Cognitive Radio Based Smart Grid Communication System

Researcher:
Sheraz Alam Khan
Reg. No. 54-FET/PHDEE/F12

Supervisor:
Prof. Dr. Aqdas Naveed Malik
Co-Supervisor:
Prof. Dr. Ijaz Mansoor Qureshi

Department of Electrical Engineering
Faculty of Engineering and Technology
INTERNATIONAL ISLAMIC UNIVERSITY
ISLAMABAD

Cognitive Radio Based Smart Grid Communication System

Sheraz Alam Khan
Reg. No. 54-FET/PHDEE/F12

Submitted in partial fulfillment of the requirements for the
PhD degree in Electrical Engineering the Faculty of Engineering and Technology,
International Islamic University,
Islamabad.

Supervisor: Prof. Dr. Aqdas Naveed Malik
Co-Supervisor: Prof. Dr. Ijaz Mansoor Qureshi
December, 2018

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

DEDICATED TO

My Teachers,

Parents, Kids

&

last but not least

My wife.

CERTIFICATE OF APPROVAL

Title of Thesis: Cognitive Radio based Smart Grid Communication System

Name of Student: Sheraz Alam Khan

Registration No: 54-FET/PHDEE/F12

Accepted by the Department of Electrical Engineering, Faculty of Engineering and Technology, International Islamic University, Islamabad, in partial fulfillment of the requirements for the Doctor of Philosophy Degree in Electrical Engineering.

Viva-voce committee:

Prof. Dr. Muhammad Amir (Dean) ____________________
Dean, Faculty of Engineering & Technology
International Islamic University, Islamabad.

Dr. Suheel Abdullah Malik (Chairman) ____________________
Associate Professor, Department of Electrical Engineering
International Islamic University, Islamabad.

Prof. Dr. Fida Muhammad Khan (External Examiner - I) ____________________
Professor, Department of Electrical Engineering
Air University, Islamabad.

Dr. Aamer Saleem Choudhry (External Examiner - II) ____________________
Associate Professor, Hamdard Institute of Engineering & Technology
Hamdard University, Islamabad.

Prof. Dr. Abdul Jaleel (Internal Examiner) ____________________
Associate Professor, Department of Electrical Engineering
International Islamic University, Islamabad.

Prof. Dr. Aqdas Naveed Malik (Supervisor) ____________________
Professor, Department of Electrical Engineering
Vice President (VP), Higher Studies & Research
International Islamic University, Islamabad

Prof. Dr. Ijaz Mansoor Qureshi (Co-Supervisor) ____________________
Professor, Department of Electrical Engineering
Air University, Islamabad.

(28 December, 2018)

ABSTRACT

Smart grid (SG) concepts have revolutionized the future of conventional electric grid by making it more efficient, resilient and reliable using state-of-the-art technologies, modern equipment, and automation control systems. However, the full realization of all the above-mentioned benefits is not possible without the implementation of a fast, reliable and economical communication network that must exhibit spectral and energy efficiency. Additionally, the data generated by various SG applications is not only in enormous proportion but also diverse in nature in terms of its delay tolerance. The crucial need to transmit a significant amount of smart grid applications data in a spectral efficient manner makes cognitive radio (CR) technology most suitable for SG environment. Identically, TV white spaces (TVWS) is the most expectant candidate for CR based smart grid communication network (CRSGCN). Using CR in SGCN will bring its own set of communication problems. There is not much of a research available for problems associated with CRSGCN and primarily, this is the motivation behind this research work.

This dissertation addresses some critical challenges in the design of CRSGCN. The research work can be divided into two parts. First, we present a comprehensive survey to establish the diverse communication requirements for three subsets of SGCN: Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide Area Network (WAN). Then, we review SG applications to analyze what kind of data is suitable to be carried over CR technology. Based on these requirements, we propose a CR based end-to-end network architecture for SGCN by using IEEE communication standards suitable for delay-tolerant data such as required by automatic metering infrastructure (AMI) and demand response (DR) etc. Then, we identify salient features of the

proposed network architecture that makes it a viable solution along with some open issues and challenges, related to CRSGCN.

The second part is then dedicated to address resource allocation in CRSGCN, in particular, the two most important researched areas related to CR, i.e., channel allocation (CA) and power allocation (PA). We modeled a communication scenario based on CRSGCN architecture proposed in part one, by dividing the service area into groups of secondary users (SUs) called NAN clusters, depending upon the distance of Smart Meters (SMs) from Data Concentrator Unit (DCU). Then, we formulated a multiple constraint NP-hard CA problem using interference avoidance strategy by considering two practical scenarios: fairness-based allocation and priority-based allocation. We then propose our CA algorithm based on Cat Swarm Optimization (CSO) to eliminate the severe integer constraints of the problem under consideration. Next, for the same NAN communication scenario using IEEE 802.11af standard via open loop regulatory framework for TVWS, we formulate a joint power and channel allocation (JPCA) problem. Next, we present an efficient PA scheme, meeting quality-of-service (QoS) requirements, followed by CA scheme based on cuckoo search algorithm (CSA). The performance of the proposed solutions is analyzed using exhaustive simulations to optimize power consumption, fairness and user rewards. The presented results in the form of graphs and numerical comparisons indicate the effectiveness of our allocation algorithm to achieve the desired objectives.

We have investigated and formulated a JPCA problem with multiple constraints considering two practical cases of fairness-based allocation and priority-based allocation in an SG environment in an innovative way, which perhaps is among pioneer and premiere works in its technical domain. We hope, this work will be regarded as a corner stone in CRSGCN and will pave way for more future studies in this domain.

ACKNOWLEDGEMENTS

In the name of Allah (Subhanahu Wa Ta'ala), who is the most gracious and merciful. I would like to thank Allah for giving me strength and patience to complete this research work. Peace and blessings of Allah be upon His last Prophet Muhammad (Sallulah-o-Alaihihe-Wassalam) and all his Sahaba (Razi-Allah-o-Anhu) who dedicated their lives for Dawah and spread of Knowledge.

Without a doubt, my most profound gratitude goes to my Ph.D. supervisors, Prof. Aqdas Naveed Malik and Prof. Ijaz Mansoor Qureshi for their guidance, support, and persistent encouragement during my Ph.D. studies. The open attitude of Prof. Aqdas towards research has granted me the freedom to explore interesting topics to work on. At the same time, the insightful advice and comments from Prof. Ijaz Mansoor Qureshi in my research are invaluable fortunes, not only to this dissertation but also to my attitude towards research in the future. Moreover, I also sincerely appreciate their foresighted advice on my career path.

I offer my sincere thanks to Dr. Sajjad Ahmed Ghauri, Muhammad Farhan Sohail, Asad Hussain, Hassan Humayun, Zohaib Ahmed, Uzair Iqbal and Mubashar Sarfraz for their never-ending support during last few years. I also thank all my respected teachers at IIU, Islamabad campus, who taught me Ph.D. courses and not only helped me in enhancing my subject knowledge but also for their encouragement and useful discussions. I would like to acknowledge the National University of Modern Languages, Islamabad Campus for providing me HEC Indigenous Scholarship for Ph.D. I am also thankful to the administration of my Engineering Department for their kind support.

Without my family, I would not be able to reach this far. I am really grateful to my father for giving me reassurance and confidence, my mother for her prayers and unconditional love, my sister, and brothers for their backing and motivation throughout my life. Finally, I am thankful to my kids; their innocent gestures have been a constant source of inspiration for me during my low times. At the last but not least, I am also very thankful to my dear wife for her care, patience, encouragement, and prayers during every stage of my Ph.D. degree. ***(Sheraz Alam Khan – July 2018)***

LIST OF PUBLICATIONS AND SUBMISSIONS

[1] **Alam, Sheraz,** M. Farhan Sohail, Sajjad A. Ghauri, I. M. Qureshi, and Naveed Aqdas. "Cognitive radio based smart grid communication network." *Renewable and Sustainable Energy Reviews* 72 (2017): 535-548. **(IF = 9.184)**

[2] **Alam, Sheraz,** Aqdas Naveed Malik, Ijaz Mansoor Qureshi, Sajjad A. Ghauri, and Mubashar Sarfraz. "Clustering-Based Channel Allocation Scheme for Neighborhood Area Network in a Cognitive Radio Based Smart Grid Communication." *IEEE Access* 6 (2018): 25773-25784. **(IF = 3.557)**

[3] **Alam, Sheraz,** Sarfraz M, Usman MB, Ahmad MA, and Iftikhar S "Dynamic resource allocation for cognitive radio based smart grid communication networks" *International Journal of Advanced and Applied Sciences* (IJAAS) (2017), 4(10): pp 76-83 **(ISI indexed)**

[4] Hussain, Asad, M. F. Sohail, **Sheraz Alam**, Sajjad A. Ghauri, and I. M. Qureshi. "Classification of M-QAM and M-PSK signals using genetic programming (GP)." *Neural Computing and Applications*: 1-9 **(IF = 4.213)**

[5] Sohail, M. Farhan, Sajjad A. Ghauri, and **Sheraz Alam**. "Channel Estimation in Massive MIMO Systems Using Heuristic Approach." *Wireless Personal Communications* 97, no. 4 (2017): 6483-6498. **(IF = 1.200)**

[6] Sohail, M. F., **Sheraz Alam**, Asad Hussain, Sajjad A. Ghauri, Mubashar Sarfraz, and M. A. Ahmed. "Multiuser detection: Comparative analysis of heuristic approach." *International Journal of Advanced and Applied Sciences* (IJAAS) 4, no. 6 (2017): 115-120. **(ISI indexed)**

[7] Hussain, Asad, M. F Sohail, S. A Ghauri, **Sheraz Alam**, I M Qureshi. "KNN based classification of digital modulated signals." *IIUM Engineering Journal* 17, no. 2 (2016): 71-82. **(ISI indexed)**

[8] **Alam, Sheraz**, and Sajjad Ahmed Ghauri, M.F Sohail, Asad Hussain. "Channel estimation using evolutionary computing techniques." *International Journal of Technology and Research* 4, no. 1 (2016). **(Ulrich indexed)**

[9] Ghauri, Sajjad Ahmed, **Sheraz Alam**, M. Farhan Sohail, Asad Ali, and Faizan Saleem. "Implementation of OFDM and Channel Estimation using LS and

MMSE Estimators." *International Journal of Computer and Electronics Research* (IJCER) 2, no. 1 (2013): 41-46. **(Ulrich indexed)**

[10] Ghauri, Sajjad Ahmed, I. M. Qureshi, M. Farhan Sohail, **Sheraz Alam**, and M. Anas Ashraf. "Spectrum Sensing for Cognitive Radio Networks over fading channels." *International Journal of Computer and Electronics Research* (IJCER) 2, no. 1 (2013): 24-27. **(Ulrich indexed)**

Submitted Papers:

[1] **Alam, Sheraz,** Aqdas Naveed Malik, Ijaz Mansoor Qureshi, Sajjad A. Ghauri, and Mubashar Sarfraz. "Joint Power and Channel allocation scheme for IEEE 802.11af based Smart Grid Communication Network *" Future Generation Computer Systems (FGCS), ELSEVIER* **(Submitted, IF = 4.639)**

[2] Hussain, Asad, **Sheraz Alam,** S. A Ghauri, I.M Qureshi, " A novel approach to Automatic Modulation Classification using Genetic Algorithm assisted linear combination of Higher Order Cummulants" *Neural Computing and Applications, SPRINGER* **(Submitted, IF = 4.213)**

[3] Syed Ihtesham Hussain Shah, Sajjad A. Ghauri, **Sheraz Alam**, Fraz Ahmed Ansari, Asad Hussain ,"A Novel Hybrid Cuckoo Search- Extreme Learning Machine Approach for Modulation Recognition" *International Journal of Computer and Electrical Engineering, ELSEVIER* **(Submitted, IF = 1.747)**

The research work presented in this dissertation is based on the published research articles 1 to 2 and the submitted publications 1.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AMI	Automatic Metering Infrastructure
CA	Channel Allocation
CNGW	Cognitive NAN Gateway
CR	Cognitive Radio
CRN	Cognitive Radio Network
CSA	Cuckoo search algorithm
CSMA	Carrier sense multiple access
CSO	Cat Swarm Optimization
CWGW	Cognitive WAN Gateway
DCU	Data Concentrator Unit
DRM	Demand Response Management
DSA	Dynamic Spectrum Access
DTV	Digital TV
DTT	Digital Terrestrial Television
ETSI	European Telecommunication Standards Institute
FCC	Federal Communications Commission
GDB	Geolocation Database
GDD	Geolocation Database Dependent
HAN	Home Area Network
HEMS	Home Energy Management System
HSM	Hybrid Spectrum Management
JFI	Jains Fairness Index
JPCA	Joint Power and Channel Allocation

MIMO	Multiple Input Multiple Output
MSR	Max-Sum Rate
NAN	Neighborhood Area Network
NSM	NAN Spectrum Manager
OFDM	Orthogonal Frequency Division Multiplexing
PA	Power Allocation
PMSE	Program Making & Special Events
PUs	Primary Users
RLSS	Registered Location Secure Server
SG	Smart Grid
SGCN	Smart Grid Communication Network
SM	Smart Meter
SUs	Secondary Users
TVBD	TV Band Devices
TVWS	TV White Spaces
WAN	Wide Area Network
WRAN	Wireless Regional Area Network
WSD	Wireless Space Devices

Chapter 1

Introduction

1.1 Background

Smart Grid (SG) is an evolution of conventional electricity grid, answering to the problems like electricity shortages, escalation in electricity prices, power quality issues and need for using environment-friendly green energy resources. The use of state-of-the-art technologies, modern equipment, and automation control systems have provided benefits such as reduced power outages, increased power quality, cheap electricity, low operational costs and integration of renewable & sustainable energy sources. However, to fully benefit from SG concepts, a reliable, resourceful, efficient and cost-effective communication network is inevitable. The design and implementation of Smart Grid Communication Network (SGCN) is a very challenging task since it requires integration of different communication network segments that connect a vast number of heterogeneous devices distributed over vast distances having diverse QoS requirements [1].

Among various challenges in SG communications, one of the most critical issues is how to tackle data in the range of thousands of terabytes over these communication links having diverse requirements. Moreover, the data produced by various SG applications itself is varied in nature, specifically regarding latency requirements. Therefore, we cannot tackle different data is the same manner. A mixture of the licensed and unlicensed spectrum will thus be needed to transport this massive, diverse data regarding time criticality [2]. Cognitive Radio (CR) technology is a natural solution to meet the random and varied traffic requirements of SGCN. Primarily, it increases the spectral efficiency by fully exploiting the under-utilized scarce wireless spectrum and alleviate the burden on the network.

CR technology is a paradigm for radio resource management, where unlicensed users (Secondary users or SUs) can opportunistically use the unused channels (called holes) in a licensed spectrum without interfering with licensed users (called Primary users or PUs). Particularly, CR based IEEE 802.11af and IEEE 802.22 Wireless Regional Area Network (WRAN) are widely adopted standards in most of the CR based SGCN architectures in literature. *IEEE 802.11af also termed as Super Wi-Fi or White-Fi,* is a CR based communication standard exploiting TV White spaces (TVWS) in 54-790 MHz band. Owing to better propagation behavior, it expands the Wi-fi to a range greater than 1 Km with a max data rate of 40Mbps [3].

To give an idea about existing literature available in the field of CRSGCN design, we present a brief review of some of the related work.

Authors in [4] have presented a recent survey highlighting research gaps in design, modelling, and utilization of CR based sensor networks in smart grids, where authors have proposed a smart and unified solution for SG communication to answer different challenges. In [5], authors have done an extensive review of CRSGCN paradigms including network architectures mainly drawing attention to potential applications, spectrum sensing classification, routing and MAC protocols. It also includes a detailed discussion of open issues and challenges along with future direction. [6] is among some pioneer systematic reviews to be conducted for communication and networking addressing issues like QoS, control management and optimizing network utilization. Authors in [7], presented a detailed review of some essential components of SG, enabling six SG applications. Issues like achieving interoperability of legacy and evolving protocols are also discussed. A detailed study on SG communication network architectures and applications along with standardization efforts is provided in [8]. In addition, some of the significant challenges in cross-functional domains of power and communication are also identified. In [9], authors have used software defined networking (SDN) paradigm to present a framework for communication in NAN using wireless sensor networks (WSN). An analytical model for NAN is developed to determine the no. of switches and controllers, and its performance is evaluated using Castalia based simulations. Comprehensive research is presented in [10], providing a full analysis and comparison of AMI related routing protocols and technologies in NAN.

A dynamic spectrum sharing (DSS) scheme comprising of designing network topology and channel allocation for CR networks is proposed in [11]. The authors have analyzed network performance for smart utility network (SUN) services using Markov chain models. In [12], authors have proposed power difference coding (PDC) scheme to model the behavior of SG power scheduling over CRNs using an On-demand approach that suggestively avoids power waste. Opportunistic transmission protocol combined with optimal power allocation and transmit beamforming for non-orthogonal random access in multiple-input-multiple-output (MIMO) CRNs is used by authors in [13], to reduce interference temperature and transmission power, thereby increasing cognitive transmission capacity. In [14], a CDMA based resource allocation technique is proposed for a secondary network in CRSGCN.

Authors have suggested with the help of numerical results that the proposed technique significantly improves the number of SUs. Authors in [15], have jointly studied heterogeneous networks (HetNets), CRNs and SGs to maximize energy efficiency and adopted the game theoretic approach to not only reduce operational expenditure but also reduce CO2 emissions. A novel routing protocol for increasing the energy efficiency in a CR based AMI networks for SGs is proposed in [16], that also provides a mechanism to protect PUs. In [17], authors have investigated interference management in CRS. Optimal precoders and decoders are then identified to reduce mean square error calculations at DCU and primary receivers. Authors in [18], have studied the suitability of Long-Term Evolution (LTE) for SG applications. The proposed novel technique for estimation and allocation of bandwidth improves packet loss, delay, and throughput.

1.2 Research Problem

CR in SGCN is an ever-emerging field as seen from some of the above-mentioned work, still a lot of new research areas are yet to be explored. Although, CR is among the most intriguing areas for a researcher for the last two decades, however, its application in SGCN is still in early stages. Using CR technology in SG brings its own set of problems and issues that become more complicated in the diverse communication environment of SG.

The present study aims to investigate the problems in the design of CR based SGCN. In particular, where exactly one can use CR technology in SGCN and for what type of data is it feasible.? We will explore the problem of resource allocation among secondary users suiting the smart grid communication matching the regulatory requirements for CR standards like IEEE 802.11af.

1.3 Research Objectives

Our research is motivated to achieve three primary objectives given below.

i. To establish the communication requirements for each segment of SGCN, i.e., Home Area Network (HAN), Neighborhood Area Network (NAN) and Wide Area Network (WAN), to implement CR technology in SG domain. In particular, the communication range, data rate, latency and reliability constraints must be considered, prior to using a communication standard for a particular segment. The diverse nature of SG application data in terms of time-criticality or delay-tolerance, is another critical factor, in deciding that which communication standard is feasible.

ii. To propose an end-to-end network architecture of CRSGCN, on the basis of communication requirements investigated in first objective and the application data type suited to CR technology.

iii. To investigate the resource allocation problem in CR technology when applied to SGCN, in particular spectrum and power assignment. A plethora of research is available for resource allocation in CR networks. However, this power and channel allocation in CR based SGCN remain comparatively unexplored to date.

1.4 Philosophy of the Work

In order to determine the exact segment in HAN, NAN and WAN where CR can be used as a communication technology, not only the communication requirements in terms of data rate and range must be known, but also the data requirements in terms of size and latency is also very important. Therefore, it is necessary to review and analyze the different SG applications for NAN and WAN.

The problem of resource allocation among SUs need to be formulated altogether keeping in mind the SG communication environment and regulatory models. The exploitation of heuristic techniques can provide a better performance for optimization problems.

