this ideal spectrum in such a way that it does not cause harmful interference to the PU [10-12]. The fruitful and effective use of Cognitive Radio for transferring data to the Smart Grid can provide stability in operation and control of the grid. **Therefore, the aim of this research is to check the feasibility of using Cognitive Radio for fast, efficient, secure and reliable machine/device to machine/device communication.**

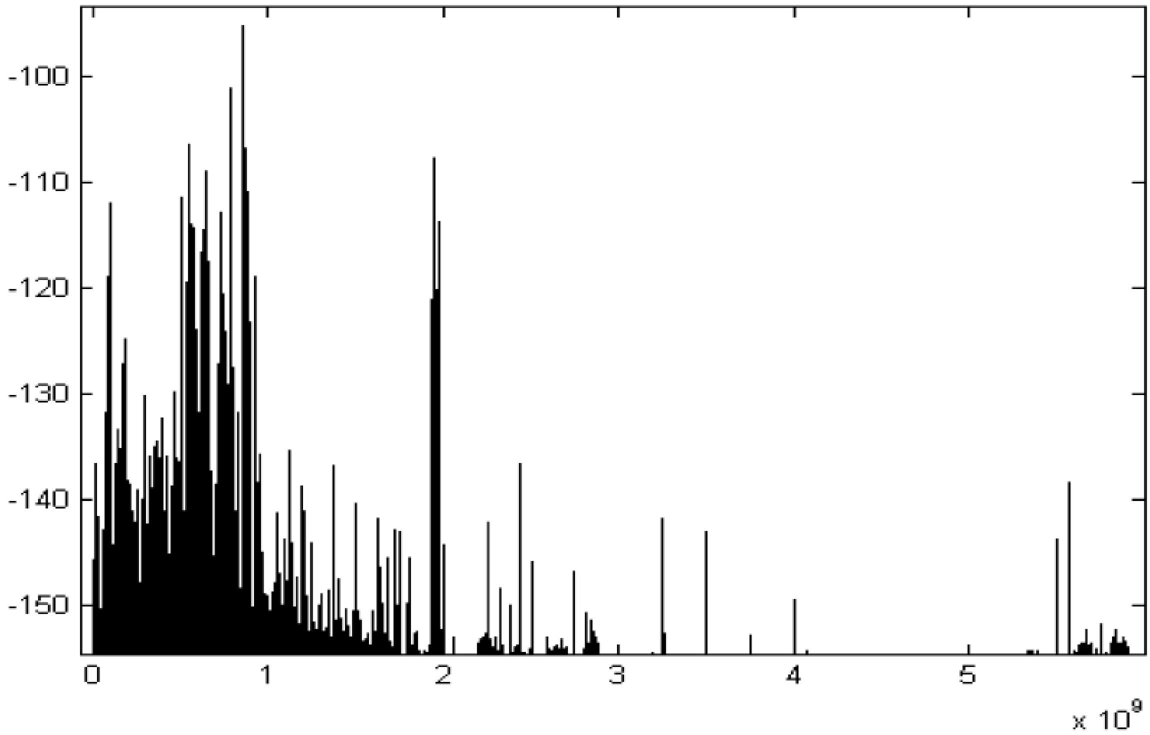



Fig. 1.1 Measurement of 0-6 GHz spectrum utilisation at BWRC [8]

## 1.2. *Electrical Grid System*

The hierarchical diagram of traditional power grid network is depicted in Figure 1.2 [13]. The top level illustrates the origin of power generation either using fossil fuel or renewal energy sources. The power is transmitted to substation through the high voltage transmission line. This high voltage transmission line is stepped-down to medium voltage for onward transmission to distribution feeder. The medium voltage is again stepped-down to the voltage desirable for the domestic and industrial consumers through transformers.

The power grid is a complex interconnection of substations, control center and market. Demand response, renewable generation, electric vehicles and energy storage introduce complexity into the system. Energy Management Systems (EMS) and Supervisory Control and Data Acquisition (SCADA) are the current technology in use for monitoring, analysis and control [1, 2]. The details of Smart Grid, Standards and challenges are discussed in Chapter 2.

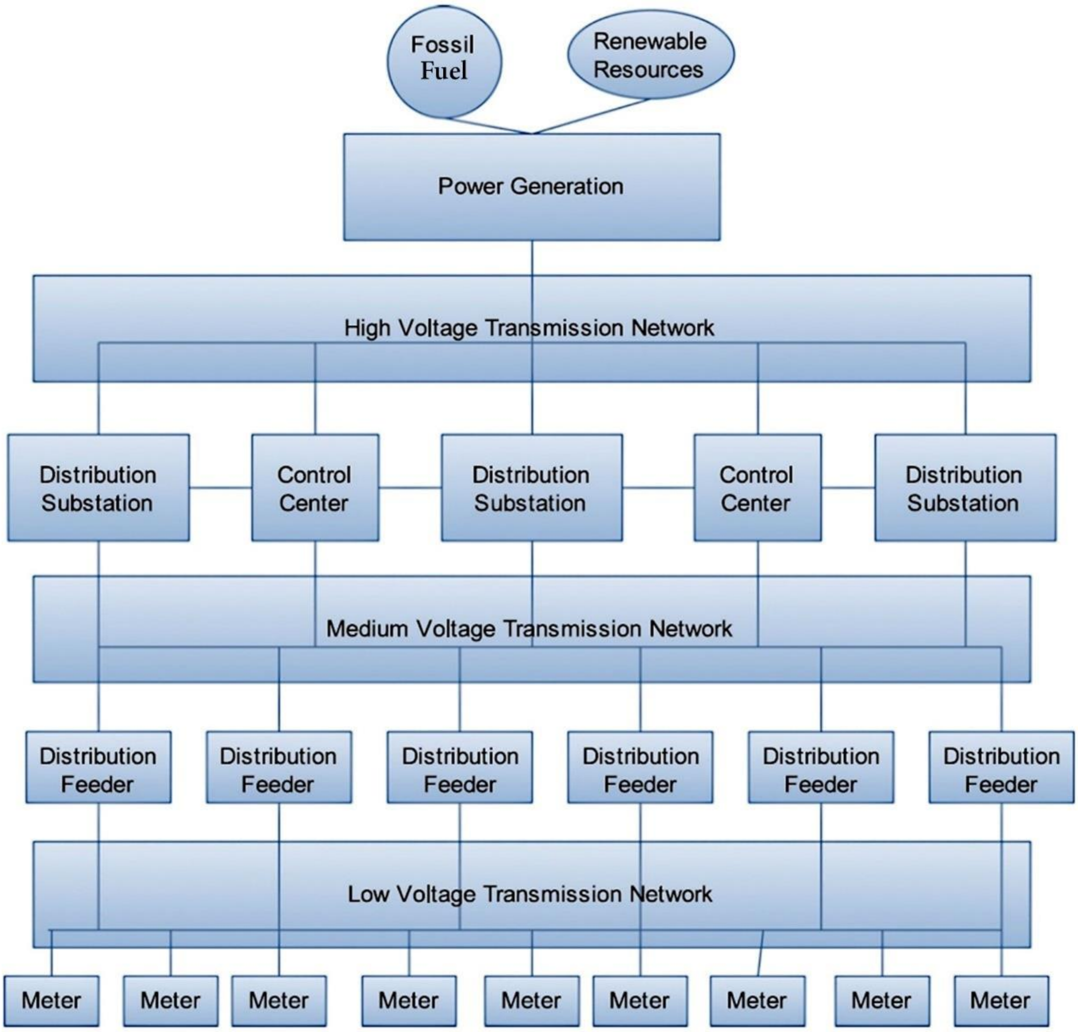



Fig. 1.2 Traditional power grid network [13]

## *1.3. Smart Grid Architecture*

The two-way communication between different components of grid are the essential characteristics of Smart Grid. The enabling technologies are digitalization, intelligence, resiliency (self-healing), Advanced Metering Infrastructure (AMI), Demand Side Management (DSM), etc. [14]. The customer premise will have smart meters which is a part of the AMI to communicate with the central control center. AMI provides bi-directional communication between the utilities and the customers to background services such as control and detection of unauthorised usage, remote meter reading, DSM, etc. [1, 5, 12] . The stability of the system is maintained by balancing demand and supply between consumption and generation through various efforts such as dynamic pricing, load shedding, etc.

National Institute of Standards and Technology (NIST), USA in its report “Framework and Roadmap for Smart Grid Interoperability Standards” [15] has proposed a conceptual architecture of the Smart Grid. The conceptual architectural of NIST divides the Smart Grid into seven domains for information exchange and smart decisions as illustrated in Figure 1.3. The domain includes:

- Customers;
- Markets;
- Service providers;
- Operations;
- Bulk generation;
- Transmission and
- Distribution.

The Smart Grid architectures categorised the customers' area into: -

- Home Area Networks (HANs);
- Neighbourhood Area networks (NAN);
- Building Area Networks (BANs) and
- Industrial Area Networks (IANs).

These customers' area network can be either wired or wireless and point of contact being Smart Meter at customer premises. This Smart Meter is a part of AMI that support messaging amongst appliances, IEDs, software applications, energy management devices and consumers. Building Automation and Control Networks (BACnet), Home Energy Management Systems (HEMS) or other EMS drive the applications and communications in these networks [6, 12, 13].

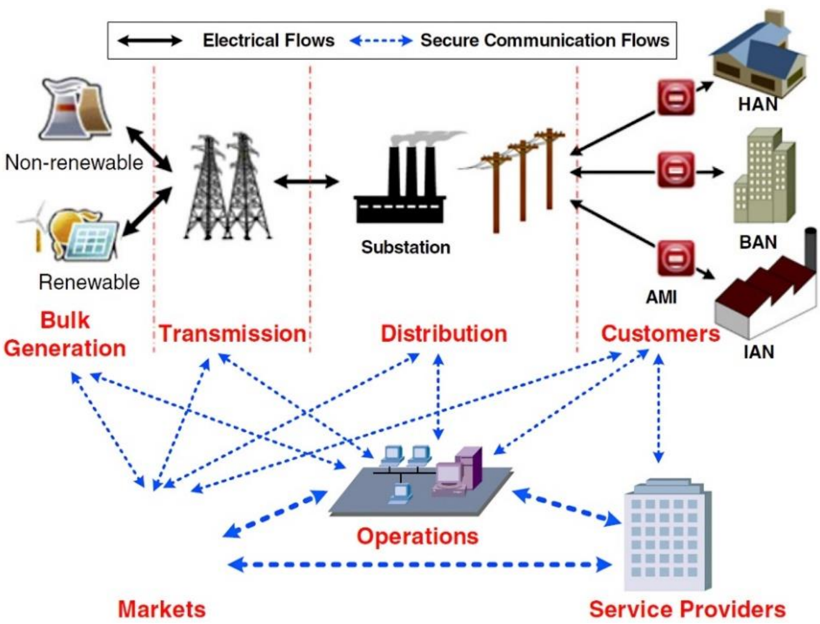



Fig. 1.3 Smart Grid system architecture [13, 15]

## 1.4. Communication Challenges in Smart Grid

As aforementioned the stability of power system is based on the balance between the electricity supply and demand. The supply side is highly regulated, while the demand side is inconsistent. The traditional Grid lack flexibility and adaptability which makes it susceptible to failure due to stress.

The fast and efficient communication infrastructure is essential for reliable and secure communication. The communications infrastructure in Smart Grid may be a hybrid mesh of heterogeneous network which inhibit internetworking. Interoperability of devices is also a big challenge. Figure 1.4 show the complexity of communication on small scale through a hierarchical diagram [13]. It depicts the essence of communication between different parts of network.

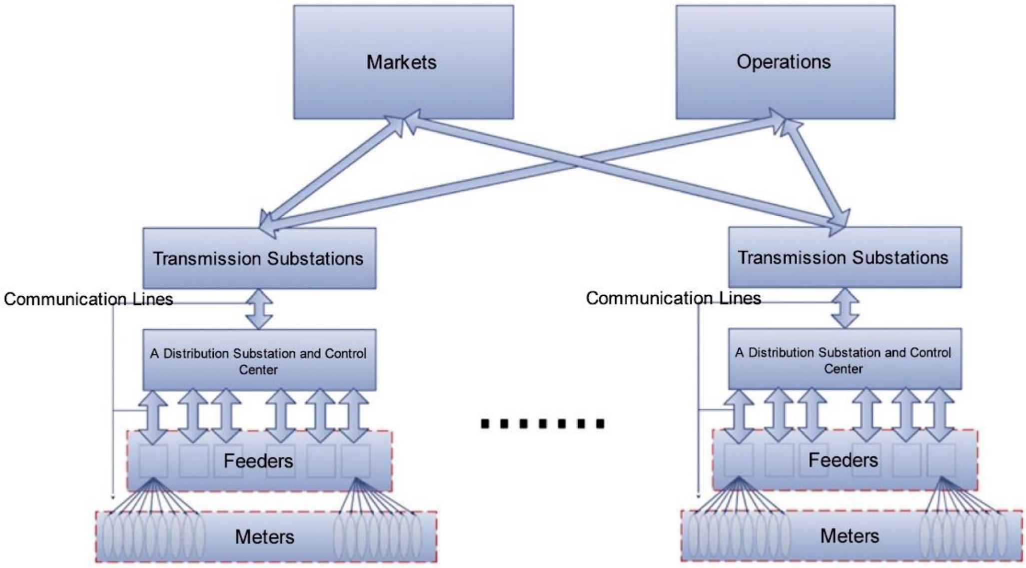



Fig. 1.4 Smart Grid communication architecture [13]

Table 1.1 summaries the communication protocols at different layers of communication architecture. Long distance will always be wired and short to medium distance can have wireless as the priority medium. **This research will generate new knowledge for using Cognitive Radio for temporal (time-dependent) Big-Data transfer.** The radio agility of Cognitive Radio helps to detect the unused spectrum opportunities in the surroundings and utilise this opportunity to transfer the data to control center without causing interference to the neighbouring channels. The use of Cognitive Radio in the Smart Grid improves spectrum utilisation and data carrying capacity of channels.

## 1.5. Cognitive Radio

Cognitive Radio is a new wireless communication technology developed for flexible use of radio spectrum. The primary step in using Cognitive Radio is to maintain the database of licenced and unlicensed spectrum. The spectrum utilisation across multiple channels is depicted in the Figure 1.5 [16-18]. The diagram shows the used and unused TV channels. Moreover, even when some channels are used the guard bands are not used which has the purpose of channel segregation and to avoid channel interference. This guard bands is made redundant in the digital technology which can be pooled in TV White Spaces (TVWS) [16].

Table 1.1 Communication Protocol at different layers [10, 13, 19, 20]

| | **Participating entities at different layers** | | **Medium used (wired/wireless)** | **Protocol Used** |
|---|---|---|---|---|
| | **From** | **To** | | |
| 1 | Markets and Operations | Transmission substation | Optical fiber | SDH/SONET/ATM |
| 2 | Transmission substation | Distribution substation and control center | Optical fiber | ATM, TCP/IP, SDH |
| 3 | Distribution substation and control center | Feeders | (a) NAN (either)<br>(b) IAN (either) | ADSL Broadband, WiMAX, Wi-Fi, LTE, Cognitive Radio |
| 4 | Feeders | AMI | (c) HAN (either) | Ethernet (LAN), Cellular (GSM, CDMA),<br>Mobile (WLAN, WPAN, Bluetooth, ZigBee, Cognitive Radio, etc.) |

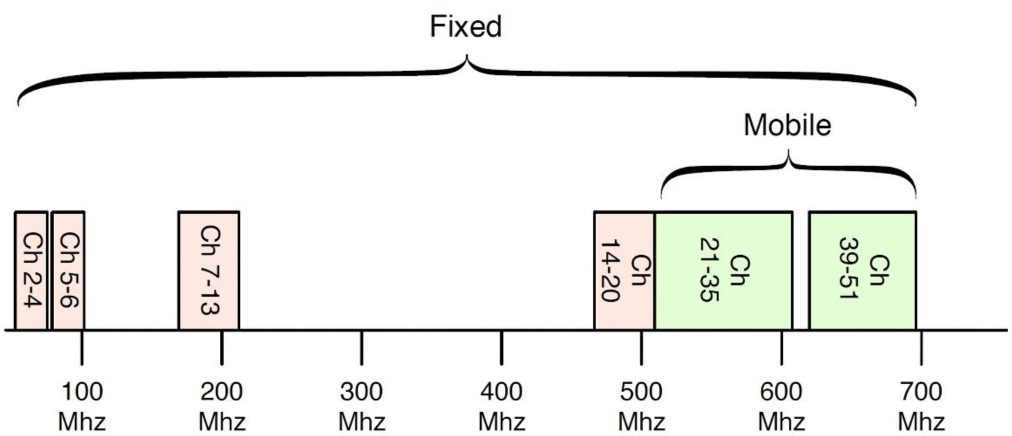



Fig. 1.5 Spectrum allocation of TV and Mobile [16]

The dynamic spectrum sensing technique can allow sharing this TVWS among multiple users. Allocation of spectrum amongst user can be coordinated through a tightly synchronised and highly accurate global clock. This clock can synchronise the SU to switch to another channel or limit the use of spectrum for a short duration in case of incumbent detection at a given time and location. Alternatively, the SU can also remain in the same band by changing the modulation scheme or altering the transmission power level to avoid interference.

The spectrum hole concept is illustrated in Figure 1.6 [21]. At a given time some of the spectrum remain under-utilised. Fig 1.7 depicts the spectrum access in infrastructure based and infrastructure-less Cognitive Radio. The infrastructure-based Cognitive Radio will have Cognitive Base Station as access point whereas in infrastructure-less Cognitive Radio any machine/device will act as access point in an ad-hoc manner.

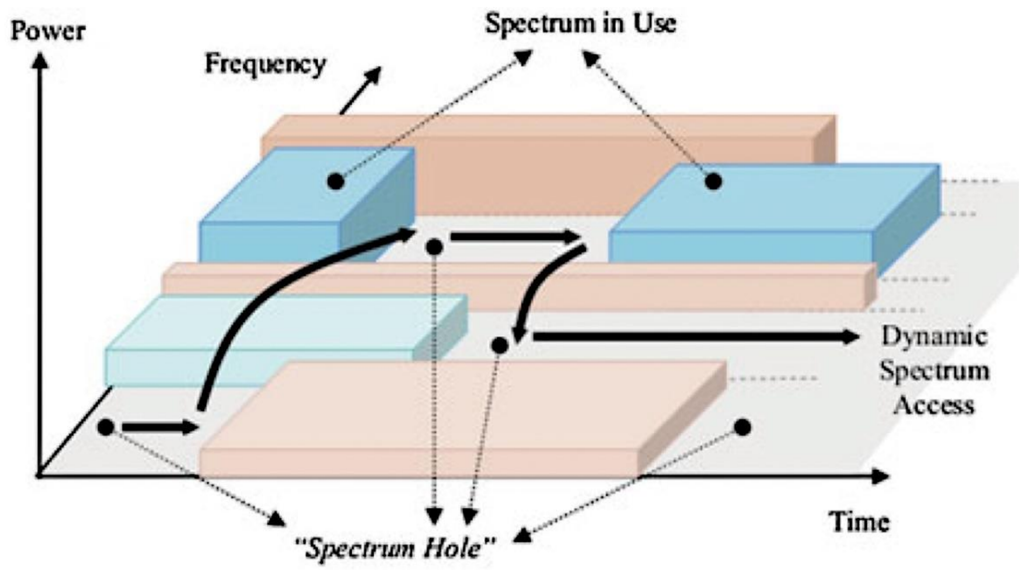



Fig. 1.6 Spectrum and Holes Concept [17, 21]

One of the research question that is relevant to this research is "**How reliably the voluminous data generated at substation can be transmitted to control center in real-time for smart decisions"?** Cognitive Radio is a blessing in bandwidth-limited wireless technology that allows secondary user to exchange information opportunistically. The concepts of Cognitive Radio are elaborated further in Chapter 3 and Chapter 5.

## *1.6. Integrating Computational Intelligence*

Computational Intelligence (CI) can contribute in achieving intelligent behaviour in complex and changing domains. CI can endow Smart Grid with innovative, powerful and effective tools as illustrated in Figure 1.8 [22]. The self-healing capability of Smart Grid

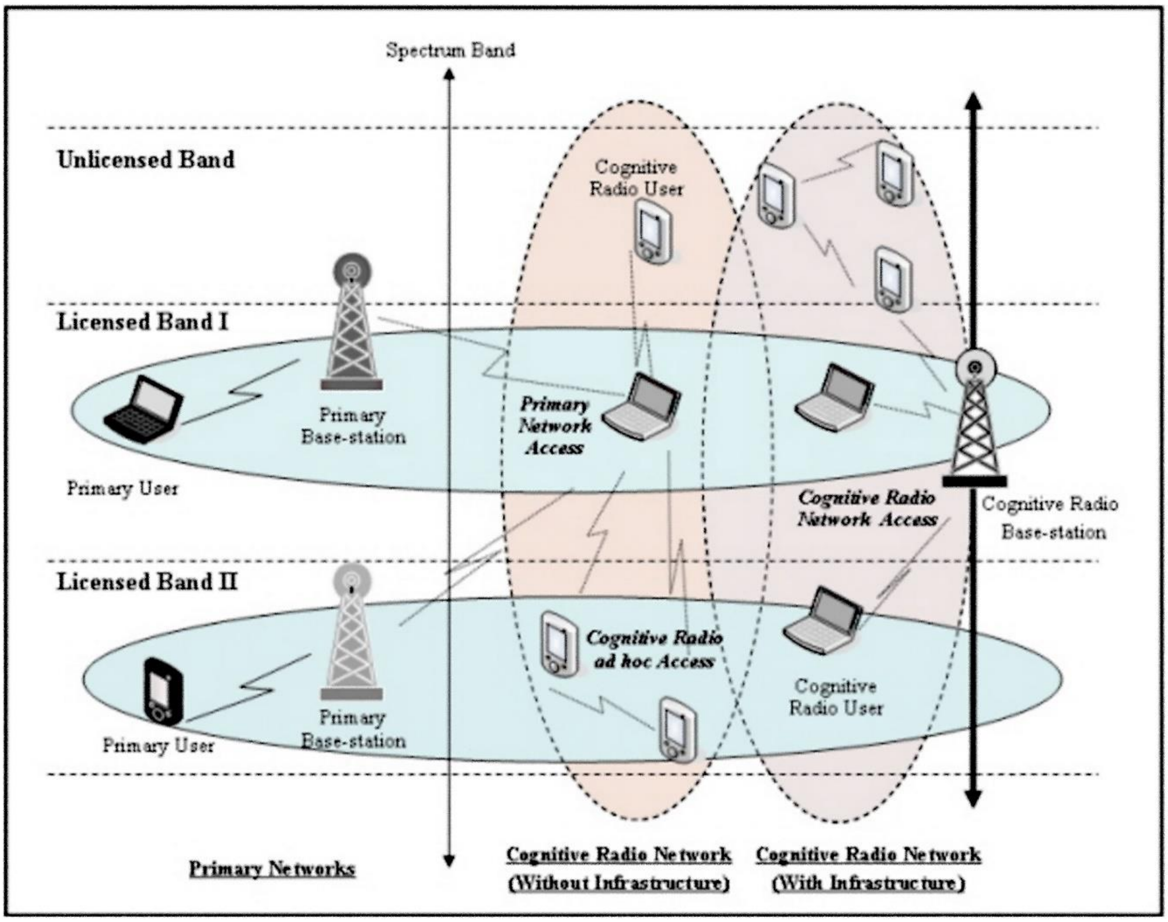



Fig. 1.7 Cognitive Radio Network Architecture [23]

enables the power grid to rapidly recover from power disturbances and dynamically reconfigure itself. The power stability can be achieved through a combination of control schemes and protection, embedded intelligence, self-awareness of the system and person's expertise. CI can be implemented using Artificial Neural Network (ANN), Genetic Algorithm (GA), Fuzzy systems, Swarm intelligence, etc. This research project will identify the methodology to be used to integrate the CI in machine/devices.

## *1.7. Literature Survey*

The literature available from various sources relevant to this study were reviewed to identify the gap in the knowledge. The issues and research challenges in this area were explored and opinions were formed after discussion with the experts in the field. Since the research is multi-disciplinary in nature, cross-references of literature were performed to systemically define the scope of this research. The literature surveys are categorised into three sections to form close clusters of research papers.

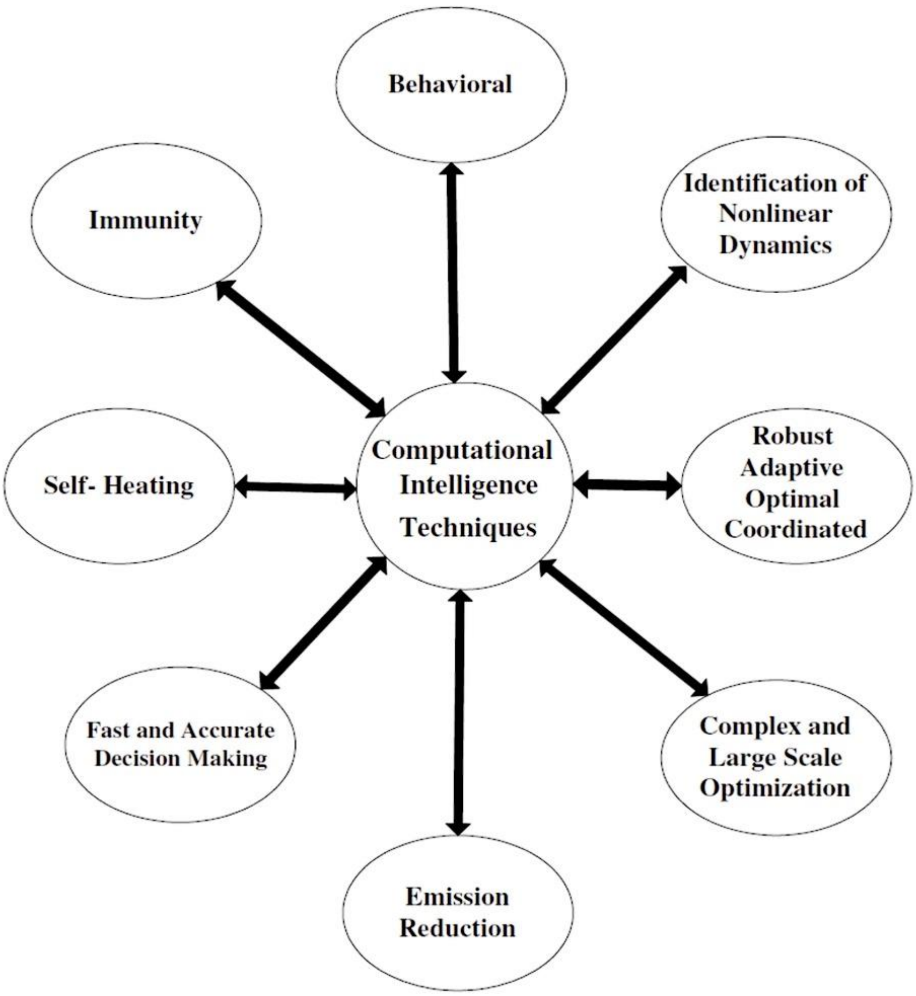



Fig. 1.8 Capabilities of Computational Intelligence Methods for Smart Grid [22]

### *1.7.1. Literature Review- Smart Grid and Data Communication*

Hauser, et al. [24] demonstrated the need for better communication to provide improved security, efficiency and reliability for power grid operation. The GridStat communication architecture based on Internet technologies proposes new communication architecture. But the IP-based Internet technology alone cannot guarantee the Quality of Service (QoS) requirements for the grid's status communication. Sollecito [25] stated the unified vision for Smart Grid and described the different attributes of Smart Grid.

Bose [26] critically examined how accurately one can measure the time for real-time operation as well as for subsequent decision making. The present phasor measurements unit/device can measure instantaneous values of voltages and currents with very accurate time stamping by using a Global Positioning System (GPS) signal.

Gao, et al. [13] conducted a systematic review of communication/networking technologies in Smart Grid including communication/networking architecture, QoS, optimised utilisation of assets, control and management.

Budka, et al.[27] investigated in detail a Smart Grid communication network architecture that supports today’s grid applications and discusses new applications necessitated by the introduction of smart metering and home area networking, support of demand response applications and incorporation of renewable energy sources in the grid. The paper also listed the QoS design requirements for all utility applications and their priority and latency.

Fangxing, et al. [2] presented a unique vision for the future of smart transmission grid which is regarded as an integrated system that functionally consists of three interactive, smart components, i.e., smart control centers, smart transmission networks and smart substations. The vision of a Smart transmission Grid is captured in Figure 1.9 [2].

The paper further stated that the backbone of the system integration is the distributed intelligence at the smart transmission networks and substations, which can assist in making decisions at a local level, based on local information to reduce the load at the control center.

NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0 [15] described the protocols, models and standards to achieve interoperability of Smart Grid devices and systems. It described a high-level conceptual reference model for the Smart Grid that divides the Smart Grid into seven domains namely [13] [15]:

- Customers;
- Markets;
- Service Providers;
- Operations;
- Bulk Generation;
- Transmission and
- Distribution.

Pei, et. al.  [28] proposed a vision of next-generation monitoring, analysis and control functions for tomorrow’s smart power system control centers. This smart control center vision is expected to be a critical part of the future smart transmission grid.

Fadlullah, et al. [29] surveyed a number of existing communication technologies that can be adopted for the machine to machine communication in a Smart Grid. A possible solution to the machine to machine communication in HAN is to send periodic messages more frequently to the HAN Gateway (GW) from active and unstable smart meter rather than a dormant and stable meter. This will reduce drastically the amount of data to be communicated to control center.

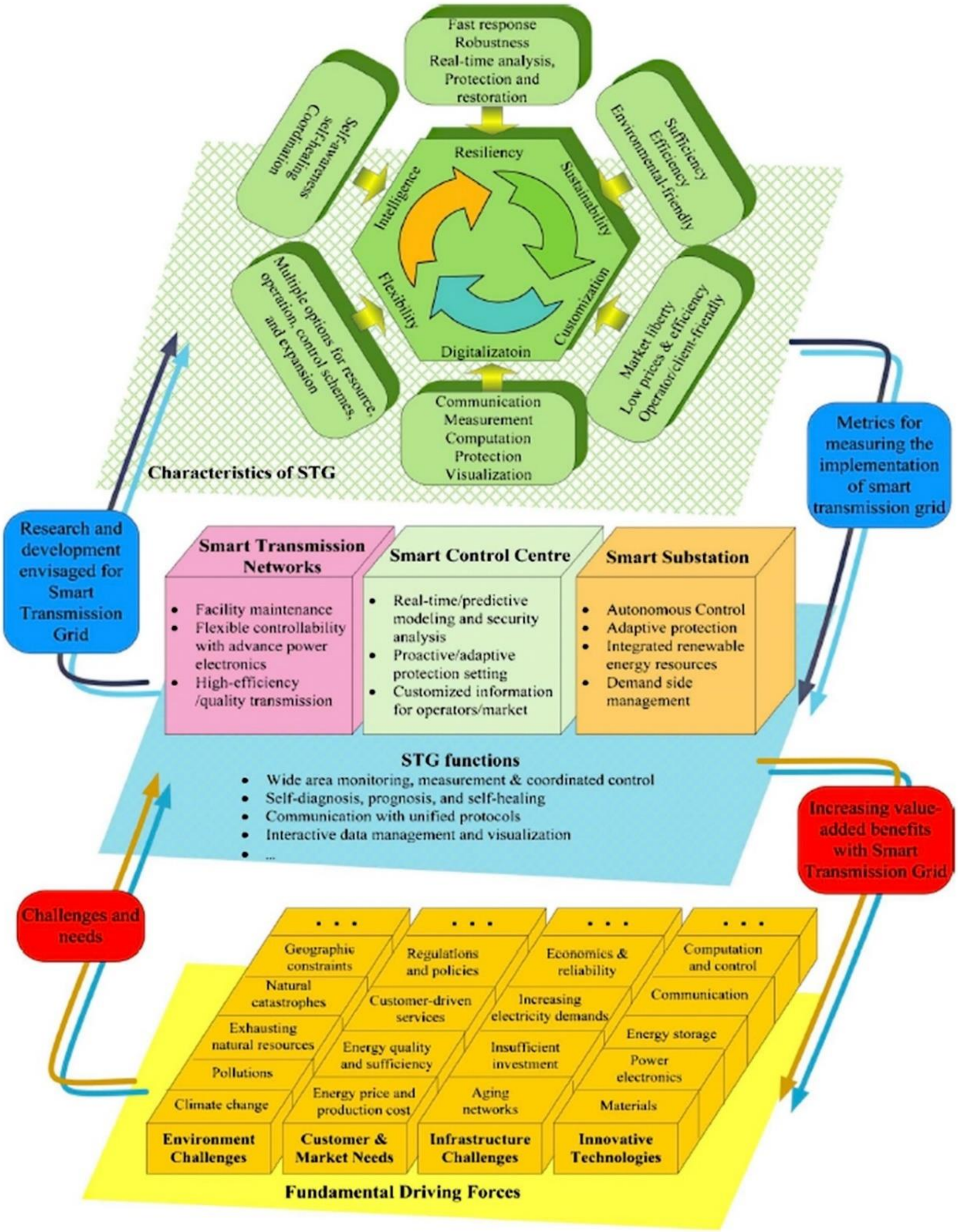



Fig. 1.9 Vision of a smart transmission grid [2].

Gungor, et al. [1] addressed critical issues in term of ICT in Smart Grid. It also provided a contemporary look at the current state of the art in Smart Grid communications as well as the open research issues in this field.

Qi, et al. [30] underlined the requirements of energy infrastructure for modern society that is secure and reliable. It described the action to be taken at the system level, device level, etc. and proposed new techniques and system architecture design that can help assure the security and reliability of the power grid.

Meliopoulos, et al. [20] discussed four specific applications:

a) Protection against downed conductors;
b) Load levelization;
c) Loss minimization; and
d) Reliability enhancement.

The paper suggested the deployment of a novel smart metering device that is synchronised with "Universal GPS Synchronised Meter (UGPSSM)", distributed, reliable and high-speed communication system. The UGPSSM performs GPS-synchronised measurements that provide accurate timing to 1µs accuracy.

### *1.7.2. Literature Review Smart Grid and Cognitive Radio*

Qiu, et al. [11] investigated the novel idea of applying the next generation wireless technology, Cognitive Radio network, for the Smart Grid. A microgrid testbed supporting both power flow and information flow are also proposed. Control strategies and security considerations are discussed.

Ranganathan, et al. [31] gave a brief overview of the Cognitive Radio, IEEE802.22 standard and Smart Grid. Experimental results obtained by using dimensionality reduction techniques such as Principal Component Analysis (PCA), kernel PCA and landmark maximum variance unfolding (LMVU) on Wi-Fi signal measurements are presented in a spectrum sensing context.

Rong, et al. [19] presented Cognitive Radio based communications architecture for the Smart Grid that is decomposed into three subareas:

- Cognitive HAN,
- Cognitive NAN and
- Cognitive WAN,

depending on the service ranges and potential applications. Finally, it focuses on dynamic spectrum access and sharing in each sub-area.

### *1.7.3. Literature Review Smart Grid, Cognitive Radio and Spectrum Access*

Jung, et al. [32] discussed how secondary users will opportunistically access spectrum licensed by PUs while protecting PU activities. The paper also considered SU that must protect multiple PUs simultaneously. This paper made a case study for new allocation scenarios in which PUs have frequent idle/busy transitions and SUs must consider PU activity statistics when allocating channels.

Raychaudhuri, et al. [33] described emerging protocols for Cognitive Radio to enable coordination between multiple systems sharing the same white space band. It predicted that convergence of cellular and Internet services will drive further integration of cellular network protocols and the next-generation of IP protocols into a more unified mobile Internet architecture.

Gabran, et al. [34] presented a mathematical analysis of the accuracy of estimating Primary User's mean duty cycle μ, as well as the mean off- and on-times. The PU channel utilisation patterns are stochastic. Consequently, acquiring knowledge about the PU traffic statistics can improve the performance of SU channel selection algorithms.

The aforementioned literature suggested that there are many issues that need to be settled before feasible implementation of Smart Grid. Cognitive Radio is one of the novel approaches to real-time communication in Smart Grid for temporal (time-dependent) Big Data.

## *1.8. Originality of the Thesis*

The goal of Smart Grid research is to provide a cost-effective, secure and reliable supply of electricity to the consumer with QoS. The integration of distributed and renewable energy into the main grid adds more complexity in the system and makes it unstable. Feedback received from installed devices will help the data and control center of the utilities to make smart decisions.

Large number of IEDs, Smart Meter, Smart Objects, etc. present in Smart Grid will generate large volumes of data in the system. The communication media must deliver these time critical data reliably in real-time or near real-time to the control center. So, the central question is **"How to transmit this Big Data reliably and securely to the data and control center of utilities in real-time for a smart decision?"**

The research objective is to:

- Explore the feasibility of using Cognitive Radio - next generation communications network for fast, efficient, secure and reliable machine/device to machine/device communication without human intervention.
- Meet the QoS requirements in the Smart Grid. The applications should be able to differentiate between different class of traffic in the network based on priorities. QoS in communication should address the key attributes of latency,

bandwidth and throughput in interference free/ avoidance wireless environment with fairness in spectrum allocation.

- The system should provide stability in demand and supply by balancing electrical load.

## *1.9. Organisation of Thesis*

The thesis comprises of eight chapters which are organised as shown in Figure 1.10.

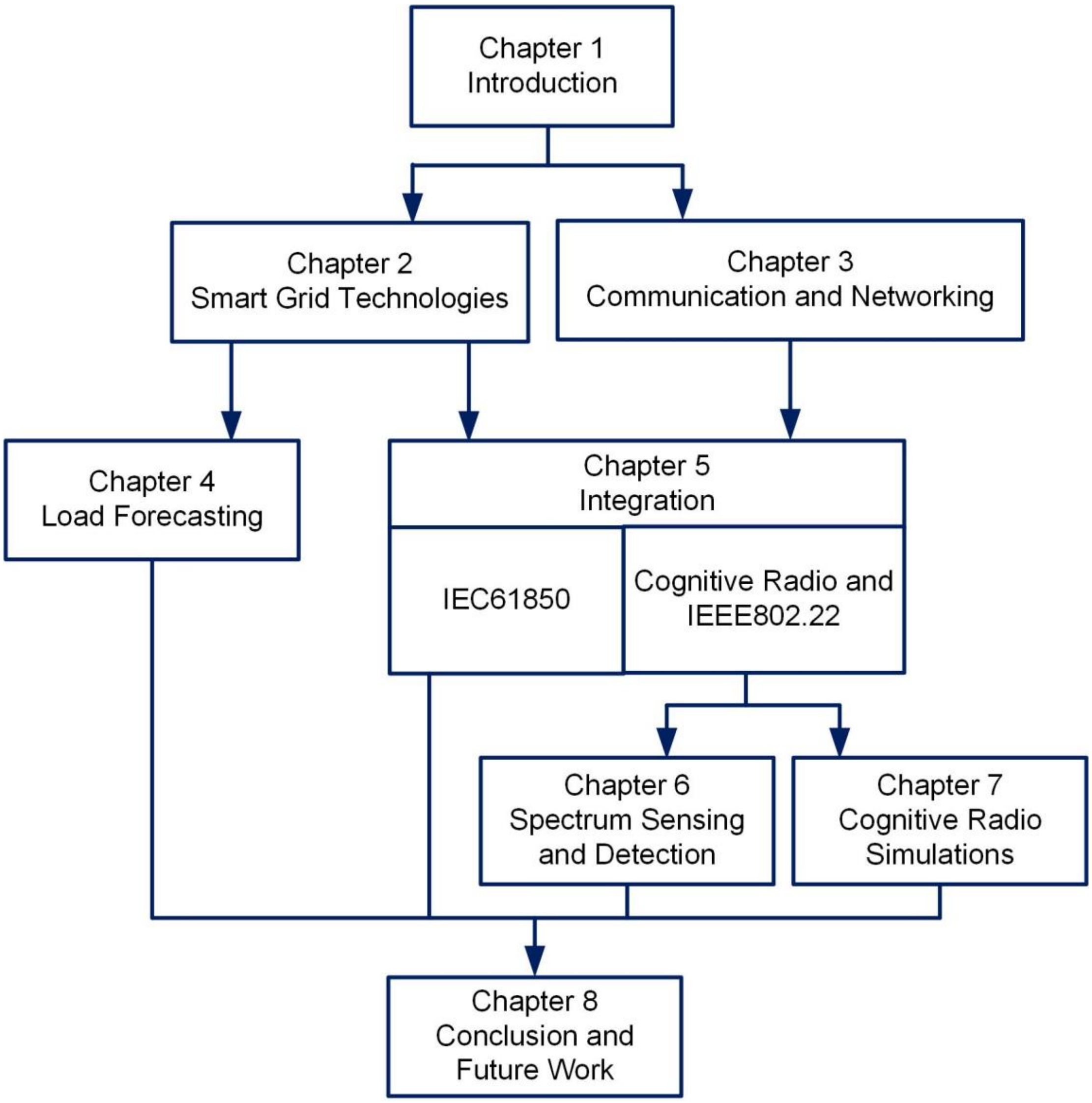



Fig. 1.10 Organisation of the Thesis

- Chapter 1: Presents the introduction to the Smart Grid and Cognitive Radio. It also discusses the challenges in Smart Grid communication. It further provides insight into the original contributions of knowledge in the form of literature survey in this area of research.

- Chapter 2: It discusses the features of Smart Grid and some challenges to the Smart Grid. The brief description of two standards in Smart Grid namely NIST and IEC61850 is presented.
- Chapter 3: This chapter elaborates the building blocks of Smart Grid. Then it goes on to elaborate the communication requirements (latency, etc.). The IEEE802.22 standards of WRAN is also discussed in the chapter.
- Chapter 4: This chapter discusses the importance of using load forecasting at customer premises for predicting next 24 hours' load based on weather forecast. The ANN and Bragged Regression tree is followed for predicting load.
- Chapter 5: This chapter discusses working of IEC61850 for substation automation. Cognitive Radio spectrum sensing and other parameters related to the spectrum is deliberated. It also demonstrates how IEC61850 Manufacturing Message Specification (MMS) can be integrated with IEEE802.22 for communication.
- Chapter 6: This chapter simulates spectrum sensing using energy detection and cyclostationary feature detection. The spectrum sensing is investigated and plotted under various noise conditions.
- Chapter 7: This chapter describes different simulators available for research studies in Cognitive Radio. Two simulators are selected to study various performance parameters such as throughput, latency, packet delivery ratio, etc. for different cases.
- Chapter 8: This chapter summaries the project followed by recommendations for future research work.

## *1.10. Summary*

The electric power grid had been in existence since last century which is subject to ageing. The traditional grid lack the modern vision of 21$^{st}$ century in terms of visibility, automation, situational awareness, etc. The integration of distributed and renewable energy to the main grid add more complexity into the system. The activities to standardise the Smart Grid is actively going on in academia and industry. NIST has proposed a conceptual architecture of Smart Grid that divides it into seven domains for smart decision making.

The advancement in ICT has enabled to transform the existing grid into Smart Grid thereby providing more stability to the grid. The Smart Grid can provide better balancing between demand and supply through dynamic pricing or load shedding. The customer premise will have AMI where smart meters is the point of contact with the central control center.

There will be large number of connected IEDs in Smart Grid which will generate high volumes of operation and control data. The present communication infrastructure is inadequate to transfer high volume data to control center. Cognitive Radio enabled Smart Grid can provide a better solution to this problem. Cognitive Radio is a context-aware communication technology that is capable to adapt itself to communication environments in surrounding area and their properties. The IEEE802.22 standard defines the air interface for a WRAN that uses Cognitive Radio for data transfer.

The challenge lies in integrating computational intelligence into the Cognitive Radio for machine learning. This research explores the possibility of using Cognitive Radio for Smart Grid communication. Different competing technologies are studied for possible solutions of integrating computational intelligence into the devices/machine of Smart Grid. The key attributes of latency, bandwidth throughput, etc. will be analysed to demonstrate the feasibility of using Cognitive Radio as a medium of communication.

# CHAPTER 2

# SMART GRID TECHNOLOGIES, STANDARDS AND CHALLENGES

The electrical grid is a network of power utilities, consumers and communication devices engaged in sharing of data at multiple levels. It provides important and sustainable benefits to the utilities and the consumer in energy production and consumption [1, 5, 13]. The Smart Grid improves the automation and coordination between suppliers, consumers and networks [35].

There is a consistent increase in demand of electricity every year which can be met either by increasing electricity production or by improving the efficiency of the grid which include reducing transmission and distribution losses. To increase the efficiency of grid and reduce losses huge investment is required. So, the only option left is to increase the generation of electricity through alternative means. The security of the grid has become point of concern due to its reliance on computer network.

## *2.1. Smart Grid Drivers*

The cost-effective and reliable electricity is the basic need of a consumer. The development in Smart Grid will facilitate active involvement of customer for real-time pricing and demand management. The flow of electricity will change from centralised top-down approach to a more distributed approach with decentralised coordination. The key factors that will play an important role is listed as follows [36, 37]:

- Convergence of IT, Communication and Power System Engineering;
- Aging Infrastructure;
- Demand for grid flexibility;
- Integration of clean and renewal energy resources;
- Secure, affordable and sustainable electricity supply with minimum disturbance; and
- Increased penetration of battery powered devices/vehicles into the grid network.

The grid infrastructure developed over last century makes it inflexible to adapt to active demand management. The global demand for electricity is also increasing every year with expected increase of 40% within next 20 years [38]. As the major electricity, globally is supplied by a coal based power plant, so it will release 25% more greenhouse gases into the atmosphere intensifying the effect of global warming. Due to climate change, there is a demand to increase electricity production through alternative energy sources that can reduce these greenhouse gases. However, renewal energy sources are not consistent in generating energy as they are dependent on external factors (weather, wind speed, solar insolation, etc.) for generating sufficient power. The improvement in material technology can help in stabilising the electricity production through these renewal energy sources.

## *2.2. Challenges to Smart Grid*

Aged equipment and demand fluctuations create a greater risk to the grid. The overhaul of the grid network is required at different levels of electricity production, transmission and distribution for bi-directional information flow. The are many challenges in implementation of Smart Grid, some of them are listed in the following sub-sections [39]:

### *2.2.1. Information Explosion*

The monitoring and control data generated in the Smart Grid will be in terabytes/sec. The transmission medium could be either wired or wireless depending on utility company's requirements of trusted and secure communication. Wireless communications have some advantages over wired technologies, such as low deployment cost and ease of connection/implementation. However, the wireless transmission is subjected to path loss, signal attenuation, interference and battery backup. On the other hand, wired communication is reliable and secure with better communication bandwidth, but a high cost of installation [1, 22].

The large fraction of data will be transmitted to control center through a wireless medium. The limited bandwidth of wireless medium poses a serious threat to the communication network. Moreover, the reliability and efficiency of the network will suffer due to increased concentration of component/devices in a network. The radio interference, congestion, path loss, etc. in a wireless medium will affect the real-time communication [3].

### *2.2.2. Interoperability*

The Smart Grid will become a large network of diverse energy distribution devices, distributed generation and consumers from different vendors. These heterogeneous components with multiple communication technologies and standards may create interoperability problem between devices. Therefore, standards must be developed soon to harmonise the co-existence of multiple devices from different vendors for effective communication.

### 2.2.3. Security

Smart Grid support bi-directional communication between consumers and generations. The dependence on ICT inevitably makes the Smart Grid vulnerable to cyber-attack which is a risk associated with data network. The intrusion of hackers into the grid network may lead to serious consequences. Therefore, security is a serious concern in Smart Grid. The authentication, access and admission of devices/IEDs into network must be strictly enforced to ward off attackers and hackers [40].

## 2.3. Features of Smart Grid

Adding a new communication link in the Smart Grid network will improve the reach and visibility of the grid. The data transport network will communicate with different entities such as [41, 42] :

- AMI;
- Energy Management Systems;
- Distribution Management Systems (DMS);
- Enterprise Resource Planning (ERP) systems; and
- Demand Management system.

It will help in maintaining the reports of faults and failures of the system. Following are some of the features of Smart Grid:

### 2.3.1. Integration of Clean and Renewal Energy Resources

There is a growing realisation to gradually shift the electricity production from fossil fuels based power plant to renewal energy sources such as solar, wind, biomass, etc. Presently, the production source is centralised and the flow of electricity is in one direction from generation to distribution. The future Smart Grid will support distributed generation which requires integration of this intermittent energy source with the existing grid. Integrating this unpredictable source into the main grid is a problem as it may seldom reverse the electricity flow from the consumer to the grid in case of excess generation at home. Figure 2.1 illustrates the integration of different renewal energy sources in Smart Grid.

### 2.3.2. Energy Efficiency

The energy consumption by consumer can be reduced by replacing the appliances with energy efficient star rated appliances. According to the study by the American Council for an Energy-Efficient Economy (ACEEE), there is a possibility of reducing the energy consumption from existing 35% to 7% if the near-commercial semiconductor components are used [39].

A research study conducted by CSIRO, Australia “Energy Efficiency Standard for Residential Buildings” reveals that heating/cooling consumes the maximum energy in a house. The refrigerators and air-conditioners consume the highest energy in 5-star rated homes. A significant energy saving can be achieved by changing the temperature by 1$^{o}$C.

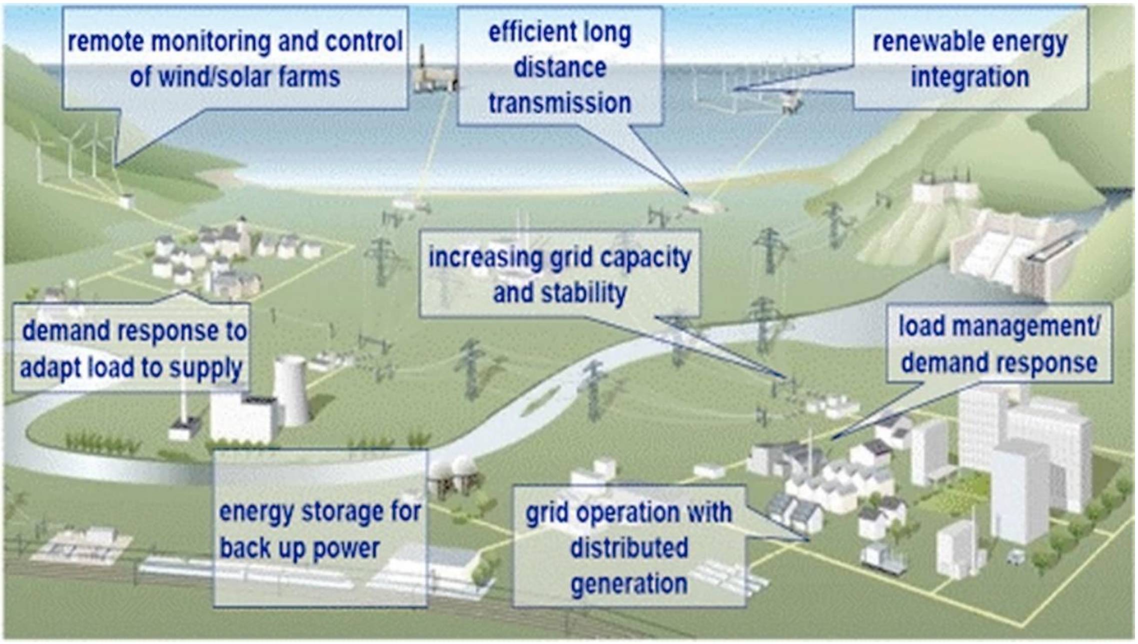



Fig. 2.1 Integration of renewal energy sources [Courtesy: ABB]

Another method that can be adopted is based on energy profiling the appliances under various load condition. The idea is to disaggregate the total electricity consumption at end-user and undertake individual appliance profiling with an objective to generate a signature pattern of appliances under various condition. This signature pattern under different load conditions can help in generating Unique Appliance Signatures (UAS). This UAS can be stored for comparison/analysis and recognition of appliance/machine using Artificial Intelligence learning techniques [43]. The appliance profiling, generation of unique signatures and recognition of a signature pattern is one of the upcoming research area.

### 2.3.3. Energy Storage

The energy storage technology allows storing excess energy from renewable energy sources during the off-peak time, which can be used during peak time. The development in the storage technology is still ongoing which is yet to be perfected for long hours of use. The energy storage technology will reduce reliance on the main grid and it will be very helpful in the time of emergency.

### 2.3.4. Demand-Side Management

Demand response or DSM implies deviation from normal consumption patterns of electricity by end-use in response to changes in electricity pricing/other consideration reported by utilities. Peak demand increases the load on the transmission and distribution networks, which can be offset by the Peaker plants. In case of dynamic pricing scheme, the wholesale price of the electricity will also increase. DSM provide incentive to customer and encourage them to reduce the electricity usage at peak time. Therefore, demand response is a mechanism in grid network that balance the demand and supply of electricity and respond to changes in the supply side [44]. It allows the utilities to control the loads and optimise the power flow across the network.

Utilities monitor and control the demand information in real-time. Customers will also receive information about dynamic pricing of electricity. The time of use electricity pricing can be managed through colour code representation by the utilities like blue for low, white for medium and red for high energy demand. This colour code may also indicate the possibility of energy demand the following day [45]. The energy use can be scheduled based on colour code, shifting some non-critical activities such as dishwashers, dryers, ovens, etc. from peak load time to low load time.

The demand response provides opportunities to improve the planning and operation of the power system. The benefits of demand response are [44, 45]:

- Improving system security and reducing the risk of blackouts;
- Planning additional generation or upgrading the existing grid;
- Reducing greenhouse gas emissions.

Studies have shown that pricing incentive alone will not help in adoption of demand-side management. The lack of awareness in pricing scheme and the lack of infrastructure to support the scheme are the main drawback in the implementation of demand response [39]. Figure 2.2 depicts one instance of demand response system in HAN.

Demand Response is closely associated with distributed energy resources, AMI and smart home and building automation systems. AMI is responsible for communicating the energy requirements (electricity, gas and water) to the users and utilities. Similarly, the EMS in the HAN is responsible for scheduling the consumption of energy in each house to minimise the total electricity bill.

### *2.3.5. Advanced Metering Infrastructure (AMI)*

AMI is an important component in home energy management system that comprises of a Smart Meter, Data Concentrator (DC), a communication module and Meter Data Management System (MDMS). The structure of AMI is depicted in Figure 2.3 [39, 46]. The meter data is collected by the DC and stored in MDMS. The data of MDMS can be analysed by the user and the service provider to get insight into the metered data. The geographic information system (GIS) and consumer information system (CIS) can also be integrated with this system to get deep insight into the data [47].

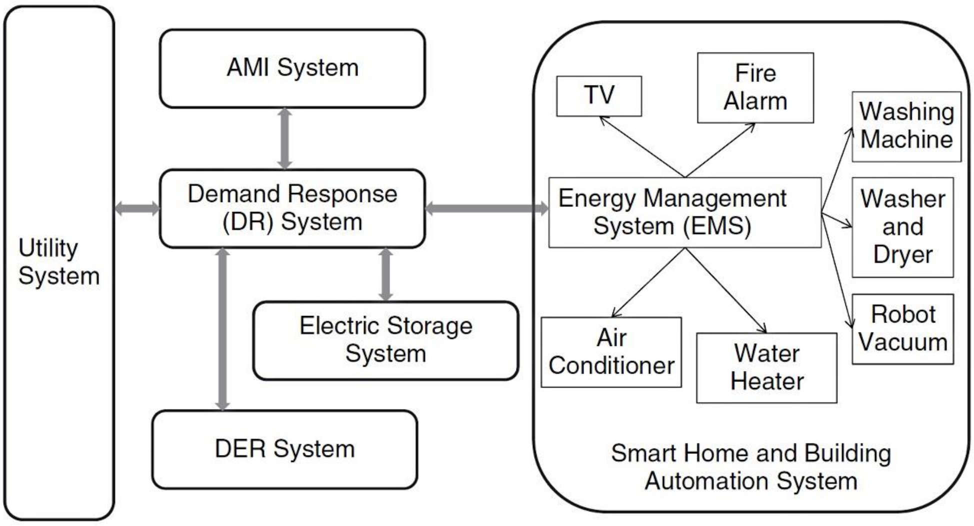



Fig. 2.2 Systems of demand response in HAN [39]

The smart meter is an interface between the utilities and consumer that help in management and planning of electricity demand. Real-time monitoring of consumption empowers the consumer to take measures to reduce electricity usage. Additionally, smart meters interact with utilities to get dynamic pricing information. Different kinds of pricing scheme proposed in literature are as follows [22, 44]:

- Time of Use (ToU) tariff: This is a static pricing scheme that is pre-determined based on demand and supply of electricity. The consumer is aware of this pricing and they are encouraged to shift their consumption from a peak-load time to off-peak time. Thus, consumer can shift non-essential job such as laundry, dish washing, etc. from peak time to off-peak time.

- Real-Time Pricing (RTP): RTP is a dynamic pricing scheme of electricity that changes hourly/half an hourly depending on supply and demand. It encourages consumers to consume the electricity when the price is low and refrain from consumption when the wholesale price of the electricity is high.
- Coincident Peak Pricing / Critical Peak Pricing (CPP): CPP tariffs is a ToU rate with a dispatchable high or “critical” price during periods of system stress. The critical price is limited to few days/hours per year when the system is severely under stress such as natural calamities (storm, flood, etc.), festival, new year celebration, etc. The customers will receive notification of high price in advance through automated control system.

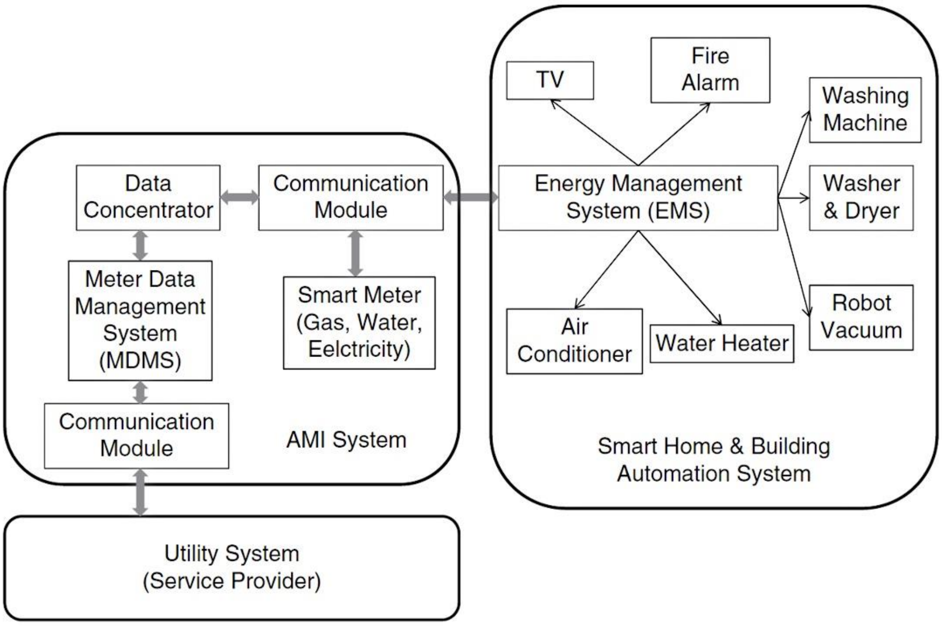



Fig. 2.3 AMI structure [39]

### *2.3.6. Quality of Service (QoS)*

Smart Grid manage and collect real-time information from established IEDs for control and automation purposes. It may also need to provide QoS over different physical media. In a case of faults, Smart Grid should have a provision to provide buffer energy to sustain the blackout for few seconds/minutes before knowing the status of the privileged customer. The privilege lighting can be categorised based on class A, class B, or class C customer depending on QoS requirement [7]. For instance, customer having class A category will continue to receive the electricity from buffer energy source in emergencies [13].

### *2.3.7. Phasor Measurement Unit (PMU)*

The PMU has become an important component of Smart Grid which is used to measure voltage and current phasors of the AC waveform and its harmonics in wide area measurement system. Due to synchronised time stamping PMUs are also called synchrophasor. Phasor values (amplitudes and phase) of voltages and currents are identical everywhere on the network. The measured data are:

1) Change in the status of any switch and
2) Currents and voltages status sampled at a high frequency (over 50/60 times per second) called phasor measurement [15, 26].

This phasor values are time-stamped using a common clock synchronised to highly accurate GPS system [27]. PMUs help to monitor the health of grid globally.

The Flexible AC Transmission System (FACTS) and High Voltage Direct Current (HVDC) are helpful for power flow, fast dynamic voltage control and stability control in power grid. It also increases utilisation of transmission system [22]. Both HVDC and FACTS will help to achieve better stability control and avoid system blackouts by using the capabilities of Wide Area Stability Control and Protection Systems.

### *2.3.8. Sensing and Measurement:*

Smart Grid power management require frequent meter readings, demand response and device management. The PMU and smart meter under AMI are the key components capable of providing power protection, monitoring and control. These devices can provide two-way communication with the control center of the service provider.

Advanced instrumentation and sensor technologies are required for communications and computing between devices and IEDs. Monitoring the health and stability of Smart Grid is the core duties of the control center. Sensors oriented machine interaction is essential in the complex decision-making process. Smart sensors are expected to provide system-level information obtained from the state measurement modules, based on PMUs [2]. The self-healing capability of Smart Grid is based on proactive actions of AMI, dynamic line rating, digital protective relays, time-of-use and real-time pricing [28].

### *2.3.9. Power System Protection*

If the sources of the instabilities and imbalance in Smart Grid can be removed from the system, the system will enter equilibrium state [48]. The electrical system will continue to remain in the steady state condition if it is not subjected to abnormal conditions due to faults/failures in the system. The common reason for faulty or flashover in lines is a lightning strike.

The predictive fault detection, isolation and restoration (FDIR) is an important protection mechanism of power system. FDIR work through three phases [48]:

1) Fault detection (a monitoring event);
2) Fault isolation (a control event) and
3) Restoration (a management event).

These steps will be automated by digital systems attached to edge devices, according to a pre-programmed algorithm.

Presently, when a device fails, the failure may not be discovered until another event occurs and the discovery process takes a longer time. If the pattern of disturbance and fault can be classified and decoded properly, the time taken to detect the disturbance can be reduced. The types of disturbance that can be easily detected are line trip, generation trip (load shedding) and oscillation, but categorising these disturbances in real-time is difficult [49]. The mathematical model to classify common disturbances pattern can be developed to proactively safeguard the electrical system.

#### *2.3.10. Teleprotection*

Teleprotection refers to notifying faults by the protection devices through alerts/signals in relay-to-relay transmission system between adjacent substations. Teleprotection should provide low latency point-to-point communication. The protection device will take protective action by tripping the power system and isolating the region of fault. The IEEE1646 standard specifies the latency requirements to tripping should be 1/4 of a cycle which is equivalent to 4ms and 5ms, for 60Hz and 50Hz AC frequencies respectively [6].

The priorities of teleprotection signals is highest in a communication network. The consequences of missing deadlines for teleprotection signals is very disastrous; therefore, the redundant communication links are provided between substations for safety. The utilities may use Multiprotocol Label Switching and virtual private networks for low latency teleprotection system.

#### *2.3.11. Security*

The increased deployment and penetration of ICT in the management of the grid makes it vulnerable to attackers and hackers. The various attacks scenarios prevalent in the data network such as denial-of-service attack, brute force attacks, botnet attacks, etc.

have potential to cripple the grid. Similarly, the end-devices is also vulnerable to attack due to malware, virus and worms which may steal critical information from the system or mislead the system by giving false information. The breach of grid security is catastrophic, so the grid should be under the constant surveillance of competent person to eliminate the possibility of attack. Developing the Trust management system and authentication of messages are very essential [50].

### *2.3.12. Database Structure*

The quality of data characterised by accuracy, timeliness and relevance to the task are important parameters for smart decision [27]. Smart Grid is distributive in nature and the database has wide variability from system to system. Fast and quick response to database queries is the key requirement of any database system. The data management system lacks common standards due to multi-vendor systems installed in the grid. Therefore, normalisation of a database should be done before extracting information.

The size of the database is enormous and complex in Smart Grid which also include temporal and geographical information. So, a strong transactional processing system is required for timely delivery of database queries. Cluster computing may be used for distributed data processing by using Map Reduce and Hadoop, a Big Data management tools. Figure 2.4 gives the basic architecture of database engine for Big Data [7].

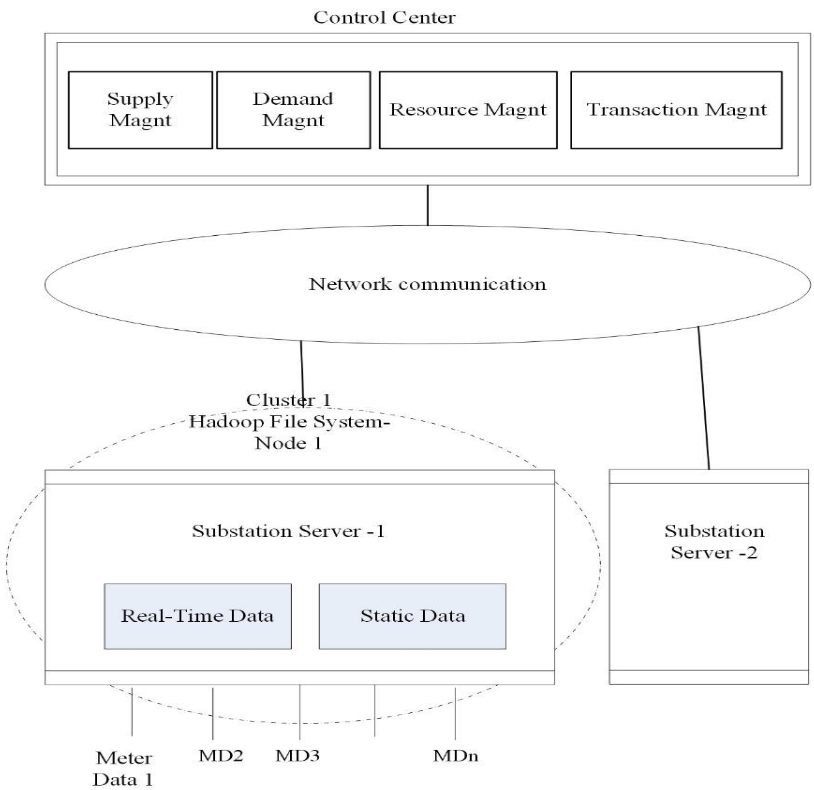



Fig. 2.4. Database structure and communication model [7]

## 2.4. Standards

The Standards Developing Organizations have been trying to develop standards to promote interoperability and harmonization in technology. An overview of the different standards in Smart Grid is given in subsequent sub-sections.

### 2.4.1. National Institute of Standards and Technology (NIST)

The National Institute of Standards and Technology (NIST) has proposed a conceptual model of Smart Grid depicted in Figure 1.3 [13, 15]. This conceptual architectural reference model divides the Smart Grid into seven domains for better operation & control, fast information exchange and smart decisions making. The seven domains are customers, markets, service providers, operations, bulk generation, transmission and distribution. The purpose of each domain is as follows:

1) Markets: This consists of buying and selling of electricity through bidding by the electricity market operators and participants. Additional operations are frequency and voltage regulation based on feedback received from this domain.
2) Operations: The objective of this domain is to support reliable and smooth power system operations, monitoring and control through SCADA and EMS. Additional management function includes fault management, operation planning and asset maintenance.
3) Service providers: The service provider gives electricity services to customers and keep record of billing, management and other services.
4) Bulk generation: This domain deals with electricity generation based on demand which is connected to transmission and distribution. It also deals with integrating renewal sources to the bulk generation.
5) Transmission: The transmission of electricity to the distribution sites through overhead lines and transformers with minimum energy losses is the functions of this domain.
6) Distribution: The distribution of electricity to the customer is the objective of this domain. It maintains the flow of electricity by balancing the demand and supply.
7) Customers: The customers are an electricity user at household, commercial and industrial complex. This domain is related to the distribution. It supports AMI, demand management, electricity pricing, etc.

### 2.4.2. International Electrotechnical Commission (IEC)

IEC has given a roadmap in 2010 related to communication, security and planning in Smart Grid. IEC has given guidelines for 13 items, that are as follows [39]:

(i) Smart transmission system and transmission level applications,
(ii) Blackout prevention/EMS,
(iii) Advanced distribution management,
(iv) Distribution automation,
(v) Smart substation automation-process bus,
(vi) Distributed Energy Resources (DERs),
(vii) Advanced metering for billing and network management,
(viii) Demand response/load management,
(ix) Smart home and building automation,
(x) Electric storage,
(xi) E-mobility,
(xii) Condition monitoring and
(xiii) Renewable energy generation.

The IEC61850 is a standard proposed to solve the issues of interoperability between IEDs of different vendors. It also gives the design of electrical substation automation system. The IEC61850 breaks down a physical device into logical devices, which is further broken down into Logical Nodes, Data Objects and Data Attributes as depicted in Fig 2.5 [51].

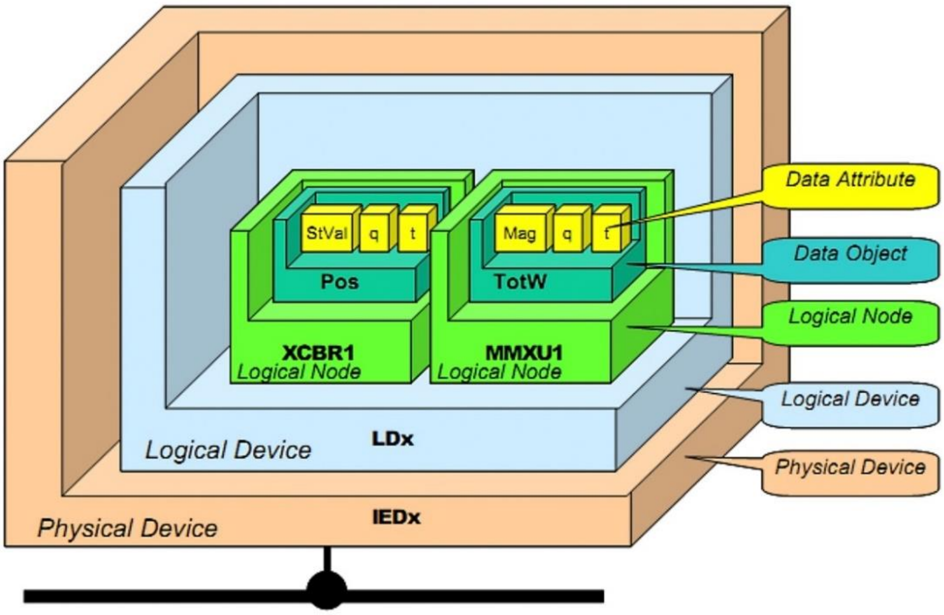



Fig. 2.5. IEC 61850 data modelling [51]

The different performance classes are mapped to different communication protocols in IEC61850 to support the specific requirement of various message types. The mappings supported are:

- GOOSE (Generic Object Oriented Substation Event);
- Time Sync and GSSE (Generic substation status event);
- SV (Sampled Values) and
- MMS (Manufacturing Message Specification)

which is also depicted in Figure 2.6. The message types that have similar performance requirements are grouped together and mapped to the same protocol. For instance, the type 1 and 1A messages are very time critical so that they are mapped to GOOSE and directly mapped to Ethernet to reduce processing time. The raw message type 4 is mapped to SV which is a protocol designed to carry raw data and is also directly mapped to Ethernet to achieve time-critical performance. Type 6 message represents time synchronised message type which is mapped to the Simple Network Time Protocol.

GOOSE and SV are directly mapped on Ethernet, but direct mapping on Ethernet has a disadvantage. This types of messages cannot be routed over WAN, which is essential criteria for teleprotection. MMS and GSSE are the other protocols that support transfer of real-time process data and supervisory information between networked devices and control center. MMS also supports the mapping of the core Abstract Communication Service Interface (ACSI) services for complex naming and services models.

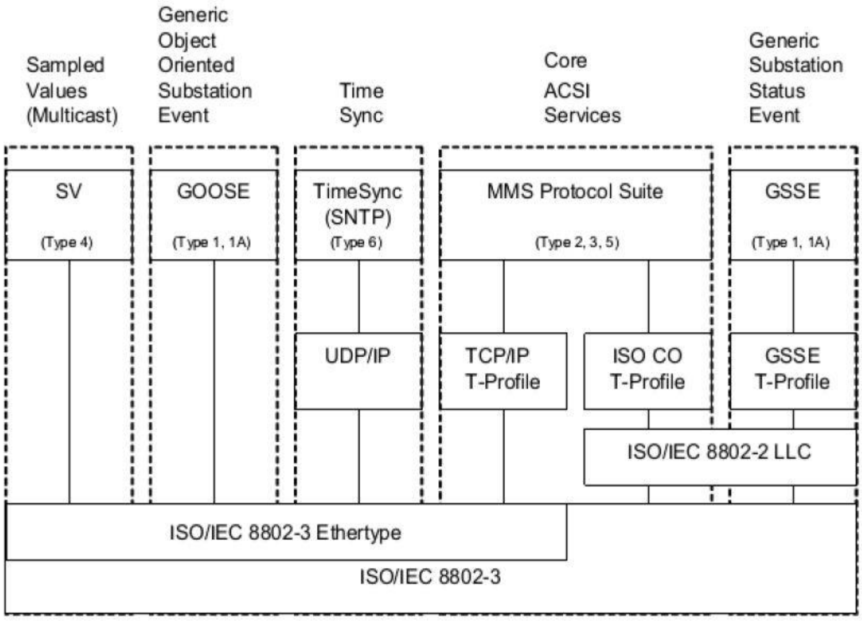



Fig. 2.6 Overview of functionality and profiles [51, 52]

The self-healing and resilient are the two important characteristics of Smart Grid research. The automation of distribution grid is an essential characteristic in Smart Grid development because 90% of the power outage and disturbance have the root cause in distribution network [53]. The first step in the transition to Smart Grid is to make microgrid smart which is the front-end of distribution. This smart microgrid must co-exist with older grid for the smooth functioning because it is very difficult to wright-off old installation.

There are many active research groups working in academia and industry to make feasible implementation of Smart Grid. Some standards have been developed and some are still under development phase. Some industries are developing prototypes of Smart Grid. The next generation of standards will converge all standards of Smart Grid for better interoperability.

## *2.5. Summary*

The electrical grid is a network of power utilities, consumers and communication devices engaged in sharing of data at multiple levels. Fast, reliable, secure and multi-way communication is important for the success of Smart Grid. So, communication backbone is significant for the transfer of data in Smart Grid. This chapter identified and discussed the main drivers of Smart Grid along with the challenges in their implementation. A comprehensive review of main drivers of Smart Grid is presented in this chapter. Additionally, interoperability and harmonisation of devices is an important issue in Smart Grid. A review of standards is also presented in this chapter.

# CHAPTER 3

## SMART GRID COMMUNICATION AND NETWORKING

### *3.1. Communication*

European Technology Platform defines Smart Grid as given in reference [37]:

"A Smart Grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.

A Smart Grid employs innovative products and services together with intelligent monitoring, control, communication and self-healing technologies to:

- better facilitate the connection and operation of generators of all sizes and technologies;
- allow consumers to play a part in optimising the operation of the system;
- provide consumers with greater information and choice of supply;
- significantly reduce the environmental impact of the whole electricity supply system and
- deliver enhanced levels of reliability and security of supply."

The Smart Grid stand for monitoring, control, communication and self-healing of grid. Fast, reliable, secure and multi-way communications are crucial to the success of Smart Grid. The importance of the communication between different entities are depicted in Figure 3.1 [7].

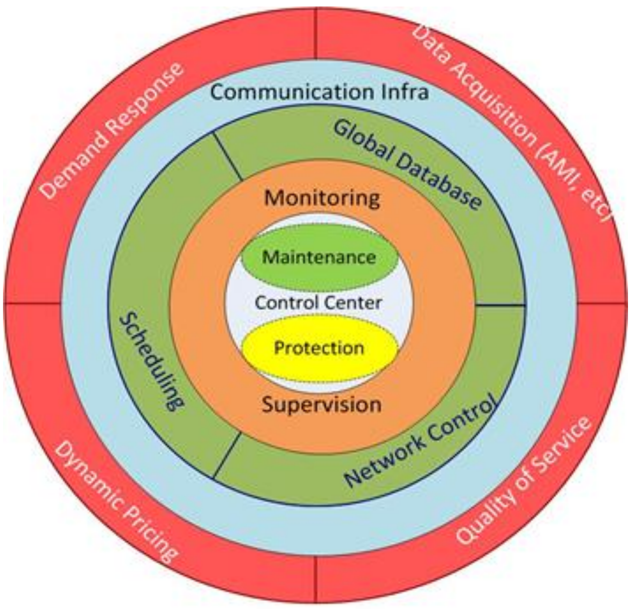



Fig. 3.1 The layered architecture of Smart Grid Functions [7].

SCADA has been used to monitor and control electrical power grid for many decades. SCADA is effective for high voltage transmission networks in limited area, but it is not suitable for large-scale monitoring and control [41]. There is a need for distributed monitoring system at micro and macro level.

There are many research group working in industry and academia to support innovation in Smart Grid. The EU ADINE is one such research project on Active Network Management that uses automation, ICT and power electronics to exploit resources management in Smart Grid [41]. This project made recommendations for mobilising resources in four keys areas namely:

- protection relay and fault location;
- coordinated protection planning;
- voltage control with microturbine and
- centralised voltage control with SCADA/DMS.

It has been observed that nearly 90% of all disturbances and power outages have their causes in the distribution network [53]. Therefore, modernising the distribution network is a priority in Smart Grid evolution. The transition to Smart Grid addresses many issues in pervasive operation, control and protection which is depicted in Figure 3.2.

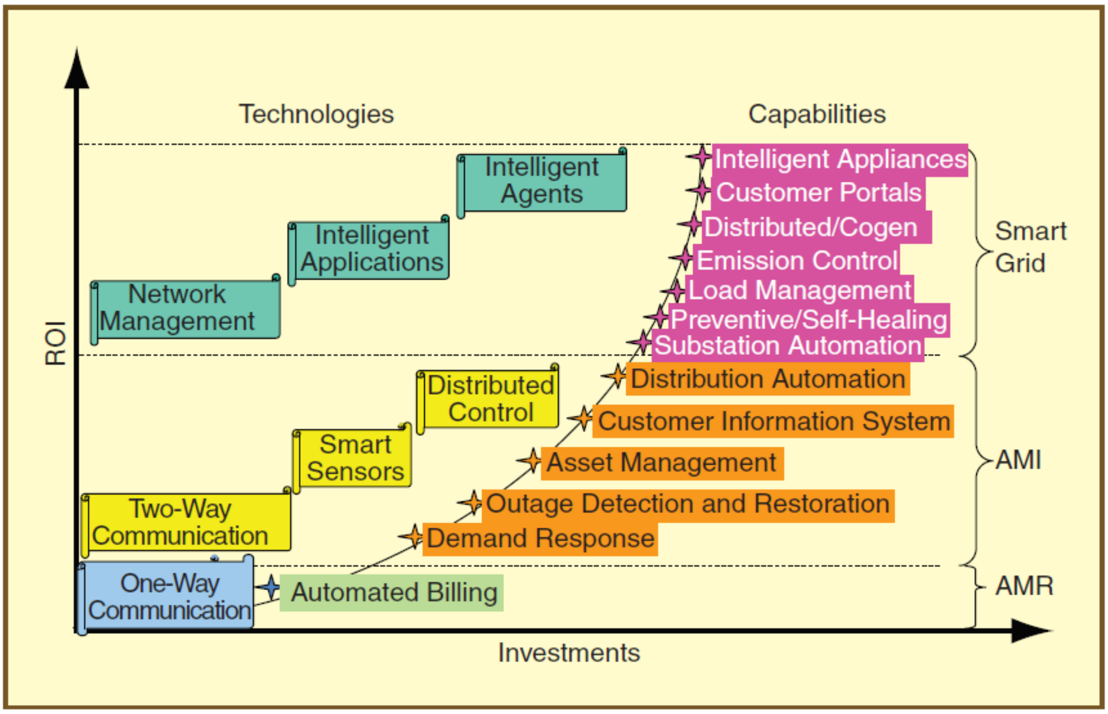



Fig. 3.2 Smart Grid returns on investments [53]

## 3.2. Smart Grid Communication Architecture

The communication network in Smart Grid requires interoperable multi-way communications between the different devices, applications and protocols for secure end-to-end communications with low latencies. Moreover, the system should ensure security to prevent cyber-attacks. The packet-switched data network is useful to provide the best effort services using the networking protocols (e.g. TCP/IP, FTP, etc.), addressing scheme, services types, etc. The ideal communication should have a common semantic (data model), common syntax (protocol) and a common network concept for the convergence and a harmonisation between different communication sub-systems.

Typically, two types of information flow in a Smart Grid system. The first flow is top-down from energy generation to energy consumption at load level and the second flow is bottom-up from the smart meters at the customer premise to the data centers of utility. The first type of data flow can be accomplished either through power line communication or traditional carrier communications. The second type of information flow is a flow of data which is bit complicated because of diversity at the distribution level. Figure 3.3 depicts the flow of energy and data in Smart Grid.