1.5 Research Hypothesis

The research hypotheses formulated for the study are:

- The use of CR technology in SGCN for delay-tolerant data such as automatic metering infrastructure (AMI) and demand response (DR) may ease-off the burden on communication links thereby increasing the overall spectral efficiency.
- The resource allocation for power and spectrum among SUs may be formulated as an optimization problem for CRSGCN keeping in mind multiple constraints like number of available channels and SUs, interference among PUs and SUs as well as regulatory frameworks.
- The heuristic based optimization methods may provide a computing mechanism for better power and channel allocations.

1.6 Research Methodology

Data produced by various SG applications is expected to range of thousands of Terabytes, which means that spectrum scarcity is a big challenge for SGCN. HAN, NAN, and WAN have different network requirements; therefore, it is a challenging task to choose where CR technology can be deployed in various sections (HAN, NAN, and WAN) of SGCN. Optimal resource allocation in CRSGCN requires in-depth knowledge about communication among various SG entities in terms of their communication requirements and operational behavior for different regulatory domains.

- A CR based SGCN network architecture is proposed fulfilling all the communication requirements of HAN, NAN and WAN.
- The resource allocation is designed for a very practical communication scenario taking account of practical considerations such as coverage area, channel bandwidth, operating frequency band, number of sub-channels and transmitted power constraints for an open loop GDD model of IEEE 802.11af standard in clustered NANs for SG communications.
- Joint power and channel allocation (JPCA) problem is investigated and formulated with multiple constraints considering two practical cases of fairness-based allocation and priority-based allocation in an SG environment in an innovative way, which perhaps is among premier works in its technical domain.
- A simple yet effective QoS based power allocation algorithm is proposed that serves the purpose of increasing power efficiency.
- A cuckoo search algorithm (CSA) based solution for the channel allocation problem, that works well for both cases having conflicting requirements.

1.7 Contribution of Research

The contributions of our research work are summarized below:

i. A detailed and comprehensive survey of SGCN is presented in an effort to identify the critical metrics in deciding the feasible communication technologies in HAN, NAN, and WAN. Followed by a thorough comparison of wired and wireless communication technologies. This contribution is part of this dissertation as chapter 2.

ii. The end-to-end network architecture of CRSGCN is proposed, based on the evaluating metrics and requirements identified in the first contribution. The salient features and some communication challenges are also listed. This contribution is included in this dissertation as chapter 3.

iii. The network architecture proposed as the previous contribution is used to model a novel communication scenario in NAN. Then we formulated a multiple constraint Non-deterministic Polynomial (NP)-hard channel allocation (CA) problem for complex and diverse communication environment using interference avoidance strategy by considering two practical scenarios: fairness-based allocation and priority-based allocation. A cat swarm algorithm (CSA) based heuristic approach is adopted to address the problem under consideration. Chapter 3, of this dissertation, is based on this contribution.

iv. In this contribution, we build a communication network model for the NAN communication around IEEE 802.11af standard with open loop regulatory framework. Joint power and channel allocation (JPCA) problem is then formulated to meet the QoS constraints by solving for achieving fairness and priority among users using cuckoo search optimization (CSO).

1.8 Research Scope

This thesis mainly focuses on the communication layer in SG multi-layer architecture. CR technology in SGCN, is widely accepted to increase spectral efficiency and hence providing a cost-effective solution for transmitting thousands of terabytes of SG application data. However, there is a lot of research to be done to solve the different problems and issues that arise from applying CR technology to SG domain. Mainly, resource allocation problem such as for power and spectrum remains unexplored, from problem formulation to a viable solution.

This dissertation covers a comprehensive survey of SG communication layer, from communication requirements of HAN, NAN, and WAN to detailed comparison of feasible wired and wireless technologies. Hence, this thesis can be a starting point for new researchers in the field of SG communication. Also, our work on the channel and power allocation, from problem formulation to proposed solutions, are a cornerstone for future studies in CRSGCN.

1.9 Thesis Organization

This thesis is organized into following chapters:

A brief introduction to CRSGCN, research objective, list of contribution and research scope is presented in chapter 1.

In chapter 2, comprehensive review of the existing literature from SGCN design, communication requirements, comparative analysis of wired and wireless technologies is presented. Some open issues and critical challenges for the communication layer are also listed.

Chapter 3, consist of our proposed end-to-end network architecture for CRSGCN. Salient features of the proposed network architecture and how it fulfills the communication requirements of CRSGCN is analyzed.

In chapter 4, based on the proposed network architecture in chapter 3, a novel approach of tackling the channel allocation problem in CR based clustered NAN communication is presented for fairness-based and priority-based allocation. A cat swarm optimization is then presented to solve these practical cases having opposite requirements.

A multiple constraint optimization problem for joint power and channel allocation is formulated in chapter 5, for the same communication scenario as detailed in chapter 3, also including TVWS based IEEE 802.11af using open loop regulatory framework. First, a simple but efficient power allocation scheme meeting the QoS constraint is introduced. Then using these allocated powers, the optimal channel allocation, for achieving fairness and priority in separate cases, using cuckoo search algorithm is furnished.

The thesis is then concluded in chapter 6, by summarizing the accomplishments and discussing the scope of future work related to this research.

Chapter 2

Literature Review

This chapter presents a critical literature review of CR and smart grid communication network (SGCN). It starts with background knowledge and design of SGCN by highlighting system requirements. After briefly mentioning SG applications, a detailed comparison of wired and wireless communication technologies is presented. The chapter is then concluded by highlighting some open issues and challenges for the communication layer.

2.1 Introduction

Conventional power/electricity grid is designed to meet the necessities of previous century keeping in mind only centralized power generation lacking from any sort of automation. The only solution to enhance the reliability has been to have excessive/spare electric power capacity with unidirectional power flow coming from fuel based or hydro-power plants to customer/consumer. The developments in communication technologies and ubiquitous computing have revolutionized all the industry sectors except the electric system that remains to operate the same way for ages. In response to ever-increasing demands on the electrical supply, massive blackouts, consistent occurrences of electricity shortages, alarming escalation in electricity prices, power quality issues, and environmental hazards problems have pressed many developed countries to optimize the electric grids in terms of reliability, efficiency, and alternative energy resources. This demand and motivation led to the need for a modernized electric power system for generation, distribution, and consumption of electricity which is called, the smart grid (SG) [1].

By definition, SG "is an automated, widely distributed energy delivery network characterized by a two-way flow of electricity and information, capable of monitoring and responding to changes in everything from power plants to customer preferences to individual appliances" [19].

Table 2-1 compares the main features of the smart grid with existing grid [20]. The primary objectives of SG are not only to make an efficient generation and distribution of electricity but also to optimize the energy consumption through customers by the bidirectional flow of information and reduction on CO2 emission using green energy sources.

The smartness in the SG is actually possible by the bi-directional flow of info and electricity thus enabling various intelligent and automated applications such as automation of home/building, distribution, meter reading, and managing outage and restoration [2, 21]. So, it is actually the communication that makes the grid smart.

Table 2-1: Features comparison of Conventional Vs. Smart Grid

	Conventional Grid	***Smart Grid***
Information Flow	One way	Bi-directional
Electricity Generation	Central	Distributed
Integrating DERs	Seldom	Often
Grid Topology	Radial	Network
Monitoring	Blind	Self-monitoring
Healing	Manual	Self-healing
Testing	Manual	Remote
Control	Passive	Active
Overall Efficiency	Low	High
Environment-Friendly	No	yes

2.2 SG Communication Network (SGCN)

Key to attaining the potential benefits of the SG is a cost-effective communication infrastructure that is not only secure and reliable but also it should fulfill the communication requirements: the ***SG communication network (SGCN).*** The design and implementation of SGCN is a very challenging task since it requires integration of different communication network segments that connect a vast number of heterogeneous devices distributed over vast distances having diverse QoS requirements. Also, the nature of network traffic for SGCN for bi-directional information flow is somewhat different as compared to conventional communication networks. Thus it is vital to understand what sort of information/data will be traveling through the SGCN along with data, reliability, latency constraints and traffic patterns.

As mentioned in literature, we also adopt a five-layer approach to conceptualize the multi-layered architecture in SG, as shown in Figure 2-1. These layers are:

Power system layer: concerned with power generation, transmission, distribution, and consumption.

Power control layer: deals with management function regarding power such monitoring and control.

Communication layer: responsible for bi-directional communication in SGCN.

Security Layer: providing features like user authentication, customer confidentiality, and integrity.

Application layer: Supporting various SG application to customers and utility companies for control and monitoring.

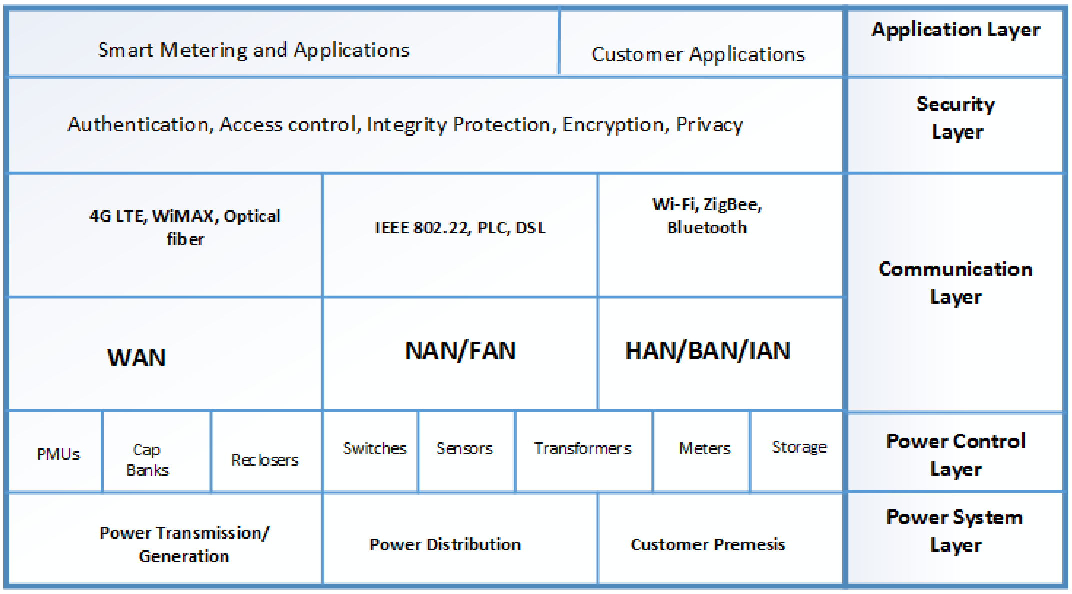

Figure 2-1: The system multi-layer architecture of SG

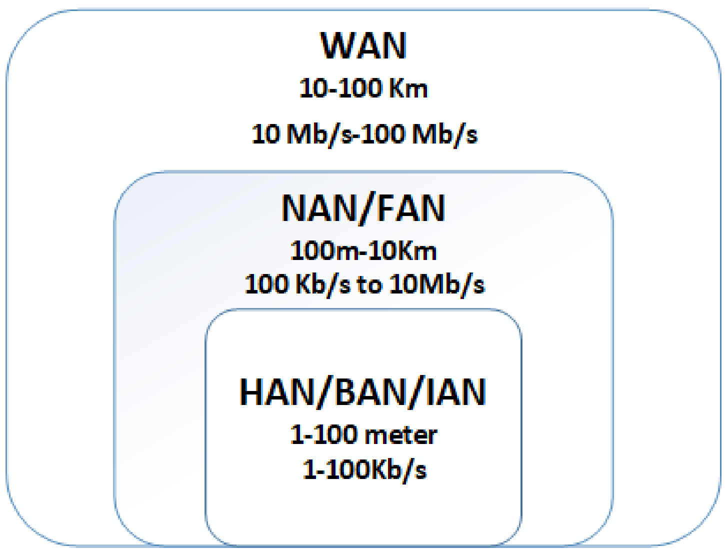

Figure 2-2: Approximate Coverage and data rate requirements for HAN, NAN, and WAN

As an example, consider an automatic reading of consumed electricity units is to be performed. Then, the automatic meter reading application will be enabled at the application layer. Power system layer will provide the electricity to the customer. Smart meter (the hardware) will operate at a Power control layer that monitors the power consumption reading. Communication layer will transmit the date from user premises to the utility company and vice versa. Security layer will be responsible for all the security features regarding data privacy and customer confidentiality.

The communication layer is one of the most significant layers in the SG multi-layer architecture. Therefore, this research mainly focuses on the communication layer. The Communication layer is further classified on the basis of the coverage area, data rate and range into:

i. ***Home Area Network (HAN)***, also termed as Building Area, Network (BAN) or Industrial Area Network (IAN)
ii. ***Neighborhood Area Networks (NAN)*** also sometimes called Field Area Network (FAN)
iii. ***Wide Area Network (WAN)***

Data rate and range requirements for HAN, NAN and WAN are summarized in Figure 2-2.

2.2.1 Home Area Network (HAN)

HAN covers the client premises where a variety of smart devices equipped with sensors communicate with a smart meter for efficient consumption of energy by monitoring and controlling devices like air conditioners, heating system, washing machines, etc. It may support other functionalities such as prepaid electricity activation, displaying electricity units consumed, current bill and mentioning peak hours, etc. Smart meters (SMs) not only monitor and control all the smart devices but also act as communication gateways between HAN and NAN. HANs support typical data rates from 10 to 100 kb/s and may cover areas up to 100-200 m^2.

2.2.2 Neighborhood Area Network (NAN)

NAN covers distribution and transmission domain. It is a critical section of SGCN transporting a large volume of diverse data and control information between the service providers in WAN and smart devices in HAN. NAN endpoints in Customer domain are SMs also controlling various SG applications, such as power outage management, power quality monitoring and distribution automation and so on. Depending upon the power grid topology (centralized/distributed) and the communication technology used, a NAN cluster may have from few hundreds to few thousands of SMs covering several square kilometers and each SM may need from 100 kb/s to 10 mb/s.

2.2.3 Wide Area Network (WAN)

WAN forms the communication backbone of SGCN since it collects information from multiple NANs and forwards it to Control Centre. It covers transmission and power generation domains enabling the long-distance communications between different data aggregation points (DAPs) of power generation plants, control centers, substations, transmission and distribution grids, distributed energy resource stations and so on. Since WAN forms a communication backbone, so a very high volume of data up to thousands of terabytes is transported thus, typical data rate required may be from 10 to 100Mb/s at least covering several hundred kilometers.

Just to give an overview, a hybrid (Wired and wireless) SGCN example is shown below in Figure 2-3 [22], where the involved technologies are explained in later sections.

2.3 Design of SGCN

A practically viable Smart Grid Communication Network (SGCN) must:

- ✓ Fulfill the data rate requirement of SG communications
- ✓ Fulfill the latency and reliability requirement of SG communications
- ✓ Support SG applications
- ✓ Solve the spectrum scarcity problem
- ✓ be flexible and scalable

There are some critical issues in the design of SGCN [22], such as:

- ✓ What network topologies and communication technologies are suitable for establishing links between different endpoints/nodes?
- ✓ How is the network topology affected by the communication technology used and the geography of the grid?
- ✓ Keeping in mind the diverse environment of SG, what communication protocols are more suitable?

Usually, it is not likely to provide a single solution to above-posed queries because SGs may function in different environments, but most of the system requirements are the same.

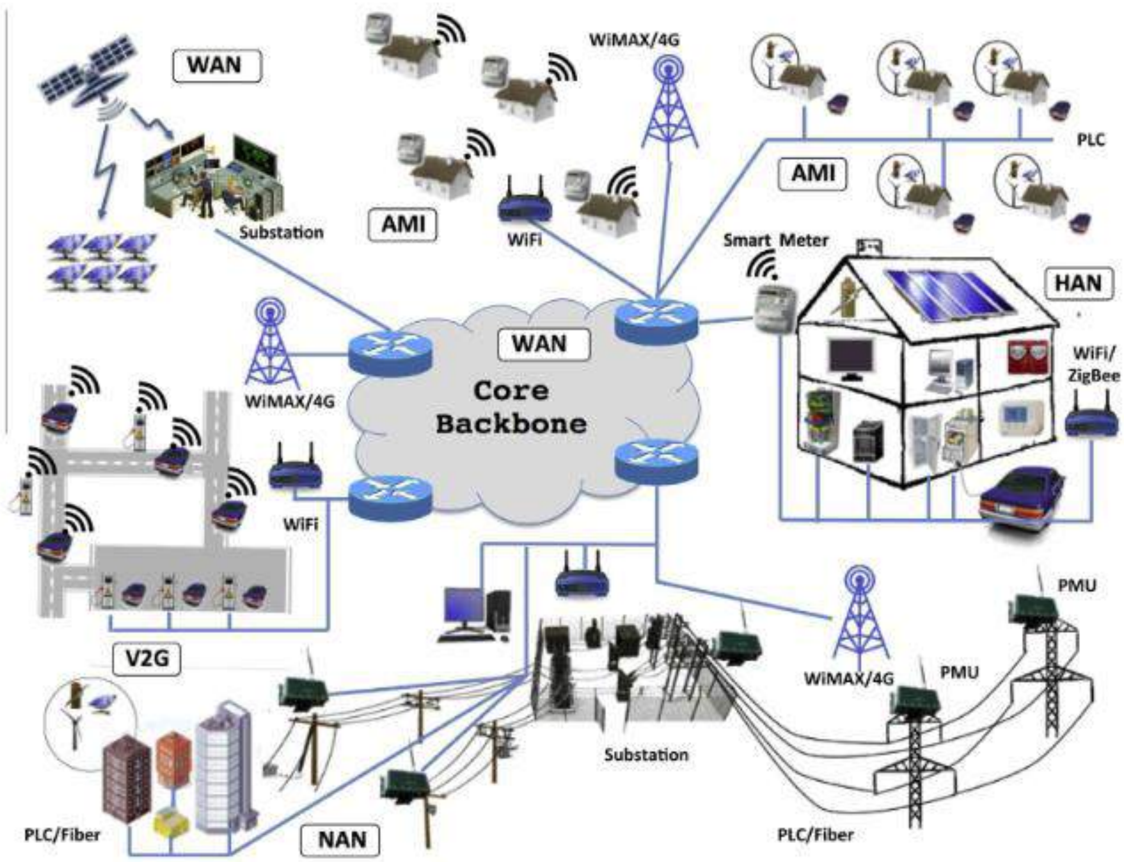

Figure 2-3: An example of a hybrid SGCN

2.3.1 System requirements

Before comparing the various communication technologies suitable for HAN, NAN, and WAN, it is essential to specify the necessary system requirements. The different research organization, utility companies, and governments have identified several critical requirements for SG in their reports in[23, 24]. In the following we concentrate on two essential types:

i. *Quantitative requirements:* key performance indicators for communications that can be specified in a measurable manner

ii. *Qualitative requirements:* supporting characteristics of a communication system that cannot be specified in a measurable manner but are desirable to service providers and users.

2.3.1.1 Quantitative requirements

There are three key performance indicators (KPIs) that can be measured to check the quantitative requirements:

Latency: latency is a measure of delay which is one of the most critical constraints especially for control and protection functionalities in any power system that requires to transmit the info immediately. Consider the example of a distribution automation system in which latency requirement for time-critical data such as transfer of measurements from Intelligent Electronic Devices (IEDs) to data aggregator may require max delay as low as 4ms, whereas the latency requirement for transfer of info between DAPs and control centers can be ≤ 8–12ms [25]. Similarly, other less time-critical applications such as Automatic meter reading (AMR) can bear comparatively higher network delays. Hence, for the time-critical data, the communication technology used must fulfill the lower latency requirements [26].