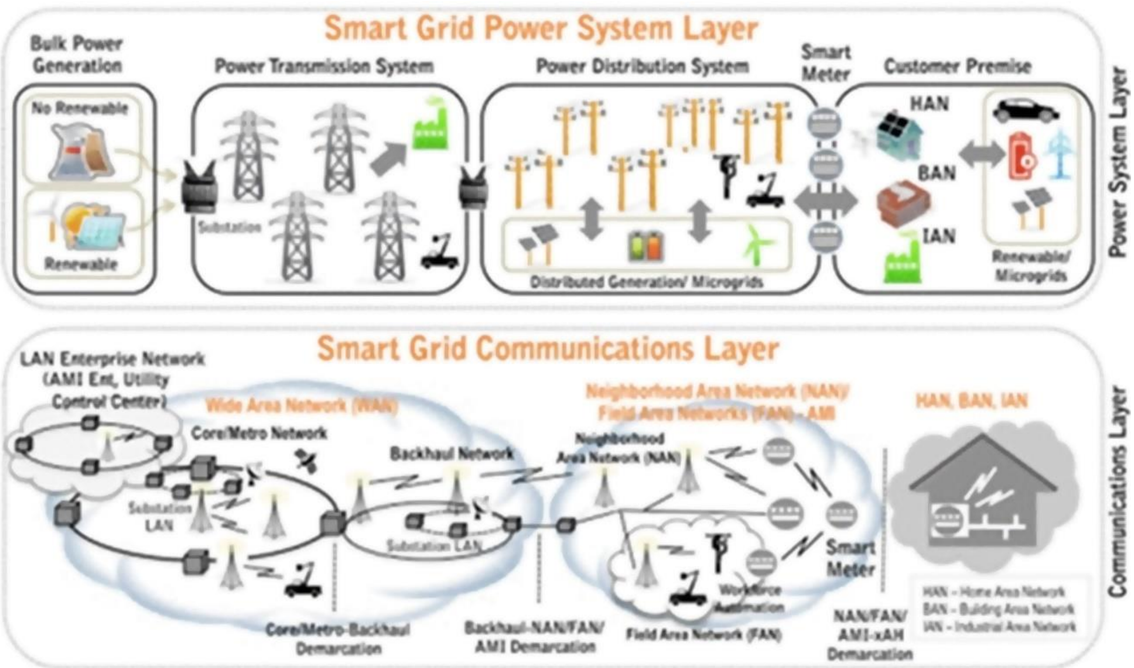



Fig. 3.3 Smart Grid communication architecture

The geographical spread of information and communications network in Smart Grid is very wide which integrates power generation, transmission and distribution. Figure 3.4

depicts multi-layer system architecture of Smart Grid which elaborates the different category of network [12]. The distribution side of Smart Grid has HAN for in-home appliances and NAN - the aggregation of many HAN connected to a local energy provider. The WAN is again an aggregation of many NAN that are connected to the central control system of the utility.

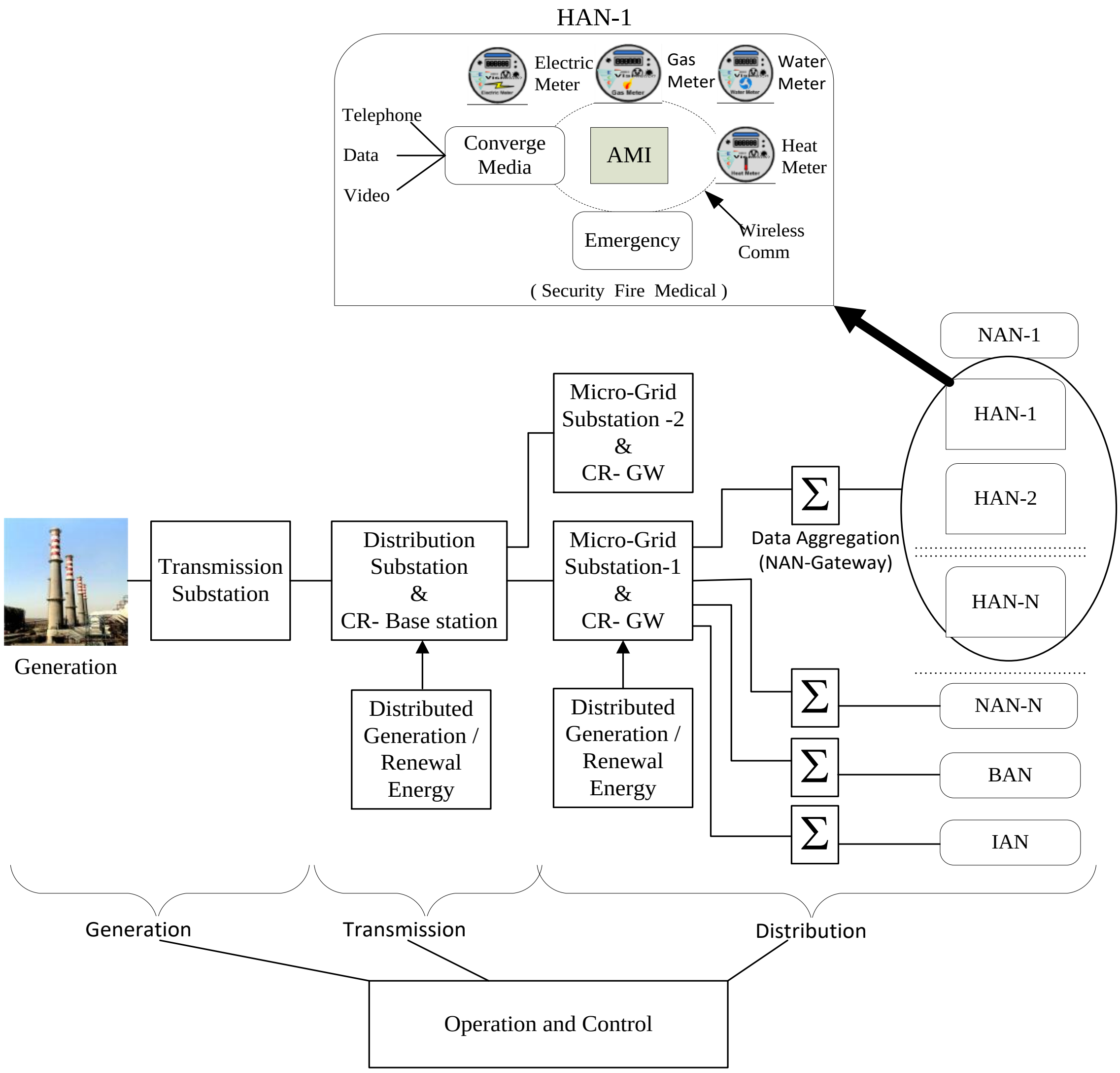



Fig. 3.4 Multi-layer network communications architecture [12]

HAN managed by AMI, support communications between smart appliances, smart meters, IEDs, EMSs, applications and consumers. The common code for real-time communication requires a highly accurate GPS clock for system-wide time synchronisation. The AMI systems include hardware, software, sensors apart from MDMS, monitoring and control. The meter of electricity, natural gas, water and heat are important components in AMI infrastructure. The extension of GPS enabled AMIs can provide support for emergency services such as police, ambulance and fire through SOS. On a broader term the AMI can even provide services of Telephone, Internet and

Cable TV on converged media if all the service agrees for the common platform. Thus, AMI can deliver integrated services in HAN at low cost if the service provider so desires.

### *3.2.1. Local Area Network/ Home Area Network*

A LAN is a network of computers and devices in a small geographical region such as home, building, etc. LAN is a part of layer 2 switch that shares the resources within the network. LAN can be Ethernet type wired connection or Wi-Fi based wireless connection. It is most widely used network protocol that has been used widely for many years. A new standards ITU-T G.hn is being developed that support 1 Gbits/s over legacy wired LAN such as coaxial cables, telephone lines and power lines [54].

Most of the time the long-haul network or the core network will be wired with fibre optic as the medium of choice. The LAN can either use wired or wireless system depending on system requirements, but there is a trade-off between the two media. Wireless medium has advantages in terms of cost of laying the infrastructure and ease of implementation, but suffer from bandwidth limitations, signal attenuation, interference, cross-talk, etc. The prominent wireless technologies that can be used at micro-grid level/HAN are IEEE802.11 (Wi-Fi), ZigBee, ultra-wideband (UWB), IEEE802.15.4, ZigBee, 6LoWPAN, etc. [2, 13, 22, 45]. On the other hand, Ethernet-based wired communication is a reliable medium, but the cost of laying wire up to customer premises is very high and time-consuming.

#### *3.2.1.1. Advanced Metering Infrastructure/ Smart Metering*

AMI can be the part of HAN that caters to HEMS. AMI is a network of smart meters, database system, network protocols and applications. The smart meters collect and analyse the energy consumption and demand data from home appliances for optimising the energy use and reporting the power quality to control center [46]. Additionally, GIS and a CIS can also help in demand management. All information processed and collected at consumer end in distribution management system are conveyed to a Smart Grid control center for data analytics and demand management [47]. There are some standards available for communications in AMI which are depicted in Figure 3.5 [55].

#### *3.2.1.2. Smart Utility Network*

Smart Utility network (SUN) co-exist with AMI and Home Energy Management for monitoring and control of utility system in the HAN. The SUN comprises of utility provider base stations (BSs), smart meters and data collectors that connects with NAN over wired/wireless link [56]. Smart meter can be used for automatic meter reading as part of utility automatic metering infrastructure. IEEE802.15.4 is also the part of SUN that operate in licence free band.

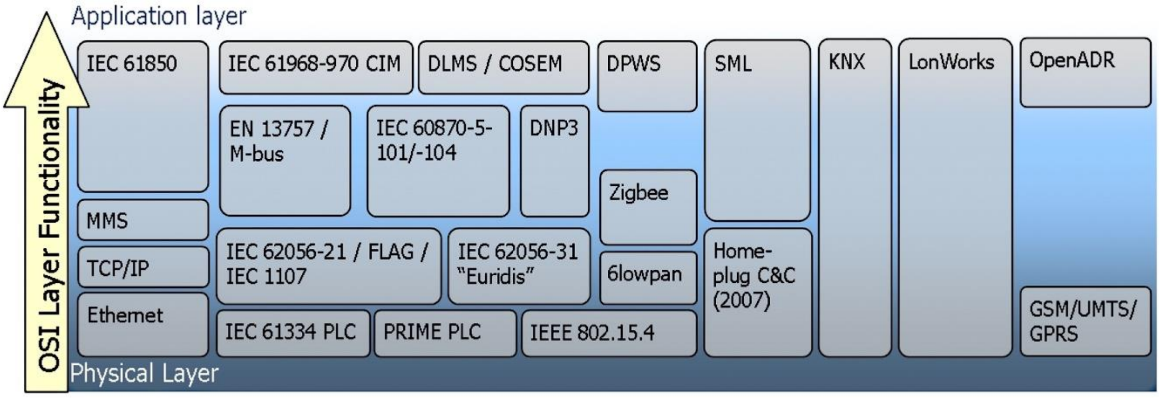



Fig. 3.5 Standards for AMI [55]

### *3.2.2. Neighbourhood Area Network*

The NAN is a buffer between HAN and WAN that aggregate the traffic in HAN and dispatch it to the utility's control center over WAN. The Field Area Networks (FAN) of utility is a special case of NAN.

#### *3.2.2.1. Field Area Network (FAN)*

In a power system network, WAN is referred to core network that interconnects substation automation, distributed generation and AMI with the control center [57]. The network of substations is called FAN which offer end-to-end connectivity between IEDs and Data and Control Center [27]. FAN gateway provides the interface between the Feeder Line communication and the substation.

The services supported by the FAN are AMI, demand response, distributed energy resources (including electric vehicle charging), etc. It also supports time-critical functions such as FDIR, conservation voltage regulation, power quality controls which are very important for system stability.

The interface router of the core network in WAN is called WAN router (WR). The FAN comprises of many such interconnected WR. The endpoints of FAN are connected to the cluster router in FANs which in turn are connected to the core network over wireless/wireline access points. The topology, placement and relationship between core-edge networks are illustrated in Figure 3.6 [27]. The placement of the WRs and cluster routers supports applications and traffic management of utility under various constraints and conditions. Similarly, the data aggregation at the substation is done by the cluster router. The cluster router in FAN collects data from different components at substations/microgrid which is depicted in Figure 3.7 [27].

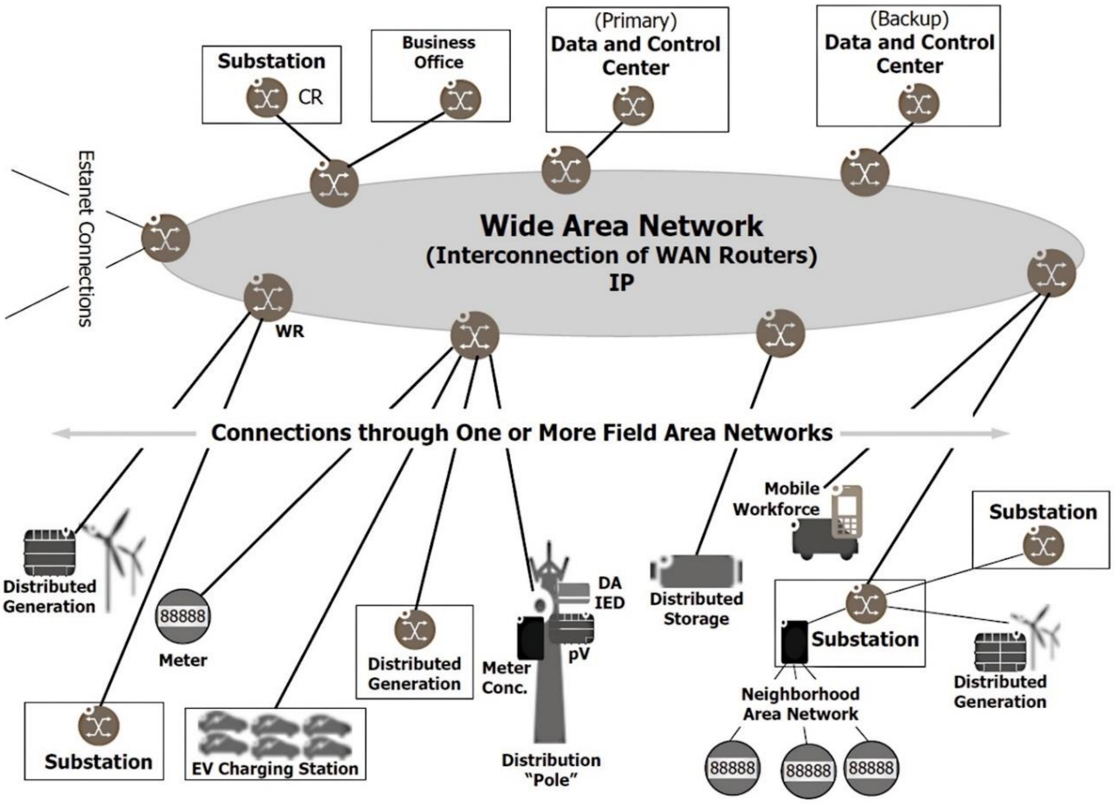



Fig. 3.6 FAN communication architecture [27]

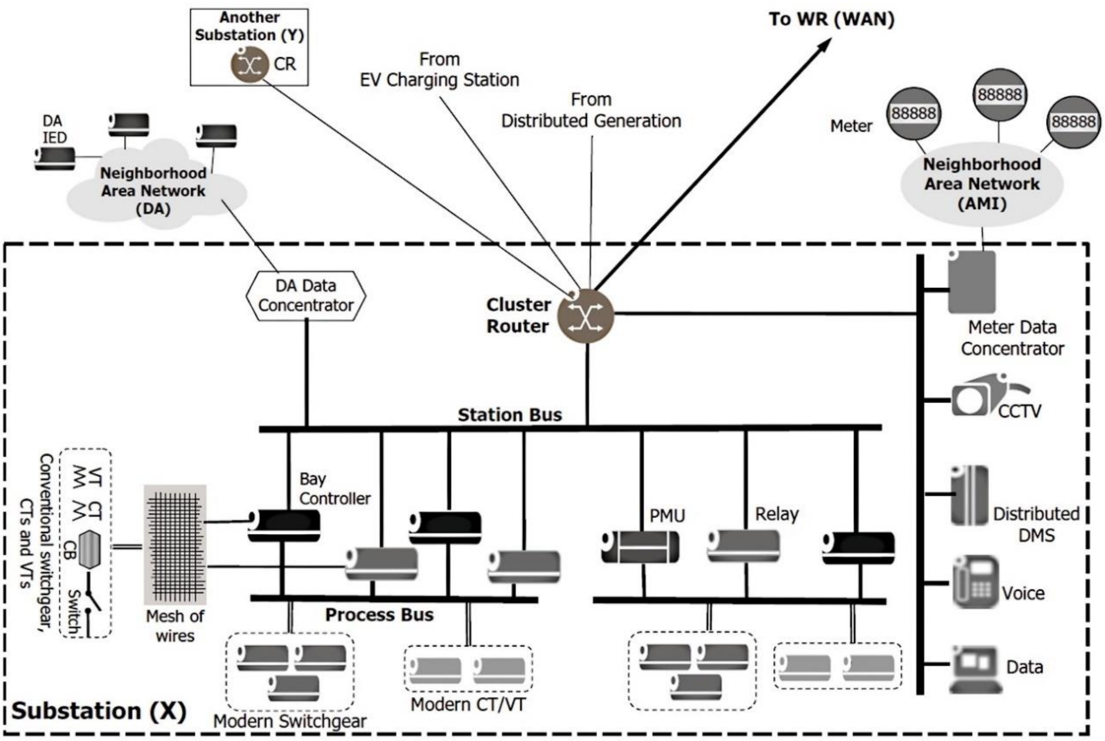



Fig. 3.7 Data traffic aggregation at cluster router [27]

### 3.2.3. Wide Area Network (WAN)

The WAN is referred as the core network of utilities that connects FAN and substations with the utilities' control center [27]. The geographic span of the core network of utilities may be a city, country, or continent. WAN comprises of diverse communication technologies over large area.

#### 3.2.3.1. Phasor Measurement Units (PMU)

Time resolution of PMU is milliseconds, which means the sampling will take place at a very high frequency which will generate large volumes of real-time data at regular intervals [26, 58]. The complex data structure which includes temporal, geographical and statistical information data must be transferred to the control center for onward processing.

A special type of PMU network called frequency monitoring networks uses Frequency Disturbance Recorders (FDRs) to monitor the phase angle, amplitude and frequency of a voltage source in an electrical grid. The FDRs display unit name, IP information, connection status and dynamic frequency curve to analyse the quality of the signals [56].

### 3.2.4. Machine to Machine (M2M) Communication

M2M is a new paradigm that enables different devices such as sensors, controllers, wireless devices, etc. to interact with each other without human intervention. One of the enabling technology in the M2M communication is IPv6 which enable addressing every device in the network. But, IPv6 has resulted in the increase of the message header which inhibit development of energy-efficient devices.

Smart Grid is one of the applications in the M2M communication that increase the level of automation and coordination in the systems. M2M communication also cover other areas such as intelligent transportation systems, supply chain management, e-healthcare, surveillance and security.

M2M communication and IoT when it uses cloud-based applications leads to evolution of new communication paradigm called Cyber-Physical System (CPS). CPS define more deeper level of M2M communication which is termed as process to process communication which is the hallmark of the next generation communication. The architecture of CPS is illustrated in Figure 3.8 [59]. All the applications have backend server at one end of the paradigm which is connected to high-speed communication link to the user at the other end.

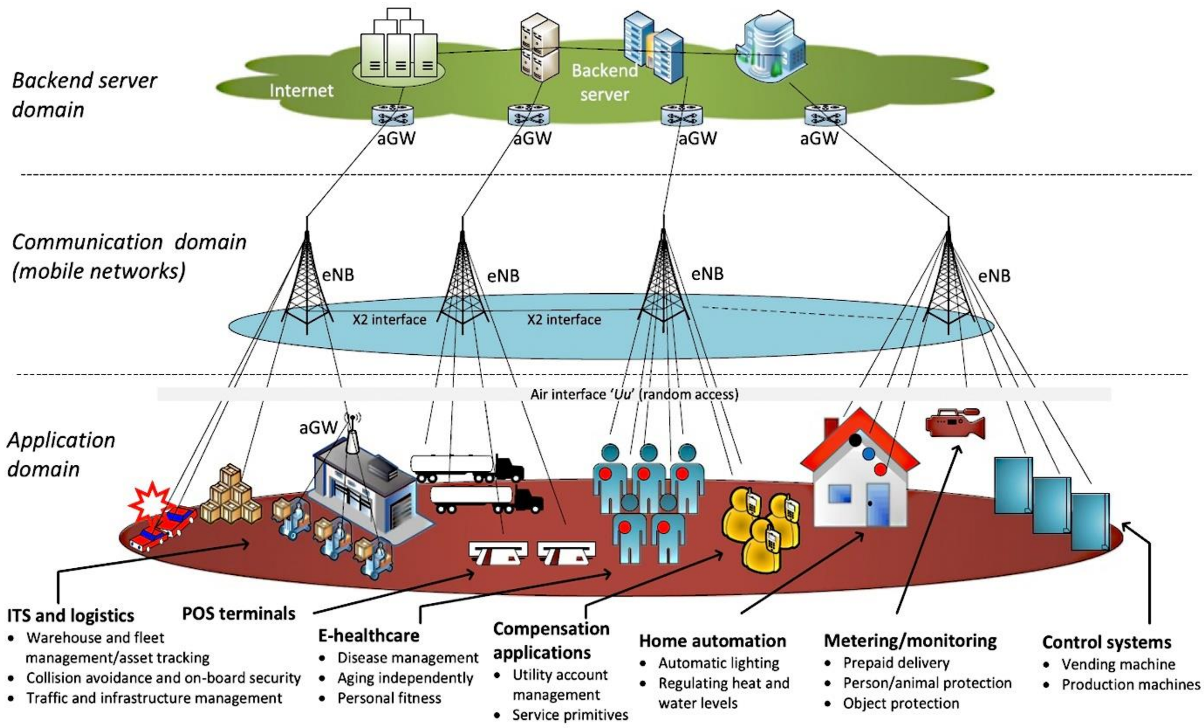



Fig. 3.8 Overview of M2M communication [59]

The data traffic generated at the network could be at regular interval called periodic or aperiodic/bursty, fixed rate or variable rate. Different communication model can be defined based on generated traffic. The large volume of data generated must be optimised for reliable communication.

### *3.2.5. Internet of Things (IoT)*

M2M communication is a subset of another communication technology called IoT. The enabling thing in IoT is the pervasive deployment of sensors, actuator, RFID tags, mobile devices, etc. The IoT paradigm enables seamless information exchange between any device/thing in the network to improve the quality of life. Figure 3.9 shows the relationship between different applications, M2M communication and IoT [60]. For the IEDs/machine/device/cyber-physical system to be successful with its peer IEDs/machine/device/cyber-physical system, the latency requirements must be strictly met.

### *3.2.6. Power Line Communications (PLC)*

Power Line Communications (PLC) is one of the potential communication technologies for the device to device communication in Smart Grid. The reason for PLC not becoming a feasible communication technology is due to attenuation of high frequencies signals in power line [41]. Moreover, the feeder cables are not designed for data communication which is prone to interference from the inverter signals. Therefore, PLC is having inherent limitations which make it inefficient for communication.

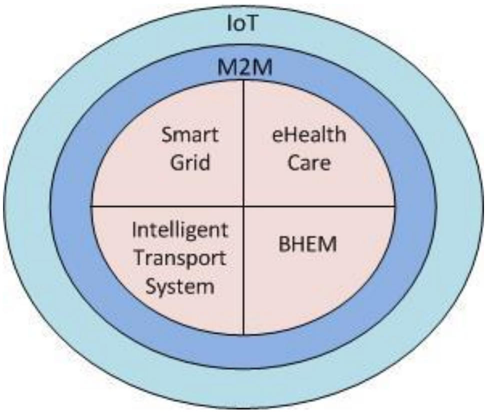



Fig. 3.9 Relationship between IoT, M2M and applications [60]

## *3.3. Communication Requirements*

Communication superhighway is required for ubiquitous connectivity and system-wide real-time monitoring. The Smart Grid comprises of many IEDs which need seamless communication with other heterogeneous devices. Harmonisation of standards and technologies is one of the priorities in device/machine to device/machine communication. Also, M2M communication should address the challenges of interference, energy efficiency and interoperability.

Different communication technologies used for different networks is given in Table 3.1 [27, 61]. A summary of communication parameters used in Smart Grid is also given in Table 3.2 [1, 61-63].

Table 3.1 Communication Technologies

| | Application Area | Technology | |
|---|---|---|---|
| | | Wired | Wireless |
| 1 | Personal Area Network | USB based data cable, FireWire | ZigBee, Bluetooth, Ultrawideband (UWD), 6LoWPAN, RFID |
| 2 | LAN/ HAN | Ethernet | Wi-Fi, ZigBee, CR |
| 3 | NAN/ FAN | FDDI, ATM, xDSL | Cognitive Radio, LTE, WiMAX, Microwave |
| 4 | Regional Area Network/ Metropolitan Area Network | FDDI, ATM | Cognitive Radio, LTE, Microwave |

Table 3.2 Specifications of different communication technologies

| | Technology | Spectrum | Data Rate | Range | Limitations |
|---|---|---|---|---|---|
| 1 | Global System for Mobile (GSM) | 900-1800 MHz | Up to 14.4 kbps | 1 – 10 km | Low data rate |
| 2 | GPRS | 900-1800 MHz | Up to 170 kbps | 1 – 10 km | Low data rate |
| 3 | 3rd Generation (3G) | 1.92 – 1.98 GHz<br>2.11 – 2.17 GHz | 384 Kbps – 2 Mbps | 10 km | Not suited for large data application, high cost of usage due to licensed band |
| 4 | Long Term Evolution (LTE) (4G) | 800 – 3500 MHz | 100 Mbps Downlink<br>50 Mbps Uplink | 30 km | Not readily available, High cost of usage |
| 5 | Wi-Fi (IEEE 802.11) | 2.4 GHz, 5 GHz | 54 Mbps | 100 m | Short distance, security issues |
| 6 | Bluetooth (IEEE 802.15.1) | 2.4 GHz | 3 Mbps | 100 m | Short range, chances of interference |
| 7 | ZigBee (IEEE 802.15.4) | 2.4 GHz, 868 – 925 MHz | 250 kbps | 50 m | Low data rate, short range, high chance of interference |
| 8 | WiMAX (IEEE 802.16) | 2.5 GHz, 3.5 GHz, 5.8 GHz | Up to 75 Mbps | 10 – 50 km (LOS)<br>1 - 5 km (NLOS) | Not widely available |
| 9 | Cognitive Radio (IEEE802.22) | 54 – 862 MHz | 19 Mbps | 30 km | Chances of hopping from one channel to another, prone to interference |
| 10 | PLC | 1 – 30 MHz | 2 – 3 Mbps | 3 km | Noisy channel environment |

### *3.3.1. Communication Challenges*

The following are some communication challenges that need to be addressed for feasible communication in Smart Grid [58]:

1) Capability to transfer high volume data: There will be a large amount of data generated by the power generators, the consumers and the distribution system. Installing additional communication facilities will be very expensive and time-consuming. There are three ways to process large volumes of data:
    a. By exploiting the spatial and temporal correlation between the data;
    b. By using adaptive messaging based on QoS and security requirements and
    c. By using decentralised processing of data and filtering the information to be transmitted to the centralised station.
2) Extensive coverage: The spread of Smart Grid is so large that covering the entire network is a big challenge.
3) Cybersecurity: The system must be secure from cyber-attacks.
4) QoS support: The system must be able to accommodate different classes of service based on reliability, delay and throughput. The parameters that are essential for QoS are jitter, delay, throughput, connection outage probability, etc.
5) Interference mitigation: The co-channel interference or cross talk can affect the signal quality in wireless communication. Therefore, a mechanism can be developed to mitigate interference so that many users can co-exist in same range and frequency. Interference avoidance, interference detection and energy-efficient routing protocols, should be implemented to improve the battery life of all devices.

### *3.3.2. Latency Requirements*

Latency is the core issue in QoS requirements. Different types of applications in Smart Grid have different delay tolerance. The jitter and packet loss can be managed by providing high flow priorities to critical operations. Table 3.3 illustrates the priority and the latency requirements of different applications in Smart Grid [6].

## *3.4. Next Generation Communication Technologies*

Bandwidth limited wireless communication technologies of today are not capable to collect, store, retrieve and deliver modern day Big Data to control center in real-time due to congestion and other factors. Cognitive Radio is a next generation wireless technology that has the potential to overcome this drawback and work efficiently as reliable and secure communication medium for Smart Grid. Cognitive Radio can also help in the event of fault and system failure by reporting the fault and taking corrective action in self-healing. The Smart Grid communication can help in reducing the transmission and distribution losses associated with electricity in a traditional grid [56].

Table 3.3 Latency requirements for Smart Grid applications

| Priorities | Application | Application setting | Latency tolerance | Remarks |
|---|---|---|---|---|
| 1 | Teleprotection | All | 8 ms, 10 ms | For 60 Hz and 50 Hz respectively |
| 2 | PMU | Class A data service | 16 ms | 60 messages per second |
| 3 | Control Messages | | 100 ms | |
| 4 | Smart meter | Connect to many meters | 200 ms | Automated demand response |
| 5 | SCADA data: poll response | | 200 ms | |
| 6 | PMU | Class C data service | 500 ms | Post events |
| 7 | On demand SCADA | | 1 sec | |
| 8 | Monitoring | | 1 sec | |
| 9 | Smart Meter | Periodic meter reading | ≥ 1 sec | 1/2 reading per hour |

Cognitive Radio is context-aware intelligent communication technology, which allows opportunistic use of unused spectrum temporally by the SU through coordinated efforts, if it is not being used by the PU (i.e. licensed user of the spectrum) at a given time and location [7, 17, 64].

The spectrum allocation in Cognitive Radio system can be coordinated using tightly synchronised and highly accurate clocks. If a specific licensed spectrum band occupied by a SU is again required by a PU then the SUs switch to another spectrum hole or stay in the same band, altering its transmission power level or modulation scheme to avoid interference.

The following fundamental cognitive tasks associated with cognition cycle, also depicted in Figure 3.10 [17]:

1) Radio-scene analysis, which encompasses:
    - estimation of interference temperature of the radio environment; and
    - detection of spectrum holes.
2) Channel identification, which encompasses the following:
    - estimation of channel-state information (CSI); and
    - prediction of channel capacity for use by the transmitter.
3) Transmit-power control and dynamic spectrum management.

Tasks 1) and 2) are carried out in the receiver and task 3) is carried out in the transmitter.

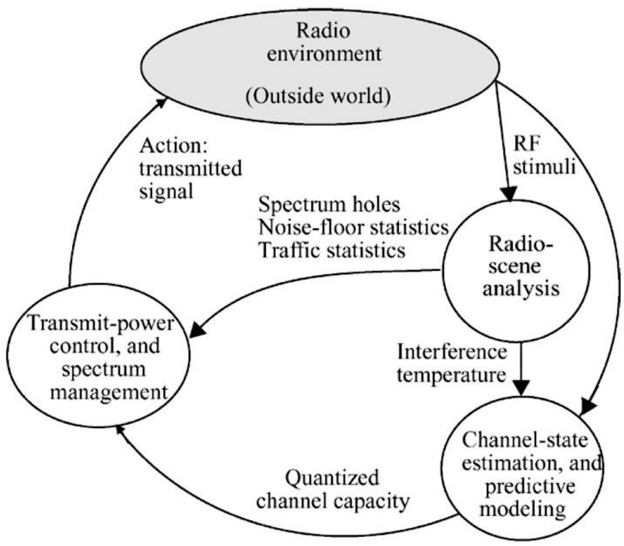



Fig. 3.10 Basics of Cognitive cycle [17]

Dynamic spectrum allocation is used for flexible use of spectrum. Artificial Intelligence and machine learning will become the “brain” of the Cognitive Radio that decides: “How to put “cognition” into the Cognitive Radio network”? The structure of Cognitive machine to machine model is presented in Figure 3.11 [19]. **Dynamic spectrum allocation** and **spectrum sensing** are the two important functions of Cognitive Radio.

### ***3.4.1. IEEE 802.22 WRAN***

The air interface of the WRAN is defined in IEEE802.22 standard [12, 20, 65]. The IEEE802.22 describes the protocol and specifications of the cellular network formed by the Base Stations (BS) and customer-premises equipment (CPE). The BS maintain the authentication, admission and authorization of CPE into the network. This standard is also endorsed by IEC another standard making body. IEEE802.22 support co-existence of licensed TV band and unlicensed broadband network in rural areas for optimal use of wireless bandwidth. It allows opportunistic use of unused TVWS by the SU if it is not being utilised by the PU.

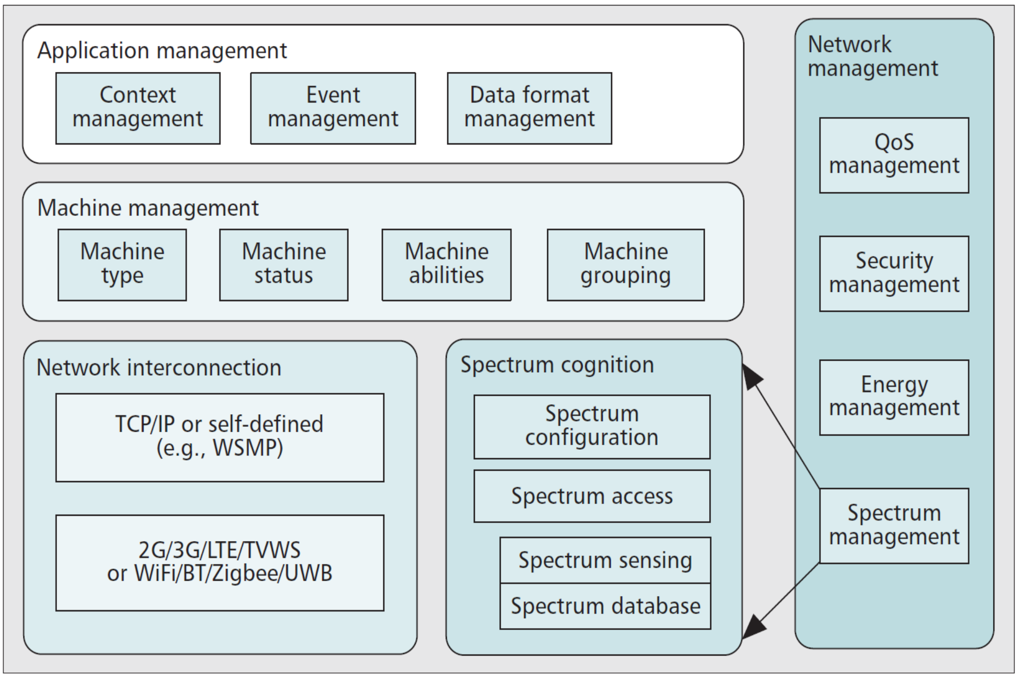



Fig. 3.11 Model of a Cognitive Machine [19]

IEEE802.22 network consists of the BS and several fixed or portable CPEs [3, 63, 66]. The BS is responsible for admitting and maintaining CPEs in the network and synchronise communications between the BS and CPEs with an acceptable QoS. The BS also provides cognitive services such as geolocation capability, database access and self-coexistence. GPS enabled CPEs are end-user devices served by the BS for spectrum-sensing and detection. Figure 3.12 depicts the communication model of Cognitive Radio depicting the relationship between Cognitive Base Station (CBS)/ Primary Base Station (PBS) in HAN and NAN [7].

The CPE is a Smart Meter of AMI in the HAN. The AMI can form the network of smart meters for electricity, gas, water, heat, solar panels, etc. The electric meter can also schedule the use of smart appliances for dynamic pricing. The network of devices in HAN can be wired/wireless making Smart meter the access point for all external/ internal connection. There are multiple connection options available for HAN that are discussed in Table 3.1 such as ZigBee, Wi-Fi, Bluetooth, etc. [1]. Communication between HAN and NAN can happen through CBS/ PBS [35].

The IEEE802.22 support orthogonal frequency division multiple access (OFDMA) schemes, where the data carriers on the downlink or uplink frames are modulated on two dimensions of frequency and time [67]. Top down time division duplex frame structure used in MAC is given in Figure 3.13. The top layer of super frame structure consists of 16 frames, each of 10 ms duration. The frame comprised of two parts:

- a downstream (DS) subframe and
- a upstream (US) subframe.

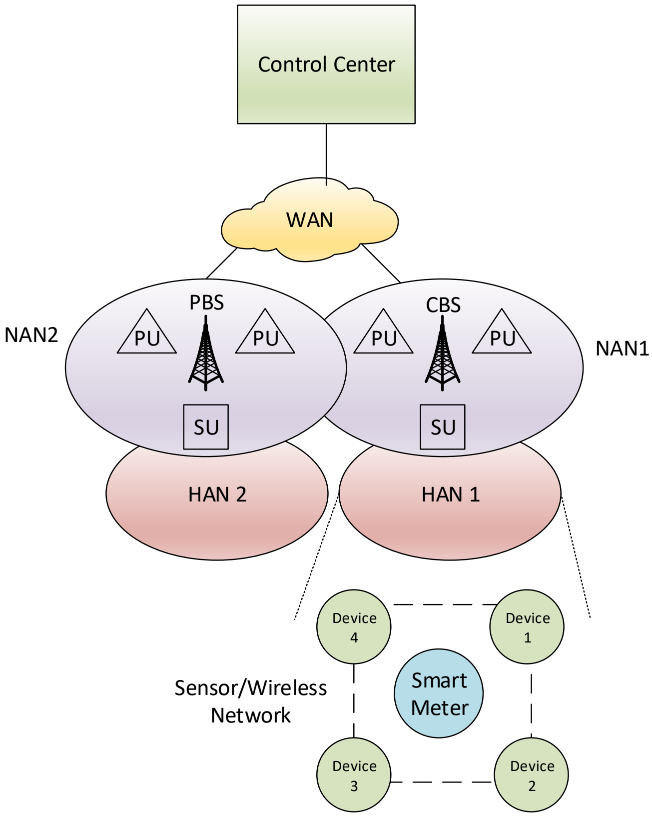



Fig. 3.12 Cognitive Radio Communication model [7].

The MAC data elements of CPE are mapped onto the US in a defined order. The data from CPE/IED is periodic in nature, but in case of emergency the data arrival is random. The periodicity of communication can be scheduled to minimise interference. When a CPE/IED is ready to send the data, it will sense the spectrum through a beacon process operated by BS. Once the CPE/IED find out which channels are available, it can schedule its transmission as per given procedure. It is also practicable to transmit teleprotection and synchrophasor information between substations and control center using US of IEEE802.22.

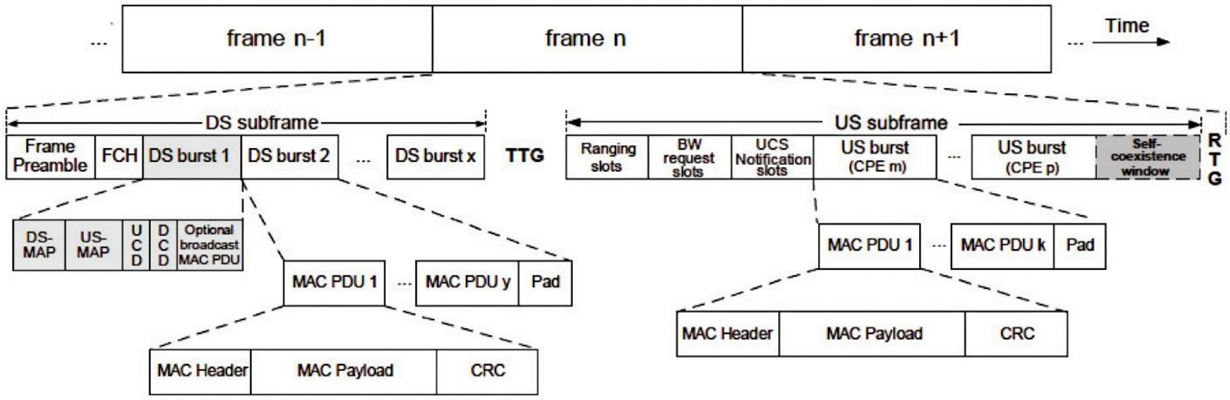



Fig. 3.13 MAC frame structure in IEEE802.22 [66]

## *3.5. Summary*

Fast and efficient communication is the backbone of Smart Grid. Different categories of communication models are explained in this chapter. The new communication technologies, IoT, M2M and Power line communication is also explored. The timing requirements of different functions in Smart Grid is also explained. A brief overview of Cognitive Radio based IEEE802.22 standard is also presented.

# CHAPTER 4

# USING ELECTRICITY LOAD FORECAST IN ENERGY MANAGEMENT SYSTEM TO REDUCE PERIODICITY OF COMMUNICATION

## *4.1. Introduction*

The load forecasting is used by the utilities to understand the future demand of electricity and it assist them in planning the electricity generation. Electricity prediction increases the safety net of a nation and helps in electricity planning for sustainable future. Smart Grid can help the utilities and consumers alike to make proper prediction of electricity consumption and understand the consumption pattern of customer which can help them to plan the consumption accordingly.