Reliability: Smart grid infrastructure has some very critical functionalities that cannot be guaranteed without a very reliable SGCN. A network failure may arise from many causes such as node/link failures, malfunctioning of gateways/devices, overloading, etc. thus redundancy is significant for critical links and devices / servers / gateways. Also, in the SG environment, the data can be very diverse in terms of criticality. There may be some messages that cannot tolerate any loss and has to be delivered immediately while some message can infrequently bear losses[27]. Therefore, it is imperative that applications must have the ability to prioritize their data for transmission depending on criticality level.

Data rate: The data rate requirements in SGCN vary depending on whether the link is in HAN, NAN or WAN. A typical requirement for HAN, NAN, and WAN is already presented in the previous section. However, the bandwidth needs are growing very fast since it may require to carry multimedia data (e.g., video surveillance of site) thus appropriate data rate for a communication link is one of the key requirements in NANs and WANs. Therefore, communication links between different nodes must be optimized, not only to increase the data rate but also to reduce delays and packet losses [6].

2.3.1.2 Qualitative requirements

An SGCN must have the following critical capabilities:

Scalability: Customers in an SG environment can be in millions and may increase on a daily basis thus scalability is intuitive, but scalability is also required in other forms. For example, a very desirable capability in SG is load scalability, which means handling excessive (more than usual) load in terms of data or service requests. Another requirement for any network is to be able to increase or decrease the size of a network and deploy different configurations on the basis of geographic requirements. Similarly, increasing the size of the routing table, increasing the communication resources in case of addition on new nodes is also scalable capability[6]. Distributed communication architectures can be applied in smart grids to increase the scalability.

Interoperability: It is evident that SGCN has a heterogeneous networks (Hetnet) environment with many different devices operating under different communication technologies and networking protocols. Thus, it is crucial to guarantee the interworking between various communication standards and devices [28]. One could deploy a communication gateway to connect segments having different communication technologies or standards. It is important to point out that interoperability is very vital in terms of both networks as well as applications, which demands standards to guarantee that exchanged data among different applications have the same meanings in each application.

Flexibility*:* In SGCN, flexibility can be a broad concept. It requires the capability to provision Hetnet services with different requirements in terms of time criticality and reliability. It also suggests that SGCN should have a diverse model for communication, e.g., for monitoring applications a multipoint to point (MP2P) model is preferred, for distribution of network commands and configuration data to different devices point to multipoint (P2MP) model is better [26]. In short, networking technologies and protocols used in SGCN are required to have a high degree of adaptability and flexibility because it must fulfill the demands of different applications.

Security: Security is another must-have the capability for SGCN to guard it against network failures due to cyber-attacks and ensuring the privacy of the customers [29]. For example, the SGCN must protect sensitive information regarding a customer's load profile and metering information from unauthorized access. Some of the security mechanism that can be used by SGCN to avert, detect and get rid of such threats are authorized authentication, intrusion detection, encrypting the sensitive data and trust [26].

2.4 Smart Grid Applications

Apart from qualitative and quantitative requirements discussed in the previous section, it is also imperative to know that what sort of information is contained in data that is to be carried, so that one may get an idea about data rate and latency requirements of the technologies to be chosen.

HAN applications mainly comprise of home and building automation, which are associated with forwarding the measurements/readings from an IED to a controller within a customer location. Therefore, HAN/BAN/IAN requires secure communication links having power consumptions, low data rates, and comparatively less coverage area. Communication technologies such as ZigBee, Wi-Fi, Z- Wave, power line carrier (PLC, or known as Home Plug), Bluetooth, and Ethernet are widely used to support HAN/ BAN/IAN applications providing data rate of up to 100 kbps with short coverage distance (up to 100 m) fulfills the requirements.

Applications in NAN such as distribution automation (DA), demand response (DR) and smart metering requires data to be transmitted from large numbers of home (SMs) to data collectors/substations or vice versa thus requiring comparatively higher data rates, typically 100 Kb/s to 10 Mb/s, low latency and coverage distance up to few kilometers. Depending upon the scenario Wi-Fi variants, ZigBee, PLC, Digital subscriber line (DSL), Cellular technologies like 3G/4G or WiMAX can be used.

Collectively the data to be transmitted on WAN is expected to be in the range of thousands of Tera-bytes. For control, monitoring and protection applications in WAN, which involve conveying a large volume of data to different nodes at higher data rates (typically 10 to 100Mb/s) with low latency to allow stability control, communication technologies offering data rates from 10 Mbps–1 Gbps up to range (~ 100 km) are suitable. Optical communication is one of the prime candidates to be used between substations (transmission/distribution) and control station because of low latency and higher data rates over longer distances. Cellular technologies like 4G LTE and WiMAX are also suitable because of wide coverage range and higher throughput. To provide redundancy and as communication backup in a remote location, satellite communication can also be used. In [2] a detailed analysis for NAN application is given, which is used here for estimating the typical data size and latency required by most of the applications. For the sake of reference, some of the comparative data from [2] are shown in Table 2-2.

2.5 Communication Technologies for SGCN

There are two general classes of communication technologies: wired and wireless.

2.5.1 Wired Technologies:

In general, wired technologies are better than wireless in terms of bandwidth, cost, reliability, security, maintenance and obviously one doesn’t pay for the spectrum. On the other hand, going wireless is the latest trend, owing to scalability, flexibility, and reconfigurability (from an operator point of view) and mobility (most attractive feature for the user). Key competing wired technologies are Powerline Communications (PLC), Optical Communications and Digital Subscriber Line (DSL). A comparison of these technologies is given in Table 2-3 [2].

Table 2-2: Network requirements of NAN applications in SG [2]

Sr #	***Application***	***Typical data size (bytes)***	***Latency***	***Reliability (%)***
1a	Meter reading – on-demand	100	<15s	>98
1b	Meter reading – scheduled manner	1.6K-2.4K	<4h	>98
1c	Meter reading – Collective manner	>= 1000K	<1h	>99.5
2a	Pricing-TOU (Time of Use) from utility to meters	100	<1min	>98
2b	Pricing-RTP (Real-Time Processing) from utility to meters	100	<1min	>98
2c	Pricing-CPP (Critical Peak Price) from utility to meters	100	<1min	>98
3	Electric service prepayment	50-150	<30s	>98
4	Demand response	100	<1min	>99.5
5	Service switch operation	25	<1min	>98
6a	Distribution automation – distribution system monitoring and maintenance data from field devices to DMS)	100-1000	<5s	>99.5
6b	Distribution automation – Volt/VAR control (command from DMS to field devices)	150-250	<5s	>99.5
6c	Distribution automation – distribution system demand response (DSDR) (command from DMS to field devices)	150-250	<4s	>99.5
6d	Distribution automation – fault detection, clearing, isolation and restoration (FCIR) (command from DMS to field devices)	25	<5s	>99.5
7	Outage and Restoration Management (ORM) (from meters to OMS)	25	<20s	>98
8	Distribution customer storage (charge/discharge command from DAC to the storage	25	<5s	>99.5
9a	Electric transportation (utility sends price info to PHEV)	255	<15s	>98
9b	Electric transportation (utility interrogates PHEV charge status)	100	<15s	>98
10a	Firmware updates (from utility to devices)	400k-2000k	<2min-7days	>98
10b	Program/configuration update (from utility to devices)	25k-50k	<5min-7days	>98
11	Informing customers in response to their requests for account info or billing info	50/200	<15s	>99
12	Administration of premises network	25	<20s	>98

2.5.1.1 Powerline Communications (PLC)

In PLC technology modulated carrier is transmitted using the existing power line cable for bi-directional communication which is a distinct advantage. Therefore, it has been one of the earliest technologies to be used for automation of electricity grid [30]. .

PLC is divided into two main classes, i.e., Narrowband PLC (NB-PLC) and Broadband PLC (BB-PLC). The NB-PLC operates between bands of 3–500 kHz. It is further divided into Low Data Rate NB-PLC and High Data Rate NB-PLC. The Low Date Rate NB-PLC uses a single carrier to achieve a data rate up to 10 kb/s, where High Data Rate NB-PLC uses multi-carriers achieving data rate less than 1 mb/s. On the other hand, BB-PLC technology has an operating range of 2–250 MHz providing up to several hundred mb/s. There are several competing standards for PLC such as G.hn/G.9960; IEEE P1901. In SG environment PLC is most suitable for applications like Substation Automation, AMI Backhaul, Remote Monitoring, and Distribution Automation, etc. Thus, PLC can be considered as a feasible solution for SG environment [30]. However, there are specific issues because of signal propagation characteristics along power cables including disruptive interference from power signals, devices or external electromagnetic interference because power lines are unshielded [22]. On top of it, the required specialized equipment makes the cost high.

2.5.1.2 Optical Communications

Optical communication is extensively used in electric grid environment for the backbone communication to connect substations with utility companies control centers due to several key advantages such as (a) It is immune to interference from electromagnetic and radio sources (b) High data carrying capacity up tens of Gb/s up to several hundred kilometers (c) Low latency.

There are two main categories of optical networks: Active-Optical Networks (AON), Passive Optical Networks (PON). AON is a shared network (sometimes called P2MP) that uses manageable active devices (electrically powered) to provide fiber access aggregation.

Depending upon the switch used, it can support up to ~80 km max. PON, on the other hand, is a shared network having passive devices such as couplers and splitters. The max supported distance is about 10 to 20 km for facilitating 32 customers. One primary benefit of PON is that the electrically powered equipment is only used at the source and receiving ends thus the most common optical communication technology Fiber-to-the-home (FTTH) uses PON. Three variants of PON are: Broadband (BPON), Ethernet (EPON), and Gigabit (GPON).

Many restoration and protection methods have been developed by providing redundancy to solve the problem of simple network failures in optical grids [31]. Optical Power ground wire (OPGW) is a special purpose optical cable build to provide higher data rates over longer distances, used in transmission and distribution lines [32]. It is realistic to consider optical communications as one of the prime wired technology in SGCN mainly because of its higher bandwidth and low latency. Recent studies are now proposing to extend the utilization of optical fibers to give SG benefits specifically to end clients [33, 34], although the main problem is the high cost of installation, equipment, and maintenance.

2.5.1.3 Digital Subscriber Lines (DSL)

DSL means transmitting digital data over telephone lines (copper wires) infrastructure which is already deployed to customers' premises thus interconnecting residential users to control center of utility companies saving additional cost of installation. However, the telecom operator maintaining the telephone lines may charge the utility company for using their infrastructure. DSL is divided into two main categories: (a) Asymmetric DSL having much download speed than upload speed (a) Symmetric DSL with equal upload and download speed. There are a number of variants of DSL providing max speed up to 100 mb/s but over comparatively smaller distances (up to 500 meters).

The main problem with DSL technology is that reliability, and potential downtime may not be acceptable for mission-critical applications. Additionally, achieving higher data rates of longer distances is very difficult. Table 2-3 shows a detailed comparison of wired technologies suitable for SGCN [22].

2.5.2 Wireless Technologies

Wireless technologies have the edge over wired technologies because of low installation cost, greater flexibility, and more scalability ensuring rapid network deployments in areas where there is no communication infrastructure or new technology is to be used. Recently a focus is shifted on energy efficiency in communication infrastructure. A survey in energy efficient wireless communication for smart grid environment is presented in [35]. With recent advancements, the wireless data rates and system capacity are very much comparable with wired technologies. Due to these advantages, electric companies are focusing on wireless technologies to deploy their communication network [36].

Table 2-3: Comparison of wired technologies in terms of communication requirements and usage in SG communication

Technology and Variants	***Data rate***	***Range***	***Use in Smart Grid***	***Pros***	***Cons***
Power Line Communication (PLC): ***NB-PLC*** ***BB-PLC***	**NB-PLC:** 1-10 Kbps (low data rate PHYs) 10-500 Kbps (High data rate PHYs) **BB-PLC:** 1-10 Mbps (long range) ~ 200Mbps (short range)	**NB-PLC:** ~ 150 Km or more **BB-PLC:** ~1.5 Km	**NB-PLC:** Large-scale AMI NAN/FAN, WAN **BB-PLC:** Small-scale AMI HAN	• Already established a long-haul communication infrastructure • Physically separate from other telecommunication networks • Low Operational Costs	• High channel distortion and signal attenuation • Disruptive interference from other electrical and EM sources • Difficult to achieve high data rates • Complex routing • Slow developments • Lack of vendors
Optical Communications: ***Active Optical N/W (AON)*** ***Passive Optical N/W (PON):*** ***BPON, EPON GPON***	**AON**: 100 Mbps up/down **PON:** BPON: 155–622 Mbps up/down GPON: 155–2448 Mbps up, 1.244–2.448 Gbps down EPON: 1 Gbps up/down	**AON:** ~ 10Km BPON, GPON: ~ 20–60 Km EPON: ~ 10–20 Km	WAN NAN/FAN AMI (with FTTH systems)	• Very High data rates over longer distances • Immunity to electromagnetic and radio interference • One of the most deployed technology in the residential area • Very low latency and delay	• High network deployment costs (particularly for AONs) • Difficult upgradation • High equipment cost • Not suitable for metering applications
Digital Subscriber Line (DSL): ***ADSL*** ***VDSL***	**ADSL:** 8 Mbps down and 1.3 Mbps up **ADSL2**: 12 Mbps down and up to 3.5 Mbps up **ADSL2+:** 24 Mbps down and up to 3.3 Mbps up **VDSL:** 52–85 Mbps down and 16–85 Mbps up **VDSL2**: up to 200 Mbps down/up	**ADSL**: ~ 4 km **ADSL2:** ~ 7 km **ADSL2+:** ~ 7 km **VDSL:** ~ 1.2 km **VDSL2: ~** 300 m (maximum rate) – 1 Km (50 Mbps)	AMI NAN/FAN	• Long-haul communication infrastructure already deployed • Most common technology for broadband customers in the residential area	• Utilities have to pay hefty amount network operators for using the network • Not feasible for network backhaul

Next, we give an overview of the conventional wireless technologies and standards on the basis of their transmission range.

2.5.2.1 ZigBee

Reference model used for physical and MAC specification of Wireless Personal Area Networks (WPANs) is IEEE 802.15.4 which has a significant advantage of low power consumption offering data rates up to 250Kb/s over a distance of 10m, although some proposed alternate physical layer variants may offer higher throughput [37]. Standards like ISA 100.11a, Wireless-HART, and ZigBee, are specifically designed for control and monitoring applications [38].

ZigBee is the most popular LR-WPANs technology for industrial and commercial scenarios because of its simplicity and less cost. Another fundamental feature of ZigBee is interoperability in its application profile which is very attractive for multiple vendors. Among these profiles, *Smart Energy Profile (SEP)* is specifically suited to smart grid environment providing an interface for monitoring, automation, and control of electrical appliances. Most of the ZigBee certified appliances used in HAN are easily available in the market thus making it easy for governments and utility companies to deploy SG solutions [38].

2.5.2.2 IEEE 802.11 xx

Commonly branded as Wi-Fi (Wireless Fidelity), the 802.11xx standards are covers the majority of wireless communication in WLANs, using license-free ISM bands with low-cost radio interfaces. It has many variants/versions with max data rates from 54Mb/s to 150Mb/s. Figure 2-4 shows a visual comparison of their ranges [39].

Among variants of 802.11 xx standards, two flavors are exciting as far as smart grid communication is concerned, i.e., 802.11ah and 802.11af.

IEEE 802.11ah (Low Power Wi-Fi) is a revision of IEEE 802.11 standard operating in unlicensed 900MHz bands promising low-power and long-range till 1 Km at different channels ranging from 1 to 16MHz with a min of 100 kb/s throughput [39]. 802.11ah based devices are likely to reach the market in 2016.

IEEE 802.11af (Super Wi-Fi or White-Fi) is another variant of IEEE 802.11 standard, allowing WLAN operation in TV White space (TVWS) using Cognitive Radio (CR) technology from 54MHz to 790MHz [40]. It is envisioned to give range beyond 1 Km with a maximum data rate of approximately 40Mbps.The standard was approved in February 2014.

2.5.2.3 IEEE 802.22 (WRAN using TVWS)

In the past, VHF (54-216 MHz) and UHF (470-698 MHz) bands were used for licensed TV broadcasting and wireless microphones, not for unlicensed use. With the transfer of TV broadcasting from Analog to digital television, most of this spectrum became free. In 2010, the FCC allowed the use of this under-utilized but highly desirable spectrum to be used by secondary (Unlicensed) wireless services. *TV White Spaces (TVWS)* means unlicensed utilization of these holes (vacant channels) among the occupied/used channels in VHF and UHF band.

IEEE 802.22, is a standard for wireless regional area network (WRAN) to provide broadband access to rural environments (difficult to access), using TVWS. It is aimed at using Cognitive Radio (CR) technology on non-interfering basis, to define a standardized interface for providing broadband access in hard-to-access areas, typically rural environments [41].

According to IEEE 802.22 specification, a cellular CR network consists of a base station (BS), managing the medium access for all customer premises equipment (CPE) in its coverage area. Several methods are considered to avoid interference to Primary User (PU).

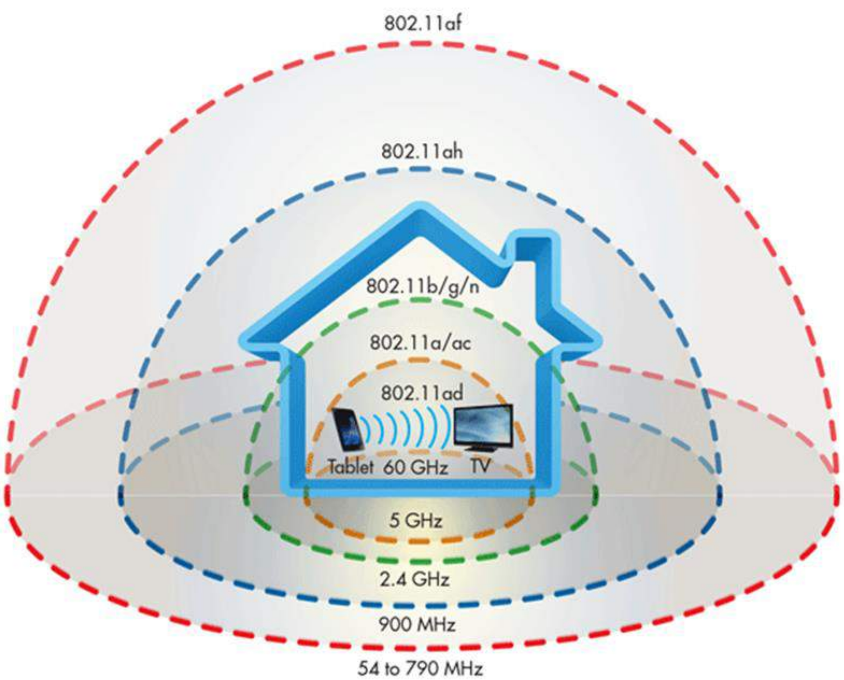

Figure 2-4: Range and Spectrum of different 802.11xx standards

The first method is based on location awareness of PU, equipping the BS with a GPS device that transmits the location of PU transmission, on various channels, to the central database. The database informs the BS about vacant channels. The second method is based on spectrum sensing information used by Base Station (BS).

Spectrum sensing can be done locally (by BS) or distributed manner in which CPEs can also sense the spectrum and share this info with BS, which then decides that which white space is to be allocated to CPEs.

Because of the desirable propagation characteristics of VHF and UHF band combined with CR technology, IEEE 802.22 standard is one of the prime candidates for SG environment. In [42] two different architectures for CR based SG communication are proposed. [43] proposes a novel technique for modulation and adaptive channel coding for communication using TVWS.

Both IEEE 802.11af and 802.22 are based on CR technology using TVWS. Table 2-4 compares the physical layer features of the two aforesaid standards [44].

Table 2-4: Comparison of the Physical layer for IEEE 802.11af and IEEE 802.22

	IEEE 802.11af (WLAN)		***IEEE 802.22 (WRAN)***
Range	Indoor: ~few 100m Outdoor: ~1 Km		30-100Km
Max delay(μs)	<1	1-10	11 to 60
Total B.W(MHz)	5, 10, 20, 40		6, 7, 8
Modulation	OFDM		OFDM
Payload Modulation	BPSK, QPSK 16-QAM, 64-QAM		QPSK, 16-QAM 64-QAM
Error Correction	Convolutional code		Convolutional code Optional: CTC, LDPC, SBTC

2.5.2.4 IEEE 802.16-based networks (WiMAX)

Wireless Interoperability for Microwave Access (WiMAX) is a commercial name for the IEEE 802.16 standard supporting long distance (50 Km radius approx.) and high data rate (70 mb/s) in rural and suburban areas [45]. WiMAX technology compliments the IEEE 802.11standard as it is designed for supporting larger areas and users and more refined QoS mechanism compared to the traffic type defined in 802.11e. One of the main disadvantages of WiMAX technology is its complex network management using licensed spectrum, thus making it more appropriate for end-user rather than service providers.

Like IEEE 802.11, WiMAX also has various flavors. The most promising one is IEEE 802.16m, designed for at least 100 Mb/s data throughput at high speeds (approx. 350 km/h) and 1Gb/s at comparatively lower speeds [46], therefore making it suitable for NAN and WAN technology in SG environment.

2.5.2.5 Cellular Communications

Evolving from 2G (GSM) to 4G (LTE), the data rate has increased from 14.4 kb/s to approx. 100Mb/s. Therefore, increased bandwidth, wide-coverage, high data rates, already deployed infrastructure and low maintenance are the main features of cellular networks that make them one of the prime candidates for SGCN [47]. The latest form of LTE, known as LTE Advanced, is in commercial use since October 2012. It offers~ 3.3 Gbps D/L and 1.5 Gbps U/L and 10 km Range, higher spectral efficiency, from a max of 16bps/Hz in Release 8 to 30 bps/Hz in Release 10 and increased number of simultaneously active subscribers [48]. Because of the wide support of large network operators and increasing user bank, prices of LTE chips are expected to be reduced further [49]. Cellular networks such as LTE can be used WAN and NAN for smart applications like Automated Demand Response (ADR), AMI and outage management [50].

2.5.2.6 Satellite Communications

Satellite Communication has been used for SCADA system traditionally. The main benefit of satellite communication is that it can be used to service a remote area which cannot be accessed through other communication means. Different satellites are placed in different orbits such as Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) supporting high bandwidth [51]. The main disadvantage is that it suffers from higher transmission delay and high cost making it unsuitable for time-critical data. However, it can be used as a backup.

With the development of low cost and smaller earth station in Satellite, networks can make it suitable to be used in SG environment such as backup for communication at critical stations or as a support of backhaul transport services for Automatic Metering infrastructure (AMI).

A summary of wireless technologies comparison is shown in Table 2-5 [22].

2.5.3 New Technologies

Apart from wired and wireless technologies mentioned in the previous section, there are some comparatively new technologies, though maturing, that can be very useful for providing communication in a Smart grid environment. These are Cognitive Radio (CR), Smart Utilities Networks (SUN) and TV White Spaces (TVWS).

2.5.3.1 Cognitive Radio

Wireless transceivers have become more compact, adaptable and controlling with the advancements in microelectronics which has revolutionized the *Software-defined radio (SDR) technology*. In SDR technology radio transceivers can switch functions and operations on demand only; it is not self-adaptable as it cannot re-configure the radios without informing the users.

Cognitive radio is an SDR platform that can quickly re-configure its operating parameters such as modulation/demodulation, compression algorithm, and error coding techniques, etc. according to changing circumstances and requirements, through cognition. It is a complementary technology to optimize the spectral efficiency of a licensed band.

Table 2-5: Comparison of wired technologies in terms of communication requirements and usage in SG communication

Technology	Data Rate	Range	Use in Smart Grid	Pros	Cons
WPAN: IEEE 802.15, ZigBee	IEEE 802.15.4: 256 Kbps	IEEE 802.15.4: Between 10 and 75 m	Vehicle-to-grid (V2G) HAN: AMI	• Very low power consumption • Cheap equipment • More appropriate for low-end devices (low memory and computational power) • Fully supports IPV-6	• Low data rates • Not scalable to bigger networks
Wi-Fi: IEEE 802.11e (QoS enhancements) IEEE 802.11n (ultra-high network throughput) IEEE 802.11s (mesh networking) IEEE 802.11p (WAVE - wireless access in vehicular environments)	IEEE 802.11e/s: ~ 54 Mbps IEEE 802.11n: ~ 600 Mbps IEEE 802.11af: ~26.7Mbps IEEE 802.11ah: ~ 40Mbps	IEEE 802.11e/s/n: ~300 m (outdoors) IEEE 802.11p: ~ 1 Km IEEE 802.11af: >1Km IEEE 802.11ah: ~1Km	V2G HAN AMI	• Low-cost network deployments (unlicensed spectrum) • Cheap equipment • High flexibility, suitable for different use cases	• High interference due to overly congested licensed-free band • Comparatively high-power consumption • Only supports simple traffic prioritization
WiMAX: IEEE 802.16 (fixed and mobile broadband wireless access) IEEE 802.16j (multi-hop relay) IEEE 802.16 m (advanced air interface)	IEEE 802.16: 128 Mbps down and 28 Mbps up IEEE 802.16 m: 100 Mbps for mobile users, 1 Gbps for fixed users	IEEE 802.16: 0–10 Km IEEE 802.16 m: 0–5Km (optimum), 5–30Km (acceptable), 30–100Km (reduced performance)	AMI NAN/FAN WAN	• Suitable for thousands of simultaneous users • Longer distances than Wi-Fi • A connection-oriented control of the channel bandwidth • More refined Quality of Service mechanisms compared to 802.11e.	• Complex N/W management • End nodes/terminals are comparatively high cost • Licensed band
Cellular Communications: 3G: HSPA, HSPA+ 4G: LTE, LTE Advanced	HSPA: 14.4 Mbps down and 5.75 Mbps up HSPA+: 84 Mbps down and 22 Mbps up LTE: 326 Mbps down and 86 Mbps up LTE-Advanced: 1 Gbps down and 500 Mbps up	HSPA+: 0–5 Km LTE-Advanced: 0–5Km (optimum), 5–30Km (acceptable), 30–100Km (reduced performance)	V2G HAN: AMI NAN WAN	• Able to support tens of millions of devices • End nodes consume comparatively less power • Cellular operators are launching solutions suited for smart grid environment • Highly flexible solution, suited for many use cases • Reduced interference due to paid spectrum	• The utility company has to pay for using the cellular services • Difficult to guarantee the desired delay
Satellite Communications: LEO, MEO, GEO	Iridium: 2.4 to 28 Kbps Inmarsat-B: 9.6 up to 128 Kbps BGAN: 384 up to 450 Kbps	Depends on the number of satellites and their beams	WAN AMI	• Long distance • Highly reliable	• Costly end terminals • Very high latency

According to U.S Federal Communications Commission (FCC) [52]: *"A Cognitive Radio (CR) is a radio that can change its transmitter parameters based on interaction with the environment in which it operates. The majority of cognitive radios will probably be SDR (Software Defined Radio) but neither having software nor being field programmable are requirements of cognitive radio."*

A most promising feature of CR technology is the improvement in spectral efficiency through sensing the spectrum for unoccupied channels (holes) that are not occupied by licensed users, called Primary Users (PUs) and opportunistically assigning them to the unlicensed users, called Secondary users (SUs). CR is an up-and-coming technology for SG environment as it can increase the spectral efficiency as well as transmission capacity to support large-scale data transmission [53].

Due to the scarcity of bandwidth and ever-increasing intensive radio communication on licensed and unlicensed bands, the use of Cognitive Radio technology in SG communication is inevitable. Therefore, many recent proposed solutions for SGCN have somehow or other utilized the CR technology. Further, we mention some of the literature for the communication solutions and problems that utilize CR technology.

In [53], technical challenges related to multimedia communications in SG communication and solutions of CR networking are investigated, and a guideline is also presented for future smart grid environment related to multimedia communication.

In[54], the authors have presented a new Machine-to-Machine (M2M) communication model and a spectrum discovery scheme driven by energy efficiency. They have numerically shown improvement in reliability and energy efficiency in SG. A detailed review of SG characteristic and architectures to provision CR based SG applications, main challenges and open issues have been presented in [55]. In [20], authors have discussed issues like Cognitive radio usage, interoperability of standards and cybersecurity in SG communications. In [56], authors have proposed a priority-based traffic scheduling method for CR based SG system according to the numerous traffic types of SG such as control commands, multimedia sensing data, and meter readings. A novel methodology for channel estimation and noise plus interference power estimation based on the IEEE 802.22 standard is presented in [57]. The simulation outcomes for a SG system with the MMSE beam-former demonstrate noteworthy enhancements in system capacity and BER. In [58], a Green Cognitive Mobile Networks with Small Cells for Multimedia Communications in the SG Environment is proposed. An attractive solution to the problem of secondary user characteristics of cognitive radio is presented in [59] by proposing a new spectrum access technique called Hybrid Spectrum Access (HSA), based in the intelligent utilization of both licensed-free and licensed frequency bands for SG communication.

2.5.3.2 Smart Utility Network (SUN)

Smart utility network (SUN) is a telemetry system that enables efficient management of utilities such as electricity, water, natural gas, and sewage. Since this efficient control of utilities leads to inspiring energy saving and decrease resource consumption, therefore SUN is very much suited to SG framework [60].

Some of the applications supported by SUN that can be very useful in SG are:

- Automatic meter reading (AMR)
- Remote service connect/disconnect,
- Outage detection
- Reliability monitoring

- Quality monitoring

A usage model of SUN consisting of four major components, i.e., smart meters, fixed data collectors, mobile data collectors and Base stations of Utility companies (BSs), is depicted in [60]. Smart meters of various utilities are connected to data collectors via RF link in NAN. Data collectors forming a mesh topology are connected to BSs by either wired or wireless link. In case of emergency or malfunctioning of the fixed data collector, mobile data collectors may be used as an alternative. A usage model for SUN is shown in Figure 2-5, and major allocated bands for SUN are mentioned in Table 2-6 [60].

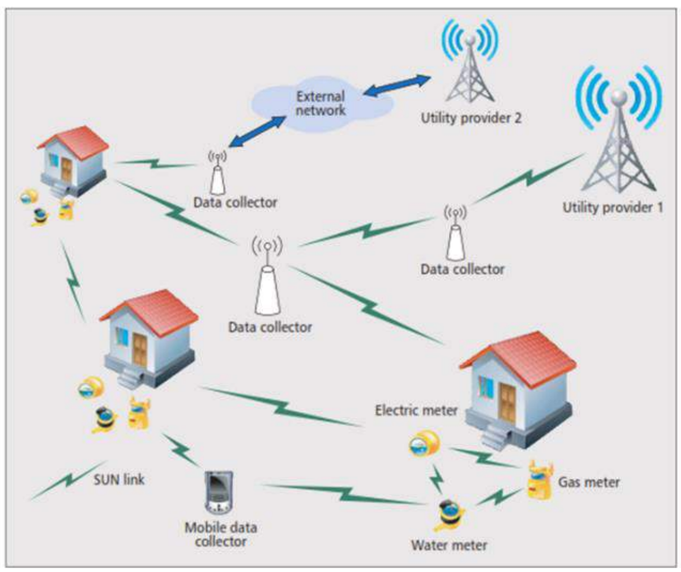

Figure 2-5: Usage model of SUN

Table 2-6: Major regulatory bands for SUN

Region	***Spectrum***
Worldwide	2.4 to 2.4835 GHz
Japan	950-958 MHz
USA	902-928 MHz
Europe	863-870 MHz
China	470-510 MHz

Task Group 4g, i.e., TG4g, initiated in December 2008, has defined physical layer (PHY) revision and related medium access control (MAC) extensions based on IEEE 802.15.4 for wireless smart utility networks (SUNs) [61].

Therefore, most of the solutions for SGCN in recent literature are using SUN especially for SG distribution system covering HAN and NAN. For example, in [20] SUN solution coexisting with IEEE 802.15g and TVWS is proposed for SG distribution system. Similarly, in [62] SUN is mentioned as the telemetry system closed to the SG.

2.5.3.3 TV White Space (TVWS) Communication

TV White Space (TVWS) Communication is another new technology receiving overwhelming consideration nowadays. TVWS is the vacant TV channels in the very high frequency (VHF) and ultra-high frequency (UHF) spectrum licensed by TV broadcasters and wireless microphones. Previously, unlicensed wireless services like Wireless Local Area Networks (WLAN) and Wireless Personal Area Network (WPAN) were not allowed to use this band but after migration of most of the analog TV to digital TV and satellite communication, the Federal Communication Commission (FCC) has granted TVWS for unlicensed use with certain restrictions and conditions. In short, TVWS is a supporting technology to re-utilize the vacant frequencies/channels (called holes) not occupied by primary users. It is a very timely opening for licensed free wireless technologies to access the more desirable unlicensed spectrum below 10GHz which already choked [60].

TVWS compliments the CR technology, that is why a lot of effort is put in developing CR enabled M2M communication over TVWS [54]. TVWS products have been developed by Spectrum Bridge [63], which has established, and currently testing, a TVWS geolocation database. Neul [64] has also developed M2M communications networked solutions over

TVWS. In a number of trials around the world, Neul is deploying smart city ideas such as management of the urban infrastructure, smart metering applications, and transport telematics. British Telecom [65] is also working on how to exploit the use of TVWS for providing broadband access to rural communities in the UK.

Unlicensed TVWS devices, also known as TV band devices (TVBDs), are broadly divided into fixed and portable devices. Fixed devices can be thought of as a BS of a cellular system: fixed location and central antenna with high transmit power. On the other hand, portable devices are lower power and could act as an access point in HAN. Portable devices operate in two different modes, Mode I: Client portable devices, and Mode II: independent portable devices that can access holes independently [66].

2.5.3.4 Smart Utility Networks in TVWS:

TVWS and SUN are entirely different technologies, but they can be combined to benefit each other. SUN works mainly in license-free bands as shown in Table 2-6, which means that traffic congestion and interference from various users can significantly degrade the performance. To optimize SUN, one can combine it with TVWS and CR to increase the spectral efficiency by increasing the range and data rate, hence decreasing the effect of interference and traffic congestion [60].

2.6 Design Challenges

Numerous difficulties exist that are concerned with overhauling communication infrastructure to allow an extensive variety of smart grid applications. By and large, major issues in the design and implementation of smart grid communications are:

i. ***Feasible communication technologies:*** SGCN consists of HAN, NAN, and WAN having different network requirements. Therefore, it is a challenging task to choose that which technologies to be deployed in various sections (HAN, NAN, and WAN) of SGCN and what topology should be used [22]. Apparently, the key metrics to compare are data rate and latency, but flexibility, maturity level and support for various applications of SG are also significant. We have already compared different communication technologies, both wired and wireless, in the previous section.

ii. ***Latency:*** For control and protection applications such as in WAN, measurement data is required to be transferred to the control center reliably, and control commands have to be delivered and implemented within a few milliseconds. This requires technology that has very low latency, like Optical communication or wireless technology that satisfies this min latency requirement such as LTE [2].

iii. ***High data rates:*** SG data will consist of data from applications like AMR, DR, etc. but also it may carry multimedia data like video surveillance for the site. Therefore, the data rate requirements are expected to be in trillions of Tera-bytes (TB), so it is a significant task for any communication networks to carry that much of data [53]. For achieving an upper limit of approx. 1 Gbps, combining latest technology like Massive MIMO with CR for backhaul network in WAN can be a viable option since Massive MIMO is envisioned to give fifty-fold or greater spectral efficiency improvements over fourth generation (4G) technologies [67].

iv. ***Spectrum Scarcity:*** Spectrum scarcity is a significant issue in any network solution designed in wireless technologies. ISM bands are already radio-intensive, and most of the lower band of the spectrum (VHF and UHF) is used. So SGCN may have to deal with this spectrum scarcity issue [55].

v. ***SG Applications:*** SGCN should support SG applications like Advanced Metering Infrastructure, Home Automation, Demand Response, Distribution Automation, Firmware updates, Program/Configuration updates and Electric service pre-payment, etc. [22].

vi. ***Interoperability:*** SGCN comprises of a Heterogeneous Network (Het-Net) environment because of different network requirements of sub-sections. So different solutions/technologies and standards will be used in different sections. The absence of required interoperability standards can damage the effective deployment of SGCN. The reason being that integration and updating of hardware and software of the exclusive network solutions preferred by is a challenging task. This may compel many utilities to adopt IP-based network solutions to answer the issue of interoperability. Thus, interoperability between these technologies will be a challenging task [2].

vii. ***Integration of distributed and renewable power sources:*** Unlike conventional electric grids, SG environment will have many distributed and renewable energy resources (e.g., solar panel and wind turbines) and the capability to balance the usage of different power sources [24].

viii. ***Regulatory Issues:*** Recently many revisions are proposed in existing standards such as IEEE 802.11af/ah operating in ISM bands along with existing standards.

Also, newly designed standards such as IEEE 802.22 can be the optimum solution for SG environment. However, using these standards will raise a lot of regulatory issues. Government policies should be defined carefully to answer them.

ix. ***Security Mechanism:*** Security is one of the biggest concerns in SG environment. Though the two-way communication and integration of data/communication network, control and data management system with power grid has brought smartness, it has also induced some security vulnerabilities. So most compelling research challenges in security mechanisms are to control the access of important/critical terminals/systems in SGCN and also to guard the confidentiality and integrity of customers' data such as load profile and metering measurements [22].

2.7 Summary

This chapter has provided a review on designing a viable communication network for Smart Grid environment from both technical and theoretical point of view, in an effort to summarize the literature on a comparison of wired and wireless technologies as well as major applications. The data rate and latency requirements for the NAN applications have been discussed. For a single customer, this data rate requirement may not be that much but collectively for millions and trillions of customers, this data is enormous. Latency requirements for most of the applications are not that challenging but for the time-critical data like data going to control centers and control commands requires very low latency, that is milliseconds. Applications in SG requires two-way M2M communication with devices, especially in customer premises (HAN). SGCN should be based on technologies and standards compatible with such applications Automatic meter reading, Demand response, Distribution automation, etc.

The lower portion of the wireless spectrum (30MHz to 11 GHz) is very congested and radio intensive including both licensed and unlicensed bands. Co-existence between different technologies may raise interference and power related problems. Owing to the significant benefits of rapid and low-cost deployment of infrastructure, easier reconfigurability ensuring higher flexibility, scalability, and desirable mobility feature, wireless technologies are preferred to using wired technologies in most of SG environment.

Already predicted that the amount of data produced by SG application will be in the range of thousands of Tera bytes (TB). This is perhaps the biggest communication challenge in designing an efficient yet cost effective smart grid communication network. Therefore, cognitive radio technology has been widely proposed in literature to not only increase the spectral efficiency of the overall communication but also make it cost-effective. The SG application data particularly for AMI and DRM related task, is delay-tolerant. Hence, it can be targeted to be transmitted using CR based communication standards.

In the next chapter, we present an end-to-end network architecture for CRSGCN based on the latest technologies discussed in this chapter that fulfills all the communication requirements for HAN, NAN and WAN.

Chapter 3

Cognitive Radio based Smart Grid Communication Network

In this chapter, an end-to-end CR based SGCN network architecture is presented, justifying the requirements of SG communication segments HAN, NAN, and WAN. Some critical and crucial challenges pertaining to CR technology are mentioned when applied to SG domain.

3.1 Network Architecture

The network architecture for the proposed SGCN is shown in Figure 3-1. The proposed SGCN is based on a three-layer hierarchy model with HAN-NAN and NAN-WAN communication is based on CR based IEEE standards primarily used for delay-tolerant data.