The global demand for energy is expected to increase by 40% in next 20 years and two-thirds of this requirement would be supplied by fossil fuels based power plants. There will be 25% increase in carbon emissions by this process which will further affect the climate change [38]. These carbon emissions can be minimised by deploying better environment-friendly HEMS at residential and commercial buildings. The load forecast module can be integrated with HEMS to understand and predict the demand for energy and improve the efficiency of the system. The data generated will give freedom to consumers in managing their energy demand through better energy pricing scheme such as ToU and CPP.

As discussed earlier, development in Smart Grid will increase the number of IEDs/Smart Object deployed in the system that will generate massive data into the system. Transferring this data to the control center is a challenge. The periodicity of data transfer can be customised if HEMS can link the load forecast of the customer premises. The algorithm work by comparing the actual energy consumption with the predicted energy consumption and if the comparison is more than a given threshold, it start transferring the data; otherwise just do nothing as the control center will copy the predicted value into its database. Thus, when the periodicity of the communication is reduced, the network remains de-congested for longer time which can be used for important tasks. The overall advantage will be reduction in bandwidth requirement and reduction in interference.

Different methods have been used to predict load forecasting. The research papers [68-70] have discussed many methods such as artificial intelligence (neural networks, decision trees, support vector machine, etc.), time series analysis, hybrid models, etc.

Load forecasting has equal importance in urban and rural areas. The advancement in technology to incorporate renewal energy sources into the system have added more complexity in load prediction. The generation of electricity through renewal energy is dependent on the weather conditions and other external factors so accuracy of the load prediction will suffer.

Various literature is surveyed to assess methods of load prediction. Load prediction of a house using neural network, based on historical data is discussed in research paper [68], but it does not consider any weather/meteorological data. Most of these studies are based on individual houses or buildings for demand prediction. Another model of power prediction based on neural network for load components e.g. electric heater, lightings, cooking, etc. is presented in research paper [71]. This information is useful for EMS. The method to find aggregated power demand of thermostatically controlled loads is given in research paper [72] and it provides information only for a particular load and calculate the energy savings for the given load. The load prediction of a commercial building is studied in another research paper [73] through computational intelligence. This paper combines regression and clustering methods for power prediction. Regional power usage and its predictions are presented in research paper [74]. A review of various energy demand forecasting models and demand side management are presented in paper [75].

## *4.2. Load Forecasting Models*

There are three categories of load forecasting based on a time duration, they are [70]:

- Short term load forecasting;
- Medium term load forecasting and
- Long term load forecasting.

The short-term load forecast deals with load forecast for few minutes up to a few hours most probably for next 24 hours (one day) on an hourly basis. The medium-term load forecasting is a load forecasting for one day to many months on an hourly basis. The long-term load forecast is a load forecast for many months to many years. Figure 4.1 depicts different types of load forecasting [70].

There are many techniques used for load prediction, prominent of them are.

1) One of the technique uses regression analysis for load forecast. The regression analysis uses a relationship between dependent and independent variables for prediction. There are many variants to regression analysis such as linear functions, exponential functions, power function, logarithmic function, etc. [76].
2) Second technique uses time series analysis for the types of data that have a cyclical repetition or auto-correlation over time and seasonality [75].

3) Third modelling technique uses Kalman filter an iterative method for load forecasting.
4) The last and most popular method is machine learning based on either:
   - Artificial Neural Network;
   - Fuzzy logic;
   - Support vector machine;
   - Regression tree or
   - A combination of any of these techniques.

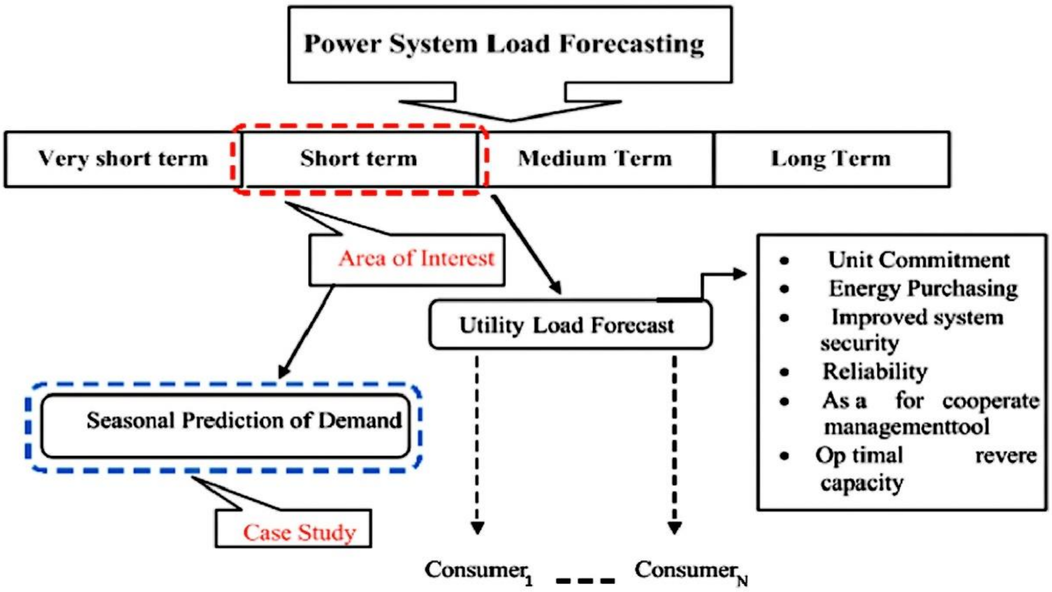



Fig. 4.1 Types of load forecasting [70]

The research for short-term load forecasting of an urban area is analysed using an artificial neural network (ANN) and Bagged Regression Trees. These two model are built and trained using urban area load data and weather/ meteorological information. Most of the prediction models discussed in the literature use historical power usage data of building or home. Some of these literature does not consider using meteorological data for load forecasting which is essentially an important factor for load forecasting. This study ensured to developed ANN and Bagged Regression Trees for load forecasting using weather information.

A Bagged regression tree ensemble a predictive model composed of a weighted combination of multiple regression trees. It has been observed that the predictive performance can increase by combining multiple regression trees. The model helps the customer to develop load profile of his house/region and keep improving progressively with updates. This predicted load profile will be very useful for load dispatch center of utilities. The dataset used in this study is historical data from the Australian Energy Market Operator (AEMO) and Bureau of Meteorology (BoM) of Sydney, NSW region from the year 2006 to 2010 [9].

## 4.3. Load Forecasting and Data Handling

The urban area load prediction is useful for integrating environment-friendly distributed energy sources with district power plant. This information will help in treating district power plant like a virtual power plant for effective coordination with high capacity power plants. Load predictions will help in designing a proper energy management system, which is crucial for sustainable development.

It has been observed that the power consumption on a given day follows a pattern which resembles with the energy consumption pattern of same day of a previous week. That means a power consumption pattern of Monday closely follows the power consumption pattern of Monday of previous week. The weekly plot of the load demand on an hourly basis for 24 hours in a day during last week of December 2010 is given in Figure 4.2. The diagram capture the load pattern of 24 hours which follows a defined trajectory in time for peak and off- peak load.

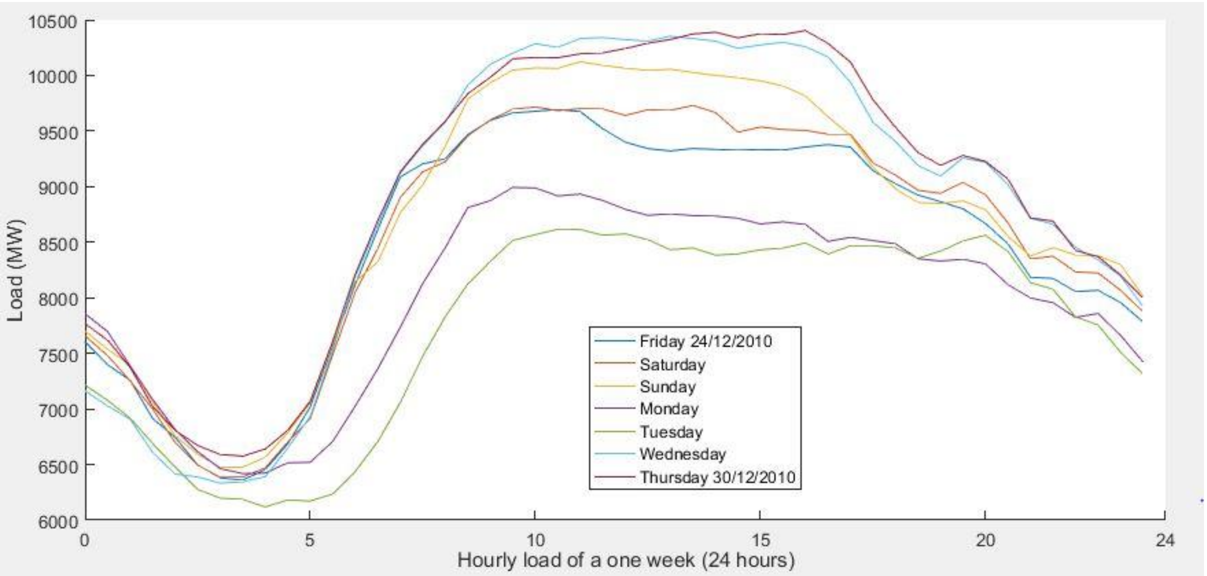



Fig. 4.2 Pattern of electricity load in Sydney region

There is also a close co-relation between the weather forecast and load demand in a region. The demand for electricity increases when the temperature falls below 10$^0$C due to heating requirements in a household. Similarly, when the temperature increases beyond 23$^0$C the electricity demand also increases due to cooling requirements.

The following three steps are used to generate the load forecast model [77]:

(i) Create a matrix of predictor based on historical weather data and electrical loads (chronological data of hourly load and meteorological parameters);

(ii) Design and calibrate a non-linear model using ANN and bagged regression trees and

(iii) Generate day-ahead load forecast based on weather data and day of the week (holiday or weekday).

Figure 4.3 illustrate all the three steps of load prediction [78]. The historical data used for training and calibration are as follows:

- dry bulb temperature,
- wet bulb temperature,
- dew point temperature,
- humidity,
- hour of day,
- day of the week,
- holiday/weekend or week day indicator (0 or 1),
- previous 24-hr average load,
- previous 24-hr lagged load and
- previous 168-hr (previous week) lagged load.

Apart from weather data, the date information (month, the day of the week and work day/holiday) is also essential for prediction.

### *4.3.1. Artificial Neural Network Based Model*

Many load forecasting procedures are given in [79, 80], where ANN is suggested as one of the most suitable methods for load forecasting. ANN are a good candidate for solving non-linear problems, that is why it is more appropriate for load forecasting [81]. The disadvantage with modelling ANN is that it requires sufficient historical data for accurately predicting the model. The implementation of ANN is a little bit complex [69, 79]. However, ANN is better than any other load forecasting method due to its self-learning capabilities and possibility of converging the result.

Two-layer feed-forward neural network with back-propagation is built to train, validat and test the result. The two layers are called hidden layer and output layer. Neurones in the hidden layer receive the input data and then each neurone sends its processed output to the outer layer (output) neurone based on activation function. There is only one neurone in the output layer. The outer layer neurone synthesises the outcome of the hidden layer and provide the load forecast. The transfer function is a Levenburg-Marquardt fitness function that uses a weighted sum of input and the bias [82].

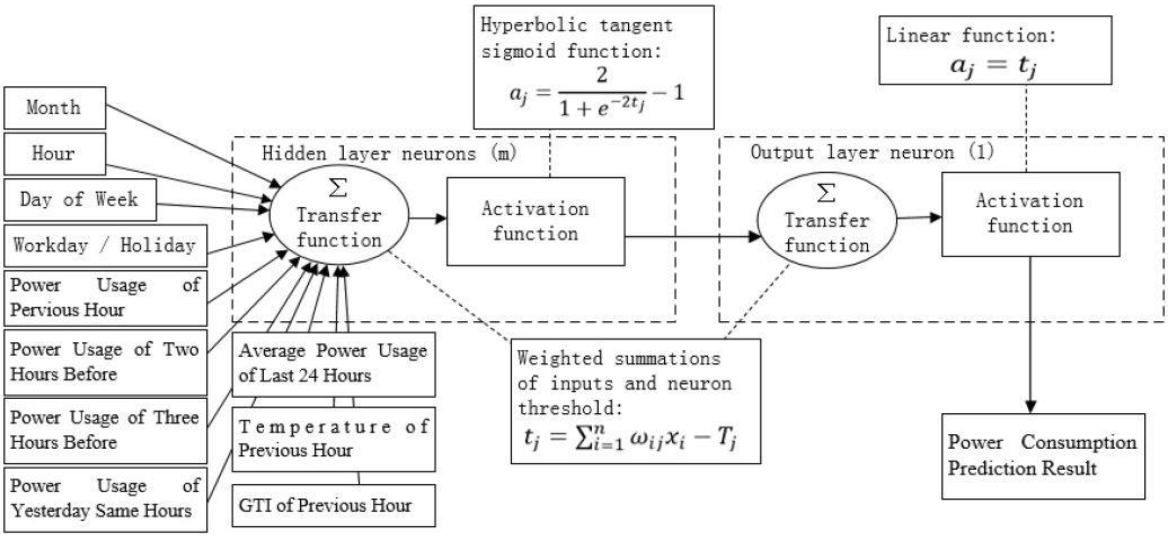



Fig. 4.3 Model for load forecast using ANN [78]

The load prediction of next hour (next step) is obtained using equation (4.1):

$$\text{Output} = \sum_{j=1}^{m} \frac{2v_j}{1 + e^{-2(\sum_{i=1}^{n} \omega_{ij} x_i) - T_j}} - T_{out}. \tag{4.1}$$

where $v_j$ (for j = 1, 2,… ,*m*) and $T_{out}$ expressed as weight and bias value of the output layer neurone respectively.

The weights and bias of each neurone are adjusted through recursive training of input data with an objective to obtain lower prediction error. The model is initialized with two layers having 20 neurones in a hidden layer. Levenburg-Marquardt fitness function makes the training period shorter [11]. The entire dataset is divided into three sets:

- Training set of 70%;
- Validation set of 15%; and
- Test set of remaining 15%.

### *4.3.2. Bagged Regression Trees*

Another prediction method called bagging or bagged regression tree is a statistical classification and regression technique designed to improve the stability and accuracy of machine learning algorithms [83]. It is a machine learning ensemble technique used to improve the predictive performance of a base procedure such as decision trees or methods that do a variable selection and fitting in a linear model. It constructs a linear combination of model fitting by generating and combining multiple predictors instead of using a single fit of the method.

The bagged regression trees are used to generate the output function. The regression tree is used to build the model, that are set of regression trees each with a different set of rules for performing the non-linear regression. The process starts with building an aggregate of 20 such trees, with a minimum leaf size of 40. The larger the leaf sizes the smaller the tree. This provides a control for overfitting and performance. The final model is built with an aggregate of 20 trees and leaf size of 20 with all the features.

The model also determines the relative feature (input) of importance which provides the relative power of the predictors. Fig 4.4 gives the relative importance of different features in prediction. So, according to the plot, weekday is having maximum importance and Dew point is having minimum importance.

## *4.4. Result and Discussion*

The model once calibrated can be used to forecast a load of any given day by providing input of weather forecast and day of a week (holiday or weekday) information. The model after processing gives day ahead (24-hours) load prediction. Comparison of the actual load with forecasted load is plotted with forecast error. The plot using ANN for actual and predicted load for the one-year duration is given in Figure 4.5(a) and the prediction error is given in Figure 4.5(b). Similarly, the plot of prediction and prediction error using Bagged Regression Trees is given in Figure 4.6(a) and Figure 4.6(b) respectively. A weekly plot of prediction and prediction error is given in Figures 4.7 and 4.8 for ANN and Bagged Regression Trees respectively.

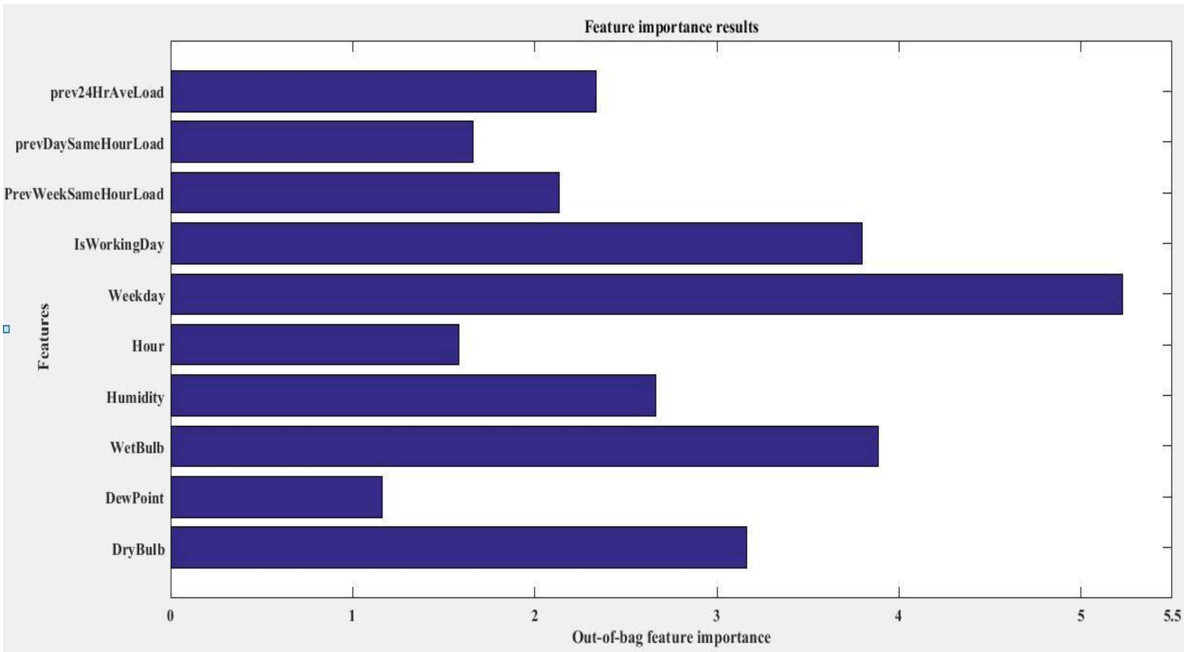



Fig. 4.4 Bagged regression tree relative importance of features

The three performance parameters are used to verify the accuracy of prediction; they are:

- Mean average error (MAE);

- Mean average percent error (MAPE); and
- Daily Peak MAPE.

MAPE measures the accuracy of prediction by comparing percentage error in actual and predicted values. The result of the different errors is compiled in Table 4.1.

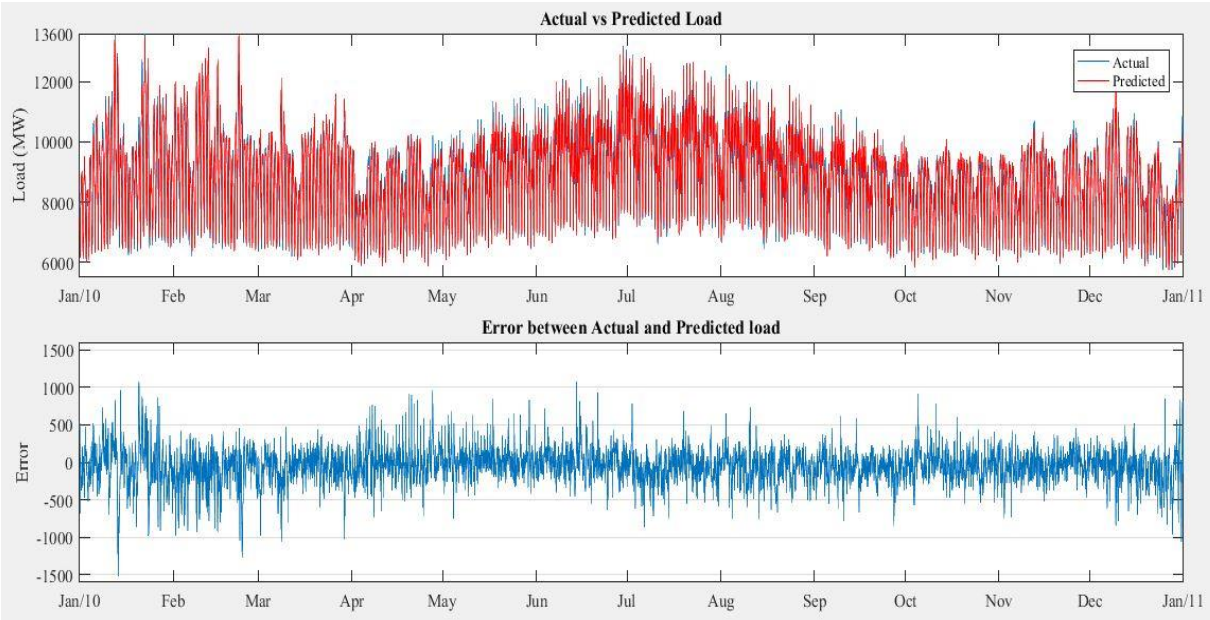



Fig. 4.5 ANN model predicting (a) Actual and Predicted Load (b) Prediction Error

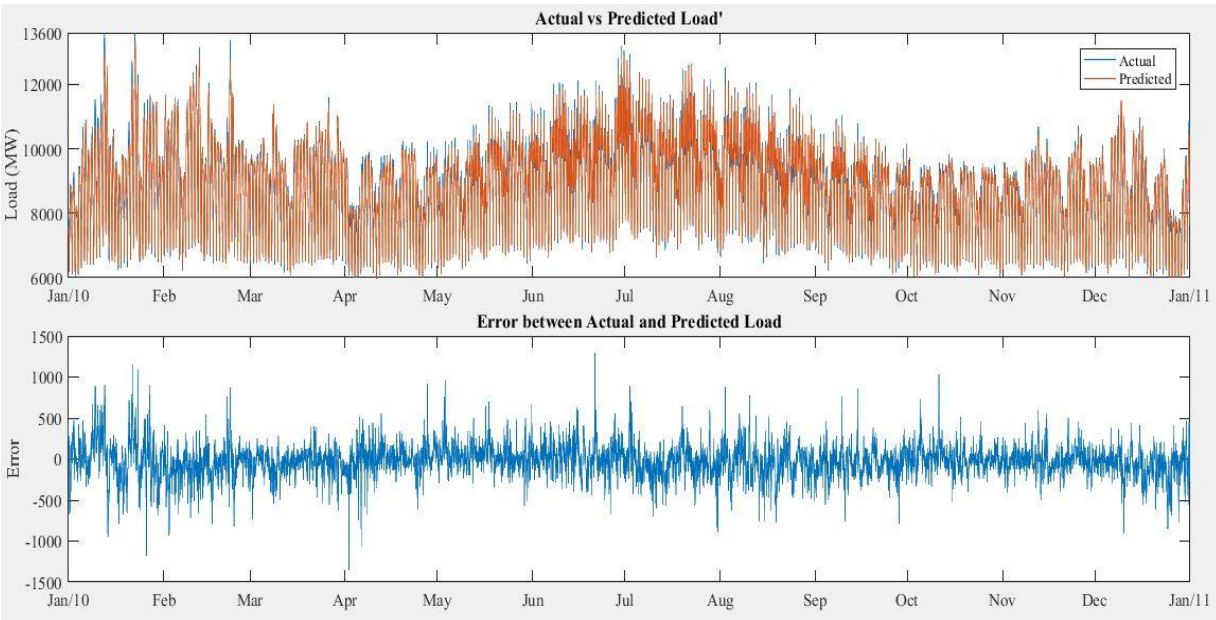



Fig. 4.6 Bagged Regression Tree model predicting (a) Actual and Predicted Load (b) Prediction Error

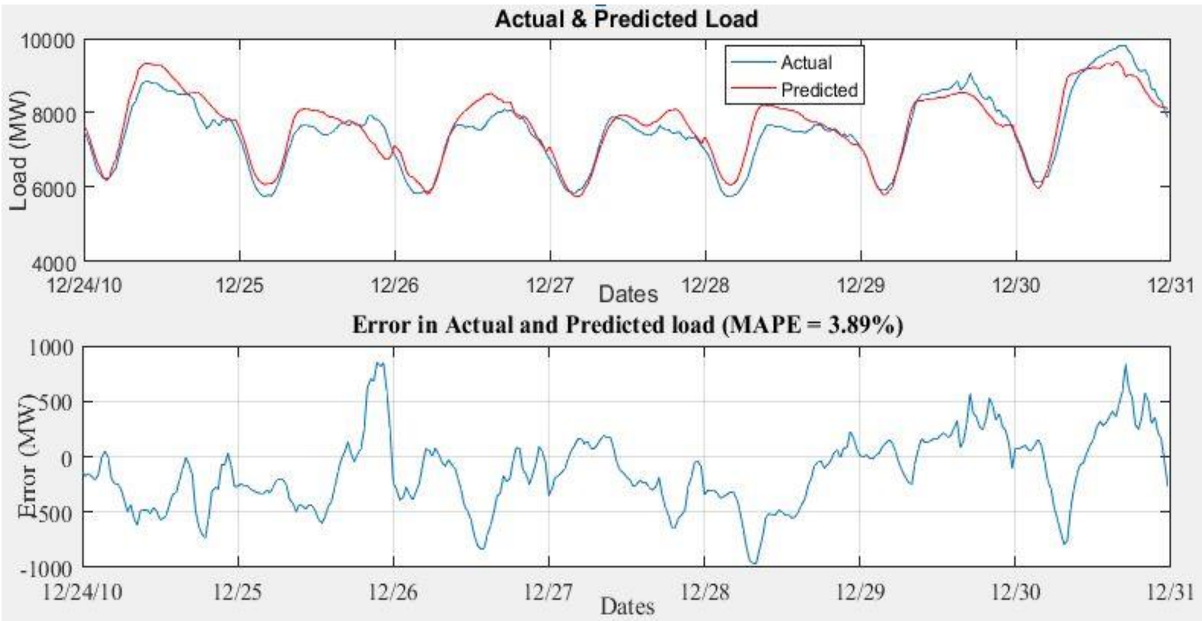



Fig. 4.7 Weekly load using ANN (a) Actual and Predicted Load (b) Prediction Error

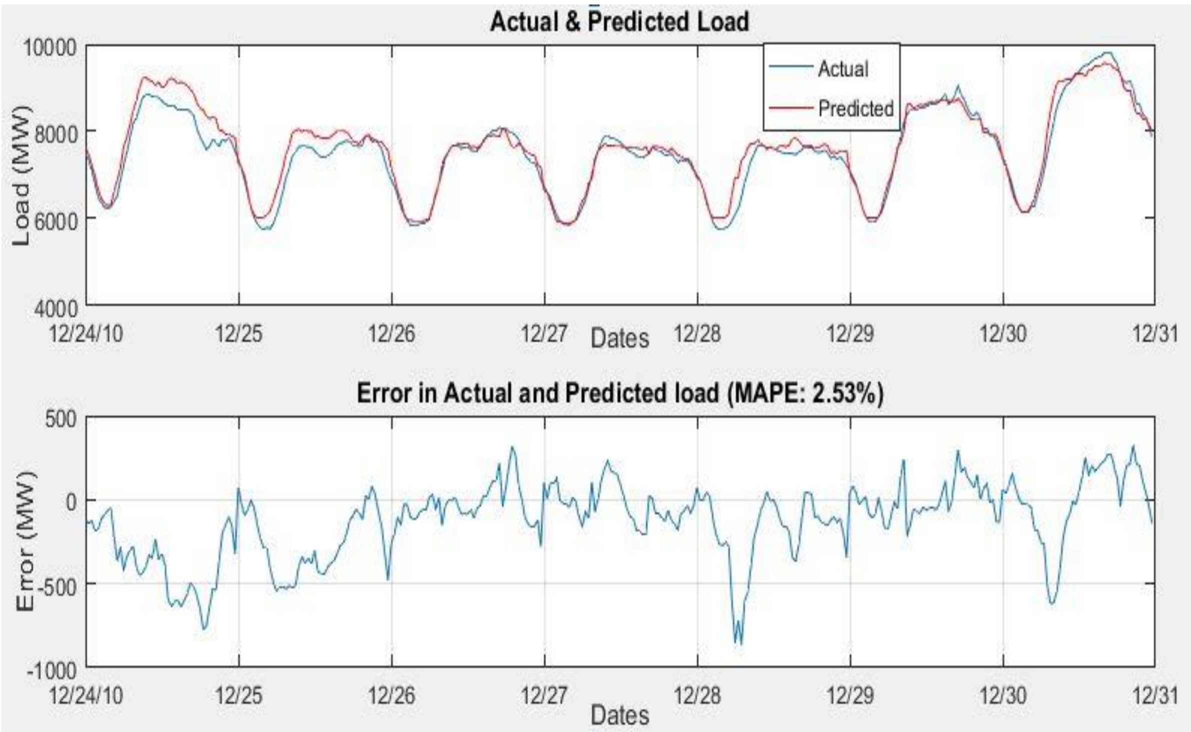



Fig. 4.8 Weekly load using Bagged Regression Tree (a) Actual and Predicted Load (b)Prediction Error

The comparison of the prediction error is also shown in Figure 4.9 and 4.10 for ANN and Bagged Regression Trees respectively. The red line indicates MAE and MAPE. Based on the above study it can be deduced that Bagged Regression Trees provide better prediction compared to ANN. However, the Bagged Regression Trees took a long time to converge compared to ANN and this is due to statistical property of calculating the result in Bagged Regression.

Table 4.1 Summary of Prediction Errors

| Models | MAPE | MAE | Daily Peak MAPE |
|---|---|---|---|
| ANN | 1.90% | 167.91 MW | 2.08% |
| Regression Trees | 1.54% | 136.39 MW | 1.67% |

The result shows high accuracy in prediction which is be very useful for load forecasting. The communication bandwidth can be saved easily with the use of prediction. If there is an agreement between the actual and predicted values, there is no need to send the data to control center. When there is deviation from the normal pattern, an alert can be sent to the control center. The corrective actions can be initiated when the alert is generated based on severity of the alert signal. Thus, the periodicity of the communication is controlled which will help in decongesting the wireless network and help in reducing the bandwidth requirements.

Table 4.2 gives the glimpses of bandwidth saving in case of automated meter reading for different frequency of meter read using the load prediction. It is evident from the table that there is an exponential increase of data read for an increase in frequency of data read. This will result in choking the bandwidth, if the communication infrastructure is not upgraded. Unregulated increase in communication data can create instability in the grid whose security can be compromised. Therefore, energy forecasting is one of the mechanisms that can help in reducing the congestion in the network.

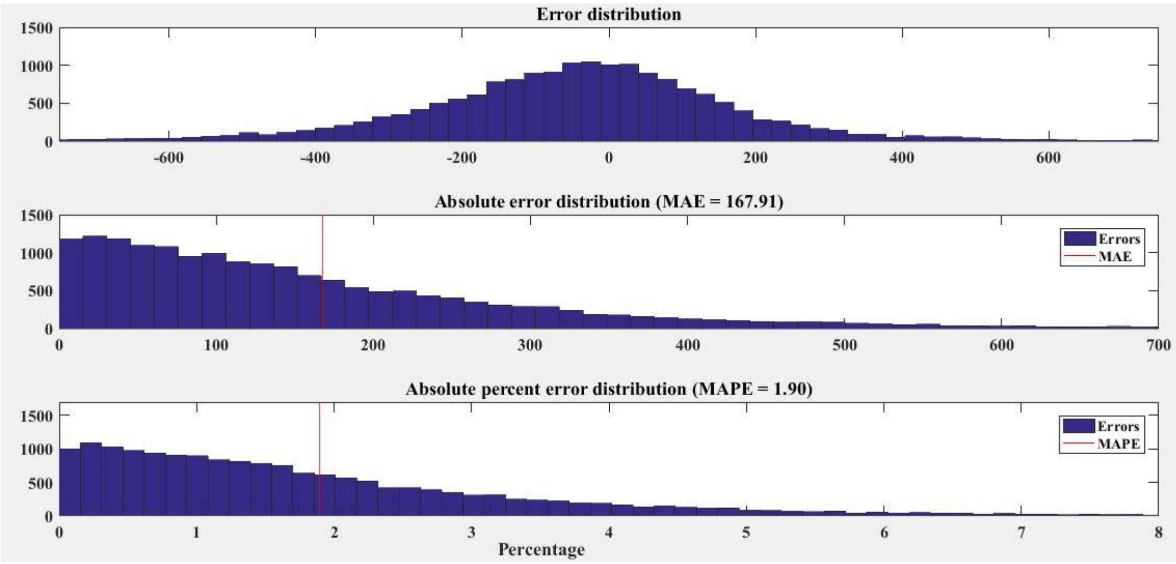



Fig. 4.9 Error plot of ANN

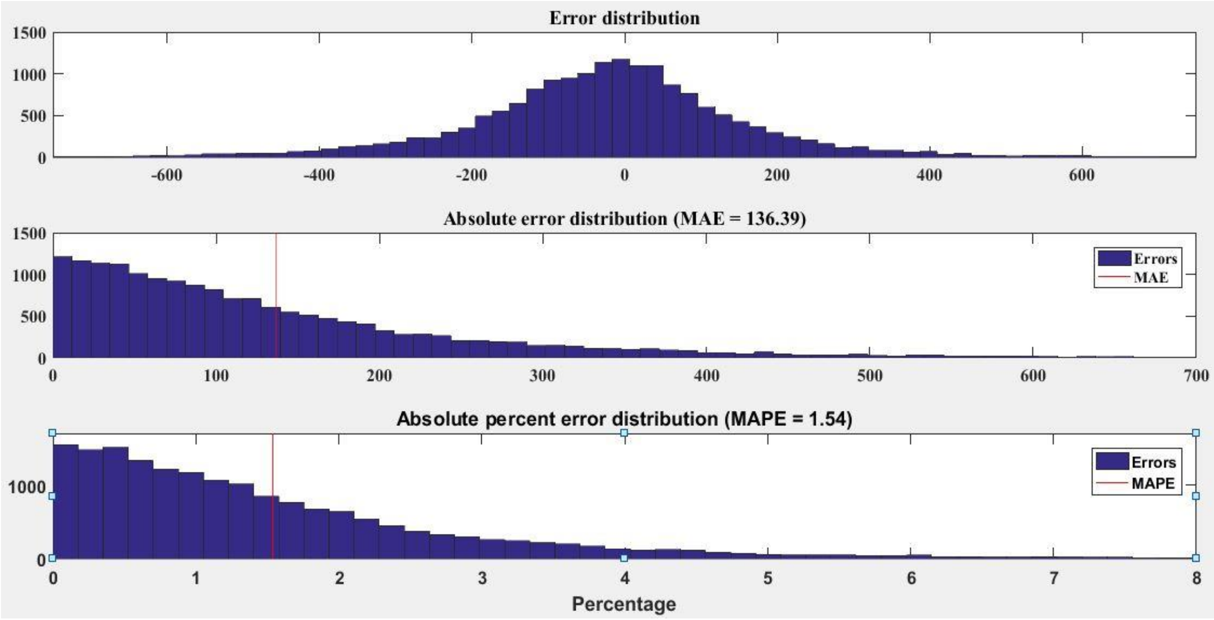



Fig. 4.10 Error plot of Bagged Regression Tree

Table 4.2 Bandwidth requirements for Meter reading

| **Frequency of Meter Reading** | **Monthly Reading** | **Meter reading for 1 million devices** | **Data Size in kilobyte (1.5 kb per message)** |
|---|---|---|---|
| One reading per month | One | 1 million per month | $1.5 * 10^6$ KB |
| One reading every 15 min (96 reading per day) | 2880 | 2880 million | $4320 * 10^6$ KB |
| 50 reading per second (PMU) | 4320000 | 4320000 million | $6480000 * 10^6$ KB<br>or 6179809.57 MB<br>or 6,034.970 GB |

## *4.5. Summary*

The development of Smart Grid with the use of ICT facilitate growth in the power industry. The pressure on energy infrastructure is increasing daily due to addition of new appliance in the network. EMS at the customer premises can help in better management and control of energy. Energy forecasting is one of the potential areas of interest in demand management at the consumer side. ANN and Bagged Regression Trees is used to forecast the energy demand in the urban area using meteorological data. The accuracy of prediction depends on reliability of historical and meteorological data. The model provides very high prediction accuracy with very less prediction error. The prediction from ANN is compared with Bagged Regression Trees and found that the latter provide a better load prediction for a day-ahead load in the urban area.

# CHAPTER 5
# IEC 61850 AND COGNITIVE RADIO

## *5.1. IEC 61850*

The IEC61850 standards are developed by Smart Grid Strategic Group for Communication Networks and Systems in Substations [84]. IEC61850 is a protocol suite that addressed the issue of interoperability between IEDs of different vendors within substation automation systems. IEDs are microprocessor based controller (e.g. circuit breaker, protective relay, etc.) that receives inputs from Current Transformer (CT), Voltage Transformer (VT), switchgear, etc. to perform protection, control and associated functions [85]. The IEDs issue control commands (e.g. trip circuit breakers) in case of anomalies in the system to maintain stability in the power grid.

The IEC61850 is an object oriented virtual programming model of substation which is an open source that can be used by any vendor to design an IEC61850 compliant products. Conceptually, IEC61850 protocol break down a physical device into logical devices, which can be further disintegrated into Logical Nodes, Data Objects and Data Attributes as shown in Figure 2.5 [14] [7].

The following are some of the characteristics of IEC61850:

- The design is based on Ethernet-based data communication protocol for LAN. The purpose is to support low-cost installation, configuration and management.
- It ensures interoperability between the devices of different vendors.
- It uses the XML-based substation configuration language (SCL) to define the configuration parameters of IEDs used at substations.
- It supports high speed communication between IEDs using priority tagging of Ethernet frame.
- It supports a comprehensive set of substation functions.
- It can be extended to support more advance functionalities and system evolution.

The IEC 61850 standard divides substation operation into three distinct levels [84]:

**Process Level**: consists of devices such as data acquisition equipment and circuit breakers that are used to measure the current, voltage and other parameters in the different parts of the substation.

**Bay Level**: consists of the IEDs that collect the measuring data provided by the process level. The IEDs are intelligent devices that can make local control decisions, exchange the data with other IEDs, or transmit the data to the local control center of substation through SCADA system for further processing and monitoring.

**Station Level**: consists of servers, Human Machine Interface or the human operators used to monitor the status of the substation which are all part of the SCADA sub-system.

Apart from the above three levels the IEC61850 standard also consists of a Process Bus and a Station Bus. Figure 5.1 illustrate the architecture of IEC61850 at substation [86]. The Process Bus act like a communication bridge between the Process Level and the Bay Level and the Station Bus is a communication bridge between the Bay Level and Station Level. The Station Bus caters to communications between various Logical Nodes, that provide control, monitoring, protection and logging functions. The mode of communications can be either connection oriented (e.g. – request of information, configuration, etc.) or a connection-less (IEC Generic Object Oriented Substation Event - GOOSE). Also, a redundant communication link is recommended for the IED to IED data communication to mitigate communication failure.

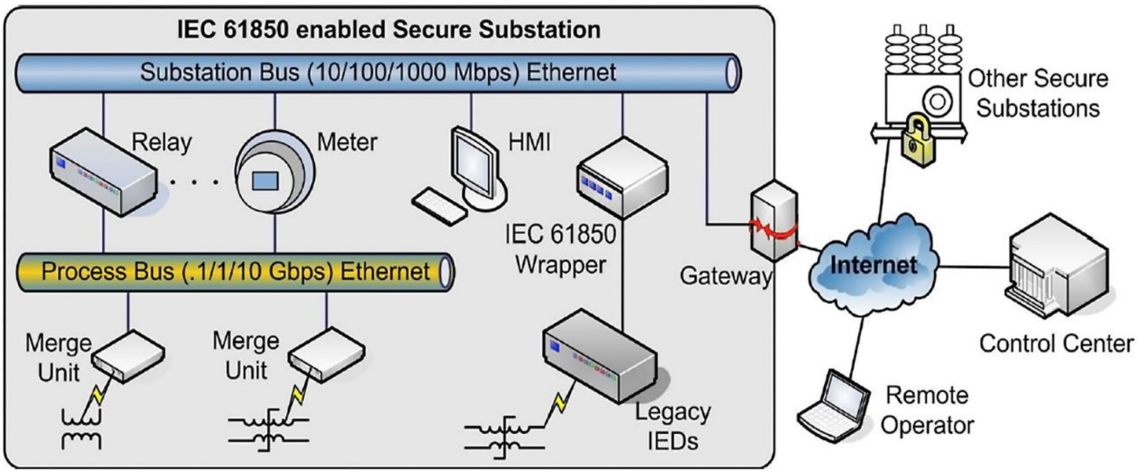



Fig. 5.1 Architecture of IEC61850 at substation [86]

The IEC61850-enabled IEDs receive digitalized data from Merger units via Process Bus. IEDs communicate with other devices using substation buses and the legacy devices communicate using the IEC61850 wrapper. The scope of communication between different levels is shown in the Fig 5.2 [86].

The substation communication consist of 10 major chapters which is shown in Figure 5.3 [86]. The data object abstracts the definition of the data items and the services, that are independent of another object. The data abstraction then allows mapping of the data objects and services to any protocol that can meet the data and service requirements.

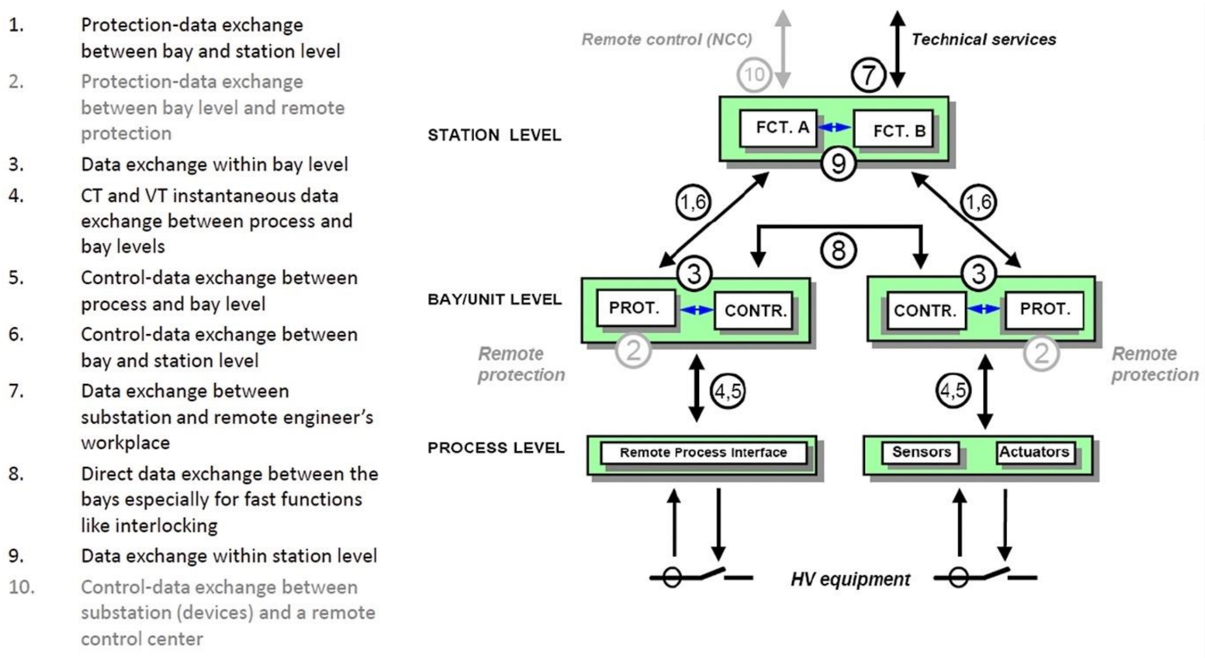



Fig. 5.2 Scope of communication between different levels [86]

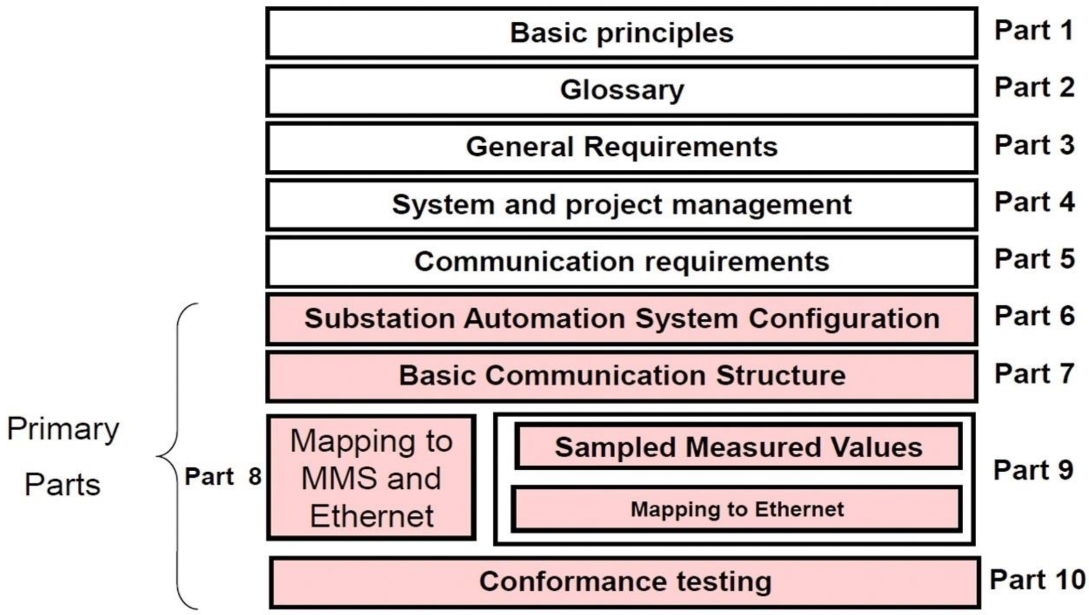



Fig. 5.3 Outline of IEC 61850 standards [86]

### *5.1.1. Mapping*

The ACSI models of IEC 61850 define a set of services and the responses to those services. The abstract model need to be operated over a set of protocols with the specific requirement of various message types as depicted in Figure 5.4 [87]. The message types that have similar performance requirements are grouped together and mapped to the same protocol [85]. The different abstract data models mapped to the protocols are:

- Sampled Values (SV) are encapsulated and transmitted as a multicast/unicast service are mapped directly to Ethernet to provide fast and cyclical data transfer of voltage and current measurement values for protection and control replacing traditional analog wiring. The raw message type 4 which is designed to carry raw data is mapped to SV to achieve time-critical performance. If the sample is lost or delayed for longer than 4 ms the IEDs functioning are considered not reliable.
- GOOSE is used for transmission of critical events and command request (e.g. tripping commands, alarms, indications, etc.) in real time between two or more IEDs using Ethernet multi-cast. Type 1 and 1A messages are very time critical so that they are mapped to GOOSE and directly mapped to Ethernet to reduce processing time. It supports multicast services.

  The GSSE (Generic substation status event) is a variant of GOOSE that deals with exchange of status data (input and output data) rather than datasets used in GOOSE for fast and reliable system-wide distribution based on specific scheme of re-transmission. It is based on multi-cast.
- MMS (Manufacturing Messaging Service) is used to transfer real time process data of monitoring and supervisory control information such as download/upload configuration, parameter setting, monitoring information, etc. related to presentation layer over the TCP/IP protocol. It supports client-server based communication.
- Time Sync (time synchronisation) is used to provide accurate timing information to all IEDs in a system for data time stamping for different accuracy level for e.g. millisecond range of reporting, logging and control and microsecond range for sample values. The Simple Network Time Protocol (SNTP) is used for time synchronisation in the network.

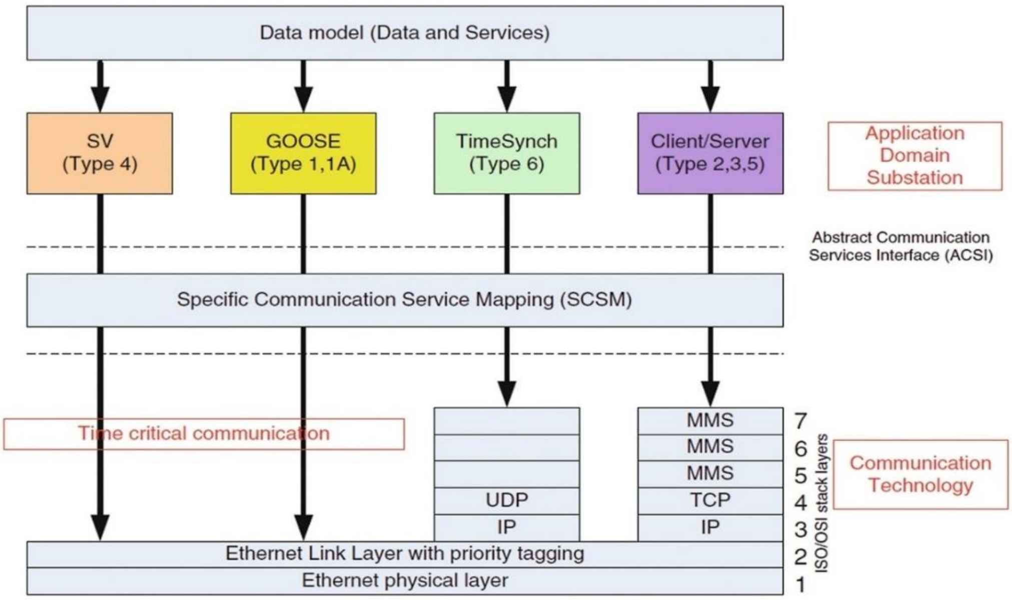



Fig. 5.4 Overview of functionality and profiles [51, 52, 87]

### *5.1.2. Working Model of IEC61850*

The ability to digitalised and transmit sampled measured values from transducers such as CTs, VTs and digital I/O back to the substation is essential. Signals are sampled at an agreed rate and form an input to the merging unit (MU). Base sampling rates for basic protection and monitoring can be defined as 80 samples/power system cycle and for high-frequency applications such as power quality and high-resolution oscillography the rate can be defined as 256 samples/power system cycle [84]. Data from multiple MUs can be input into IED that can automatically align and process the data. Figure 5.5 shows the MU for the Support Vector Machine (SVM) and the process bus. The signals from CT, VT and status information are input into the Merging unit.

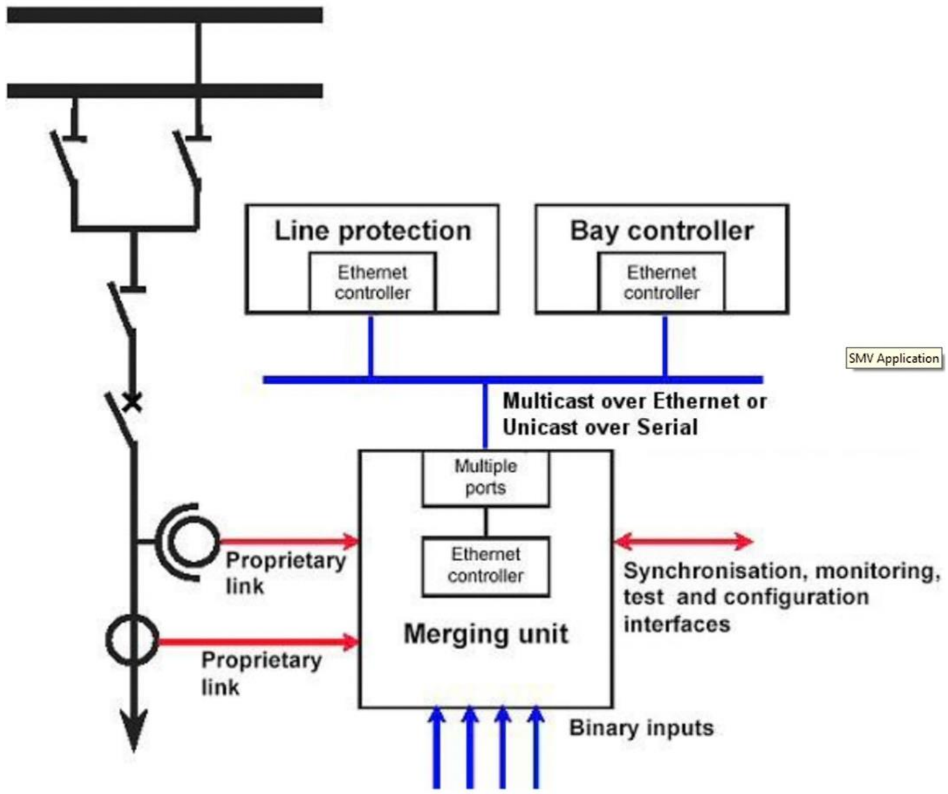



Fig. 5.5 Merging unit for the SVM [84]

Procedure of fault detection and subsequent response is referenced from [86] and depicted in Figure 5.6.

1. PDIS (distance protection) detects a fault.
2. PTRC issues a <Trip> command to XCBR0 (circuit break); the switchgear opens the circuit breaker.
3. The new status information is immediately sent; the reporting model may report the change.

4. RREC (auto-reclosing) issues <Reclose> to XCBR0 according to the configured behaviour.
5. XCBR0 receives the GOOSE message with the value <Reclose>; the switchgear closes the circuit breaker. XCBR0 issues another GOOSE message with the new position value.

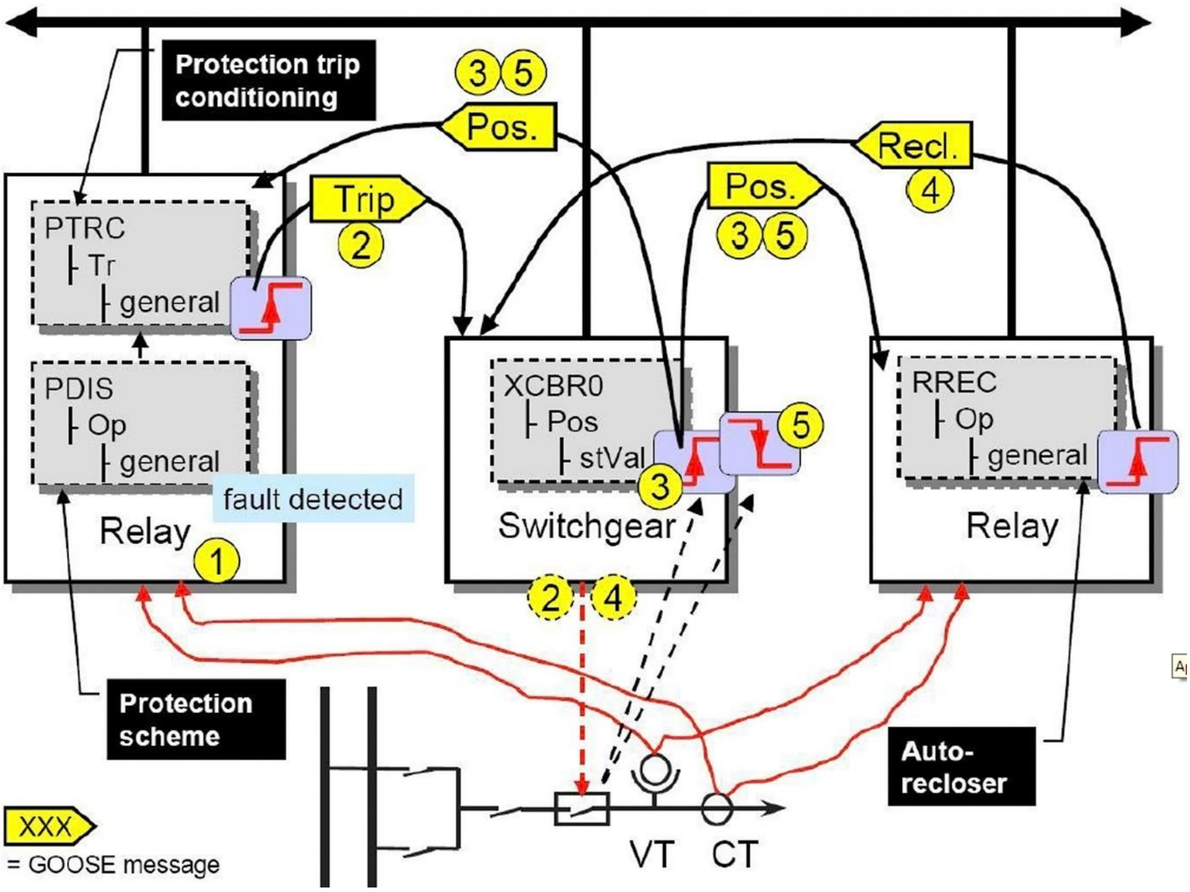



Fig. 5.6 Process of communication in substation for protection [86]

### *5.1.3. Substation Configuration Language (SCL)*

The objective of IEC61850 to simplify communication between IEDs and provide an opportunity for vendor independent engineering design process. IEC61850 support SCL a programming language based on Extensible Markup Language (XML) which is understandable to human and computers [14]. SCL consists of hierarchical configuration files that specifies multiple levels of system in unambiguous and standardized codes. The types of SCL files include system specification description (SSD), IED capability description, substation configuration description (SCD) and configured IED description [84]. All these are built in the same way and format but as per different scopes and need.

## 5.2. Cognitive Radio Communication

The objective of the Cognitive Radio is to use frequency, time and transmitted power optimally. IEEE802.22 standard provide air-interface for electrical, electronic and related technologies of WRAN. The IEEE P802.22b is the name given to IEEE802.22 standard for Cognitive M2M Control and Monitoring Applications.

IEEE802.22 support co-existence of licensed TV band and unlicensed broadband network in rural areas for optimal use of wireless bandwidth. It allows opportunistic use of unused TVWS by the secondary user if it is not being utilised by the primary user (licensed user). IEEE802.22 network consists of the BS and several fixed or portable CPEs [3, 63, 66]. The CPE and BS behave as per the Network Control and Management Systems (NCMS) [66]. The BS and CPEs will collect and store the information as a managed object in the format defined by WRAN Management Information Base. The Network Control System contains the QoS information and service flow that is pre-populated in service classes at the BS and instantiated when a CPE requests the services. The services supported by NCMS are Authentication, Authorization and Accounting (AAA), Radio Resources Management, Security, Service Flow Management, Location-Based Services Management and Network Management.

BS is responsible for admitting CPEs to be the members of the network, keep their information for maintaining the network, synchronise communications between the BS and CPEs and provide different QoS. BS also provides Cognitive Radio facilities such as geolocation capability, database access and self-coexistence. Geolocation enabled CPEs are end-user devices served by the BS in a WRAN with capabilities of spectrum-sensing and detection.

### 5.2.1. Spectrum Sensing and Radio-Scene Analysis

The transmission of primary users should be detected reliably without causing interference through spectrum sensing techniques in wide bandwidths environment. Transmission parameters must be adapted based on the channel estimation and the sensed spectrum. Radio-scene analysis can help in detecting spectrum holes based on interference of radio environment at a given location. BS and CPEs perform spectrum sensing both in-band (used channels) and out-of-band (channels not used). The BS perform out-of-band sensing when CPEs are idle.

#### 5.2.1.1. Spectrum Manager (SM)

Spectral efficiency plays an important role in all communication including the future wireless communication systems that accommodate more and more users and high performance services. The following cognitive tasks are to be implemented in IEEE802.22 for communication through SM:

1) Spectrum sensing and radio-scene analysis with geo-location at BS and CPE.
2) Channel management and categorization
3) Maintain spectrum availability Information in database along with channel capabilities/status.
4) Chanel selection, movement and transmit power control.
5) Co-existence services with other channels and specially designed beacon management.

The SM is the brain of the entire system that is responsible for selecting the most appropriate channel of operations in the system. Figure 5.7 depicts the SM functions at BS [88].

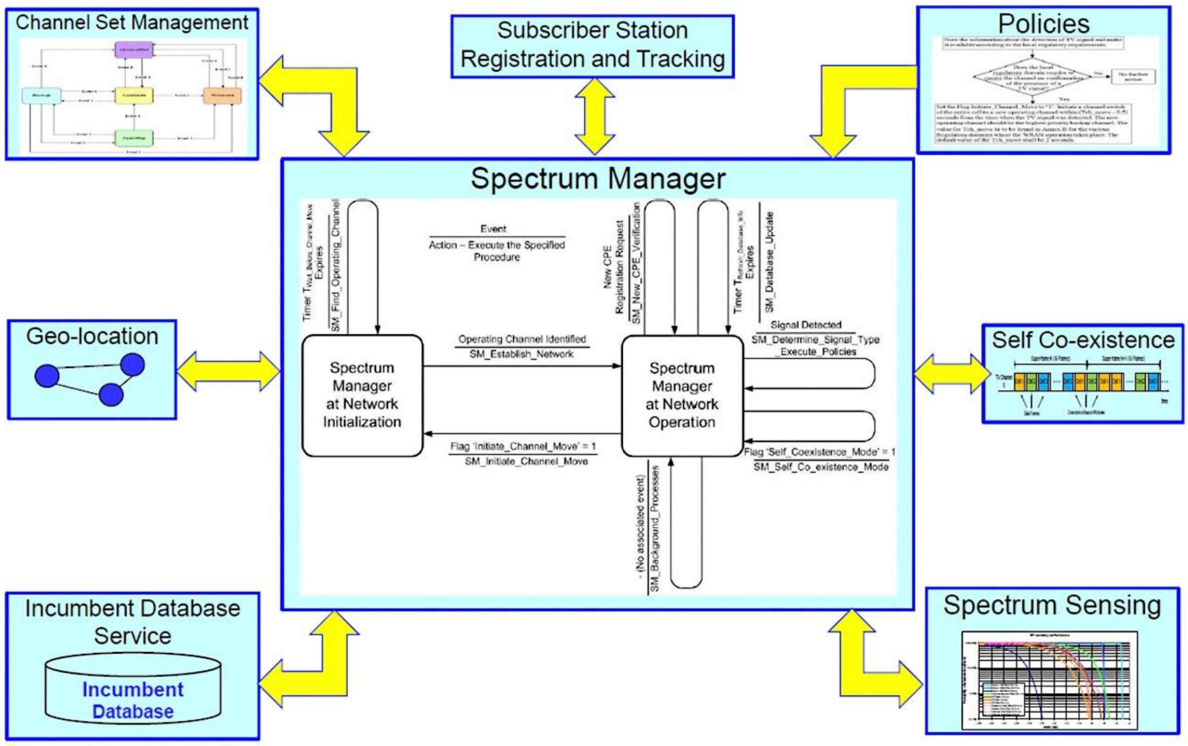



Fig. 5.7 Spectrum manager at BS [88]

SM maintain spectrum information, channel list, quiet period scheduling and co-existence mechanisms. Following are the other functions of the SM [89]:

- Configure and manage the SM itself, also set policies;
- Communicate with MAC layers (top and bottom) of the Network control and management layer of BS;
- MAC notifies SM if excessive interference is sensed;
- Schedules quiet period where CPEs sense in-band channels (N-1, N, N+1);
- Updated backup and candidate channels in order of priority
- Authenticates sender of beacons to each other through security mechanism.

#### 5.2.1.2. *Spectrum Sensing Function*

The spectrum sensing is performed by BS and CPE by scanning all set of channels for BSs and incumbent services and synchronises the network to neighbouring BSs. The CPE will recognize the existence of a BS transmission and operating channels. The BS send concentrated OFDM symbols composed of a superframe preamble, a frame preamble and an SCH once every superframe in its operating channel. The channels N and N±1 are scan by CPE to pass the sensing and timing requirements. If these channels pass the selection criteria, BS and CPE perform initial ranging, authentication and key exchange functions.

Switching of channels is performed by CPE with the assistance of the BS in several ways using the Frame Control Header or dedicated MAC messages. Subscribers stations can alert the BS of the presence of incumbents using:

- Dedicated - Urgent Co-Existence Situation (UCS) messages or
- Lower priority MAC messages

A simpler spectrum management entity called Spectrum Sensing Automaton (SSA) co-exist with Spectrum manager in Cognitive plane of IEEE802.22. SSA is implemented by BS and CPEs through procedures of RF sensing at initialization of the BS and before the registration of a CPE with the BS. SSF is driven by SSA. Base station and all CPEs shall observe the RF spectrum of a television channel and implement the SSF. SSF shall report the results of that observation to the SM (at the BS) via its associated SSA. Figure 5.8 illustrates the input and output of the SSF.

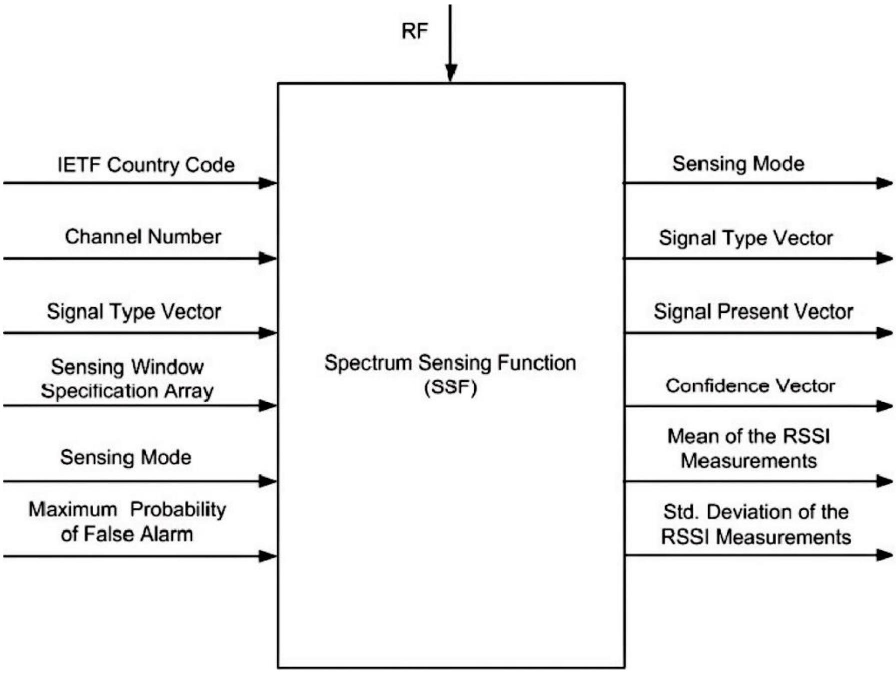



Fig. 5.8 SSF functions

**Spectrum sensing function (SSF) include [89]:**

- Spectrum Sensing: Quiet period and two phase sensing;
  - Fast sensing: Some quiet time allocated in a frame and
  - Fine sensing with several ms in occupied channels to look for transmitter information: Quiet period of multiple frames
- Dynamic Frequency Hopping: Sensing is done in parallel (Optional);
- Quiet Period for sensing → QoS Interruption;
- Intra-frame sensing and inter-frame sensing;

**Dynamic and adaptive scheduling of quiet period** allow the system to support spectrum sensing and balancing QoS requirements of users with the requirements to quiet the network for effective spectrum sensing. Quiet period range from 1 symbol (approx. 1/3 ms) to one super-frame (160 ms) as depicted in Figure 5.9.

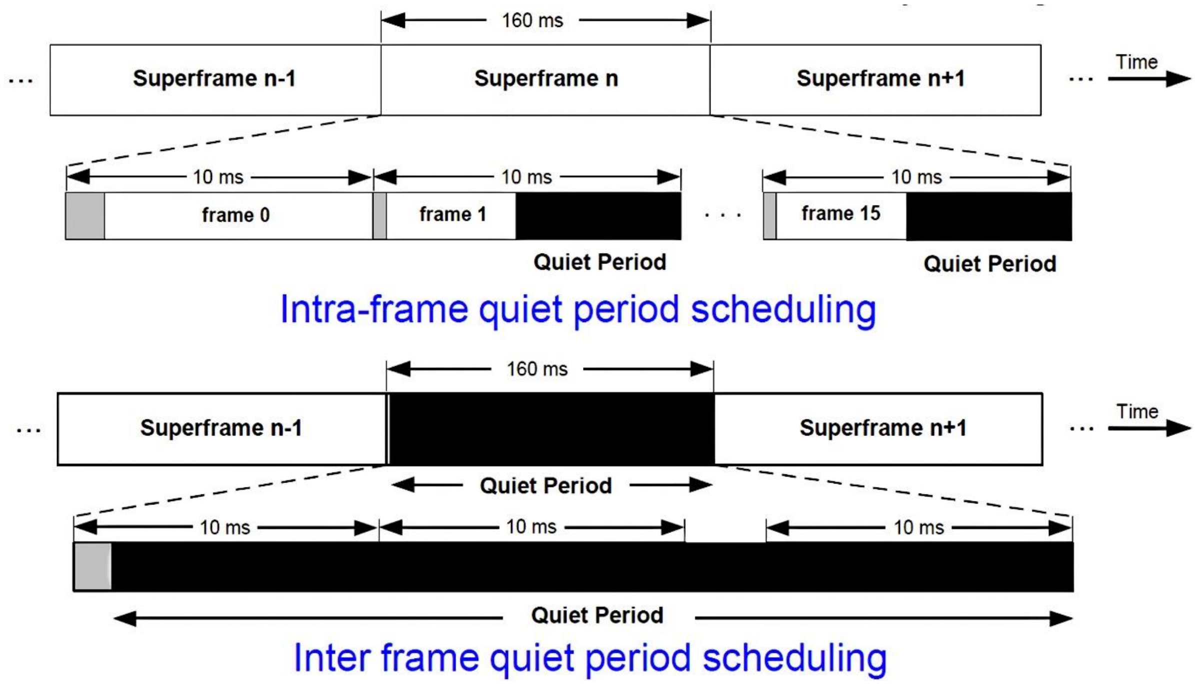



Fig. 5.9 Quite Period scheduling [88]

#### *5.2.1.3. Spectrum Sensing Technique*

Two different types of sensing are performed at MAC layer they are fast and fine sensing [12, 89]. The fast sensing is performed by CPEs and the BS under 1ms per channel period using a simple sensing algorithm such as energy detector. The fine sensing is initiates by the BS on the outcome of the fast sensing as mentioned above, over a longer time-period (approximately 25ms per channel). The multiple IEEE802.22 BSs a regional geographical area is synchronised in Quiet Times for fast and fine sensing. The available bandwidth, modulation and coding schemes is managed by IEEE802.22 PHY layer. The OFDMA is preferred modulation scheme for uplink and downlink as it provides better allocation of sub-carrier to CPEs.

There is no spectrum sensing technique recommended in IEEE802.22 standard. However, any sensing technique that meet the input, output and behaviour requirements of the sensing with respect to IEEE802.22 can be used. Some of the techniques discussed in IEEE802.22 [89] are blind sensing and features specific signal sensing technique. The blind sensing does not rely on any feature of signal type, but feature specific signal sensing technique is based on feature of signal type.

Spectrum sensing technique are also classified as fine sensing or coarse sensing. A fine sensing can detect the presence of a signal at required signal power level. A coarse sensing cannot detect the presence of a signal at the required signal power, but it can detect higher-power signals in a shorter time-period. Following are the compilation of common spectrum sensing techniques used in literature [90]:

- **Energy detector**: is one of the common sensing technique used in literature. When there is little or no knowledge signal occupancy energy detection is very useful. By comparing the energy of received signal with a pre-determined threshold (which depends on the noise variance) the possibility of PU signal can be detected. Due to low computational and implementation complexities it is one of the most common spectrum sensing technique [64, 90].
- **Cyclostationary:** feature detection exploit the cyclostationary features of received signal for detecting the presence of PU channel. Cyclostationary features are the periodicity in the signal or in its statistics like mean and auto-correlation. Mean and autocorrelation change periodically as function of time. Thus, cyclostationary feature detection utilise the built-in periodicity of the modulated signal [64, 90].
- **Match filtering:** is defined as the signal s(t) is corrupted by additive white Gaussian noise (AWGN), the filter with an impulse response matched to the signal s(t) maximizes the output signal-to-noise ratio (SNR). In the matched filter, the input y(t) is correlated with a stored replica of the signal s(t). The output is compared to a threshold to decide the signal.
- **Waveform-based sensing:** uses a known pattern of primary user to perform sensing by correlating the received signal with a known copy of the known pattern [91].

Figure 5.10 depicts the spectrum sensing techniques in terms of its complexity and accuracy.

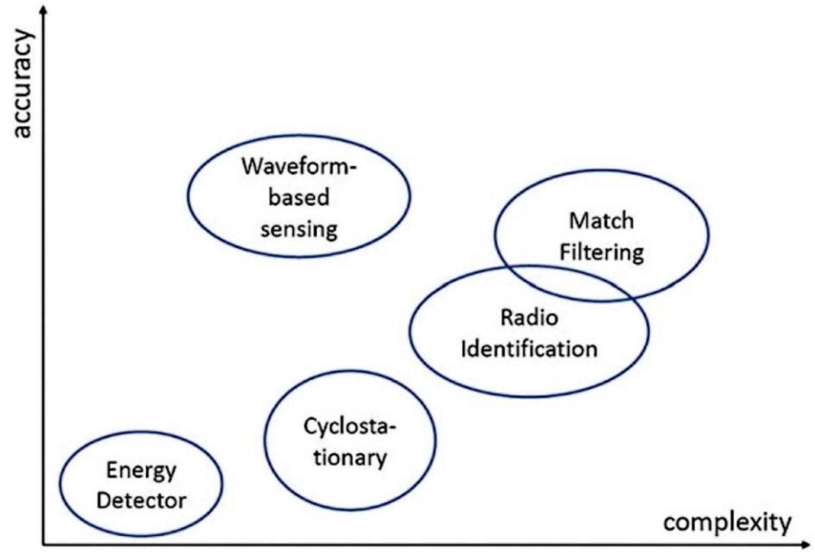



Fig. 5.10 Comparison of different spectrum sensing schemes [90]

#### *5.2.1.4. Spectrum/Channel Management and Categorisation*

A robust and efficient channel management component is a critical feature of IEEE802.22. It allows to efficiently and dynamically use the available channels as the radio environment utilisation changes. The channels are classified as follows [89, 90]:

1. **Disallowed**: Channels that are forbidden from use by the operator due to operational or local regulatory constraints.
2. **Operating**: This is the set of channel used by CPE and BS for communication and it is regularly sensed after every 2 s for signal types and IEEE802.22.1 beacon.
3. **Backup**: Channels that are available to become an operating channel in case of incumbent detection or other emergency conditions by BS. These channels are scanned for at least once every 6s and remains in backup list until incumbent is not found.
4. **Candidate**: Channels possible to be listed in backup. These are channels, BS may request CPE for sensing to upgrading to Backup. These are sensed infrequently for at least every 6s but not more than 30s for incumbent presence.
5. **Protected**: Channel in which incumbent or WRAN operation detected through sensing. As soon as incumbents or WRAN vacated can be moved to candidate or backup based sensing at least every 6s but less than 30s.
6. **Unclassified**: Channels which are sensed but may be classified as candidate or protected based on sensing results.

At the end of the quiet period, depending on the activity of incumbent users and channel quality each channel may transit to other states as shown by the state transition diagram in Figure 5.11. The possible events for each state transition are described as follows:

- Event 1: The channel in the operating, backup or candidate set becomes a member of the protected set as an incumbent is detected using spectrum sensing.
- Event 2: No incumbent service has been detected on the channel.
- Event 3: No incumbent has been detected on this channel and the timing requirements for sensing as per the definition of the backup channel are satisfied by all CPEs reporting to the BS.
- Event 4: The channel is released due to the termination of WRAN usage.
- Event 5: The channel becomes Operating by its new allocation to the WRAN service.
- Event 6: The timing requirements for sensing are not satisfied as required by the definition of the backup channel by one or more CPEs.
- Event 7: Once an Unclassified channel has been sensed by all active CPEs, it can be re-classified as a Candidate channel by the SM if no incumbent service has been detected.
- Event 8: If the channel is not sensed within the timing requirements as specified in IEEE802.22 standard or according to the regulatory domain requirements, the channel becomes Unclassified. However, if the channel is in the Protected state and it has not been sensed as required, it shall remain in the Protected state.

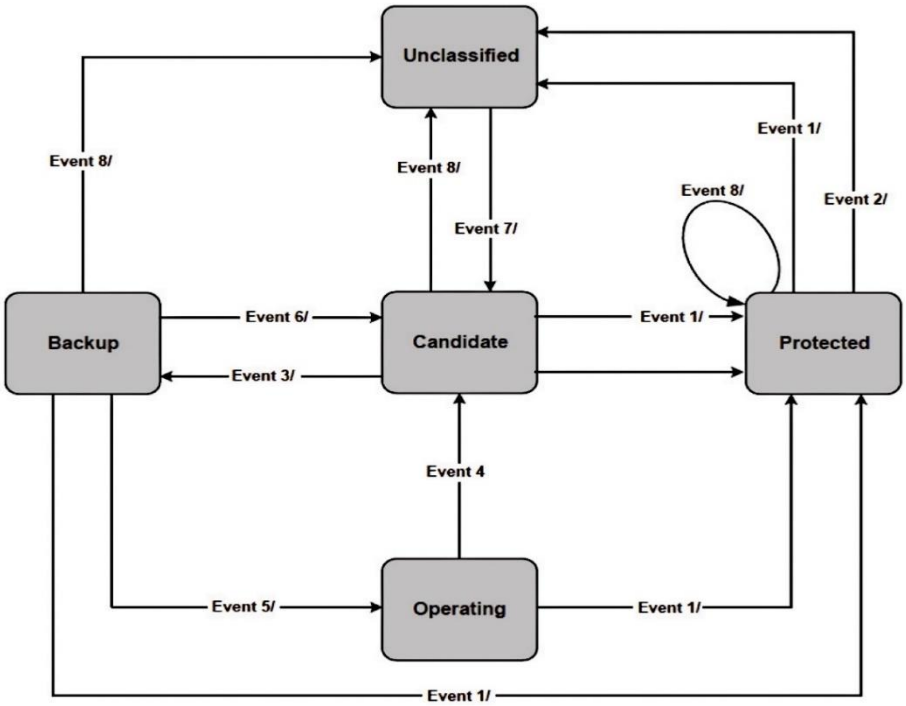



Fig. 5.11 Channel state transition diagram [89].

The spectrum selection from the pool of unused spectrum is based on the least recently used (LRU) technique which selects a channel that is not being used for the longest time. The LRU along with probability of free channel can provide better chance of channel selection with maximum stability and minimum switching. The probability of free channel can be developed based on historical use of the channel and modelling with Artificial Neural Network over a defined period. The queuing model developed for candidate and backup channel by using this technique will provide better chance of spectrum utilisation with minimum switching.

#### *5.2.1.5. Spectrum Access*

CPEs and BSs shall treat channel management commands with high priority, especially when they refer to the protection of incumbent services. Once the BS detects or receives the report about the presence of an incumbent system on the operating channel, it should send channel management commands to the effected receivers. Depending of the urgency of the channel management command (the requirements of certain incumbent users may be stricter than others), the BS shall calculate the expected time the channel management message should arrive at the CPEs and appropriately set the scheduling fields (e.g., count, offset, duration, period) in the message header.

As the traffic pattern of primary user is non-deterministic, secondary user is not able to deterministically predict when a detected whitespace will end. But, there are some non-deterministic approaches using which secondary user can make the transmission decision. There are three approaches to access the spectrum which is as follows:

1) First approach is a random way of occupying the spectrum;
2) Second approach is based on least used spectrum; and
3) The third approach is least used with channel hopping.

Ideally the bandwidth requirement in case of machine communication is very less and infrequent, hence least used spectrum access may be used.

#### *5.2.1.6. Scheduling Services*

Spectrum Access is a part of spectrum management that identifies the whitespace and access the white space. But before accessing the white space, it is desirable to find the probability of completing the transmission before the whitespace ends. Thus, the efficiency of whitespace access depends upon two factors (a) Effective Secondary User Throughput (EST) and (b) Primary User Interference (PUI). To have successful whitespace utilisation, the EST should be maximum and the PUI should be minimum.

In an IEEE802.22 cell, multiple CPEs are managed by a single BS that controls and schedule all transmission in medium access. The downstream is TDM where the BS transmits and the

CPE receives. The upstream transmissions, where the CPEs transmit and the BS receives, are shared by CPEs on a demand basis, according to a DAMA/OFDMA scheme. Depending on the class of service utilised, a CPE may be issued continuing rights to transmit, or is dynamically allocated by the BS after receipt of a request from the CPE. The MAC implements a combination of access schemes that efficiently control contention between CPEs within a cell and overlapping cells sharing the same channel while at the same time attempting to meet the latency and bandwidth requirements of each user application. Each connection is associated with a single data service. Each data service is associated with a set of QoS parameters that quantify aspects of its behaviour. This is accomplished through five different types of scheduling services mention as follows:

1) **Unsolicited Grant Service (UGS)**: Constant Bit Rate (CBR) traffic, e.g., voice. Specified throughput, delay and delay jitter;
2) **Real-Time Polling Services (rtPS)**: Real-time variable bit rate (rtVBR), e.g., streaming video. Specified peak and average throughput, delay and delay jitter;
3) **Non-Real-Time Polling Service (nrtPS)**: nrtVBR, e.g., FTP. Specified peak and average throughput;
4) **Best Effort (BE)**; No throughput or delay guarantees; and
5) **Contention for bandwidth request.**

Table 5.1 give the use of scheduling services for different applications.

Table 5.1 Examples of different types of services.

| **QoS** | **Application** |
|---|---|
| UGS | VoIP, T1 / E1 |
| rtPS | MPEG video streaming |
| nrtPS | FTP |
| BE | E-mail |
| Contention | Bandwidth request etc. |

### *5.2.2. Database Services and Channel Status*

The system model that has been assumed in IEEE802.22 is a point-to-multipoint model communication which is also supported by IEC61850. The BS is assumed to control all RF parameters of associated CPE (frequency, EIRP, modulation, etc.) in a "master-slave" relationship. The SM will consult this database to find the backup channel for operation. This database provides Radio Environment Maps containing information of parameters to SM. So, before allocating any channel the SM will consult the database to find the parameters they can use, such as channel number and transmit power.