HAN is the actual user premises, consisting of smart meters as a central device to which all intelligent devices are attached. In fact, smart meters acts as a gateway between HAN and NAN thus called Home gateway (HGW). NAN covers the distribution system. Several HGWs are connected to data collectors (DC) that are then connected to the Cognitive radio-based gateway of NAN, called Cognitive NAN gateways (CNGW). A spectrum manager is connected to both DCs and CNGWs to manage the CR communication. CNGWs in NANs are connected to the base station of WAN co-located with CR based WAN gateway (CWGW) through relays. WAN portion of the network is the transmission systems. Each

CWGW is managed by a WAN spectrum manager and connected to control center using relays.

3.1.1 Communication in HAN:

Home area networks are needed in the customer domain to implement monitoring and control of smart devices in customer premises and to implement new functionalities like DR and AMI. The HAN provides real-time smart meter power data and load information from the user sides to the utility center controls and also provides dynamic electricity price info in the reverse direction.

Devices: HGW, smart meters, sensor, actuators and other intelligent devices

Topology: Star

HAN is inherently heterogeneous N/W with a number of complementary technologies that are licensed exempted. Within the HAN, devices can be connected to Smart meter or HGW either IEEE 802.15g or IEEE 802.11standards, both unlicensed operating in ISM band. The leading standard is IEEE 802.15g (ZigBee). ZigBee smart energy profile-based devices make it easy for utilities and governments to deploy smart grid solutions that are secure, easy to install and consumer-friendly. IEEE 802.11ah is operating in sub GHz band can also be used to connect sensors with smart meters, having extended range ~1Km because of better propagation behavior.

3.1.2 Communication in NAN

NAN is the next immediate tier of HAN. In our proposed solution DC collects the energy consumption information from HAN and pass it to the control center of a utility company through WAN.

Devices: Data collectors, CNGW, relays

Topology: Centralized/multiple gateways mesh N/W

HGW to DC link: It can be based on EEE 802.15g (ZigBee) or IEEE based 802.11ah/of (unlicensed) for which the HGWs needs to be placed < 1Km radius of the DC.

DC to CNGW link: We use ***Hybrid Spectrum Management (HSM)*** scheme for this link. Hybrid Spectrum Management is proposed to improve spectrum efficiency and to reduce the cost of buying spectrum bands. Licensed and unlicensed access modes are intelligently scheduled and seamlessly switched [59].

The utility company may purchase some portion of the spectrum from a cellular operator using optimum technology like 4G LTE. For time-critical data it may use the LTE band portion which is always available, hence solving the problem of "secondary user" characteristics. For less critical data one may use the IEEE 802.11af (White-Fi) technology for which the communication nods needed to be placed within a 5Km radius. A spectrum manager is used to cognitively share these licensed and unlicensed bands, which is connected to both DC and CNGWs.

CNGW to CWGW: This link may employ same HSM using LTE band and IEEE 802.11af/ IEEE 802.22. For longer distance, one may use relays in between the NAN and WAN gateways. If a WAN covers a large service area, then several NANs may share the same spectrum bands without causing interference to each other (keeping in mind the re-use distance and directional antennas).

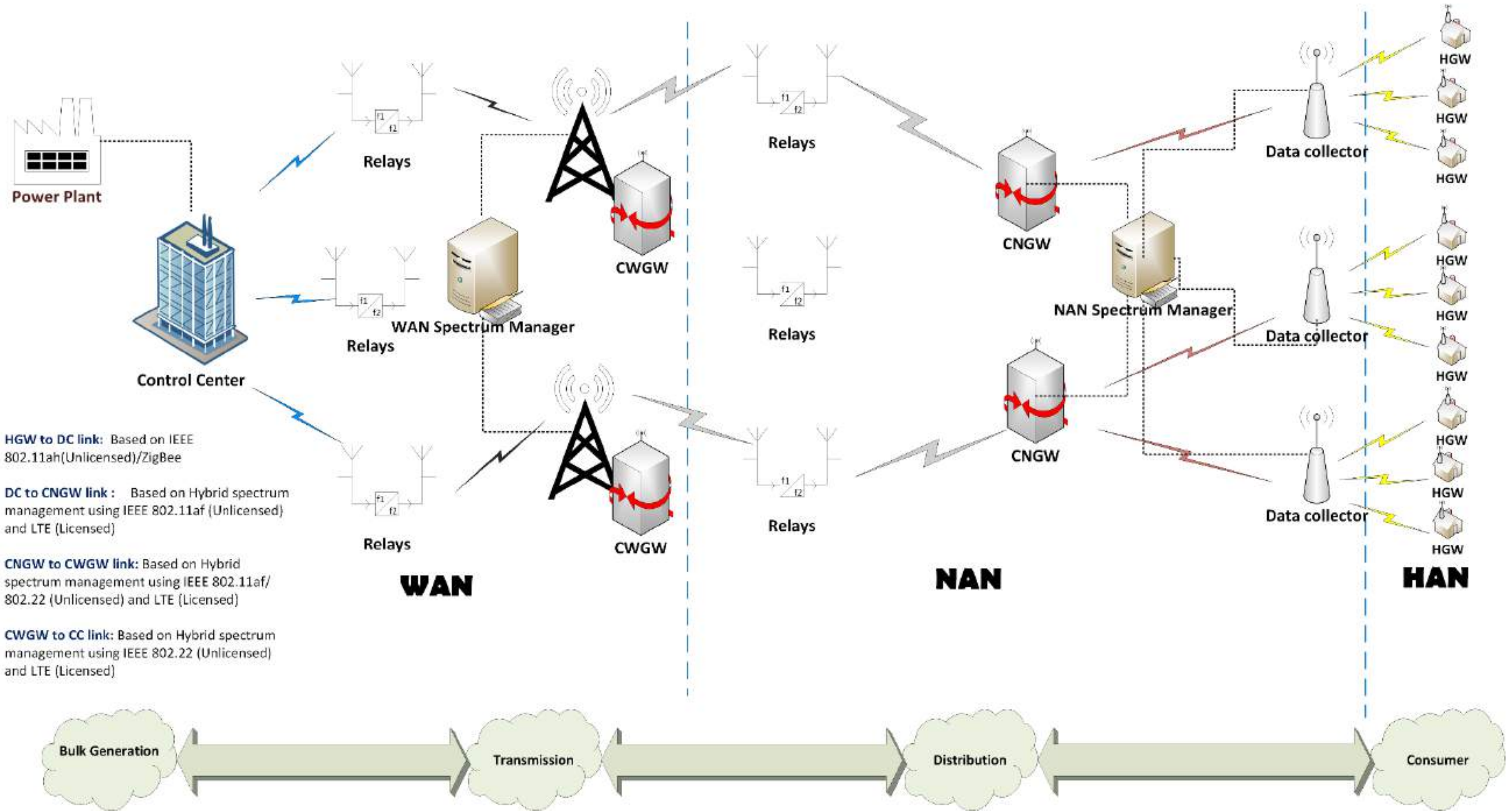

Figure 3-1: Cognitive Radio based Smart Grid Communication Network (SGCN) architecture

3.1.3 Communication in WAN

WAN forms the communication backbone to connect the highly distributed smaller area networks that serve the power systems at different locations. When the control centers are located far from the substations or the end consumers, the real-time measurements taken at the electric devices are transported to the control centers through the WAN and, in the reverse direction, the WAN undertake the instruction communications from control centers to the electric devices. WAN connects Control Centre to NAN exchanging energy consumption info in one direction, and exchanges Demand Response & control info in other direction.

Devices: CWGW, CR Base stations, Relays

Topology: Centralized/Multi-hop

CWGW to CC link: We propose HSM using LTE bands (Licensed) and IEEE 802.22 (WAN using TVWS based on CR technology). A WAN spectrum manager is connected to all base stations in close proximity for managing spectrum. For long distances, relays are used to connect to Control Centre (CC).

3.2 Salient Features of Proposed Solution

Following are some of the salient features of the proposed solution:

i. The solution is based on some of the latest communication technologies and standards, most of which are leading candidates for SG environment such as IEEE 802.22, IEEE 802.11af, IEEE 802.11ah, IEEE 802.15g, TVWS, and SUN.

ii. Using Cognitive Radio based communication solves the spectrum scarcity problem, hence can ease the traffic load on licensed spectrum, therefore considerably reducing transmission costs.

iii. CR based communication networks have an issue of a secondary user characteristic, for which all services have to be disrupted in the presence/arrival of the primary user. Thus, for time-critical data, this is a major concern. We have used HSM scheme using both licensed and unlicensed bands, which can overcome this problem [59].

iv. All the technologies used in the solution fulfills the data rate and latency requirements. However, one may use data compression to improve the efficiency of data flow and hence reducing latency further. Congestion management can also be used to reduce latency under the condition of heavy traffic as it allows data classification and prioritization of communication channels for emergency situations [2].

v. Only wireless technologies are utilized form SG communications in HAN, NAN, and WAN, therefore, the solution is more flexible and scalable.

3.3 Summary

In this chapter an end-to-end network architecture of CRSGCN is proposed that utilizes some of the most suitable communication technologies and standards for SG environment fulfilling all the communication requirements identified in previous chapter, thus making it efficient, flexible and scalable. Most of the end devices/terminals in the proposed CRSGCN solutions are fixed, which is a significant advantage. Using highly directional antennae and beamforming techniques can not only significantly reduce the interference from multiple users and devices but also can increase the data rate, therefore increasing the overall efficiency.

On the contrary, using CR technologies will bring its own set of problems and issues to smart grid. For example, channel and power allocation among secondary users suiting the smart grid communication scenario is a very challenging task since this area is almost unexplored for SGCN. Incorporating the regulatory constraints for CR standards like IEEE 802.11af and IEEE 802.22 WRAN, for different regions is also a major concern. These two research areas are the main focus of our work for next chapters.

Chapter 4

Clustering-based Channel Allocation scheme for Neighborhood Area Network

This chapter addresses the standalone problem of spectrum allocation in CRSGCN, which is yet to be fully explored in the literature. One of the key contributions of our research work in the form of network modeling of communication scenario in NAN and problem formulation considering SG constraints and heuristic approach based on cat swarm optimization to solve the channel allocation problem is presented.

4.1 Introduction to the Problem Area

CR technology is a natural solution to meet the random and varied traffic requirements of SGCN. Primarily, it increases the spectral efficiency by fully exploiting the under-utilized scarce wireless spectrum and alleviate the burden on the network. CR technology is a paradigm for radio resource management, where unlicensed users (Secondary users or SUs) can opportunistically use the unused channels (called holes) in a licensed spectrum without interfering with licensed users (called Primary users or PUs). Particularly, CR based IEEE 802.11af and IEEE 802.22 WRAN are widely adopted standards in most of the CR based SGCN architectures in literature. *IEEE 802.11af also termed as Super Wi-Fi or White-Fi,* is a CR based communication standard exploiting TV White spaces (TVWS) in 54-790 MHz band. Owing to better propagation behavior, it expands the Wi-Fi to a range greater than 1 Km with a max data rate of 40Mbps.

For a NAN scenario, using any CR based communication technology can ease of the burden on licensed spectrum, but one of the primary concerns is how to allocate these free spectrum (holes) to different SUs in an optimized fashion since the number of SUs are much more than available holes. This is the prime objective of spectrum/channel allocation problem. Moreover, how nodes are arranged for better spectrum management, is another concern.

Evolutionary or heuristic algorithms are bio-inspired solutions that follow the natural behavior of living systems. These solutions are widely adopted in many fields owing to their flexibility, proficiency, and robustness, to solve optimization problems where a number of constraints are significant, and search space is enormous that makes them very challenging for conventional computing techniques. In literature many nature-inspired solutions for CA problem are proposed [68-74]. However, we focus on CSO which a comparatively new heuristic algorithm that is based on the natural behavior of cats (detailed in a later section).

Clustering is usually arranging of nodes in groups to optimize the network performance. In CR networks, the main reason for clustering is the better management and facilitation of essential operational tasks such as spectrum sensing and sharing [75]. Most of the existing research on clustering in smart grid is either on load profiling or data analysis[76-81]. However, it is not straightforward to extend the same approach to CR based SG for CA problem. Nevertheless, it can be instrumental to manage transmissions to ease off some spectrum congestion. Mainly, CR has a simple infrastructure without the requirement of providing seamless coverage to all users but only those SUs that have some latency-tolerant data to transmit. Thus, using clustering-based CA to manage interference and allocate channels in a way to improve utilization and fairness of the network, is the motivation of our research. In fact, we have considered two cases, perhaps first work of its kind, that is common in practical scenarios. First one is fairness-based allocation: when all the SMs are treated equally and the second is priority-based allocation: when some of the SMs are given a significant share of resources.

We investigate a channel allocation (CA) problem in a typical CRSGCN scenario where IEEE 802.11af based communication is used for opportunistically transmitting less time-critical data for applications such as Advanced Metering Infrastructure (AMI), Demand Response Management (DRM), and Home Energy Management System (HEMS) within NAN. Therefore, it is indispensable to restrict number of simultaneous transmissions in a particular service area. Notably, for CR communication it is imperative to manage the channel assignment among SUs meeting the interference constraints. The clustered approach offers better spectrum management to deal with the mutual interference between SUs by controlling their transmissions, which is motivated by the co-tier interference avoidance strategy in the heterogeneous environment.

Before, explaining the network model and problem formulation, a brief review of related work is presented next.

4.2 Related Work

Although, a plethora of literature is available on CA in CR networks, investigating CA in SGCN scenario is still in early stages. Some of the recent researches addressing the problem under consideration are reviewed below:

In [82], authors have proposed a non-cooperative CA strategy based on game theory for 750MHz TV band in SG scenario to improve isomerism and capacity of the system. A Dynamic Spectrum Allocation (DSA) scheme based on fairness is proposed for SGCN using Binary Particle Swarm Optimization (BPSO) in [83]. A novel Orthogonal Chip Sequence (OCS) based allocation in Code Division Multiple Access (CDMA) for SU transmission is used in [14], to improve the number of SUs. Authors in [84], have proposed a heuristic approach to address the problem of finding location and minimum number of central nodes to fulfill connectivity of the clustered smart meter network. In [69], authors have discussed a general CRSGCN scenario and used metaheuristic techniques like Genetic Algorithm (GA), BPSO and CSO to solve the channel allocation problem using fairness and Max-Sum Reward (MSR). GA based allocation scheme for both channel and power using the Spectrum Engineering Advanced Montel Carlo Simulation Tool (SEAMCAT), by interference limitation, is proposed in [85]. Authors in [86], have used a Hungarian Algorithm (HA) based joint power allocation and CA method to maximize the channel capacity under minimum interference constraint to PU. A comprehensive survey on resource allocation (RA) for underlay CRNs is presented in [87], covering RA process, components, taxonomy to state-of-the-art algorithms. In [88], authors have done some comprehensive work on clustering-based spectrum sharing in CRNs using multi-user Orthogonal Frequency Division Multiplexing (OFDM). First, a clustering approach is introduced to group SUs by mutual interference, and then optimal resource allocation is done to maximize the sum rate in a cluster.

In [89], a clustered resource allocation approach is adopted by authors to reduce co-tier and cross-tier interferences in femtocells. Analysis and simulation of DSA using master-slave parallel immune optimization in comparison to serial algorithms are discussed in [70]. Authors of [90], in their revolutionary paper, have presented detailed research on spectrum assignment considering fairness and utilization in opportunistic spectrum access. They have based their CA strategy using color graph theory. Authors in [71-73], have extended the work of [90] using evolutionary computing techniques. In [91], authors have used a low-complexity heuristic algorithm to solve a multi-constraint problem having coverage, interference, minimum data rate, and power budget constraints in cognitive sensor networks. Authors in [92], have proposed a novel solution by weighting and categorizing interference as an extension to graph coloring approach to CA problem. The results of this interference sensitive algorithm in comparison with benchmark algorithm have shown improved spectral efficiency, reduced interference, and higher throughput. A Novel decentralized spectrum allocation algorithm using history of spectrum usage, to solve channel assignment problem in CRNs, is presented in [93].

4.3 System Model

We start by discussing the network model to fully explain the CR based communication scenario NAN, which is essential to understand the necessary design constraints in problem formulation.

4.3.1 Network Model

We model our scenario for a rural area on a fixed topology where SUs are fixed, and radio environment is slow-varying, meaning location and duration of holes do not change during a single channel assignment exercise (rounds). Data Concentrator Unit (DCU) continually updates its database (DB) to adapt quickly to the changes in spectrum availability. This assumption is realistic considering the open-loop regulatory paradigm where the list of channels remains unchanged for as long as 48hrs [40].

Figure 4-1 shows a typical CR based Smart Grid communication network (CRSGCN) architecture along with the feasible communication links for CR technology which is just a modification of the end-to-end network architecture already proposed in chapter 2. SG application data can be classified as less-time critical or delay-tolerant and time-critical or delay sensitive data on the basis of latency requirements. Data generated by many HAN and NAN applications such as home and building automation, Automatic metering infrastructure (AMI), Demand Response Management (DRM), Firmware updates and PEV, etc. is less critical in terms of latency requirements, while control and monitoring data such as outage detection, power restore acknowledgments, remote connection, and disconnection, tampering detection, out-of-range voltage conditions, etc. has to be delivered immediately. Therefore, we have considered only delay-tolerant data to be transmitted over CR links.

Clustering is performed merely on the basis of the distance of a node from cluster head, fulfilling the constraint that a service node can only be registered in a single cluster and all the clusters are independent of each other. Use of clustering strategy is justified in our scenario since a single cluster head has to manage all the resources and facilitate the several hundred nodes within the 1km^2 area. NAN is a cluster of several HGWs and a single DCU using IEEE 802.11af/LTE, as shown in Figure 4-2.