This database contains the spectrum usage of all licensed and unlicensed user. Thus, conflicts between licensed and unlicensed users can be avoided. The interface to the database services is depicted in Fig 5.12. The database service will enlist all CPEs with their geographic location, device identification, etc. on a real-time basis since its association may depend on the response from the database service.

The SM of BS queries the database using the message script to obtain information of the channel status about the presence of incumbent and other WRANs in the area. This information will be used for channel selection, channel state management and self-co-existence mechanisms. The status of the channel is maintained and updated using spectrum sensing, geolocation and previous status in database.

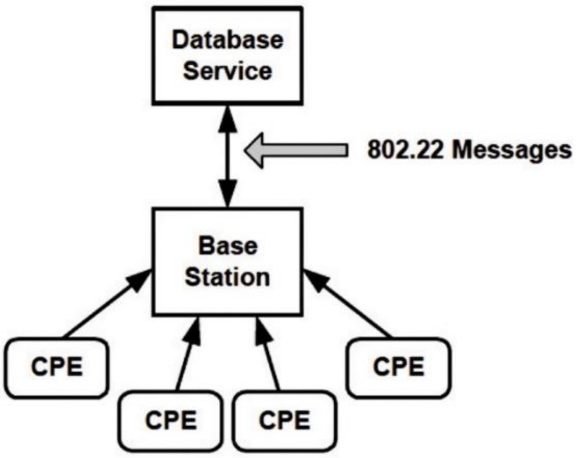



Fig. 5.12 Base station access to database services

### *5.2.3. Co-Existence Beacon Protocol*

To cope with serious self-interference issues that may arise in a real deployment scenario, the CBP protocol is employed. The CBP is a best-effort protocol based on co-existence beacon transmissions. Given the mechanism for synchronisation of overlapping BSs and that many CPEs can be used to augment redundancy of the transmission, successful delivery of co-existence beacon transmissions can be made highly reliable. At the end of US subframe, CBP bursts are transmitted by selected CPEs for signalling to adjacent and overlapping WRAN cells and for geolocation. CPEs decode CBP packets from CPEs in cells operating on the same TV channel or adjacent channels. CPE beacons are transmitted by the CPEs and contain the TV channel number, backup channel numbers, BS ID, CPE ID.

### *5.2.4. Transmit Power Control and Ranging*

Transmitter power control is essential part for reliable communication in the dynamic environment to ward off harmful interference to other users. According to the property of free space propagation loss the received power is inversely proportional to the square of the distance. It means the CPE at a farthest distance will require more power than the CPE at a shorter distance. So, as per the inverse power control law, lower transmission power levels are allocated to good channel realizations and higher power levels are allocated to deeper fading, with an aim to minimizing the interference. Moreover, truncation/cutting off transmission in poor channel helps to improve the performance.

There is a trade-off between transmitted power and frequency, to optimise the spectral and energy efficiency transmitted power and frequency must be jointly controlled. CPE sends frames on upstream to BS which find distance and determine frequency, time and power adjustments. Geolocation also use ranging to find the relative coordinates. The maximum effective isotropic radiated power (EIRP) is fixed as 4W in USA with maximum antenna height above ground level is 30m for both BS and CPE [89]. For case of portable mode EIRP is 100mW [63]. Dynamic ranging is used to support Transmit Power Control between near and far BS/CPE using minimum EIRP for reliable connection which also minimise interference to the incumbent. The top-down time division duplex (TDD) superframe structure employed in the MAC is illustrated in Fig 5.13 [66]. The Bandwidth Request, Ranging and Urgent co-existence message may be transmitted during any upstream allocation in the first frame of upstream.

## *5.3. Integration of IEC61850 MMS with IEEE802.22*

MMS traffic model is designed and implemented based on the technical specifications of the IEC61850. MMS is an application layer protocol that defines how the messages must be transported by underlying protocols. Figure 5.14 depicts different message types supported by IEC61850 including the MMS and integration of IEEE802.22 at MAC layer.

MMS is a protocol that is based on client-server model which run over TCP/IP to support IEC61850 services. Currently the MMS uses Ethernet as the layer 2 protocol. The Ethernet is a good option at Substation level for wired communication. However, Ethernet may not be a favorable protocol for transferring real-time process data and supervisory control information between networked devices and control center. WRAN a new Cognitive Radio based communication standard is better for high volume data traffic in Smart Grid. WRAN can provide high-capacity, low-latency, secure and reliable data transfer over long wireless network.

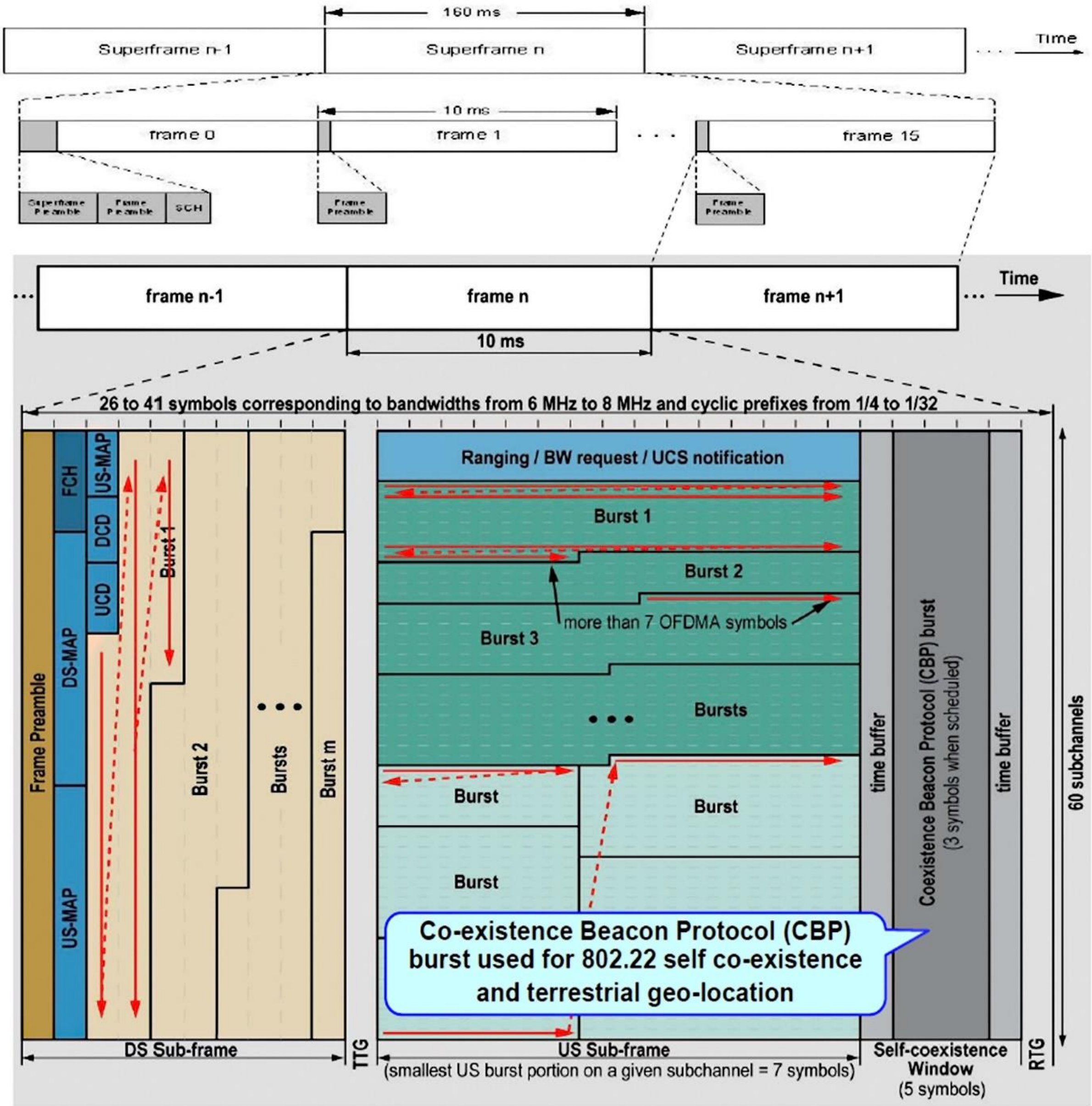



Fig. 5.13 Superframe and frame structure [66, 88]

GOOSE and SV are directly mapped on Ethernet. However direct mapping on Ethernet has a disadvantage in a sense it cannot be routed over Wide Area Network (WAN) which is required for teleprotection between substations and transmitting synchrophasors. Instead some application such as transfer of smart meter data to MDMS at control center are not time critical which can be mapped to MMS. MMS is a protocol that support transfer of real-time process data and supervisory control information between networked devices and control center. MMS also supports the mapping of the core ACSI services for complex naming and services models.

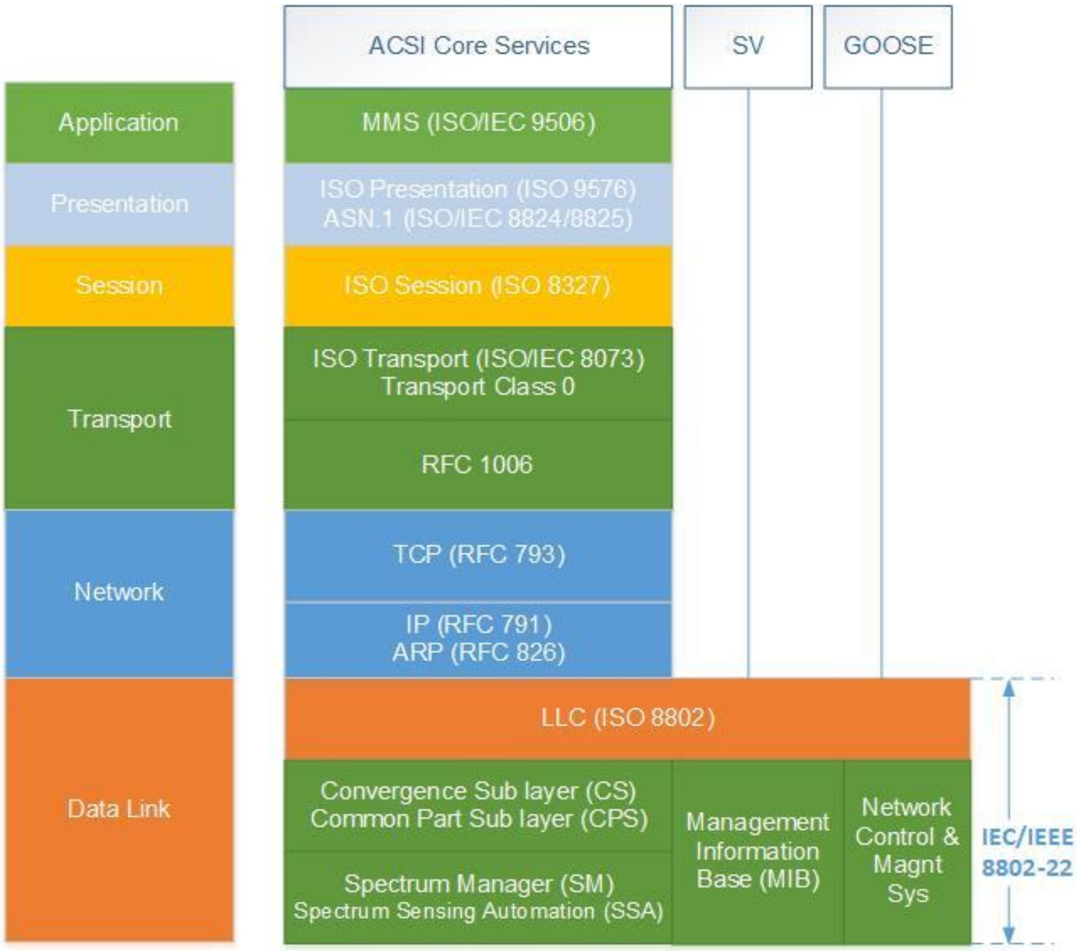



Fig. 5.14 Integration of IEC 61850 and IEEE802.22

The design and configuration of the Cognitive Radio network for the data exchange with the remote-control center(s) and other external users of the substation automation is depicted in Figure 5.15. The communication service structure of IEC61850 support [14]:

- Client–server and
- Publisher–subscriber communication protocol for the multicast of urgent messages using the GOOSE or the transfer of SV.

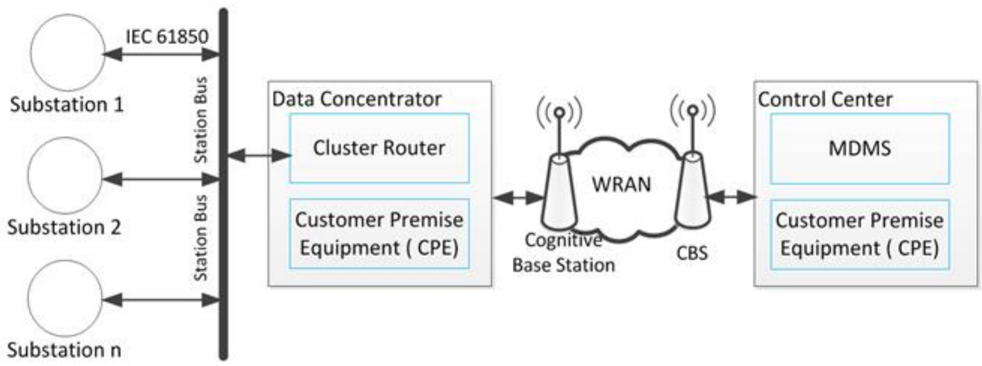



Fig. 5.15 Communication model of IEC 61850 & IEEE802.22.

The engineering steps are depicted in Figure 5.16. They are related to:

1. the specification of the SAS in general,
2. the IED configuration,
3. the design of the communication network,
4. the connection schemes between the IEDs and the process equipment and
5. the configuration of the data exchange with the remote-control center(s) and other external users of the substation automation.

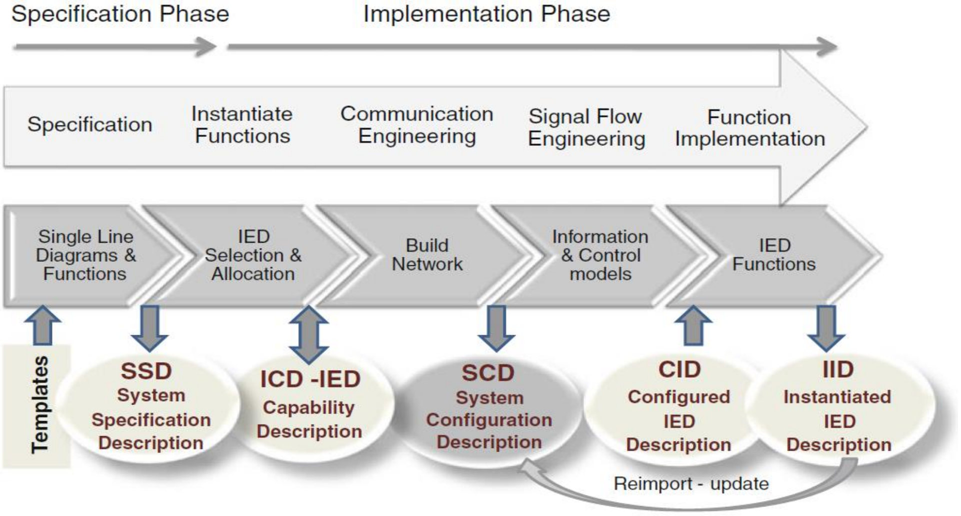



Fig. 5.16 Engineering steps to IEC 61850 implementation

## 5.4. Data management

The Smart Grid generate Big Data which is a collection of large and complex data sets that is difficult to process using conventional database tools or data processing applications. There is a challenge to analyse, capture, store, retrieve, search, share, transfer and visualise this complex data.

The common data type is a time-serialized database that is commonly used to gather streaming data from sources such as SCADA. This technology stores data, with a timestamp and generate alerts, only when it values changes. The data-management technologies of the past do not have the option of managing temporal data.

CIM is the standard of IEC61850 used to describe the assets, topology and processes that make up the grid [92]. CIM allow application software to exchange information about the configuration and status of the grid. The CIM is a UML model, which describes information used by the utility as an object-oriented database model.

NoSQL systems referred to as "Not only SQL" allow SQL-like query language to be used by power Industry for Big Data. NoSQL improves the ability of electric power grid operators to detect and react to system faults. It takes advantage of streaming data available to grid operators. The technology can rapidly and reliably screen, analyse and detect faulty data; and correct the missing elements in real-time.

## 5.5. Summary

IEC61850 and IEEE802.22 standards are discussed in details. IEC61850 divide the entire structure of IEDs into Process Level, Bay Level and Station Level. State transition diagram describes the working of IEDs. The different methods and protocols used in IEEE802.22 are explained in details. The special type of time-serialized database has to be maintained for gathering streaming data from different sources for teleprotection. The database also maintained the list of different channels for use. The possible integration of IEC61850 with IEEE802.22 for MMS services is also presented.

# CHAPTER 6

## SPECTRUM SENSING AND DETECTION

The process flow of transferring IEC61850 MMS data to control center is given in Figure 6.1.

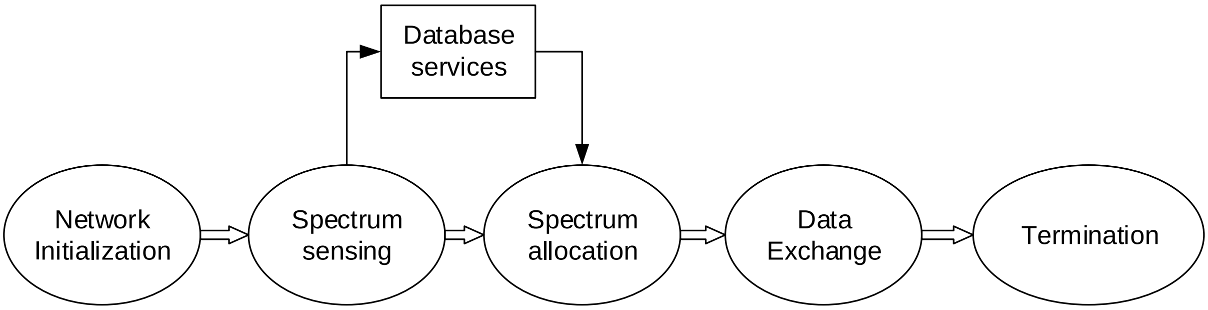



Fig. 6.1 Process Flow of transferring MMS data

## *6.1. Network Initialization and Association at BS*

The spectrum sensing techniques is an opportunity to check the availability of spectrum holes that are vacant at a given time and place. The procedure of spectrum sensing at BS is given as follows (assuming the BS and CPE are working error free and geographical location of all the devices in the network is known) [66]:

i. If the channels are available for use at a BS, the SM will receive the initial list of available channels. If there are no database available of unused channels, the SM initially considers all channels available.

ii. The BS will perform incumbent detection on all usable channels and synchronise network to neighbouring BSs. The spectrum database is build and updated at regular interval.

iii. Once the list of available channel is confirmed the SM will present the list to the higher layers for selection of an operating channel.

iv. The BS/CPE commences operation on the selected channel recommended by SM.

The flow chart of the radio scene analysis and channel identification at BS is given in Figure 6.2 [66].

## *6.2. Initialization and Network association at CPE*

The steps performed by the BS and the CPE for spectrum sensing at CPE are given as follows (presuming CPE is initialized properly and working error free) [66]:

i. CPE senses the spectrum and synchronises to WRAN services. The sensing thread also begins detecting broadcasting incumbents.

ii. CPE presents sensing results to the higher layers.

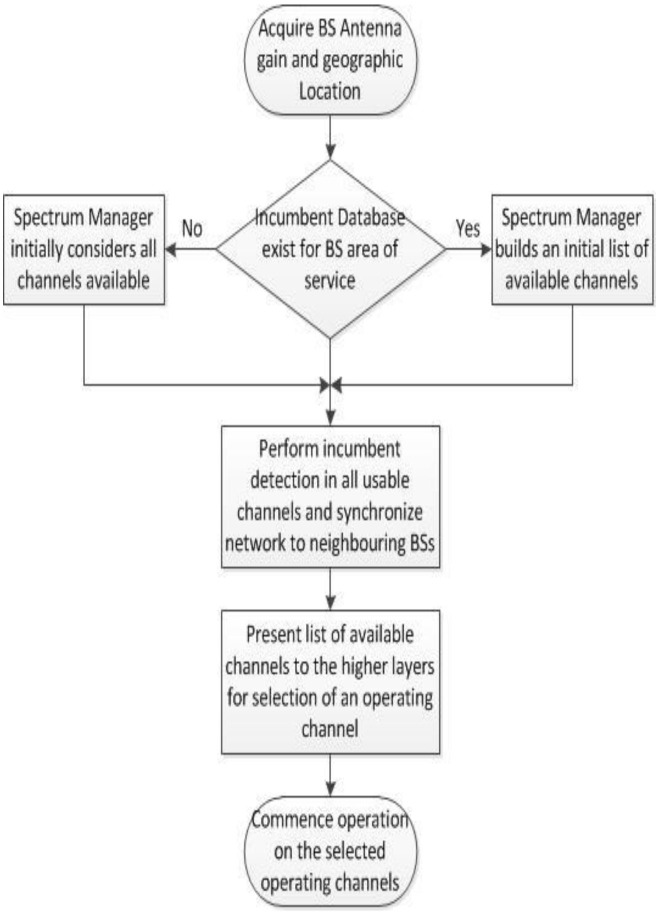



Fig. 6.2 Procedure of Spectrum Sensing at BS [66].

iii. CPE chooses a WRAN service.

iv. CPE acquires a valid geolocation information from the satellites. If the data acquisition is not possible, CPE initialization will discontinue.

v. CPE acquires the downstream and upstream parameters from the selected WRAN service.

vi. If channels N and N±1 pass the sensing and timing requirements, BS and CPE perform initial ranging. Ranging is the process of collecting the propagation delay characteristics and quality of RF links of different channels necessary for CPE and BS synchronisation.

vii. CPE transmits its basic capabilities.

viii. If the basic capabilities are present in the CPE, the AAA procedure will be initiated by the BS which authenticates the given CPE and secure key exchange is performed; otherwise, the CPE does not proceed to registration and the BS de-registers the CPE.

ix. Once the CPE passed the AAA, the BS performs CPE registration.

x. Upon completing registration. BS transmits channel sets to CPE.

xi. CPE establish IP connectivity.

xii. Transfer operational parameters.

xiii. Establish dynamic service flows.

xiv. Report sensing result and discovered neighbouring networks to a higher layer.

xv. Commence operation on the selected operating channels.

The flow chart of the radio scene analysis and spectrum sensing is given in Figure 6.3. The regulatory constraints given in research paper [93] must be followed to maintain integrity of communication.

## 6.3. Spectrum Sensing

Cognitive Radio users must be able to identify the spectrum used by the PU and the spectrum available for use by SU. Different spectrum sensing techniques are already discussed in section 5.2.1.3. This study chooses **energy detection and cyclostationary feature detection** for the spectrum sensing implementation**.**

### 6.4.1. Energy detection

A binary hypothesis test is performed to determine whether a primary signals is present in a particular channel as a part of spectrum sensing exercise [94]. If there are no activities on the channel it is considered as a null hypothesis or it is considered as busy as shown in equation 6.1:

$$H_0 \text{ (idle) vs. } H_1 \text{ (busy)} \qquad (6.1)$$

Ideally, in a radio frequency (RF) environment, received signal is either a busy signal that consist of the PU's signal and the white Gaussian noise, or an ideal signal that consist of an ambient noise; thus,

$$\left.\begin{aligned} H_0&: y(n) = w(n) \\ H_1&: y(n) = s(n) + w(n) \end{aligned}\right\} \qquad (6.2)$$

for n= 1, 2, 3 …., k, where k is the number of received samples. *w(n)* represents white Gaussian noise and *s(n)* represents the PU signal.

The channel will have more energy when it is busy than when it is idle. Here, *w(n)* and *s(n)* are zero-mean complex Gaussian random variables with variances $\sigma_w^2$ and $\sigma_s^2$ per dimension. Let y = [*y(*1*)*, ..., *y(k)*]' denote the vector of the k observed samples. It is convenient to denote $\sigma_0^2 = \sigma_w^2$ and $\sigma_1^2 = \sigma_s^2 + \sigma_w^2$.

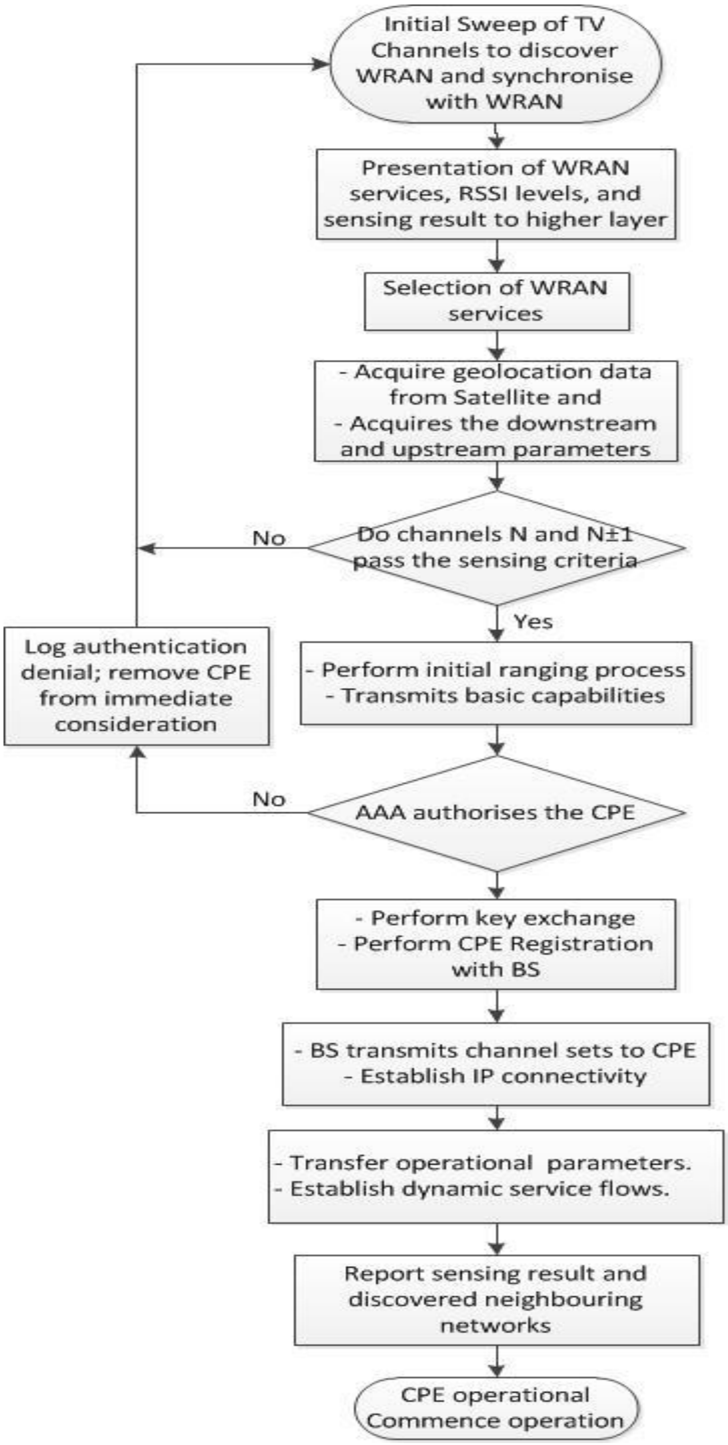



Fig. 6.3 Procedure of Spectrum Sensing at CPE [66]

The energy detection is subjected to errors due to additive noise, limited observations and the inherent randomness of the observed data. Two types of errors are common in energy detection. **False alarm** is one type of errors which occurs if an idle channel is detected as busy. The other type of error is a **missed detection** which occurs when a busy channel is detected as idle. A false alarm may lead to a potentially wasted opportunity for the SU to transmit. A missed detection could potentially lead to a collision with the PU, leading to wasted transmissions for both PU and SU.

The two performance parameters used to optimise the detections are probability of detection ($P_d$) and the probability of false alarm($P_f$) which is defined in equation 6.3 and 6.4:

$$P_f = P\ (S > \lambda | H_0) \qquad (6.3)$$

$$P_d = P\ (S > \lambda | H_1) \qquad (6.4)$$

where the average of total energy detected is $S$ using k samples. S is defined in equation 6.5:

$$S = \frac{1}{k} \sum_{n=1}^{k} |\ y(n)|^2 \qquad (6.5)$$

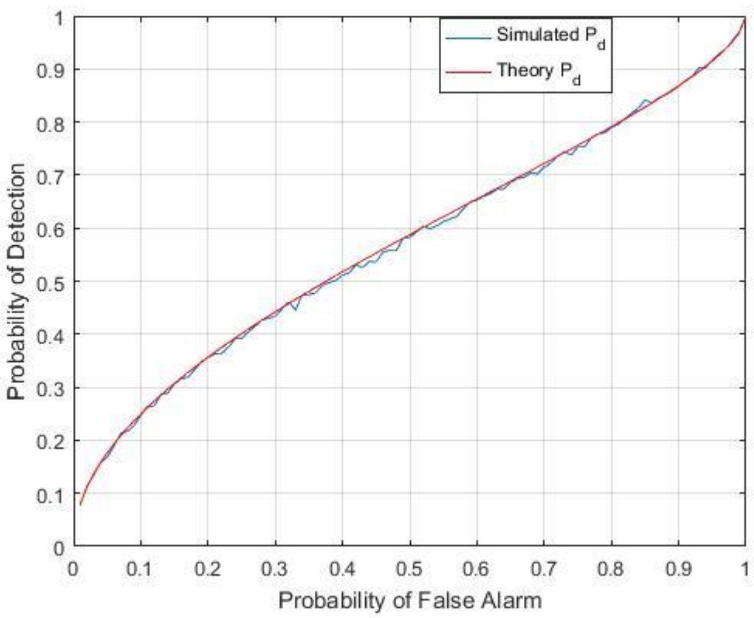
which is compared to a predefined threshold λ is defined in equation 6.3 and 6.4. Usually λ is calculated based on $P_f$, where $P_f$ is the probability that the hypothesis test incorrectly decides $H_1$ instead of $H_0$ i.e. false alarm. $P_d$ is the probability that $H_1$ has been correctly determined. To maximise channel utilisation, $P_d$ should be close to one and $P_f$ should be closer to zero [94, 95]. In ideal case the probability of detection $P_d$ = 0.9 and the probability of false alarm $P_f$ = 0.1 as per IEEE802.22. Other parameters used for simulation are listed in Table 6.1 which are derived from IEEE802.22 standards [66].

Table 6.1 Sensing Requirements for IEEE802.22

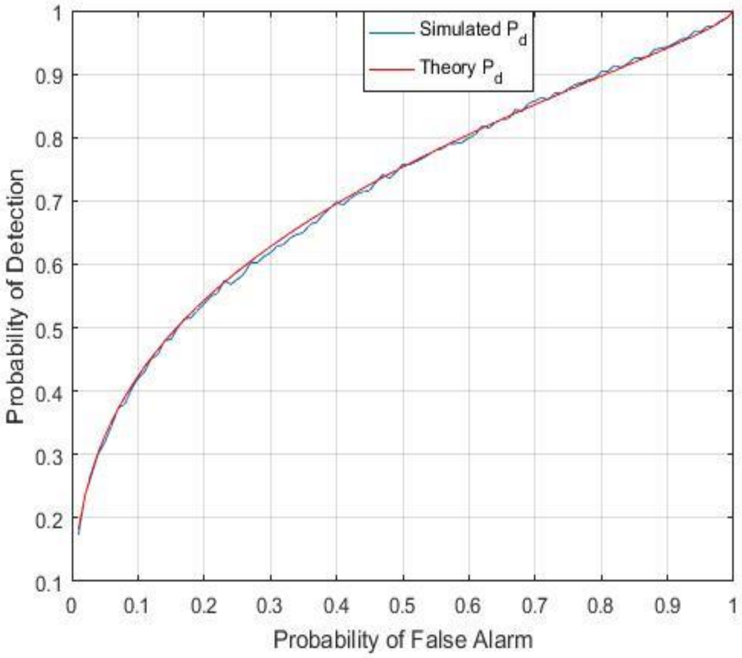
| | Parameters | Digital TV |
|---|---|---|
| 1 | Channel detection time | ≤ 5 ms |
| 2 | Channel move time | 2 secs |
| 3 | Detection threshold (required sensitivity) | -114 dBm (over 6 MHz) |
| 4 | Probability of detection ($P_d$) | 0.9 |
| 5 | Probability of missed detection ($P_{md}$) | 0.1 |
| 6 | Probability of false alarm ($P_f$) | 0.1 |
| 7 | SNR | -18 dB |

| | | |
|---|---|---|
| 8 | Spectral efficiency | 0.76 to 3.78 bit/(sHz) |
| 9 | Payload modulation | QPSK, 16-QAM, 64-QAM |
| 10 | Multiple access | OFDMA |

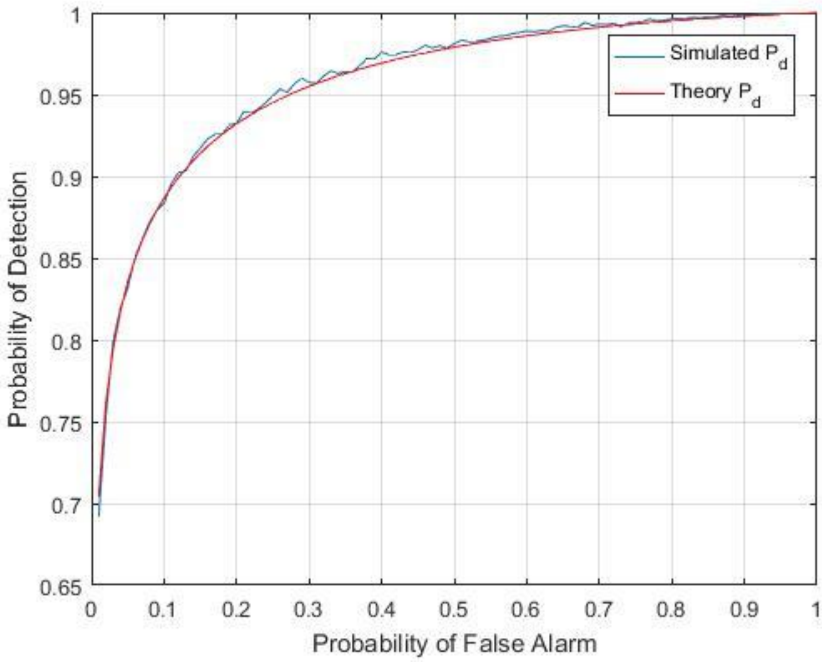
The receiver operating characteristic (ROC) plot of the probability of detection $P_d$ versus $P_f$, for different SNR is given in Figure 6.4 [96]. The primary signal is real Gaussian signal and noise is additive white real Gaussian. Monte Carlo Simulation is followed to simulate the communication system and it is compared with the theoretical results for different SNRs. **The plot shows that the probability of detection is high when the probability of false alarm is less for SNR = -10dB.** Furthermore, the simulated results match closely with the theoretical results. The SNR is very low in the operating regime. The disadvantage with the energy detector scheme is that in case of low SNR the number of samples required to achieve specific performance ($P_d$, $P_f$) is proportional to $1/SNR^2$.




(a)



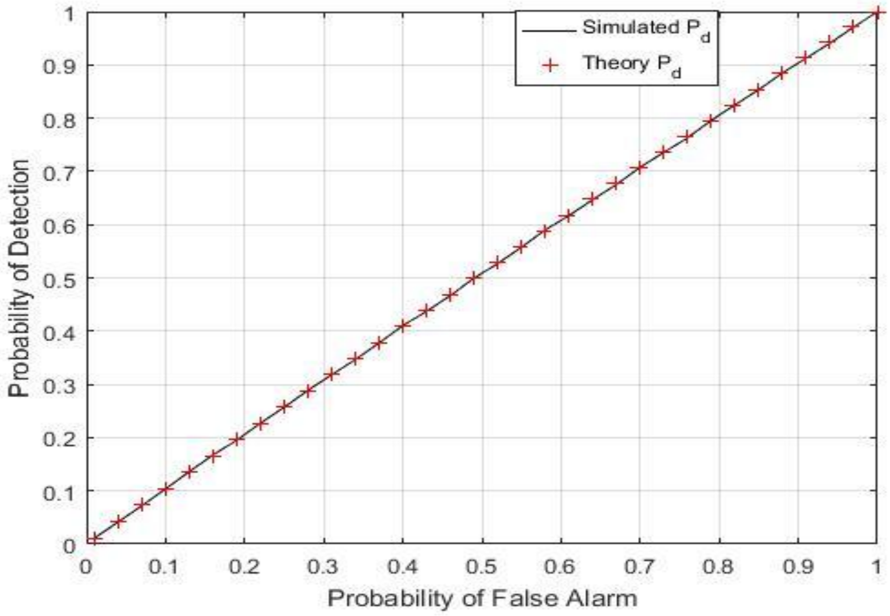

(b)



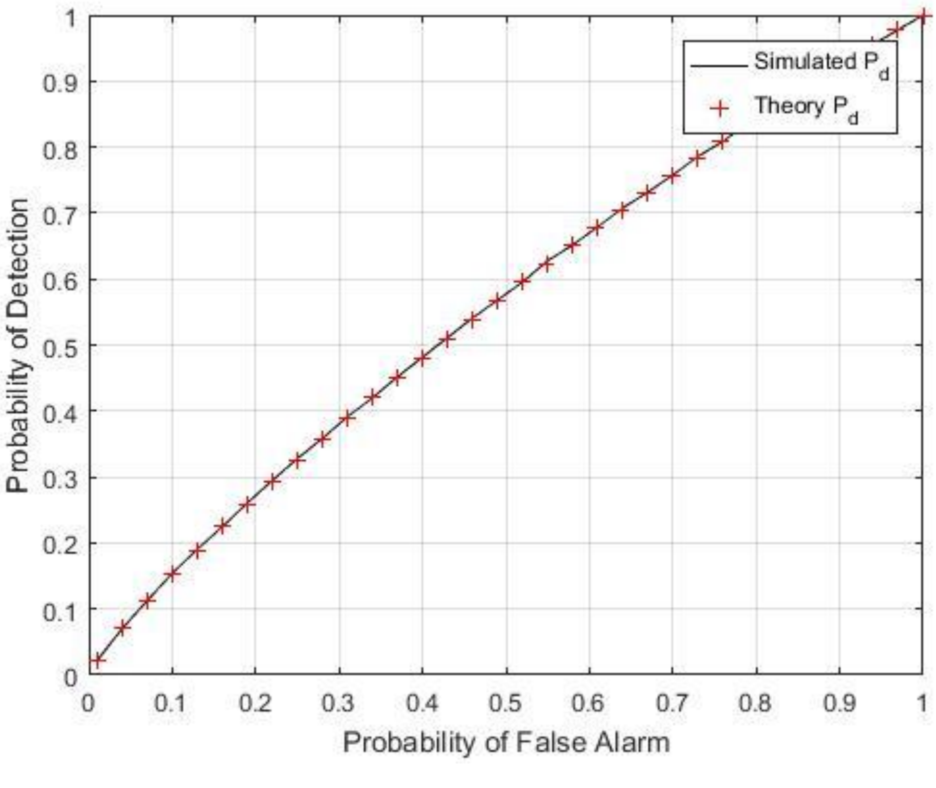

(c)

Fig. 6.4 Probability of False Alarm Vs Probability of Detection for Gaussian signal (a) ROC of energy detection for SNR = −20dB, (b) ROC of energy detection for SNR = −15dB, (c) ROC of energy detection for SNR = −10dB.

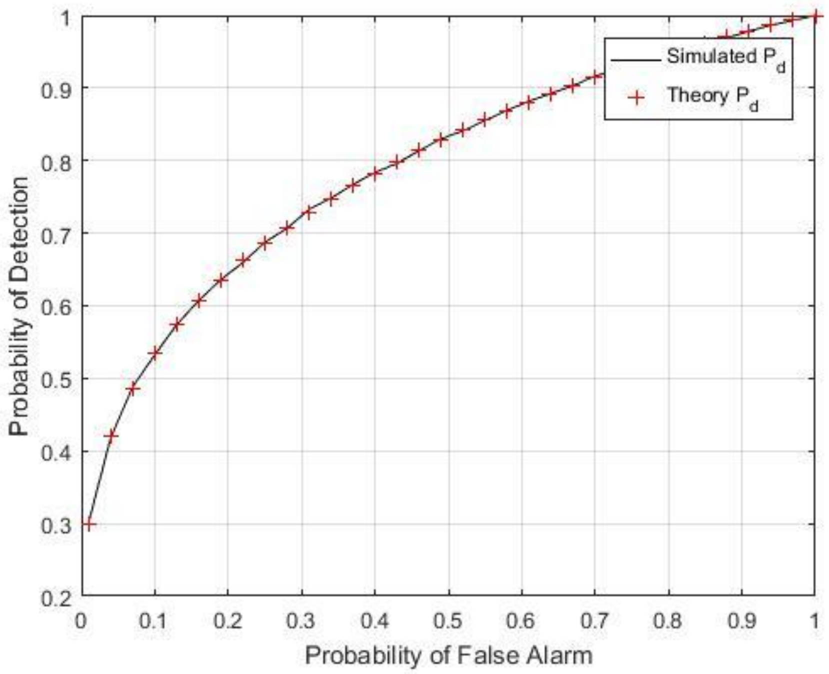
The ROC for the probability of detection $P_d$ versus probability of false alarm $P_f$ for Rayleigh flat-fading channel is given in Figure 6.5 under various SNR.




(a)




(b)




(c)

Fig. 6.5 Probability of False Alarm Vs Probability of Detection for Rayleigh flat-fading channel (a) ROC of energy detection for SNR = −20dB (b) ROC of energy detection for SNR = −10dB (c) ROC of energy detection for SNR = 0dB.

The energy detection in non-fading and fading environments is compared, complementary ROC curve between probability of false alarm $P_f$ versus probability of missed detection $P_m$ is plotted on logarithmic scale as given in Figure 6.6. The probability of missed detection $P_m$ = 1- $P_f$. It observed that in case Rayleigh fading the energy detection performs poorly for SNR of 20dB [95].

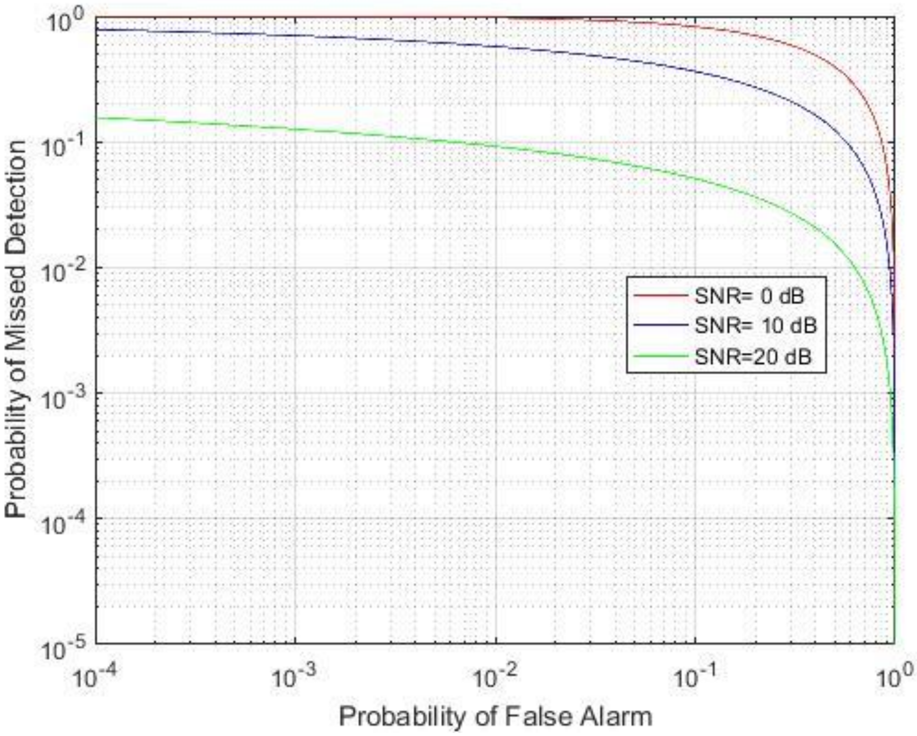



Fig. 6.6 ROC curve over Rayleigh fading channels for different SNR.

The threshold λ corresponds to Eq. 6.5 is considered for determining the presence of primary users. λ can be approximately by Gaussian distribution. Figure 6.7 gives the plot of threshold under different sampling rates.

### *6.4.2. Cyclostationary Feature Detector*

One of the other spectrum sensing method is cyclostationary feature detection. It utilises the cyclostationary property of the signals to achieve the sensing requirements. **It is good candidate for sensing detection due to its noise rejection ability.** The stationary Gaussian process has a zero-valued cyclic spectrum or spectrum correlation density function (SCD) at non-zero cyclic frequency. Therefore, it is easy to detect the desired signal by calculating its cyclic spectrum provided the signal is cyclostationary such that its cyclic spectrum is not identically zero at some non-zero cyclic frequency [97]. The derivation is compiled from the paper [97].

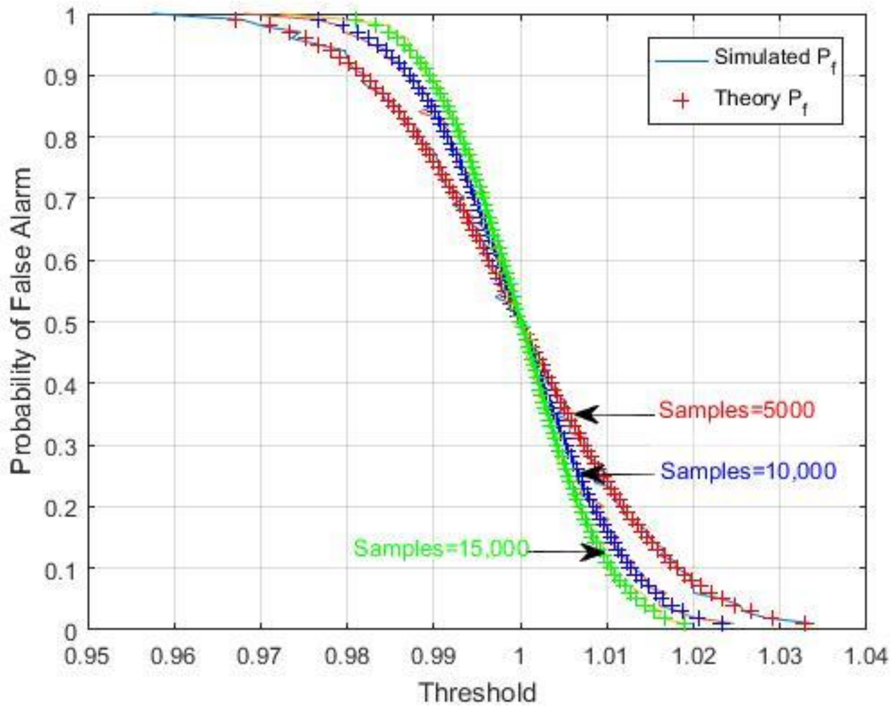



Fig. 6.7 Threshold Vs Probability of False alarm.

The cyclic autocorrelation function of a stochastic process *x*(*t*) for a cyclic frequency *α* is defined as given in equation 6.6 and 6.7 [97]:

$$R_x^{\alpha}(\tau) = \lim_{\Delta t \to \infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{\Delta t/2} x\left(t + \frac{\tau}{2}\right) x^*\left(t - \frac{\tau}{2}\right) e^{-j2\pi\alpha t} dt \qquad (6.6)$$

Or

$$R_x^{\alpha}(\tau) = \lim_{\Delta t \to \infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{\Delta t/2} u\left(t + \frac{\tau}{2}\right) v^*\left(t - \frac{\tau}{2}\right) dt \qquad (6.7)$$

where $u(t) = x(t)e^{-j\pi\alpha t}$ and $v(t) = x(t)e^{+j\pi\alpha t}$ are, frequency shifted versions of x(t) so that $R_x^{\alpha}(\tau)$ can be considered as the cross-correlation of u(t) and v(t). The cyclic spectrum of x(t) for a given cyclic frequency *α* is expressed as given in equation 6.8

$$S_x^{\alpha}(f) = \int_{-\infty}^{\infty} R_x^{\alpha}(\tau) e^{-j2\pi\alpha\tau} d\tau = S_{uv}(f) \qquad (6.8)$$

where second equality comes from equation 6.7. So, the cyclic spectrum $S_x^{\alpha}(f)$ is the cross-spectral density of frequency shifted signals u(t) and v(t). So, the SCD function is derived from cyclic spectrum.

### 6.4.2.1. *Measurement of Spectral Correlation*

The cyclic spectrum is derived from the equation following limit of spectral components as shown in equation 6.9:

$$S_x^{\propto}(f) = \lim_{\Delta f \to 0} \lim_{\Delta t \to \infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{\Delta t/2} \Delta f X_{\frac{1}{\Delta f}}\left(t, f + \frac{\propto}{2}\right) . X^*_{\frac{1}{\Delta f}}\left(t, f - \frac{\propto}{2}\right) dt \qquad (6.9)$$

where, $X_{\frac{1}{\Delta f}}(t, v)$ is a short-term Fourier transform of x(t) with approximate bandwidth $\Delta f$ and central frequency *v*.

$$X_{\frac{1}{\Delta f}}(t, v) \triangleq \int_{t-1/2\Delta f}^{t+1/2\Delta f} x(\lambda) e^{-j2\pi v \lambda} d\lambda \qquad (6.10)$$

It is shown that $S_x^{\propto}(f)$ is given by the limit of spectrally smoothed products of spectral component using fast Fourier transform (FFT) algorithm. The frequency *f* and cyclic frequency ∝ should be multiple of $F_s$. The parameter $T_s$ is the time-sampling increment and $F_s = 1/NT_s$ is the frequency-sampling increment. The discrete-frequency method for $f = \ell F_s$ and $\propto = 2DF_s$ as shown in equation 6.11,

$$S_x^{\propto}[\ell] = \frac{1}{(N-1)T_s} \frac{1}{M} \sum_{v=-(M-1)/2}^{(M-1)/2} X[\ell + D + v] . X^*[\ell - D + v] \qquad (6.11)$$

where,

$$X[v] = \sum_{k=0}^{N-1} x[k] e^{-j2\pi vk/N} \qquad (6.12)$$

which is the DFT of the sampled signal $x[k] = x(kT_s)$ *and* M is the smoothing factor. The number of time samples used in DFT is given by N. The frequency smoothing method is shown in equation 6.13

$$S_x^{\propto}[\ell] = \frac{1}{(N-1)T_s} \frac{1}{M} \sum_{\mu=-(M-1)/2}^{(M-1)/2} X[\ell + D, \mu] . X^*[\ell - D, \mu] \qquad (6.13)$$

where

$$X[v, \mu] = \sum_{k=0}^{N-1} x[k, \mu] e^{-j2\pi vk/N} \qquad (6.14)$$

and $x[k, \mu] = x(kT_s, f_{IF} + \mu . \delta f)$ is a frequency down-converted signal having carrier frequency $f_{If} + \mu . \delta f$. The intermediate frequency is $f_{If}$. *x*(*t*) is the frequency down-converted signal that has central frequency $f_{If}$. Thus, more precise frequency resolution can be obtained by controlling the parameter *δf*, without increasing the DFT size. The discrete-time average method is calculated as shown in equation 6.15

$$S_x^{\propto}[\ell] = \frac{1}{(N-1)T_s} \frac{1}{KM} \sum_{u=0}^{KM-1} X_u[\ell + D] . X_u^*[\ell - D] \qquad (6.15)$$

where

$$X_u[v] = \sum_{k=0}^{N-1} x_u[k] e^{-j2\pi vk/N} \qquad (6.16)$$

which is the DFT of the sampled signal $x_u[k] = x\left(\frac{u(N-1)T_s}{K} + kT_s\right)$. The parameter K is the block overlapping factor. If *K* =1, all data segments are non-overlapping.

This process does not require the knowledge of the noise variance to set the detection threshold; so, the detector does not suffer from the “SNR wall” problem as in the case of the energy detector. However, the detection degrades due to frequency, jitters and RF non-linearities (which induce spurious peaks).

#### *6.4.2.2. General Spectrum Sensing System Model*

If *x*(*t*) is transmitted time signal and *h*(*t*) is a linear time-invariant channel then, the additive white Gaussian noise (AWGN) noise *w*(*t*) corrupted the channel [97]. The signal received *y*(*t*) is given by equation 6.17

$$y(t) = x(t) \otimes h(t) + w(t) \qquad (6.17)$$

where *w*(*t*) is a zero-mean and its cyclic auto-correlation function is given by equation 6.18

$$R_x^{\propto}(\tau) = \begin{cases} \sigma^2\delta(\tau), & \propto = 0 \\ 0 & \propto \neq 0 \end{cases} \qquad (6.18)$$

The equation divided the signals into two categories, one with $R_x^{\propto}(\tau) \neq 0$ for $\alpha = 0$ are called *cyclostationary* and those with $R_x^{\propto}(\tau) = 0$ for $\alpha \neq 0$ are called as *purely stationary*. Thus, it can be stated that AWGN is a purely stationary signal. It can be shown that when a signal *x*(*t*) undergoes a linear time-invariant transformation (*z*(*t*) = *x*(*t*) $\otimes$ *h*(*t*)), the output SCD and input SCD are related as shown in equation 6.19

$$S_z^{\propto}(f) = H\left(f + \frac{\propto}{2}\right) H^*\left(f - \frac{\propto}{2}\right) S_x^{\propto}(f) \qquad (6.19)$$

The function *H*(*f*) is the frequency response of the channel impulse. Finally, as per equation 6.17 *z*(*t*) = *x*(*t*) $\otimes$ *h*(*t*) and *w*(*t*) are independent. The cyclic spectrum of the received signal y(t) is given by equation 6.20

$$\begin{aligned} S_y^{\propto}(f) &= S_z^{\propto}(f) + S_w^{\propto}(f) \\ &= \begin{cases} S_z(f) + S_w(f), & \propto = 0 \\ S_z^{\propto}(f) & \propto \neq 0 \end{cases} \end{aligned} \qquad (6.20)$$

therefore,

$$S_y^{\propto}(f) = H\left(f + \frac{\propto}{2}\right) H^*\left(f - \frac{\propto}{2}\right) S_x^{\propto}(f), \quad \propto \neq 0 \qquad (6.21)$$

The equation 6.20 illustrate the method to separate random noise from cyclostationary signals which is purely stationary. So, spectrum sensing can be performed by measuring the cyclic spectrum of the received signal, when the SCD of the received signal is not identically zero. The block diagram of Figure 6.8 shows the method of cyclostationary feature detection. The detail procedure is given in the paper [97].

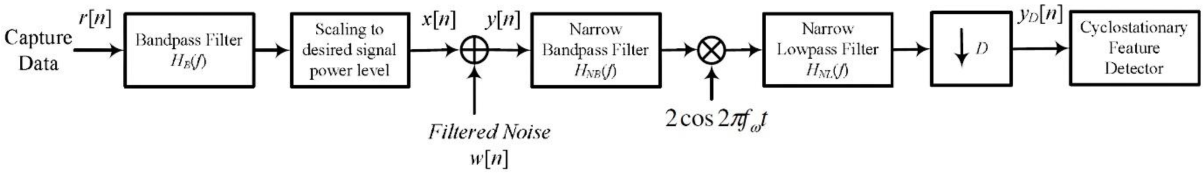



Fig. 6.8 Cyclostationary feature detector procedure [97]

The plot of the cyclostationary signal is shown in the Fig 6.9 [98]. The sampling frequency is $F_s$ = 1000Hz and the signal length is L = $10^5$ samples and produces a frequency resolution of 4Hz and a cyclic frequency resolution 0.01Hz [99]. The spectral coherence (SC) is given in Figure 6.10 (a) with a colour-map. The SC evaluated at the resonance frequency $S_y^{\propto}(f)$ is given in Figure 6.10 (b). The Fourier spectrum of the square modulation whose theoretical envelope (the cardinal sin function) is indicated by the black dotted line.

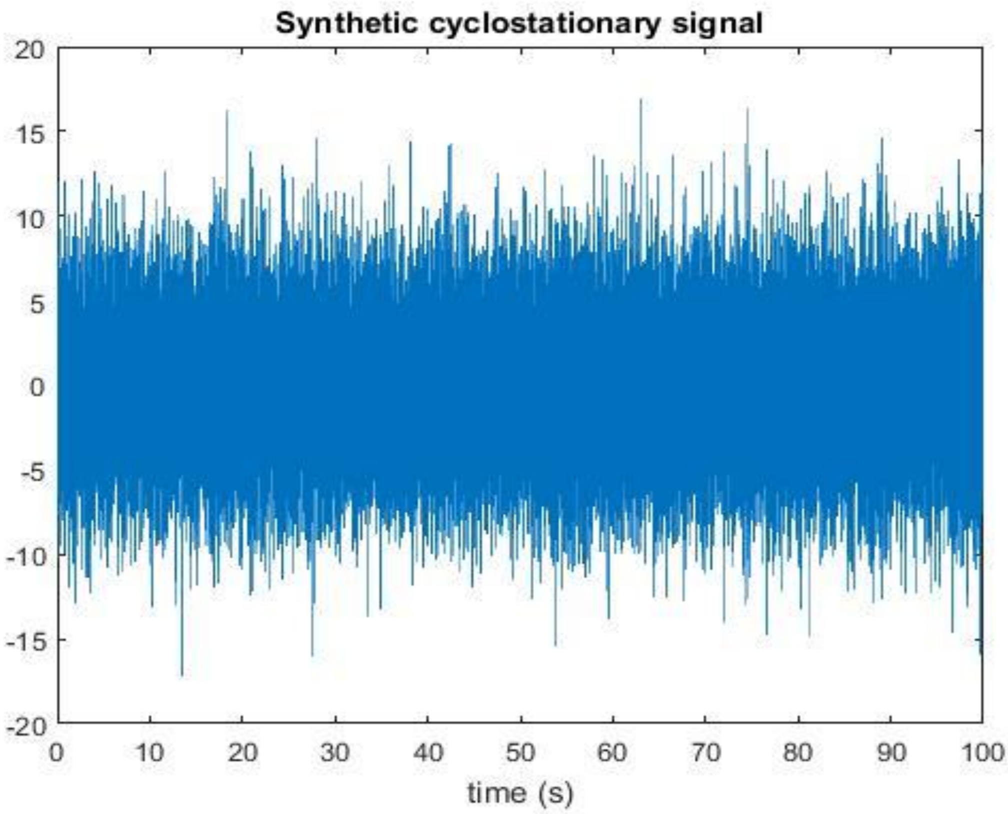



Fig. 6.9 Time signals of cyclostationary wave.

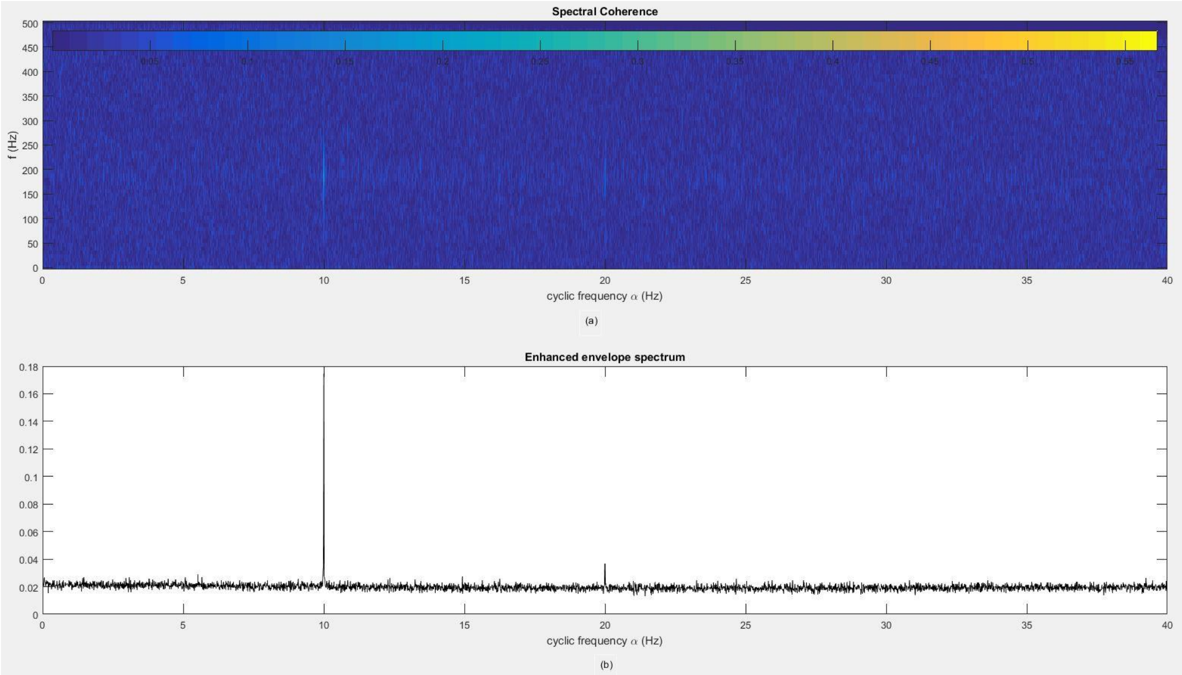



Fig. 6.10 (a) Spectral correlation estimation (b) theoretical envelope of the peaks (dotted line).

## *6.4. Summary*

The process flow of transferring IEC61850 MMS data to control center using IEEE802.22 is presented in this chapter. The process of network initialization and association for BS and CPE is given. The process of admission, authentication, authorization, and accounting of new CPE is done by BS. Different spectrum sensing methods are reviewed and complexities of their use are discussed. Simulation of spectrum sensing using energy detection and cyclostationary feature detection are performed under different conditions. The results are analysed and plotted for better visualisation.

# CHAPTER 7

# COGNITIVE RADIO SIMULATION

## 7.1. Introduction

Many network simulators were explored to simulate discrete events in Cognitive Radio. The performance parameters expected to be studied are throughput, latency, packet delivery ratio, etc. based on various protocols and topologies. The network simulators considered for simulation are:

(i) Cognitive Radio Cognitive Network (CRCN) based on Network Simulator 2 (NS-2) [100];

(ii) Cognitive Radio Cognitive Network (CRCN) based on Network Simulator 3 (NS-3) (incomplete) [101];

(iii) CogNS based on NS-2 [102];

(iv) OMNeT++ [103];

(v) Cognitive Radio extension for NS-3 (CRE-NS3) [104];

(vi) NetSim [105];

(vii) QualNet [106]; and

(vii) MATLAB.

Every simulator has some limitations and strengths. The simulators of CRCN and CogNS are based on NS-2 which is an open source software and very popular for network simulation. They both have similar features, but CRCN has more flexibility and options of working and integrating new protocols at different network layer. NS-2 also provides support for many radio models such as 802.11, 802.16, 802.15.3, 802.15.4 and users can make use of these radio models to generate codes for Cognitive Radio networks. Additionally, NS-2 also incorporate different topologies and traffic generators, which enable users to create different simulation scenarios. The drawback with CRCN is that its installation and configuration is very tedious, time consuming and full of bugs/error due to limited support and strong binding with NS-2.31 version 2.31. Also, many of NS-2 libraries have been depreciated due to NS-2 upgradation.

CogNS is based on NS-2 that can be used to investigate and evaluate impact of lower layers, i.e., MAC and physical layer, on transport and network layer protocols. The modification has been done on MAC layer of the mobile node. CogNS made major changes at MAC layer which is named as CogMAC. However, CogNS does not provide the same level of flexibility that is available for CRCN.

Another variant of CRCN is based on NS-3. It is still under development phase. The software installation and libraries are yet to be released for research. The architecture of the simulator is very exhaustive covering wide ranging features such as dynamic spectrum management, resource allocation, power control algorithms, co-existence mechanisms and many adaptive networking protocols. It supports many features of IEEE802.22. NS-3 provides support for many radio models such as 802.11, 802.16, 802.15.3, 802.15.4. So, CRCN based on NS-3 may be more suitable for Cognitive Radio simulation. The release of CRCN is long awaited.

OMNeT is a C++ based simulation environment for network simulation of wired and wireless network. It is a good tool for someone who is interested in simulation of spectrum related project such as spectrum sensing, spectrum allocation, spectrum usage, incumbent detection, interference analysis, etc. It is one of the simplest simulator to work with but it lacks flexibility to work with various simulation topologies and scenarios.

The CRE-NS3 based on NS-3 provides the basic building blocks of spectrum sensing, spectrum mobility and database query necessary in Cognitive Radio, however the scope of CRE-NS3 is very limited.

NetSim is another network simulation software used for network design and planning of various networks such as Cognitive Radio, Wireless Sensor Networks, Wireless LAN, WiMAX, TCP-IP, etc. NetSim facilitates in modelling the network and traffic analysis. NetSim is not an open source and user have to buy the license to work with NetSim.

QualNet is a network simulator that provides a comprehensive environment for designing protocols, creating and animating network scenarios and analysing their performance. It is a simulator which is good for wireless communication protocols especially Ad-hoc network, Wireless sensor network, WLAN, Wi-Fi, etc. But, it has not been upgraded to support Cognitive Radio. The software is not free and user have to buy license for working with QualNet.

MATLAB is also a good tool for spectrum sensing and associated computing related to wireless communication. This study has analysed spectrum sensing using MATLAB which has been discussed in section 6.4. But MATLAB has limited support for Cognitive Radio and it does not have any Cognitive Radio toolbox. So, generating the scenario of resource sharing, spectrum mobility, incumbent detection, etc. is difficult to model.

The NS-2 and NetSim was originally designed for simulation of data network. QualNet is used for the ordinary wireless network, but not for Cognitive Radio simulation. NS-3 is a simulation environment especially for wireless communication with some extensions to Cognitive Radio. So, after comparing different simulators, it can be concluded that CRCN and CRE-NS3 are good for simulating Cognitive Radio environment.

## 7.2. NS-2 Simulator

The simulation scenarios of Cognitive Radio in NS-2 are generated using network topologies and number of nodes. Figure 7.1 gives the building blocks of the NS-2 simulator [107]. The NS-2 consist of Object-oriented Tcl (OTcl) script/program that is interpreted by an OTcl interpreter which have simulation event scheduler, network component object libraries and network setup (plumbing) module libraries. Two types of files are generated when the program is executed, the NAM (. nam) file for network animator and trace (.tr) file for the analysis of the simulation data. The brief outline of simple wireless script of OTcl is given in Table 7.1.

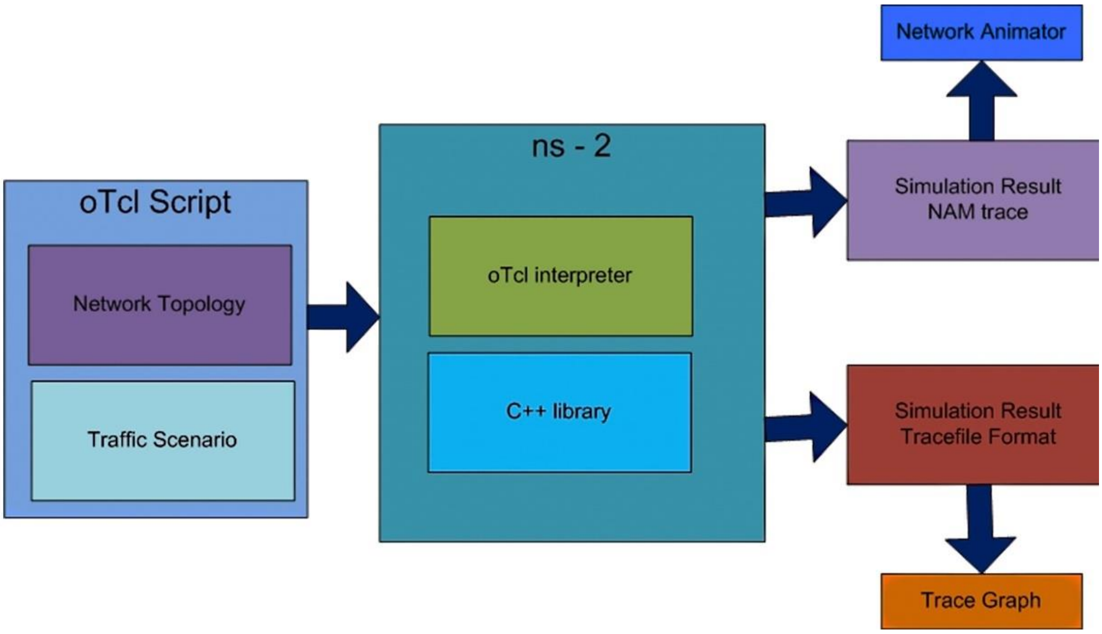



Fig. 7.1 Structure of NS-2 simulator

### 7.2.1. CRCN Simulator

CRCN simulator supports performance evaluations of power control algorithms, dynamic spectrum allocation and the adaptive Cognitive Radio networking protocols including the Cognitive Radio MAC and the Cognitive Radio Routing protocols. The architecture of CRCN simulator is illustrated in Fig 7.2 [100].

Table 7.1 OTcl Simulation Script in NS-2

| |
|---|
| • **Initialise the wireless simulation parameters**<br>set val(chan) Channel/WirelessChannel ;<br>set val(prop) Propagation/TwoRayGround ;<br>. . . . . . . . . |
| • **Create a simulator object**<br>set ns [new Simulator]<br>. . . . . . . . . |
| • **Open the trace and NAM file**<br>set ns [new Simulator]<br>set tracefd [open ./test.tr w]<br>set namtrace [open ./test.nam w]<br>$ns namtrace-all-wireless $namtrace 1000 1000<br>. . . . . . . . . |
| • **Set up topography object**<br>set topo [new Topography]<br>$topo load_flatgrid 1000 1000<br>. . . . . . . . . |
| • **Create and Configure Nodes and God**<br>set god_ [create-god $val(nn)]<br>. . . . . . . . . |
| • **Configure channels**<br>. . . . . . . . . |
| • **Call topology and Traffic File generator**<br>. . . . . . . . . |
| • **Set the end time**<br>$ns at 10<br>. . . . . . . . . |
| • **Execute NAM file**<br>exec nam ./test.nam &<br>. . . . . . . . . |
| • **Start Simulation**<br>$ns run |

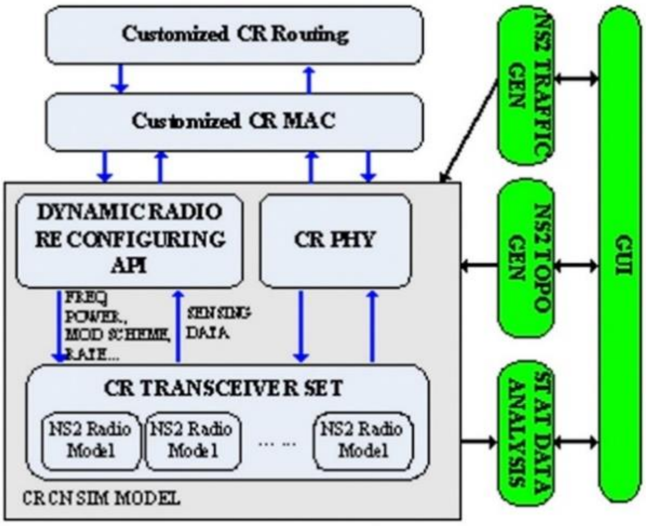



Fig. 7.2 Architecture of CRCN simulator [100]

#### *7.2.1.1. Simulation of Single Radio*

**Case 1: Simulation of Single radio with 2 Channels per radio**

Fig 7.3 shows the design structure of a single-radio having multi-channel i.e. the simulator has one interface and multiple channels. The simulation is based on the parameter of Cognitive Radio mentioned in Table 6.1. The input parameter for simulation of case 1 is given in Table 7.2(a) and the corresponding Throughput is given in Table 7.2(b).

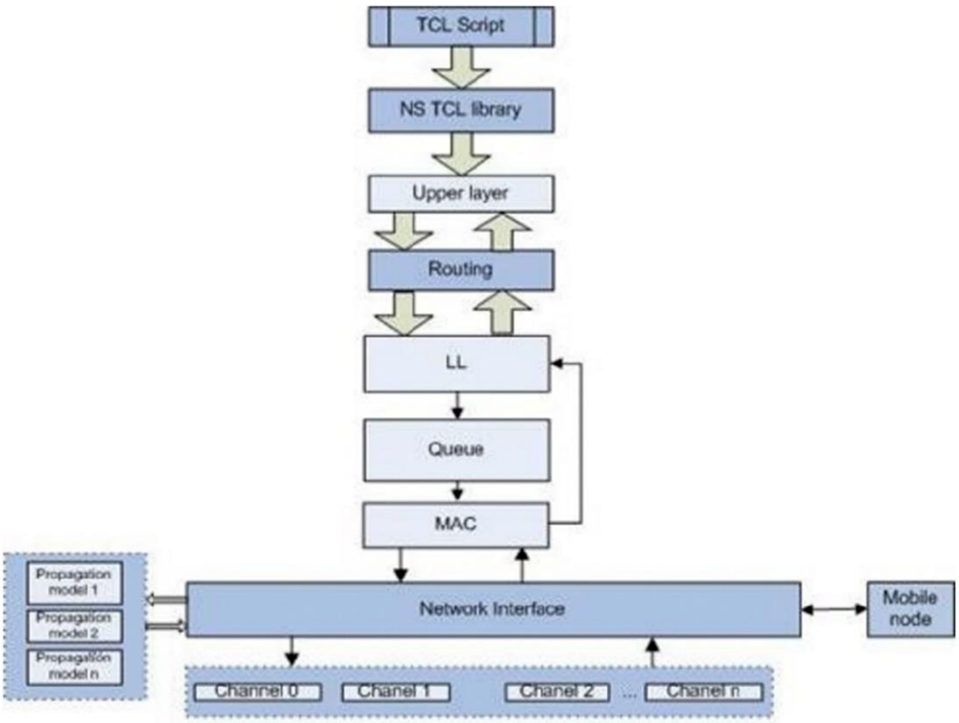



Fig. 7.3 Structure of single radio with multi-channel [100]

Table 7.2 (a) Simulation for Case 1: Input Parameters

| | Parameters | Specifications |
|---|---|---|
| 1 | Number of mobile nodes | 10 |
| 2 | Number of channels per radio | 2 |
| 3 | Topology | Random |
| 4 | Interface | MAC |
| 5 | Simulation Runtime | 100 secs |

Table 7.2 (b) Throughput

| | Parameters | Values |
|---|---|---|
| 1 | Average Throughput | 49.18 kbps |
| 2 | Number of packets sent | 5489 |
| 3 | Number of packets received | 4785 |
| 4 | Average latency | 0.007561889870 sec |
| 5 | Packet Delivery Ratio (Received/Sent) | 87.17 % |
| 6 | Simulation start time | 2.56 sec |
| 7 | Simulation stop time | 99.86 sec |

The network animator (NAM) diagram for random topology is given in Fig 7.4. The plot of throughput is given in Fig 7.5. The number of packets received are less than packets sent. As the medium of communication is wireless, it is likely that some packets may be lost. However, the packet delivery ratio is 87.17% which is good indicator of packet delivery even in case of wireless communication. Retransmission of packet is the only method to compensate for the lost packet which will incur some delay. Depending on the types of message being send the delay may be classified as tolerable or non-tolerable. The latency requirements are enumerated in Table 3.3. So, the packets of teleprotection, PMU (class A), control messages, Smart meter, etc. are tolerable, as the minimum latency requirements is 8ms. The average latency of simulation is 7ms which agrees with the theoretical limit.

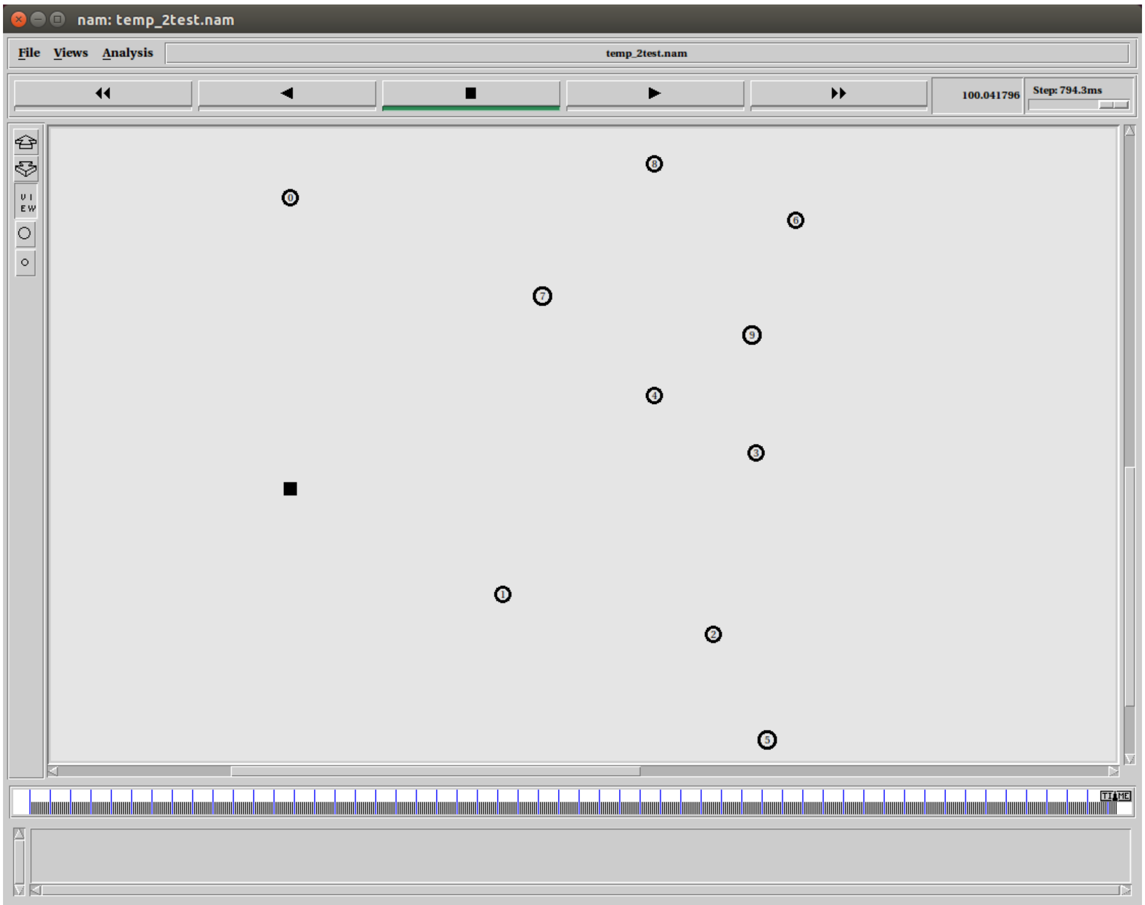



Fig. 7.4 Random topology

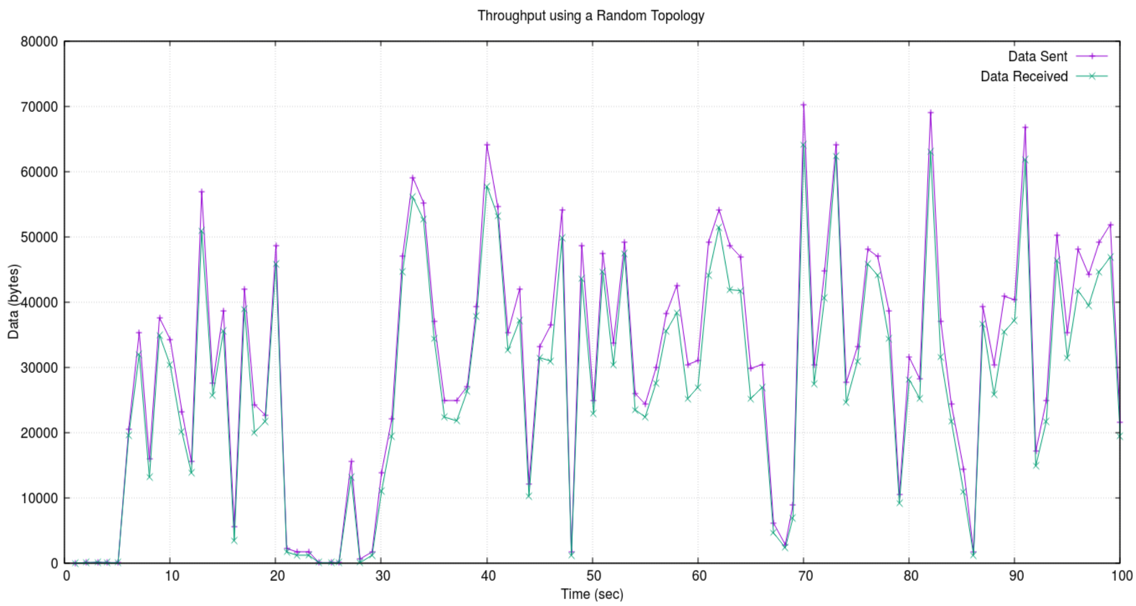



Fig. 7.5 Throughput of random topology

**Case 2 Simulation of Single radio with 5 Channels per radio**

In the simulation of Cognitive Radio for five channels per radio, the input parameters are given in Table 7.3(a) and the corresponding output is given in Table 7.3(b).