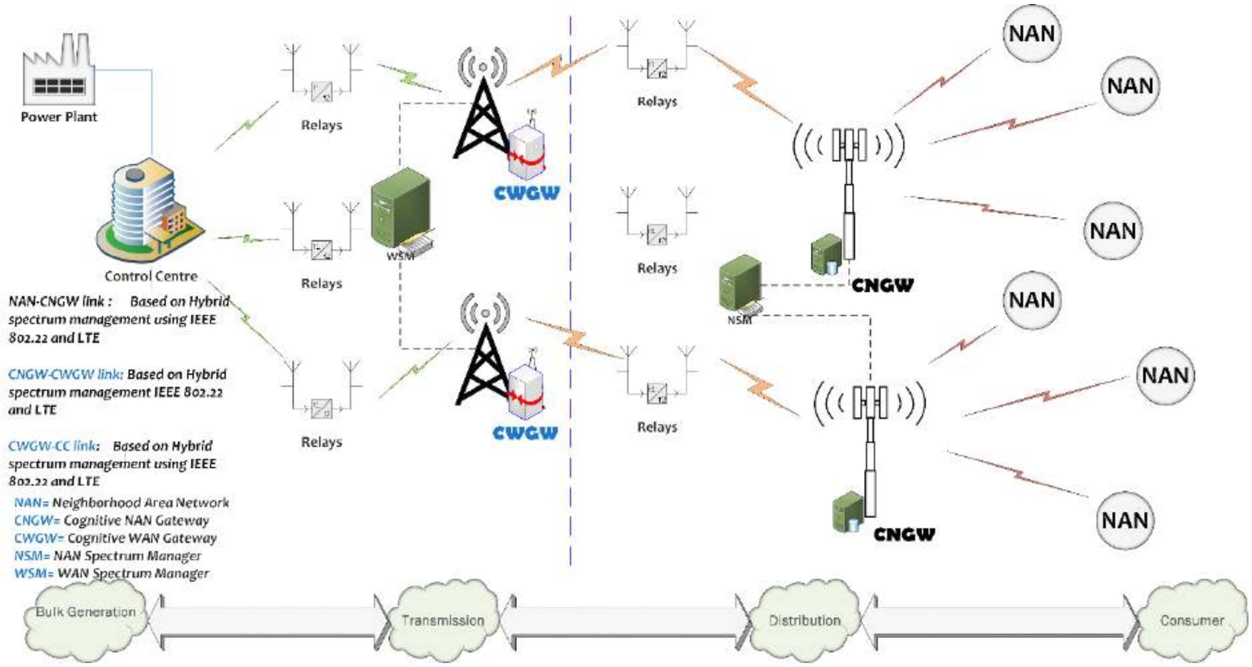

Figure 4-1: Communication in SG using CR based IEEE standards

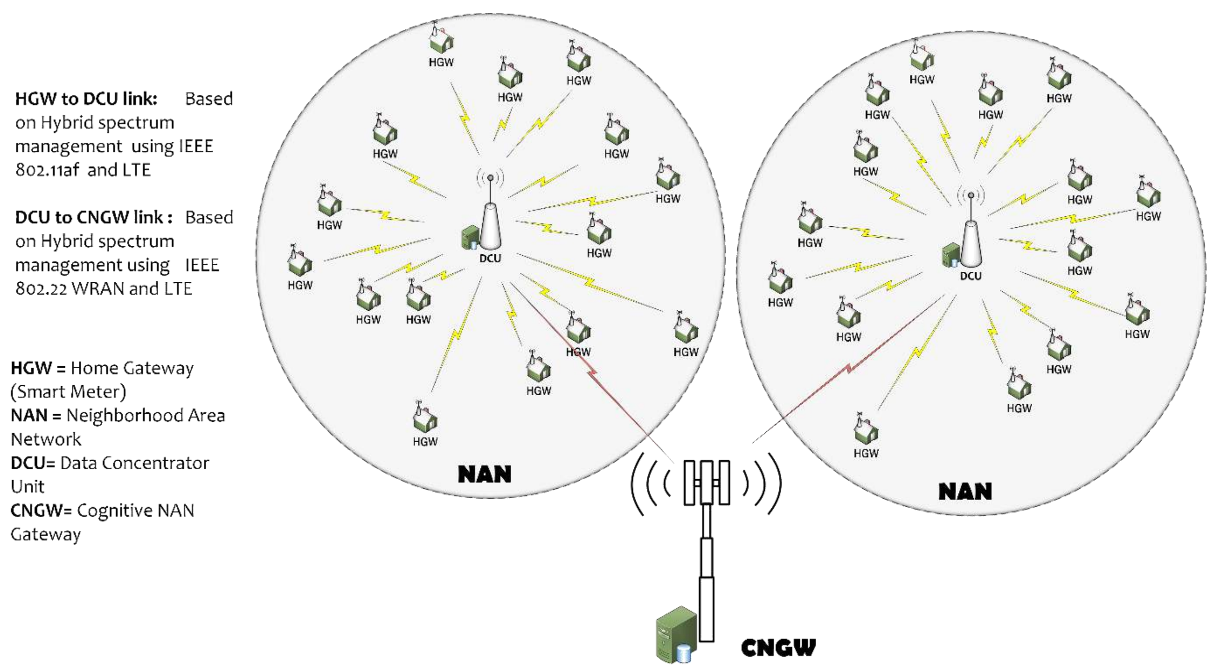

Figure 4-2: CR based Clustered NAN Architecture

DCU is a central entity, acting as a cluster head in a NAN cluster, responsible for spectrum management in a NAN. DCU is equipped with a Database (DB) carrying all the related information such as availability of holes to manage the transmission of all HGWs within a NAN cluster. In general, a DCU can connect to several hundred to more than thousands of SMs in a particular region but is limited by the communication technology used and congestion due to mutual interference between smart meters (SMs). SMs acting as a gateway between HAN and NAN are termed as HGWs, and all HGWs behave as cluster members. Several NAN clusters communicate with a CNGW using IEEE 802.22/LTE link and these CNGWs communicate with the control center (CC) through CWGW. NAN spectrum manager (NSM) and WAN spectrum manager are used for spectrum management in their respective domains. Size of a NAN cluster, supporting a data rate of 100 kb/s-10Mb/s, depends upon power grid topology (distributed or centralized) and smart grid applications.

A severe Quality of Service (QoS) constraint will occur without adopting any optimal spectrum allocation strategy since the number of HGWs are more than the available channels (holes). DCU is responsible for CA within each cluster using the DB that is continuously updating by spectrum sensing information which can be done in a centralized manner or distributed manner.

Our channel allocation scheme is based on interference avoidance strategy that ensures conflict-free assignment meeting two primary constraints:

i. Interference with Incumbent service or PUs: Digital Television (DTV) or wireless microphones services are considered as incumbent users or PUs. All SUs are assigned those channels which are left vacant by PUs.

ii. Interference among SUs: Both HGWs and DCU are considered as SUs. Within a cluster, a separate channel is assigned to each SUs thus avoiding the co-channel interference.

It must be noted that all the channels are not available for every SU at every time and location due to spectrum heterogeneity and presence of cognitive users (CUs), other than smart grid SUs (HGWs + DCU). A single channel cannot be re-used within a cluster during a single channel assignment, but SUs may have more than one channel assignments provided that no channel is re-used and availability conditions are satisfied.

4.3.2 Mathematical Model

Consider a CR based SG communication scenario having *S* number of SUs (HGWs + DCUs), coexisting with *P* active incumbent services (PUs). Consistent with literature in [76, 77], we group SUs into C disjunct NAN clusters having a single cluster head (DCU). All cluster members (HGWs) in a specific range connects to a single DCU. Let **S** denotes set of all the SUs in a service area, **S** = {1,2,3……S} and **C** denotes set of all clusters, **C** = {1,2,3…….C} where. A NAN cluster $C_i \subseteq \mathbf{S}$, $\forall$ i $\in$ **C**, C1: $\cup_{i=1}^{C} C_i = \mathbf{S}$ and each SU can be part of a single cluster only, i.e., C2: $\cap_{i=1}^{C} C_i = \emptyset$, where C1 & C2 denotes clustering constraints. Let **N =** {1,2,3……N} be set of channels left vacant by active PUs that can be assigned by DCU to **K =** {1,2,3……K}, set of all SUs in a NAN cluster; then we define following key components essential to our mathematical model:

Channel Availability, L: Since all the channels are not available for every SU in a cluster, so binary matrix **L** defines the list of available channels (holes) for each SU for a single channel assignment exercise (round) such that $\boldsymbol{L} = \{l_k^n | \ l_k^n \ \in \{0,1\}\}_{KxN}$, where l_k^n denotes that n^{th} channel for k^{th} SU. If the n^{th} channel is available for k^{th} SU, then l_k^n = 1 otherwise 0.

Channel Reward, B: Each available channel for every SU in a NAN cluster, carries a reward or weight which is represented by reward matrix $\boldsymbol{B} = \{b_k^n\}_{KxN}$, where b_k^n denotes reward of the n^{th} channel that is available to k^{th} SU. Obviously for l_k^n = 0, the reward $b_k^n =$ 0. This channel reward b can be taken in terms of throughput or bandwidth or coverage area depending upon the problem and scenario under consideration. Further discussion on choosing the suitable reward for our CR based SGCN scenario is presented in the later section.

Interference Matrix, F: Within a NAN cluster, active PUs may use any available channel first, and the rest of the pool is available to SUs.

A necessary condition to avoid co-channel interference among SUs in a single cluster is that no channel can be re-used in a single cluster. Then we define a binary interference matrix $\boldsymbol{F} = \{ f_{k,m}^n | \, f_{k,m}^n \in \{1,0\} \}_{KxKxN}$, where $f_{k,m}^n$ denotes that n^{th} channel is assigned to both k^{th} and m^{th} SUs. If $f_{k,m}^n = 1$, it means that same channel is used by two SUs at the same time. So $f_{k,m}^n = 0$ must be true for any single channel assignment exercise for k^{th} and m^{th} SUs belonging to same cluster.

Assignment Matrix, A: The binary matrix $\boldsymbol{A} = \{ a_k^n | \; a_k^n \in \{0,1\}\}$ represents the conflict-free channel allocation meeting both interference constraints C3 and C4.

C3: l_k^n x $l_p^n = 0, where\ p, k \in C\ and\ n \in \mathbf{N}$, means n^{th} channel cannot be available to both k^{th} SU and p^{th} PU in a same cluster at the same time i.e., if $l_p^n = 1$, then l_k^n = 0.

C4: $f_{k,m}^{n} = 0, \forall\, k \neq m \; where \; k, m \; \in \mathbf{K} \; and \; n \in \mathbf{N}$, means n^{th} channel cannot be re-used in a single NAN cluster.

It must be noted that a particular hole may be available to many SUs at the same time, but it cannot be allocated to more than one SU during a single round. Therefore, the conflict-free assignment demands that: $a_k^n \times a_m^n = 0, where \; m, k \in C \; and \; n \in \mathbf{N}$.

Assignment Limit, a_{max}: A single channel may not be re-used during a single round, but theoretically one may have more than one assignment to a single SUs provided both availability and interference constraints be met. Thus, a_{max} represents the maximum allowed channel allocation to a single SU, which facilitates in implementing our two allocation cases, i.e., fairness-based allocation and priority-based allocation, explained in later sections.

User Reward, R: let $\boldsymbol{R} = \{\, \gamma_k \,\}_{Kx1}$, where γ_k denotes the reward of k^{th} user, where

$$\gamma_k = \sum_{n=1}^{N} a_k^n \, b_k^n \tag{1}$$

Where, $a_k^n \in \{0,1\}$ and b_k^n a reward of the n^{th} channel assigned to the k^{th} SU.

History Matrix, H: This matrix $\boldsymbol{H} = \{h_k^t\}_{Kx1}$ represents user reward history of each channel assignment exercise (round). The term h_k^t denotes user reward history of the k^{th} user at the end of round t, given by:

$$h_k^t = \gamma_k^{t-1} + \gamma_k^t \tag{2}$$

Where γ_k^t is k^th user reward in current round t and γ_k^{t-1} is the k^th user reward in the previous round. History matrix (**H**) is updated at the end of every round. It is imperative for implementing overall fairness through our proposed algorithm.

The fairness among user is measured by calculating number of allocations to each SU during a single round, represented by:

$$\rho_k = \sum_{n=1}^{N} a_k^n \tag{3}$$

Jain's Fairness Index (J.F.I), given by (4), is another way of evaluating fairness among SUs.

$$J.F.I = \frac{\left(\sum_{k=1}^{K} \gamma_k\right)^2}{\sum_{k=1}^{K} (\gamma_k)^2} \tag{4}$$

Max-Sum Reward (MSR) which aims to optimize the overall reward during a single channel assignment exercise, given by:

$$U_{sum} = \sum_{k=1}^{K} \gamma_k \tag{5}$$

Utilization Factor, U(R): The utilization factor U(R) depends upon the objective of the problem under consideration. To maximize the utilization factor U(R), we have to optimize the channel assignment ***A*** meeting multiple constraints, which can be written as:

$$\boldsymbol{A}^* = \max_{\boldsymbol{C,f,l,b,\rho}} \boldsymbol{U}(\boldsymbol{R}) \tag{6}$$

$s.t$ C1: $\cup_{i=1}^{C} C_i = \mathbf{S}$, where $C_i \subseteq \mathbf{S}$

C2: $\cap_{i=1}^{C} C_i = \emptyset$, where $C_i \subseteq \mathbf{S}$

C3: $l_k^n \text{ x } l_p^n = 0, where\ p, k \in C\ and\ n \in \mathbf{N}$

C4: $f_{k,m}^{n} = 0, \forall\, k \neq m \; where \; k, m \in \mathbf{K} \; and \; n \in \mathbf{N}$

C5: $\rho_k \leq a_{max}$

C6: $b_k^n \in [0,1] \; and \; b_k^n = 0 \; if \; a_k^n = 0$

C1 and C2 represent clustering requirements. C3 ensures that SUs can only be assigned channels left vacant by PUs and C4 dictates that no channel is re-used in a single round. C5 puts an upper limit of maximum allocations to any SU and C6 is intuitive.

4.4 Cat Swarm Optimization (CSO) based Channel Allocation Scheme

In this section, we first brief CSO technique and general steps involved. Then we present our proposed algorithm applied to CA problem under consideration.

In 2006 S.C Chu et al. [94] proposed a new heuristic algorithm, Cat Swarm Optimization (CSO) is based on the natural behavior of cats. Most of the time cats remain in seeking mode (SM) to rest and analyze the surroundings of the possible target [95]. In tracing mode (TM), cats move towards the prey depending upon its velocity. A parameter called mixing ratio (MR) is used to define how many cats are in SM and TM, where Flag is used to tell whether the cat is in SM or TM. A generic CSO algorithm can be described in the following steps:

Step 1: Parameter Initialization

Initialize the parameters such as number of cats, SPC (self-position consideration), SMP (seeking memory pool), CDC (counts of dimensions to change), SRD (seeking a range of the dimensions), flags and MR.

Step 2: Mode selection (TM or SM)

Mode selection is determined by checking flag indicator, and MR determines that how many cats will be in SM and TM.

Step 3: Fitness check

Calculate the fitness of each candidate/Cat according to fitness function and keep the cat with the best fitness.

Step 4: Seeking Mode (SM)

According to SMP value, j copies of the cats are created in SM mode. CDC and SRD values are used to update each copy randomly. The fitness of each cat is calculated, and a cat is selected at random.

Step 5: Tracing Mode (TM)

The next best possible mode of each cat is then determined through TM. To update the position and velocity of each cat, the following equations are used:

$$V_{i,j}^{/} = V_{i,j} + r_1 c_1 (X_{gb,j} - X_{i,j}) \tag{7}$$

$$X_{i,j}^{/} = X_{i,j} + V_{i,j} \tag{8}$$

Where $V_{i,j}^{/}$ = updated velocity, $V_{i,j}$ = previous velocity, r_1= random number from [0,1], c_1= constant factor for global best (X_{gb}), $X_{gb,j}$= cat with the best fitness, $X_{i,j}$= previous position and $X_{i,j}^{/}$= updated position of the cat. Cats in both TM and SM are then combined.

Step 6: Re-picking

Re-select number of cats and according to MR set them into TM and rest of the cats to SM

Step 7: Stoppage criteria

Terminate the algorithm if required fitness is achieved, or number of the rounds have reached to the max value, otherwise, repeat step 2 to step 6.

In our scenario, we are dealing with two types of allocation modes: Fairness based allocation and Priority based allocation, described below.

4.4.1 Case 1: Fairness-based Channel Allocation

An everyday routine, when all the SMs have scheduled data regarding AMI and DRM, to be transmitted to DCU. Fairness based allocation demands that all SMs to be treated fairly, thus available channels are assigned the SMs during first channel assignment exercise (round). User rewards and allocated channels are measured using (1) and (3), and J.F.I (4) is used as the fitness function. History matrix H is updated with the reward of each user at the end of each round. Both allocations $\boldsymbol{a_k^n}$ and channel rewards $\boldsymbol{b_k^n}$ affect the user reward $\boldsymbol{\gamma_k}$. They are assigned in each round in a way to maximize the fairness indicator J.F.I. After number of rounds, all SUs should have an almost the same number of allocations and per user reward. The fitness function in this case is J.F.I, as describes by (4) used as utilization function in (6). To compare the user reward among SUs, we formulate Mean Square Error (MSE) to represent Max-Min Reward (MMR) which aims at optimizing the share of the SU with the least reward given by:

$$\boldsymbol{\gamma_e = ||\gamma_{max} - \gamma_{min}||^2} \tag{9}$$

Where, $\boldsymbol{\gamma_{max}}$ is the maximum user reward and $\boldsymbol{\gamma_{min}}$ is the minimum user reward in one round.

4.4.2 Case 2: Priority-based Channel Allocation

In this case, we consider another practical scenario where priority is required for few SUs for a short period of time. For example, customer needs to check the load profile of his/her house remotely, or DCU needs to transmit some data on a priority basis so such SUs must be assigned more resources. Thus, we deal with such cases in a way that 50% available channels are allocated to SUs with priority and rest of the channels are distributed among remaining SUs. Moreover, available channels with the best rewards are also allocated first to priority users. Let *K* be the total number of SUs and *Pr* be a number of Priority users in one NAN cluster. The fitness function used in (6) for this case is the reward of priority users, given by:

$$Avg\ \gamma_{pr} = \frac{1}{Pr}\sum \gamma_{pr} \qquad where\ \ pr = Priority\ user \tag{10}$$

Where γ_{pr} is user reward for priority users, then average reward for standard users D (other than priority users) is given by:

$$Avg\ \gamma_{d} = \frac{1}{D}\sum_{d=1}^{D} \gamma_{d} \qquad where\ d \neq pr \tag{11}$$

Pr =1 is taken as a special case where single priority user is assigned 25% of total available channels otherwise 50% of channels are divided among priority users. After some rounds, prioritized SUs should have more allocations, and user reward compared to other standard users.

Figure 4-3 shows the step-wise summary of the CSO based CA algorithm for both fairness-based and priority-based allocation. The flowchart of the same algorithm is shown in Figure 4-4. In this problem under consideration, number of users are greater than the channels and also the availability of the channels is not the same for each user. Moreover, the channel assignment objective has to meet multiple constraints as shown in (6). The two practical cases of fairness-based and priority-based channel allocation have contrasting requirements. This solve this channel assignment problem, we have applied Cat Swarm Optimization.

4.5.1 Simulation Configuration

Consider the service area is divided into NAN clusters, each covering the 1x1 Km^2 area where a number of PUs and SUs are randomly placed with a single DCU at the center, as shown in Figure 4-5. We have set the range of each DCU as ~1Km and channel bandwidths, consistent with IEEE 802.11af PHY specification. Since each NAN cluster is independent of each other, so our proposed algorithm can be implemented in all clusters at the same time. Each PU occupies one channel from the pool of available channels and rest of the channels are then allocated among SUs. The parameter values used to initialize BCSO is shown in Table 4-1. We evaluate our CA algorithm for two particular scenarios: *Fairness based allocation and Priority based allocation*.

CSO based CA Algorithm

Step I: ***Initialization***

Set P, K, N, T, Pr, D, a_{max} meeting C1, C2, C3

Set CSO parameters ($Cats_k$, MR, SMP, w, CDC, SRD, SPC)

Step II:

Generate availability matrix $\mathbf{L}_{KxN}$

for n=1: N

Assign channel reward b meeting C6

end

Case1: Fairness-based allocation selected

Step III:

for all K

Using CSO, assign a channel to each SU according to availability matrix **L** meeting C4, C5 with (4) as the fitness function

Calculate γ_k and store in history matrix **H**

end

Step IV:

for all K

Using CSO, assign channels with max reward *b* to the SUs with min user reward and channel with min reward to SUs with max reward in the previous allocation, according to availability matrix **L** meeting C4, C5 with (4) as the fitness function

Calculate γ_k , J.F.I, ρ_k and update history matrix **H** using (2)

end

Step V:

Repeat IV until the termination criteria are reached.

Case 2: Priority-based allocation selected

Step III:

for all K

Using CSO, assign 50% channels with max reward *b* to among priority users Pr and remaining among standard users *D* according to availability matrix **L** meeting C4, C5 with (10) as the fitness function

Calculate γ_k and store in history matrix **H**

end

Step V:

Repeat III until the termination criteria are reached.

Figure 4-3: Proposed CSO based channel allocation algorithm for CRSGCN

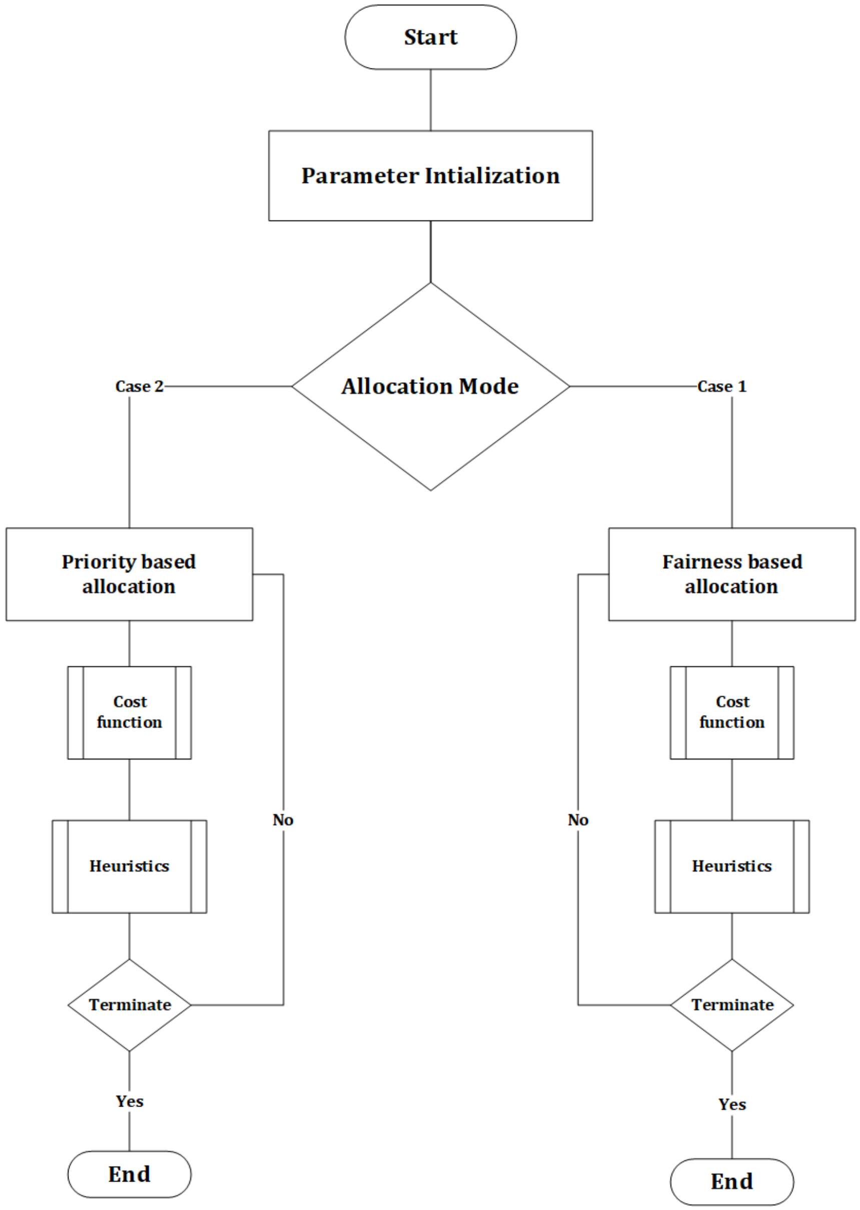

Figure 4-4: Flowchart CSO based CA algorithm

4.5 Performance Analysis

In this section, we evaluate the performance of our proposed channel allocation (CA) scheme via intensive computer simulations using MATLAB R2015a. First, we describe the simulation parameters and scenario, followed by analysis and discussion on results for both cases.

For ***case 1*** we take number of channels available to SMs, N=40, and number of SMs, K=50. Availability matrix $\mathbf{L}$ is generated randomly, and channels are allocated meeting constraints C1-C6. The reward of each allocated channel ($\boldsymbol{b_k^n} \in [\mathbf{0}, \mathbf{1}]$) is randomly assigned according to supported bandwidths of IEEE 802.11af standard i.e., 5 MHz, 10 MHz, 20 MHz and 40 MHz. Number of allocations per SU (3) and J.F.I (4) are calculated at the end of each round and algorithm is allowed to run for 20 rounds using a_{max} =1.

For ***case 2*** we take No. of channels available to SMs, N=40, No. of SMs, K=50, and No. of priority users, Pr=2. Availability matrix L is generated randomly, and channels are allocated meeting constraints C1-C6. The reward of each allocated channel ($\boldsymbol{b_k^n} \in [\mathbf{0}, \mathbf{1}]$) is randomly assigned according to supported bandwidths of IEEE 802.11af standard i.e., 5 MHz, 10 MHz, 20 MHz and 40 MHz. Number of allocations per SU (3), priority user reward $\boldsymbol{\gamma_{pr}}, \boldsymbol{\gamma_d}$ (10-11) are calculated at the end of each round and algorithm is allowed to run for 50 rounds using a_{max} =25% of N for each priority user.

Next, we present the results and discussion on the performance analysis of the proposed solution.

Table 4-1: Parameter initialization for BCSO

Sr no	***Parameter***	***Value***
1	No. of Cats	20
2	Mixing Ratio (MR)	0.7
3	Seeking Memory Pool (SMP)	10
4	Inertia weight (w)	0.7
5	Count of dimension to change (CDC)	10%
6	Seeking range of dimension (SRD)	10
7	Self-position consideration (SPC)	20x1

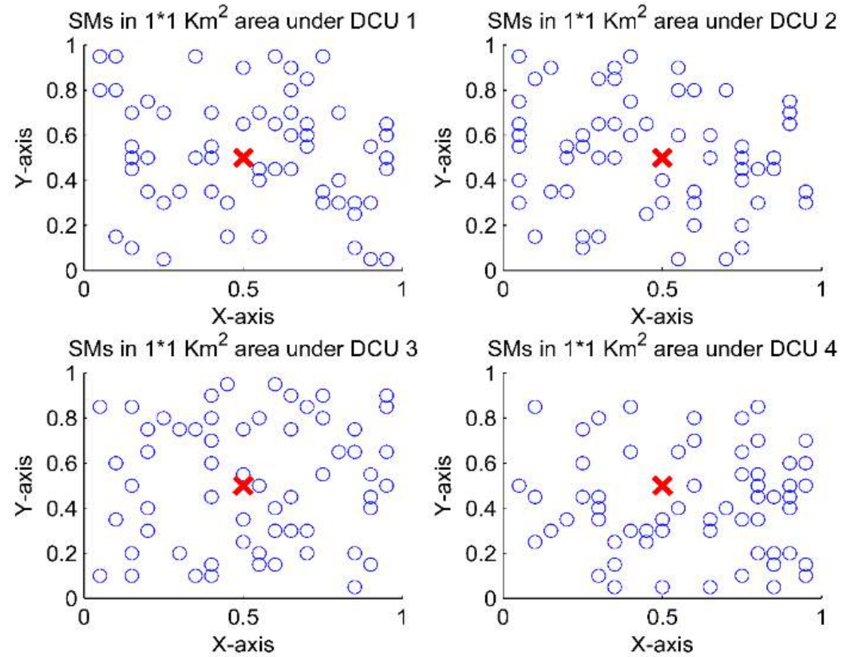

Figure 4-5: Random mapping of SUs in a NAN cluster of 1 x1 Km sq. area

4.5.2 Results and Analysis

For *case 1,* Fairness (4) and MSE (9) are plotted against No. of rounds in Figure 4-6 and 4-7 respectively. Fairness plot is increasing gradually and MSE, which shows the difference between max and min reward, is minimizing after each round. The improvement at the end of each round is the result of a heuristic approach that every new assignment shows better fitness than the previous generation. Total no. of allocations per SU is plotted for 20 rounds in Figure 4-8 considering (3). It can be seen that only 6 out of total 50 SUs have been allocated 15 channels and 44 SUs are at 16 allocations each.

It can be seen through Figures [4-6 to 4-8], that after completion of 20 rounds, almost all the users have same reward and no. of allocations even though the availability is not same for each SU, which proves and validates the effectiveness of proposed algorithm regarding fairness.

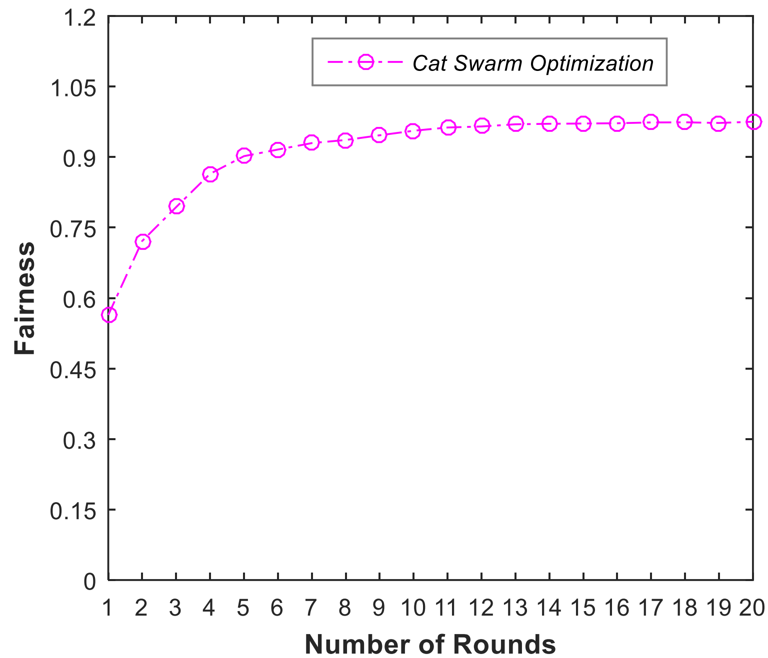

Figure 4-6: Case 1: Fairness vs. No. of rounds for No. of SUs = 50, No. Of channels = 40

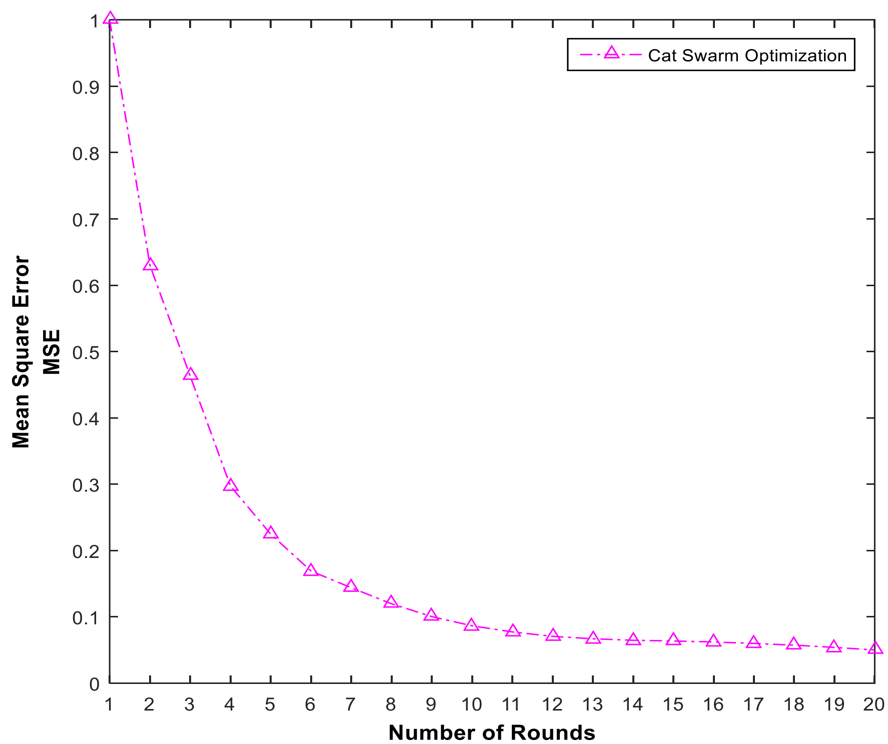

Figure 4-7: Case 1: MSE VS Rounds plot for No. of SUs = 50, No. Of channels = 40

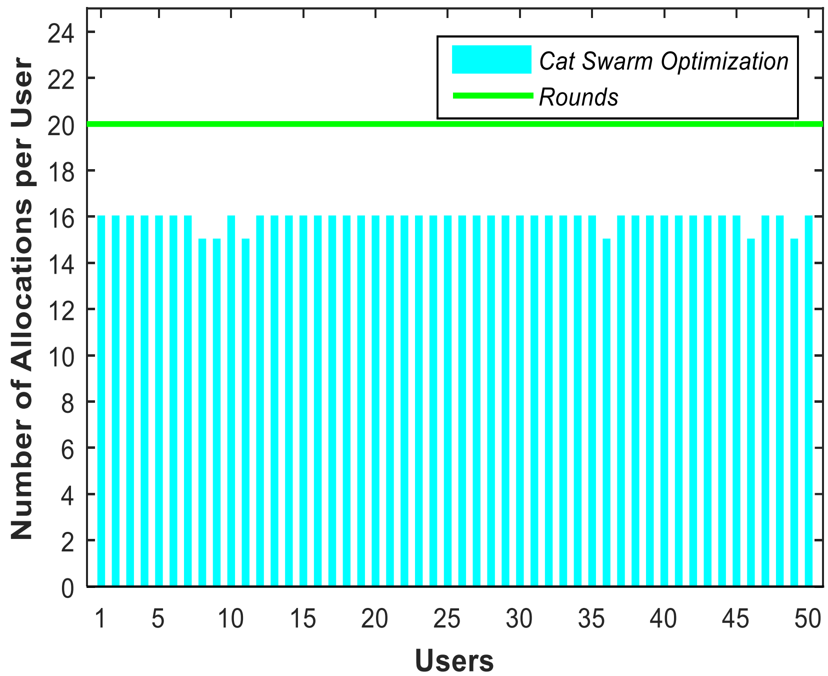

Figure 4-8: Case 1: Comparing no. of allocations per users after 20 rounds

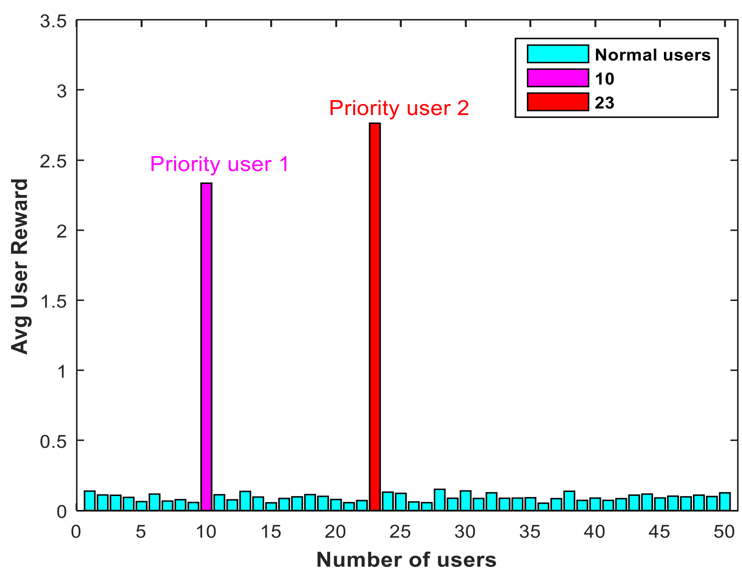

Figure 4-9: Case 2: Average user reward for 50 rounds

For *case 2*, SM 10 and 23 are randomly picked as priority users and rest 48 SMs are treated as standard users. User rewards (1) averaged over 50 rounds is plotted in Figure 4-9.

Round-wise comparison of priority users with standard users for user reward (1) is shown in Figure 4-10. No. of channel allocations (3) after 50 rounds are plotted in Figure 4-11.

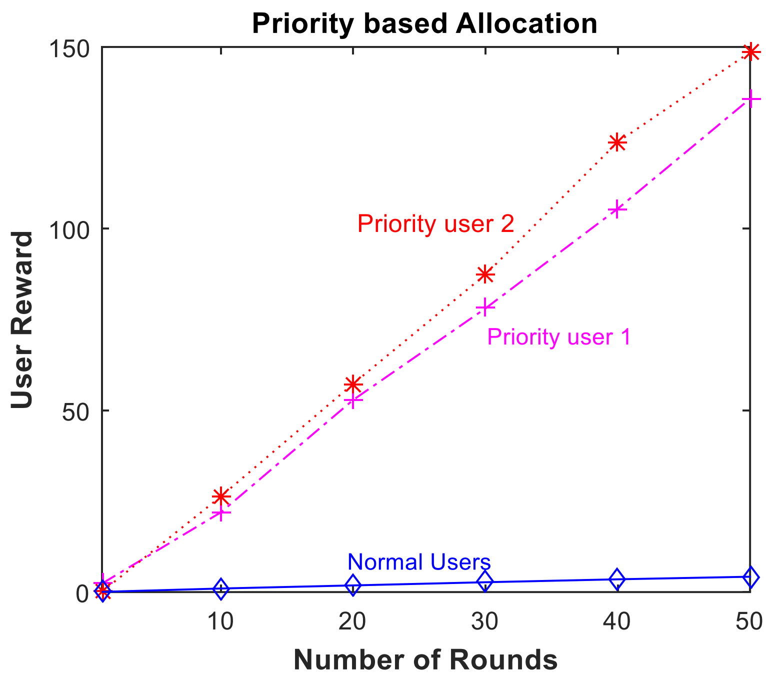

Figure 4-10: Case 2: User Reward vs. Rounds

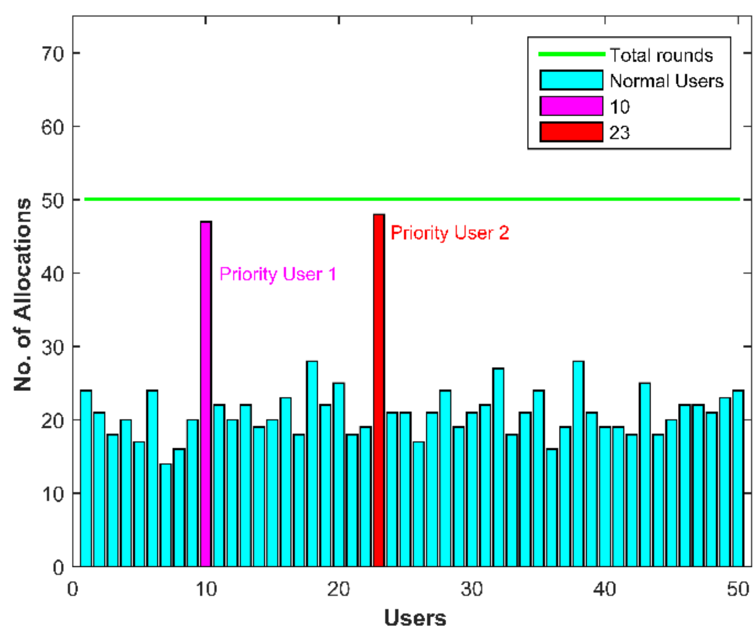

Figure 4-11: Case 2: No. of Allocations per user after 50 rounds

Both priority users have a substantial share of resources as depicted in Figure [4-9 to 4-11], which shows the effectiveness of our proposed algorithm in achieving objectives for priority-based allocation. The difference between the rewards of two priority users is due to the different availability of channels for both priority users.

Effect of varying number of available channels and SUs:

We now investigate how our proposed algorithm performs for a different number of available channels and different user density. MSR, U_{sum} (5) averaged over 50 rounds for ***case 1*** is shown in Table 4-2. It can be observed through Table 4-2 that avg. MSR only improves if channels are increased keeping no. of SUs fixed because increasing channels means more availability and reward. On the other hand, increasing user density keeping channel fixed has little or no effect on MSR as long as no. of channels are below no. of SUs since most of the SUs go allocation less.

It must be noted that we have considered a rural area, explicitly focusing on dealing with data that is suitable to transmit using CR technology. Therefore, a maximum of 100 users is considered bearing in mind a practical 1x1 km^2 area using IEEE 802.11af standard. As far as DCU is concerned, it can facilitate up to 1000 nodes, but we are transmitting data that is not time-critical. So, users can be scheduled in a way that all the remaining users/nodes can be serviced/facilitated within the required time frame.