Table 7.3(a) Simulation for Case 2: Input Parameters

| | Parameters | Specifications |
|---|---|---|
| 1 | Number of mobile nodes | 10 |
| 2 | Number of channels per radio | 5 |
| 3 | Topology | Random |
| 4 | Interface | MAC |
| 5 | Simulation Runtime | 100 secs |

Table 7.3(b) Throughput

| | Parameters | Values |
|---|---|---|
| 1 | Average Throughput | 52.53 kbps |
| 2 | Number of packets sent | 5883 |
| 3 | Number of packets received | 5119 |
| 4 | Average latency | 0.0074878713 sec |
| 5 | Packet Delivery Ratio | 87.01 % |
| 6 | Simulation start time | 2.56 sec |
| 7 | Simulation stop time | 100 secs |

The plot of throughput is given in Fig 7.6 for random topology. It can be seen from the analysis of the output that the throughput increases when the number of channel per radio is increased. The number of packets received are less than packets sent. The packet delivery ratio is 87.01% which is good indicator of packet delivery in case of wireless communication. Retransmission of packet is the only method to compensate for the lost packet which will incur some delay. The latency requirements are enumerated in Table 3.3. So, the packets of teleprotection, PMU (class A), control messages, Smart meter, etc. are tolerable, as the minimum latency requirements is 8ms. The average latency of simulation is 7.4ms which agrees with the theoretical limit of data transmission for different power protection applications.

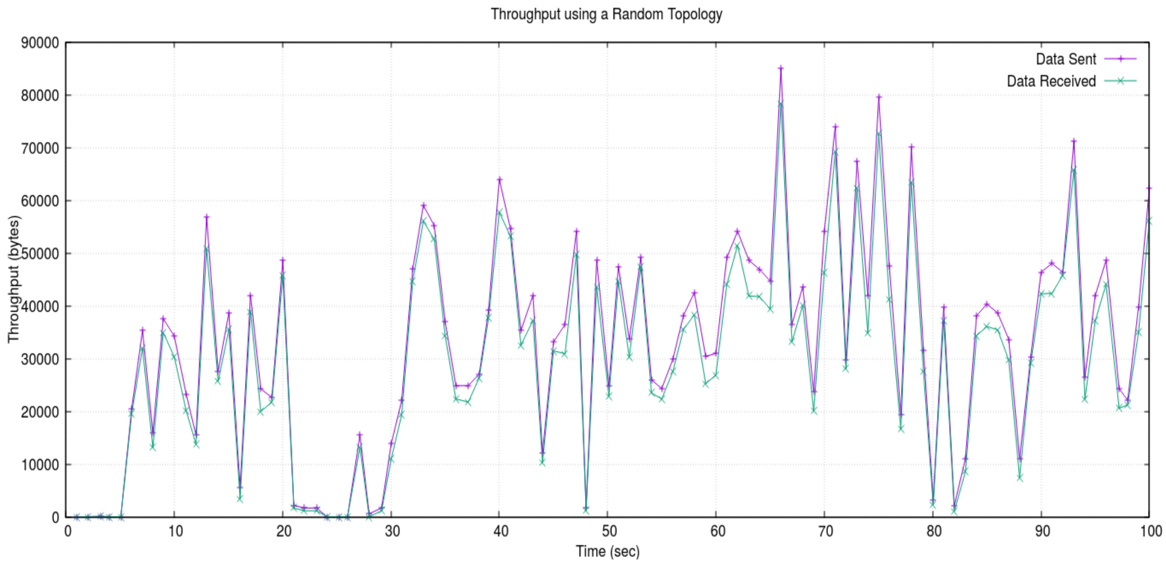



Fig. 7.6 Throughput

### *7.2.1.2. Multi-Radio, Multi-Channel*

**Case 3 Simulation of two radio with 2 Channels per radio**

Figure 7.7 gives the structure of multi-radio multi-channel for MAC and PHY layer using multiple network interface. The simulation of the input parameters given in Table 7.4(a) and the corresponding output in Table 7.4(b).

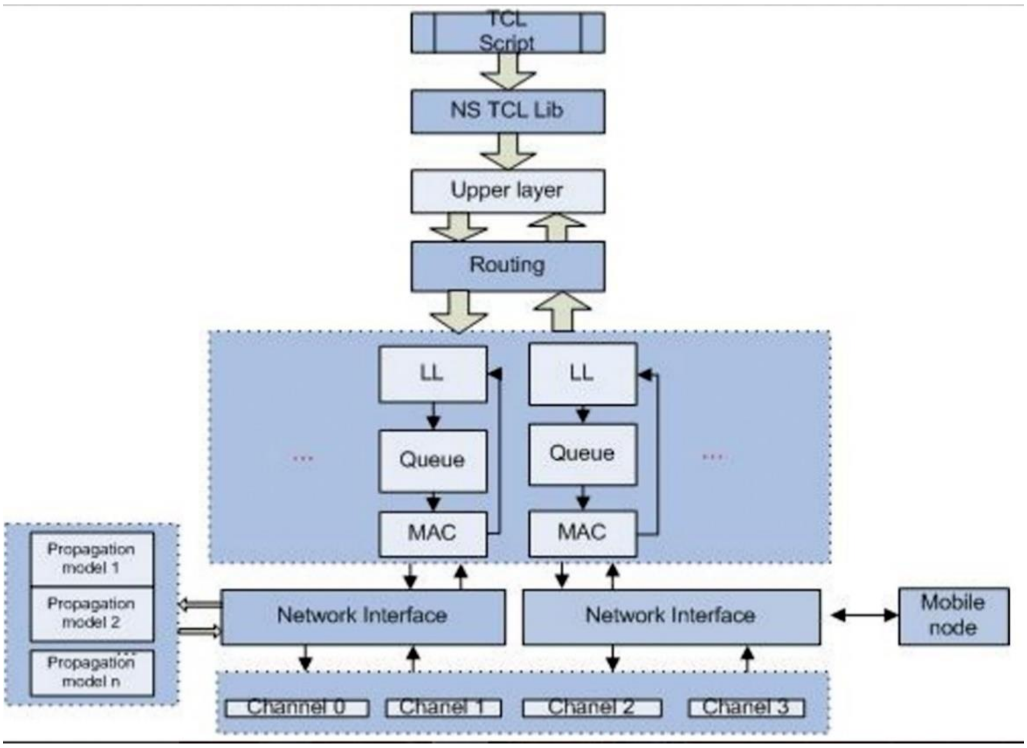



Fig. 7.7 Structure of Multi-radio with multi-channel [100]

Table 7.4(a) Simulation for Case 3: Input Parameters

| | Parameters | Specifications |
|---|---|---|
| 1 | Number of mobile nodes | 10 |
| 2 | Number of channels per radio | 2 |
| 3 | Topology | Random |
| 4 | Interface | MAC |
| 5 | Number of Interface | 2 |
| 6 | Simulation Runtime | 100 secs |

Table 7.4(b) Throughput

| | Parameters | Values |
|---|---|---|
| 1 | Average Throughput | 101.25 kbps |
| 2 | Number of packets sent | 9919 |
| 3 | Number of packets received | 9865 |
| 4 | Average latency | 0.032858305795 sec |
| 5 | Packet Delivery Fraction | 99.46 % |
| 6 | Simulation start time | 2.56 sec |
| 7 | Simulation stop time | 99.99 sec |

The plot of throughput is given in Fig 7.8.

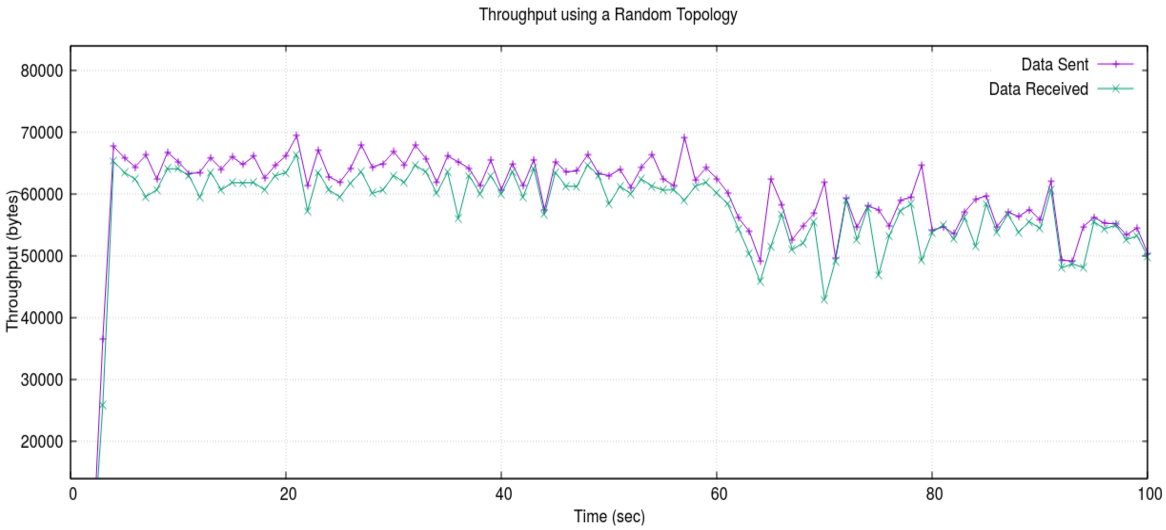



Fig. 7.8 Throughput for Multi-radio multi-channel

It can be seen from the Table 7.4(b) that the average throughput increase considerably in case of the two interfaces. However, the average latency of the packet has increased to 30ms. The packet delivery ratio is nearly 100% which means all the packets that is sent will be received at the other end. It is good indicator of reliable packet delivery in case of wireless communication medium. The latency requirements are enumerated in Table 3.3. So, the packets of teleprotection, PMU (class A), etc. are not good candidate to be delivered through this method. Other categories of messages such as control messages, Smart meter, Monitoring, etc. are tolerable as they have the minimum latency of more than 30ms.

### *7.2.2. Simulation using CRE-NS3*

Cognitive Radio extension for NS-3 (CRE-NS3) is a simulator extension for Cognitive Radio based on Network Simulator (NS-3). The basic building block of CRE-NS-3 is given in Figure 7.9 [104].

The SM is the point of contact for all user whether it is a PU or a SU. The spectrum manager will reside in MAC layer.  Spectrum Sensing/DB Query, Spectrum Mobility, Spectrum Decision and Spectrum Sharing are the modules of the spectrum manager. The database maintains the list of primary user and their on/off time. The regular NS-3 wireless node may have multiple wireless/wired interfaces with different IP addresses and subnets. The transition for one state to another is done through the state diagram as shown in Fig 7.10.

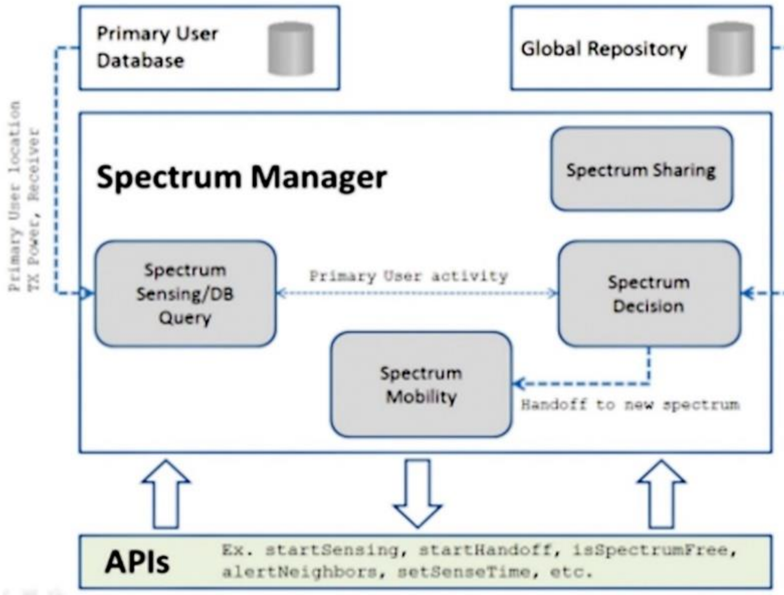



Fig. 7.9 CRE-NS-3 block diagram

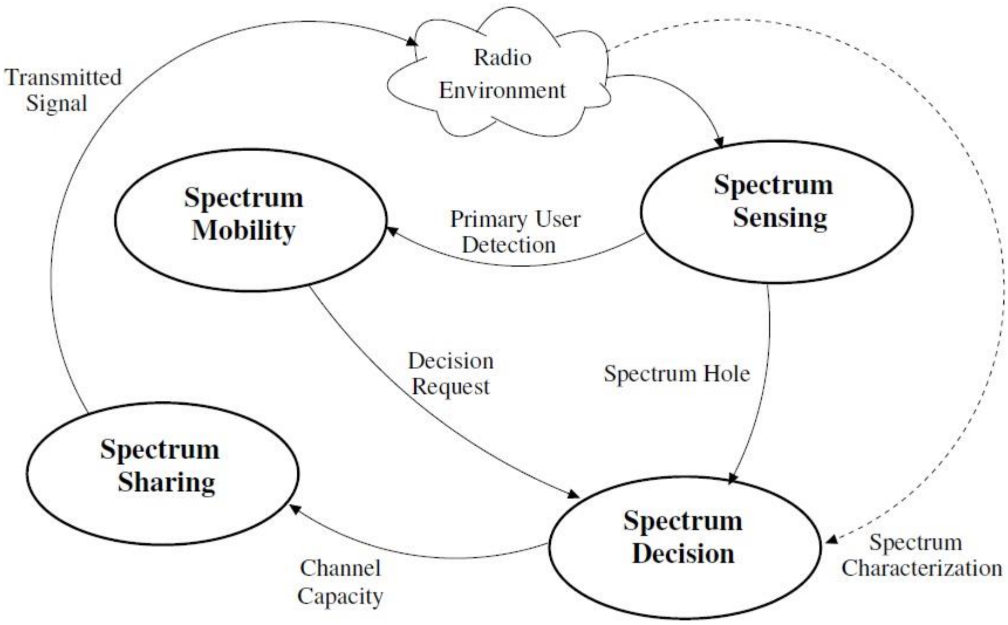



Fig. 7.10 Cognitive Radio cycle

The NS-3 uses C++ as the programming language to run and configure the simulation environment. The Cognitive Radio node transmit data from node 0 to node n and the outcome is the number of bytes received successfully at the receiver node for a network of 2/3 nodes. The simulation parameters and the corresponding output is given in Table 7.5(a) and 7.5(b) respectively.

Table 7.5(a) Input Parameters

| | Parameters | Specifications |
|---|---|---|
| 1 | Number of mobile nodes | 2 or 3 |
| 2 | Topology | Random |
| 3 | Interface | MAC |

Table 7.5B Throughput

| | Parameters | 2 nodes | 3 nodes |
|---|---|---|---|
| 1 | Total bytes received (throughput) | 7200256 | 3692032 |

The simulation runs for 2 and 3 network nodes. It can be concluded that if the number of nodes in a network is increased the throughput will decrease considerably.

## *7.3. Summary*

Many network simulators were explored to simulate discrete events in Cognitive Radio. CRCN and CRE-NS3 are considered to be good simulators for simulating Cognitive Radio environment. The performance of protocols is tested in different conditions. The parameters studied are throughput, latency, packet delivery ratio, etc. for various topologies. The results are analysed and plotted for visualisation.

# CHAPTER 8

# CONCLUSION AND FUTURE WORK

## *8.1 Conclusion*

The electric power grid has been developed over the last century which lacks bi-directional data flow. The Information and Communication Technology has been the main contributor to the development of Smart Grid. The Sensors, IEDs, PMU, etc. are the part of network backbone of Smart Grid.  The installed components will generate high volumes of operation and control data. Transferring the data generated by this network of large number of devices is a big challenge. The latency requirement for different types of application is mentioned in this research. The present communication technology has limitations in delivering the Big Data of Smart Grid to control center in real-time. The IEEE802.22 standard uses Cognitive Radio for communication which has the potential to support Big Data communication.

There are two standards widely followed for Smart Grid implementation. They are NIST for Smart Grid implementation and IEC61850 for communication, security and planning. NIST has proposed a conceptual architecture of Smart Grid that divides it into seven domains for smart decision making. IEC61850 is a protocol suite that addressed the issue of interoperability between IEDs of different vendors within substation automation systems.

The research also studied how load can help the utilities to understand the future demand for electricity and it assist them in planning the electricity generation. Various load forecasting methods were surveyed to assess their prediction accuracy. Artificial Neural Network and Bagged Regression Trees model are selected for load prediction. The prediction was very successful with a prediction error of less than 3% was achieved.

IEC61850 can be integrated with IEEE802.22 to provide seamless communication. Manufacturing Message Specification (MMS) protocol of IEC61850 can be used for teleprotection at the substation. The MMS is a protocol that supports the transfer of real-time process data and supervisory control information between networked devices and control center. IEEE802.22 can effectively support flexible, reliable and secure communication over diverse topography.

Different spectrum sensing techniques has been discussed in this thesis. Energy detection and cyclostationary feature detection has been implemented for spectrum sensing. This has demonstrated that cyclostationary spectrum sensing can separate random noise from cyclostationary signals which are a better sensing method in comparison to energy detection.

This research also explored the suitability of using Cognitive Radio for real-time communication. Various network simulators are examined to build Cognitive Radio scenarios based on topologies. The study considered Cognitive Radio Cognitive Network (CRCN) based on Network Simulator 2 (NS-2) and Cognitive Radio extension (CRE-NS3) based on NS-3 and both of them are good choice for simulating Cognitive Radio environment. The performance parameters studied are throughput, latency, packet delivery ratio, etc. for different protocols and topologies. The study found that Cognitive Radio communication meets the latency requirements of Smart Grid to a larger extent.

This thesis concluded that IEEE802.22 has the capability to use the frequency range of 54MHz to 862MHz occupied by TV band effectively for real-time communication. IEEE802.22 also has the provision for flexible, reliable and secure communication over diverse topography.

## *8.2 Future Work*

Cognitive Radio is one of the thrust area of research in wireless communication. It provides ample opportunities to the researcher to explore many potential challenges in this area. The following are some of the opportunities we plan to investigate in our future research:

(i) Co-existence of a Primary and Secondary user in the same channel with modification of channel parameters and modulation.

Co-existence is critical for the IEEE 802.22 which is required to include incumbent detection and protection mechanisms as well as self-coexistence. Co-existence is required Intra/Inter-WRAN communication which will enable many users (PU and SU) to co-exist in the same cell. The spectral efficiency will increase by this method of co-existence.

(ii) Cognitive Radio for Internet of Things

The ubiquitous deployment of IoT in Smart Grid will have many challenges such as dynamic environmental conditions, poor signal, interference, energy efficiency, availability of free spectrum, etc. The mobility of the devices is also another challenge. The Smart Grid is required to record real-time information about the important devices in terms of digital fault recorders (DFR), the sequence of event (SOE), etc. for analysis purpose. QoS requirements are essential criteria for power protection. The IoT objects having the capabilities of self-discovery, self-configuration and automatic software deployments will be important.

(iii) Adding cognitive intelligence in the device.

AI, machine learning, deep machine learning and natural language processing will play an important role in future communication and gaming. The task to combine the abilities and limitations of both machines and humans enable the researcher to achieve better productivity and great learning experience. It will transform many things in the world including transportation, energy, education and retail. The Big Data analytics demand deep learning techniques that can be provided by cognitive intelligence.

(iv) Smart Grid Security and Privacy

Security is an important consideration for the Smart Grid and it pervades all aspects of system design (generation, distribution, and transmission). Wirelesses communication due to its broadcast nature is still vulnerable to attack. The biggest issue in security is the processing overheads associated with it. The Big Data of Smart Grid will increase latency in data communication. The strategy must be devised to deal with the risk of data integrity, authenticity, confidentiality, intrusion, denial of services, etc. in Smart Grid.

## References


[1] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, *et al.*, "Smart Grid Technologies: Communication Technologies and Standards," *Industrial Informatics, IEEE Transactions on,* vol. 7, pp. 529-539, 2011.

[2] L. Fangxing, Q. Wei, S. Hongbin, W. Hui, W. Jianhui, X. Yan, *et al.*, "Smart Transmission Grid: Vision and Framework," *Smart Grid, IEEE Transactions on,* vol. 1, pp. 168-177, 2010.

[3] F. Zhong, P. Kulkarni, S. Gormus, C. Efthymiou, G. Kalogridis, M. Sooriyabandara, *et al.*, "Smart Grid Communications: Overview of Research Challenges, Solutions, and Standardization Activities," *Communications Surveys & Tutorials, IEEE,* vol. 15, pp. 21-38, 2013.

[4] Electropaedia. Electricity Generation from Fossil Fuels. : http://www.mpoweruk.com/fossil_fuels.htm

[5] M. Kolhe, "Smart Grid: Charting a New Energy Future: Research, Development and Demonstration," *The Electricity Journal,* vol. 25, pp. 88-93, 3// 2012.

[6] K. C. Budka, J. G. Deshpande, T. L. Doumi, M. Madden, and T. Mew, "Communication network architecture and design principles for smart grids," *Bell Labs Technical Journal,* vol. 15, pp. 205-227, 2010.

[7] V. Dehalwar, A. Kalam, M. L. Kolhe, and A. Zayegh, "Review of IEEE 802.22 and IEC 61850 for real-time communication in Smart Grid," in *2015 International Conference on Computing and Network Communications (CoCoNet)*, 2015, pp. 571-575.

[8] D. Cabric, S. M. Mishra, and R. W. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," in *Signals, Systems and Computers, 2004. Conference Record of the Thirty-Eighth Asilomar Conference on*, 2004, pp. 772-776 Vol.1.

[9] FCC, "ET Docket No 03-222 Notice of proposed rule making and order," F. C. Commission, Ed., ed: Federal Communications Commission, 2003.

[10] H. Yinghua, W. Jinkuan, Z. Qiang, and H. Peng, "Cognitive information communication network for smart grid," in *Information Science and Technology (ICIST), 2012 International Conference on*, 2012, pp. 847-850.

[11] R. C. Qiu, H. Zhen, C. Zhe, G. Nan, R. Ranganathan, H. Shujie, *et al.*, "Cognitive Radio Network for the Smart Grid: Experimental System Architecture, Control Algorithms, Security, and Microgrid Testbed," *Smart Grid, IEEE Transactions on,* vol. 2, pp. 724-740, 2011.

[12] A. Ghassemi, S. Bavarian, and L. Lampe, "Cognitive Radio for Smart Grid Communications," in *Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference on*, 2010, pp. 297-302.

[13] J. Gao, Y. Xiao, J. Liu, W. Liang, and C. L. P. Chen, "A survey of communication/networking in Smart Grids," *Future Generation Computer Systems,* vol. 28, pp. 391-404, 2012.

[14] B. M. Buchholz and Z. A. Styczynski, *Smart grids : fundamentals and technologies in electricity networks*: Heidelberg : New York : Springer, [2014], 2014.

[15] G. Locke and P. D. Gallagher, "NIST framework and roadmap for smart grid interoperability standards, release 1.0," in *National Institute of Standards and Technology*, ed, 2010, p. 33.

[16] D. Grunwald, "How New Technologies can Turn a Spectrum Crisis into Spectrum Opportunity," 2011.

[17] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *Selected Areas in Communications, IEEE Journal on,* vol. 23, pp. 201-220, 2005.

[18] M. K. Dehalwar Vasudev , Sunita Kolhe, "Cognitive Radio Application for Smart Grid," *Intelnational Journal of Smart Grid and Clean Energy,* vol. 1, Sept, 2012 2012.

[19] Y. Rong, Z. Yan, S. Gjessing, Y. Chau, X. Shengli, and M. Guizani, "Cognitive radio based hierarchical communications infrastructure for smart grid," *Network, IEEE,* vol. 25, pp. 6-14, 2011.

[20] A. P. S. Meliopoulos, G. J. Cokkinides, R. Huang, E. Farantatos, C. Sungyun, L. Yonghee*, et al.*, "Smart Grid Technologies for Autonomous Operation and Control," *Smart Grid, IEEE Transactions on,* vol. 2, pp. 1-10, 2011.

[21] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "NeXt generation/dynamic spectrum access/cognitive radio wireless networks: A survey," *Computer Networks,* vol. 50, pp. 2127-2159, 2006.

[22] C. Cecati, G. Mokryani, A. Piccolo, and P. Siano, "An overview on the smart grid concept," in *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 3322-3327.

[23] *Cognitive Radio Networks*. : http://bwn.ece.gatech.edu/CR/projectdescription.html

[24] C. H. Hauser, D. E. Bakken, and A. Bose, "A failure to communicate: next generation communication requirements, technologies, and architecture for the electric power grid," *Power and Energy Magazine, IEEE,* vol. 3, pp. 47-55, 2005.

[25] L. Sollecito, "Smart Grid: The Road Ahead," *Protection and Control Journal,* pp. 15-19, 2009.

[26] A. Bose, "Smart Transmission Grid Applications and Their Supporting Infrastructure," *Smart Grid, IEEE Transactions on,* vol. 1, pp. 11-19, 2010.

[27] J. G. D. Kenneth C. Budka, Marina Thottan, *Communication Networks for Smart Grids*: Springer-Verlag London, 2014.

[28] Z. Pei, L. Fangxing, and N. Bhatt, "Next-Generation Monitoring, Analysis, and Control for the Future Smart Control Center," *Smart Grid, IEEE Transactions on,* vol. 1, pp. 186-192, 2010.

[29] Z. M. Fadlullah, M. M. Fouda, N. Kato, A. Takeuchi, N. Iwasaki, and Y. Nozaki, "Toward intelligent machine-to-machine communications in smart grid," *Communications Magazine, IEEE,* vol. 49, pp. 60-65, 2011.

[30] F. Z. P. N. A. Hairong Qi; Xiaorui Wang; Tolbert L.M.; Fangxing Li; Peng, M, "A Resilient Real-Time System Design for a Secure and Reconfigurable Power Grid," *Smart Grid, IEEE Transactions on,* vol. 2, p. 770, Dec. 2011 2011.

[31] R. Ranganathan, R. Qiu, Z. Hu, S. Hou, M. Pazos-Revilla, G. Zheng*, et al.*, "Cognitive Radio for Smart Grid: Theory, Algorithms, and Security," *International Journal of Digital Multimedia Broadcasting,* vol. 2011, 2011.

[32] E. Jung and L. Xin, "Opportunistic Spectrum Access in Multiple-Primary-User Environments Under the Packet Collision Constraint," *Networking, IEEE/ACM Transactions on,* vol. 20, pp. 501-514, 2012.

[33] D. Raychaudhuri and N. B. Mandayam, "Frontiers of Wireless and Mobile Communications," *Proceedings of the IEEE,* vol. 100, pp. 824-840, 2012.

[34] W. Gabran, L. Chun-Hao, P. Pawelczak, and D. Cabric, "Primary User Traffic Estimation for Dynamic Spectrum Access," *Selected Areas in Communications, IEEE Journal on,* vol. 31, pp. 544-558, 2013.

[35] W. Honggang, Q. Yi, and H. Sharif, "Multimedia communications over cognitive radio networks for smart grid applications," *Wireless Communications, IEEE,* vol. 20, pp. 125-132, 2013.

[36] F. Sioshansi, *Smart Grid, Integrating Renewable, Distributed & Efficient Energy*, 2011.

[37] S. S. G. S. Group, "IEC Smart Grid Standardization Roadmap," 2010.

[38] I. E. Agency. (2014, World Energy Outlook 2014, Executive Summary. : http://www.iea.org/textbase/npsum/weo2014sum.pdf

[39] T. Sato, *Smart Grid Standards: Specifications, Requirements, and Technologies*: IEEE Wiley, 2014.

[40] W. Wang and Z. Lu, "Cyber security in the Smart Grid: Survey and challenges," *Computer Networks,* vol. 57, pp. 1344-1371, 2013.

[41] Y. Ye, Q. Yi, H. Sharif, and D. Tipper, "A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements and Challenges," *Communications Surveys & Tutorials, IEEE,* vol. 15, pp. 5-20, 2013.

[42] H. A. Khan, X. Zhen, H. Iu, and V. Sreeram, "Review of technologies and implementation strategies in the area of Smart Grid," in *Power Engineering Conference, 2009. AUPEC 2009. Australasian Universities*, 2009, pp. 1-6.

[43] A. G. Ruzzelli, C. Nicolas, A. Schoofs, and G. M. P. O'Hare, "Real-Time Recognition and Profiling of Appliances through a Single Electricity Sensor," in *Sensor Mesh and Ad Hoc Communications and Networks (SECON), 2010 7th Annual IEEE Communications Society Conference on*, 2010, pp. 1-9.

[44] V. Hamidi, K. S. Smith, and R. C. Wilson, "Smart Grid technology review within the Transmission and Distribution sector," in *Innovative Smart Grid Technologies Conference Europe (ISGT Europe), 2010 IEEE PES*, 2010, pp. 1-8.

[45] G. Wang, Y. Xu, and M. Khanna, "A survey on the communication architectures in smart grid," *Computer Networks,* vol. 55, pp. 3604-3629, 2011.

[46] T. Mehra, V. Dehalwar, and M. Kolhe, "Data Communication Security of Advanced Metering Infrastructure in Smart Grid," in *Computational Intelligence and Communication Networks (CICN), 2013 5th International Conference on*, 2013, pp. 394-399.

[47] A. Zaballos, A. Vallejo, and J. M. Selga, "Heterogeneous communication architecture for the smart grid," *Network, IEEE,* vol. 25, pp. 30-37, 2011.

[48] G. Andersson, *Modelling and Analysis of Electric Power Systems*, 2006.

[49] Z. Gang, "Classification of power system disturbances based on wide-area frequency measurements," in *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES*, 2011, pp. 1-4.

[50] V. Dehalwar, R. K. Baghel, and M. Kolhe, "Multi-agent based public key infrastructure for smart grid," in *Computer Science & Education (ICCSE), 2012 7th International Conference on*, 2012, pp. 415-418.

[51] I.-T. Ed.2, "Communication networks and systems for power utility automation – Part 1: Introduction and Overview," ed, 2012.

[52] R. E. Mackiewicz, "Overview of IEC 61850 and Benefits," in *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, 2006, pp. 623-630.

[53] H. Farhangi, "The path of the smart grid," *Power and Energy Magazine, IEEE,* vol. 8, pp. 18-28, 2010.

[54] E. Padilla, *Substation Automation Systems: Design and Implementation*: John Wiley & Sons, 2015.

[55] K. De Craemer and G. Deconinck, "Analysis of state-of-the-art smart metering communication standards," in *Proceedings of the 5th young researchers symposium*, 2010.

[56] M. Ruofei, C. Hsiao-Hwa, H. Yu-Ren, and M. Weixiao, "Smart Grid Communication: Its Challenges and Opportunities," *Smart Grid, IEEE Transactions on,* vol. 4, pp. 36-46, 2013.

[57] V. Dehalwar, A. Kalam, M. L. Kolhe, and A. Zayegh, "Compliance of IEEE 802.22 WRAN for field area network in smart grid," in *2016 IEEE International Conference on Power System Technology (POWERCON)*, 2016, pp. 1-6.

[58] D. Mah, *Smart Grid Applications and Developments*: Springer, 2014.

[59] Y. Mehmood, C. Görg, M. Muehleisen, and A. Timm-Giel, "Mobile M2M communication architectures, upcoming challenges, applications, and future directions," *EURASIP Journal on Wireless Communications and Networking,* vol. 2015, pp. 1-37, 2015.

[60] A. K. Vasudev Dehalwar, Mohan Lal Kolhe, Aladin Zayegh, "Review of Machine to Machine Communication in Smart Grid," presented at the IEEE 2016 International Conference on Power and Renewable Energy, Shanghai, China, 2016.

[61] Q.-D. Ho, *Wireless Communications Networks for the Smart Grid*: Springer, 2014.

[62] Z. Chilamkurti, Chaouchi,, *Next-Generation Wireless Technologies - 4G and Beyond*: Springer-Verlag London, 2013.

[63] S. Hiremath, A. Mishra, and S. Patra, *White Space Communication*: Springer International Publishing, 2015.

[64] M. H. Marja Matinmikko (editor), Miia Mustonen, Heli Sarvanko, Atso Hekkala, Marcos Katz, Aarne Mämmelä, Markku Kiviranta, Aino Kautio, "Cognitive radio: An intelligent wireless communication system," 2008.

[65] V. C. Gungor and D. Sahin, "Cognitive Radio Networks for Smart Grid Applications: A Promising Technology to Overcome Spectrum Inefficiency," *Vehicular Technology Magazine, IEEE,* vol. 7, pp. 41-46, 2012.

[66] IEEE, "ISO/IEC/IEEE International Standard -- Information technology -- Telecommunications and information exchange between systems -- Local and metropolitan area networks-- Specific requirements -- Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Policies and procedures for operation in the TV Band," in *ISO/IEC/IEEE 8802-22:2015*, ed, 2015, pp. 1-678.

[67] P. Chang-Woo, Z. Xin, S. Chunyi, Z. Ming-Tuo, and H. Harada, "A new standard activity in IEEE 802.22 wireless regional area networks: Enhancement for broadband services and monitoring applications in TV whitespace," in *Wireless Personal Multimedia Communications (WPMC), 2012 15th International Symposium on*, 2012, pp. 108-112.

[68] A. Songpu, M. L. Kolhe, L. Jiao, and Q. Zhang, "Domestic load forecasting using neural network and its use for missing data analysis," in *2015 9th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*, 2015, pp. 535-538.

[69] A. Songpu, M. L. Kolhe, and L. Jiao. (2015, External parameters contribution in domestic load forecasting using neural network. *IET Conference Proceedings,* 6 .-6 . : http://digital-library.theiet.org/content/conferences/10.1049/cp.2015.0344

[70] M. Q. Raza and A. Khosravi, "A review on artificial intelligence based load demand forecasting techniques for smart grid and buildings," *Renewable and Sustainable Energy Reviews,* vol. 50, pp. 1352-1372, 10// 2015.

[71] L. Jong-Pil, J. Pyeong-Shik, L. Jae-Yoon, K. Ki-Dong, P. Si-Woo, and K. Jung-Hoon, "A load modeling using ANN for power system analysis," in *TENCON 99. Proceedings of the IEEE Region 10 Conference*, 1999, pp. 1475-1478 vol.2.

[72] C. Perfumo, J. H. Braslavsky, and J. K. Ward, "Model-Based Estimation of Energy Savings in Load Control Events for Thermostatically Controlled Loads," *IEEE Transactions on Smart Grid,* vol. 5, pp. 1410-1420, 2014.

[73] V. Cherkassky, S. R. Chowdhury, V. Landenberger, S. Tewari, and P. Bursch, "Prediction of electric power consumption for commercial buildings," in *Neural Networks (IJCNN), The 2011 International Joint Conference on*, 2011, pp. 666-672.

[74] A. Deoras. (2011). *Electricity Load and Price Forecasting Webinar Case Study*. : http://www.mathworks.com/matlabcentral/fileexchange/28684-electricity-load-and-price-forecasting-webinar-case-study

[75] L. Suganthi and A. A. Samuel, "Energy models for demand forecasting—A review," *Renewable and Sustainable Energy Reviews,* vol. 16, pp. 1223-1240, 2// 2012.

[76] A. Aprelkin, "Short Term Household Electricity Load Forecasting Using a Distributed In-Memory Event Stream Processing System," Master’s Thesis in Informatics, Department of Informatics, Technische universität münchen munich, Munich, Germany, 2014.

[77] David Willingham. (2011). *Electricity Load Forecasting for the Australian Market Case Study*. : http://au.mathworks.com/matlabcentral/fileexchange/31877-electricity-load-forecasting-for-the-australian-market-case-study

[78] A. Songpu, M. L. Kolhe, L. Jiao, N. Ulltveit-Moe, and Q. Zhang, "Domestic demand predictions considering influence of external environmental parameters," in *2015 IEEE 13th International Conference on Industrial Informatics (INDIN)*, 2015, pp. 640-644.

[79] E. L. Taylor, "Short-term Electrical Load Forecasting for an Institutional/Industrial Power System Using an Artificial Neural Network " Master's Thesis, University of Tennessee, 2013.

[80] L. Xu, J. Chen, D. Huang, J. Lu, and L. Fang, "Analysis of Boundedness and Convergence of Online Gradient Method for Two-Layer Feedforward Neural Networks," *IEEE Transactions on Neural Networks and Learning Systems,* vol. 24, pp. 1327-1338, 2013.

[81] H.-x. Zhao and F. Magoulès, "A review on the prediction of building energy consumption," *Renewable and Sustainable Energy Reviews,* vol. 16, pp. 3586-3592, 8// 2012.

[82] J. M. Zurada, *Introduction to artificial neural systems*: West St. Paul, 1992.

[83] P. Bühlmann, "Bagging, boosting and ensemble methods," in *Handbook of Computational Statistics*, ed: Springer, 2012, pp. 985-1022.

[84] M. Adamiak, D. Baigent, and R. Mackiewicz. (2010) IEC 61850 Communication Networks and Systems In Substations.

[85] G. T. Pham, "Integration of IEC 61850 MMS and LTE to support smart metering communications," 2013.

[86] J. Z. a. C. A. Gunter, "IEC 61850 - Communication Networks and Systems in Substations: An Overview of Computer Science," University of Illinois at Urbana-Champaign2011.

[87] C. Samitier, *Utility Communication Networks and Services*: Springer International Publishing, 2017.

[88] A. N. Mody, "Enabling Technologies and Standards for Spectrum Forensics," ed. ISART 2016, 2016.

[89] IEEE, "IEEE Standard for Information Technology--Telecommunications and information exchange between systems - Wireless Regional Area Networks (WRAN)--Specific requirements - Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications:Policies and Procedures for Operation in the TV Bands - Amendment 2: Enhancement for Broadband Services and Monitoring Applications," in *IEEE Std 802.22b-2015 (Amendment to IEEE Std 802.22-2011 as amended by IEEE Std 802.22a-2014)*, ed, 2015, pp. 1-299.

[90] M. A. Matin, *Spectrum Access and Management for Cognitive Radio Networks*: Springer Singapore, 2017.

[91] M. Ridouani, A. Hayar, and A. Haqiq, "Perform sensing and transmission in parallel in cognitive radio systems: Spectrum and energy efficiency," *Digital Signal Processing,* vol. 62, pp. 65-80, 3// 2017.

[92] A. Naumann, I. Bielchev, N. Voropai, and Z. Styczynski, "Smart grid automation using IEC 61850 and CIM standards," *Control Engineering Practice,* vol. 25, pp. 102-111, 4// 2014.

[93] M. S. Baig, S. Das, and P. Rajalakshmi, "CR based WSAN for Field Area Network in Smart Grid," in *Advances in Computing, Communications and Informatics (ICACCI), 2013 International Conference on*, 2013, pp. 811-816.

[94] N. Wyglinski, Hou, *Cognitive Radio Communications and Networks Principles and Practice*, 2010.

[95] A. Wisniewska, "Spectrum sharing in Cognitive Radio Networks: A Survey," 2014.

[96] Y. C. Liang, Y. Zeng, E. C. Y. Peh, and A. T. Hoang, "Sensing-Throughput Tradeoff for Cognitive Radio Networks," *IEEE Transactions on Wireless Communications,* vol. 7, pp. 1326-1337, 2008.

[97] H. S. Chen, W. Gao, and D. G. Daut, "Spectrum Sensing Using Cyclostationary Properties and Application to IEEE 802.22 WRAN," in *IEEE GLOBECOM 2007 - IEEE Global Telecommunications Conference*, 2007, pp. 3133-3138.

[98] J. Antoni. (2016). *Fast_SC(x,Nw,alpha_max,Fs,opt)*. : https://au.mathworks.com/matlabcentral/fileexchange/60561-fast-sc-x-nw-alpha-max-fs-opt-

[99] J. Antoni, G. Xin, and N. Hamzaoui, "Fast computation of the spectral correlation," *Mechanical Systems and Signal Processing,* vol. 92, pp. 248-277, 8// 2017.

[100] *Cognitive Radio Cognitive Network Simulator (NS2 Based)*, Cognitive Radio Cognitive Network Simulator (NS2 Based)

[101] *Cognitive Radio Cognitive Network Simulator (based on NS-3)* : http://faculty.uml.edu/Tricia_Chigan/Research/CRCN_NS3.html

[102] *CogNS: A Simulation Framework For Cognitive Radio Networks*. : http://cogns.net/

[103] *OMNeT++ Discrete Event Simulator*. : https://omnetpp.org/

[104] A. Al-Ali and K. Chowdhury, "Simulating dynamic spectrum access using ns-3 for wireless networks in smart environments," in *Sensing, Communication, and Networking Workshops (SECON Workshops), 2014 Eleventh Annual IEEE International Conference on*, 2014, pp. 28-33.

[105] *NetSim*, http://www.tetcos.com/

[106] *QualNet*., http://web.scalable-networks.com/qualnet-network-simulator-software