Table 4-3 compares the average user rewards for priority users (10), and standard users (11) averaged over 50 rounds for case 2 considering Pr = 2 for all combinations. As the number of channels is increased, the difference between avg. rewards of both users also increased. On the other hand, increasing user density and keeping a number of channels fixed degrades the rewards.

*Table 4-2: Max-Sum Reward **(U_{sum})** averaged over 50 rounds for different channels and SUs*

No. of Channels		No. of SUs		
		50	**70**	**100**
		U_{sum}	**U_{sum}**	**U_{sum}**
	40	17.9	18	18
	60	21.95	26.475	26.97
	80	21.975	30.6	35.675

Table 4-3: Comparison of avg. priority user reward (γ_{pr}) and standard user reward (γ_d) for 50 rounds considering Pr=2 for all combinations

No. of Channels		No. of SUs					
		50		**70**		**100**	
		Avg. γ_{pr}	**Avg. γ_d**	**Avg. γ_{pr}**	**Avg. γ_d**	**Avg. γ_{pr}**	**Avg. γ_d**
	40	2.8431	0.0864	5.3712	0.0251	4.6738	0.0162
	60	3.8532	0.1265	7.895	0.0601	7.3262	0.0363
	80	4.535	0.1493	10.865	0.0701	10.915	0.0485

Table 4-4: Comparison of avg. priority user reward (γ_{pr}) and standard user reward (γ_d) for 50 rounds considering Pr=4 % of K

No. of Channels		No. of SUs					
		50		**70**		**100**	
		Avg. γ_{pr}	**Avg. γ_d**	**Avg. γ_{pr}**	**Avg. γ_d**	**Avg. γ_{pr}**	**Avg. γ_d**
	40	2.8368	0.2002	1.4971	0.1482	0.9797	0.0929
	60	3.4419	0.2762	2.2996	0.2113	1.4528	0.1446
	80	4.4369	0.3417	2.7621	0.2519	1.7778	0.1684

Effect of varying number of priority users:

To evaluate the effect of varying the number of priority users we simulate the same scenario of case 2 which is used to present Table 4-3 except we now take Pr = 4% of total SUs. Results are compared in Table 4-4, showing a decrease in average rewards as the number of users is increased, which is justified since it also increases the priority users. On the other hand, increasing channels, keeping user constant improves both average rewards.

It must be noted that slight variations while comparing Table 4-3 & 4-4, are because for Table 4-3 we have Pr=4% of total SUs while for Table 4-4 we have fixed Pr=2. Another reason for different values of average rewards under same combinations of K and N is that channel availability is generated randomly. Nevertheless, our proposed algorithm performs well for all cases.

Impact of allocating 50% channels to priority users

Impact of allocating 50% of the resources (available channels) can be seen by comparing user rewards and no. of allocations per users for both cases 1 and 2. Apparently, the significant increase can be observed in the rewards and allocations of priority users, which actually affects the overall fairness of the system. However, it must be noted that in a practical case scenario, this priority demand is not of very long duration. So, as soon as the on-demand data from priority users is completed, the channels can be again allocated to maximize fairness.

4.6 Summary

Optimum channel allocation on CR networks among SUs for a practical application has always been an area of interest for researchers. In this chapter, we intended to provide a framework to further explore the CA problem in CR technology when applied to SG. We investigated the problem of CA in CRSGCN, where first an efficient clustering technique is used for better spectrum management for the novel scenario of a clustered NAN. A system model is presented next considering IEEE 802.11af CR standard as the leading communication technology to connect DCU with SMs. Then a mathematical model is developed, considering practical limitations and boundary values. We then proposed a CSO based CA allocation algorithm, dealing with two allocation objectives that are totally opposite i.e., fairness-based and priority-based. The simulation results presented in Section 4.5 in the form of plots and comparison tables have shown that our proposed algorithm attains desirable outcomes to this multi-constraint problem for both practical cases under consideration.

In this chapter, the channel allocation problem was formulated for a clustered-NAN scenario for CRSGCN only considering channel rewards on the basis of bandwidth of available channel. In the next chapter, for the same CRSGCN communication scenario, this work is further extended to jointly solve power and channel allocation.

Chapter 5

Joint Power and Channel allocation scheme for TVWS based Smart Grid Communication Network

In this chapter, we try to formulate and solve the problem of power and channel allocation in CRSGCN jointly. The network model from the previous chapter is further updated to include TVWS band and open-loop regulatory framework. An efficient and straightforward power allocation scheme is proposed meeting QoS constraints. Then channels are allocated among SUs in an optimal fashion using a cuckoo search algorithm to solve for the same cases of fairness and priority.

5.1 Introduction to Problem Area

TV white space (TVWS) has been envisioned as the most promising spectrum contender for CR based smart grid communication network (CRSGCN), owing to its desirable propagation behavior, Spectrum under-utilization, better non-line of sight (NLOS) coverage due to less harmful material obstruction and simplified secondary access paradigm using geo-location database (GDB) for incumbent service protection [96]. Currently, two IEEE communication standards: IEEE 802.11af (Wi-Fi) and IEEE 802.22 (Wireless Regional Area Network -WRAN) designed for TVWS with CR paradigm are most commonly used by researchers for different SGCN scenarios. Both standards are very well-suited for SG environment and fulfil all the communication requirements [97]. However, we have used IEEE 802.11af in this thesis to model our communication scenario. Unlike other variants of IEEE 802.11 Wireless Local Area Network (WLAN) standard, the modification in physical and medium access layer (MAC) in IEEE 802.11af have increased the range up to ~ 1 km by incorporating TVWS. One fundamental difference is the entity geo-location database (GDB) that contains all the necessary information regarding operational parameters. The whole working of this standard revolves around GDB which itself is authorized and regulated by various countries. Regulatory implementation of GDB is governed by two approaches: open loop model and closed-loop model. We restrict our discussion to the open-loop model since it is more suitable for our scenario. Both fundamental concepts of IEEE 802.11af and open loop model are discussed in detail in Section 5.3.

A significant amount of research is available on joint power and channel allocation (JPCA) as far as cognitive radio is concerned. However, we feel that a lot of effort is required to extend this work in SG environment. Therefore, we have tried to formulate a problem of JPCA for a very practical scenario in CRSGCN. Since the CR technology in implemented in licensed bands, TVWS is the most suitable contender for CR communication. Not only most of the traffic in analog TV band is shifted to digital, but the propagation behavior in this band itself is also a desirable advantage. But it cannot be implemented without the approval of regulatory authorities. Hence to make our communication scenario more practical, we have considered open loop regulatory framework to specify the operational parameters such as Max Tx power, frequency range, TV channels, Channel bandwidth and coverage area, etc.

Next, we briefly review some of the related research work from the field of TVWS in SG communication, JPCA and fairness in CR networks.

5.2 Related Work

TVWS based on CR technology is widely used in a smart grid, owing to their better propagation characteristics. Authors in [98], proposed an online algorithm using a Lyapunov drift and penalty function, that can provide a trade-off between total cost and QoS in the internet of things (IoT) and SG applications. A case study to solve the service coverage for internet and SGs in Ecuador using TVWS is presented in [99]. Another research work utilizing TVWS for smart metering applications in an SG is shown in [100], in which authors have presented novel idea of high priority channel (HPC) leasing by CR operators. They developed a real-time support model that can help in the trade-off between HPC cost and QoS. In [96], authors have addressed the interference among multiple NANs in urban SG scenario, aiming at maximizing the achievable capacity. The problem of optimal power allocation and channel selection for TVWS for smart metering data between SMs and DCU is discussed in [85]. The authors have used spectrum engineering advanced Monte Carlo simulation tool (SEAMCAT) for interference analysis and optimized the SM configurations to achieve optimal channel and power efficiency using a genetic algorithm. Authors in [60], have provided a review of smart utility network (SUN) and TVWS. Then in an effort to combine these two separate and independent technologies, a hybrid solution is proposed, merging their individual strengths. In addition to identifying the opportunities and challenges, several regulatory and technical recommendations are listed, to help in the realization of a practical solution.

Both optimal channel and power allocation are essential objectives for CRNs since they contribute to goals such as spectral efficiency, interference mitigation, and maximizing throughputs. A JPCA problem is formulated for heterogeneous cognitive networks in [101], using a game theoretic approach. Then an algorithm using Nash bargaining solution is proposed, whose computational complexity is further reduced heuristically, thereby increasing spectral efficiency but also guaranteeing fairness among SUs. In [102], a JPCA algorithm is proposed on presented that not only optimizes fairness among SUs but also considers the signal to interference ratio (SIR) to protect PUs. Authors in [103], investigated JPCA under fading channels in a CRNs to optimize the ergodic sum-rate of SUs under multiple power and interference constraints. A Joint opportunistic power and rate allocation algorithm based on the adaptive evolutionary algorithm is proposed in [104] to minimize the power and maximize the sum of source utilities with minimum power for wireless Ad hoc networks. An auction scheme for cooperation between PUs and SUs in CRNs is investigated in an exciting way in [105], where PUs relay data for SUs to earn revenue. SUs are given the option to select either purchase only PUs spectrum or both spectrum and power. Walrasian equilibrium is used to prove the convergence of the proposed algorithm and performance is verified using simulations. Considering constraints like SUs-PU interference and QoS for SUs, the problem is formulated as a maximization problem for CRNs in [106]. First, the available channels are dynamically allocated in a distributed manner meeting interference constraint, and then an iterative power allocation algorithm is applied considering both constraints. Another heuristic power control scheme named as joint with dynamic spectrum access (DSA) is presented in [107], that aims at maximizing spectral efficiency, throughput, and fairness among SUs. The optimization problem is formulated by cooperative game perspective and solved using the differential algorithm.

Fairness is a desirable trait in most of the CRNs applications where all SUs demands an equal share of resources. A cooperative CRN scenario where a hybrid access point (HAP) powers multiple SUs wirelessly is modelled in [108], where the SUs transmits in their respective timeslots to HAP. The objective is to prioritize SU transmission to enhance fairness among SUs by proposing three resource allocation schemes: equal time-allocation, min throughput maximization, and proportional time-allocation. It is shown that min throughput maximization outperforms the other two schemes in terms of fairness. A different resource allocation based on heuristic algorithms for controlling power and allocating spectrum in a dynamic way is proposed in [109], aiming at maximizing the overall fairness among SUs. The idea is to give priority to the nodes with less available holes thus increasing the throughput of the bottleneck user. The proposed algorithm is shown to achieve better fairness compared to traditional resource allocation schemes. A new scenario for fairness among SUs in CRSGCN is modelled in [69]. A cat swarm optimization (CSO) CA algorithm is proposed to solve the optimization problem for max-sum reward and fairness among SUs. The proposed algorithm is then compared with traditional heuristic approaches like GA and PSO to show that performs better for the problem under consideration. Authors in [90], have presented a ground-breaking work in the field of opportunistic spectrum access, latterly become CR. The problem is formulated using color graph theory as to maximize utilization fairness among users. A detailed analysis of different configurations is presented, and it is shown that proposed algorithms efficiently reduces interference and increases throughput. A novel and efficient decentralized spectrum access strategy for CRNs is presented in [93]. The proposed channel assignment scheme is based on spectrum usage history that provides stable network operation in addition to minimal interference, optimized throughput and improved fairness since SUs do not require to change their frequency regularly. A worthy contribution in the form of a comprehensive and detailed survey on resource allocation in underlay CR is presented in [110]. Authors have summed up state-of-the-art algorithms for resource allocation based on network architecture, objectives, management strategies and solving techniques. In addition to a review of some current problems, prospective future directions are also outlined. In our previous research work [111], we have modeled the same SG communication scenario in NAN as in this thesis, for solving the problem of CA only, using CSO for the cases of fairness-based and priority-based allocation. Unlike this research, only channel allocation problem is addressed using cat swarm optimization by considering user rewards on the basis of channel bandwidth rather than channel capacity, as in this thesis.

5.3 IEEE 802.11af: Fundamentals

In order to fully understand the network and communication model, we present fundamental concepts of IEEE 802.11af regarding network architecture and some key functionalities in open loop regulatory framework.

5.3.1 Network Architecture

The network architecture of IEEE 802.11af, also known as white-fi, comprises three primary entities: Geo-location database, Registered location secure server, and Geo-location database dependent entities. The brief functionality of these elements is described below.

i. **Geo-location Database (GDB)** is the primary element that stores list of vacant channels and operating parameters for white space devices (WSDs) administered and authorized by the regulatory authority.

ii. **Registered Location Secure Server (RLSS)** is a local database (DB) that stores operational parameters and geographic location for a small number of basic service sets (BSSs). The RLSS controls access points (APs), and stations (STAs) connected to it by providing them with operating parameters.

iii. **Geo-location Database Dependent (GDD) Entities** are rest of the two elements in the white-fi network that are controlled by authorized GDB to satisfy regulatory requirements. These entities are GDD-Enabling Station (ES) and GDD-Dependent Station (DS). The ***GDD-ESs*** are actually APs governed by GDB or RLSS controlling GDD-DS in its serving BSS. They ensure the updating and distribution of operational parameters received from GDB, represented as white space map (WSM). The ***GDD-DSs*** get their operational parameters from GDD-ES or RLSS in the form of WSM. The GDD-ES confirms the validity of WSM by transmitting a contact verification signal (CVS). This channel utilization and WSM sharing between two GDD entities are performed using Registered location query protocol (RLQP) [112]. An example of a TVWS network is shown in Figure 5-1.

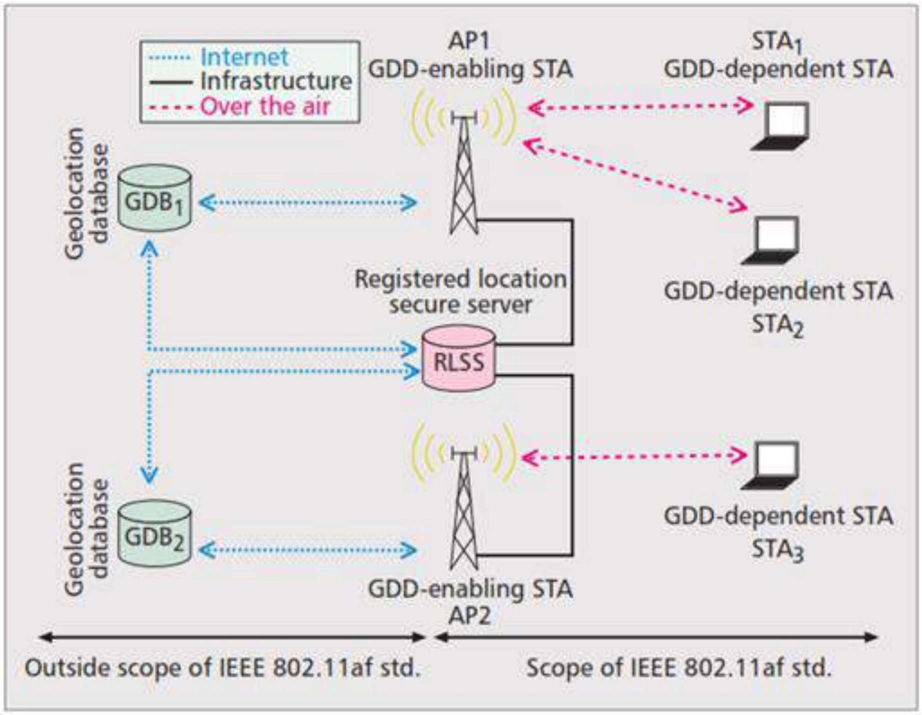

Figure 5-1: Example of IEEE 802.11af network entities communicating with each other

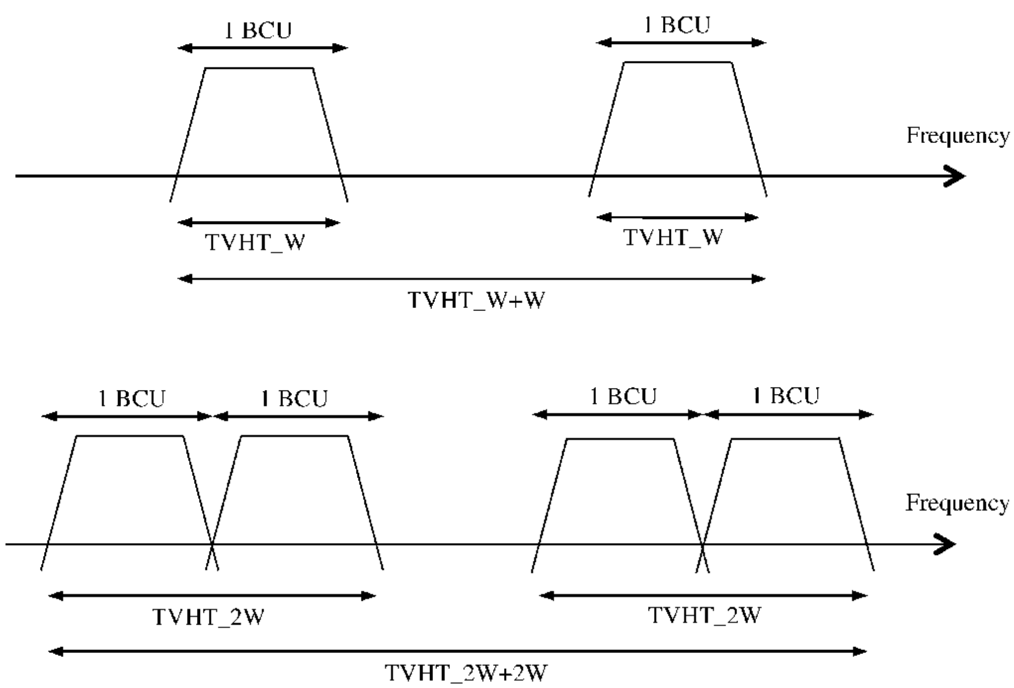

Figure 5-2: TVHT different bandwidth combinations

Table 5-1: Summary of PHY specifications for IEEE 802.11af

Parameter	***PHY Specifications***	
Bandwidth (MHz)	Mandatory: TVHT_W (Single BCU) 6, 7, and 8 depending upon the regulatory domain	Optional: i. TVHT_2W: Two contiguous BCUs (12, 14, or 16) ii. TVHT_W+ W: Two non-contiguous BCUs (6 + 6, 7 + 7, or 8 + 8) iii. TVHT_4W: Four contiguous BCUs (24, 28, or 32) iv. TVHT_2W + 2W: Two non-contiguous frequency segments, each composed of two BCUs (12 + 12, 14 + 14, or 16 + 16)
Coding	Mandatory: Convolutional	Optional: Space-Time block codes (STBC)
Modulation	OFDM	
Payload modulations	BPSK, QPSK, 16-QAM, 64-QAM, and 256-QAM	
Coverage	Indoor: up to 100 meters	Outdoor: More than 1 Km
Coding Rate	1/2, 2/3, 3/4, 5/6	
Guard interval (μs)	6 and 3 (6, 7 MHz) 4.5 and 2.25 (8 MHz)	
Max. data rate (Mbps)	26.7 (6,7 MHz) and 35.6 (8 MHz) using single spatial stream	

5.3.2 Physical Layer Specifications

The PHY layer specifications in IEEE 802.11af, defined as TV high throughput (TVHT), that supports channel bandwidth of basic channel units (BCU) of 6, 7, and 8 MHz according to regulations of the operating regions. Single channel bandwidth (TVHT_W), single spatial stream and binary convolutional coding are mandatory. Additionally, the different bandwidth combinations of BCUs (both contiguous or non-contiguous) are also possible as shown in Figure 5-2 [3]. Other supported features include MIMO transmissions with 4 times space-time block coding (STBC) and 4 times multi-user (MU) diversity. A summary of PHY specifications is presented in Table 5-1.

5.3.3 Regulatory framework

As mentioned previously, IEEE 802.11af or white-fi is driven by regulatory domain thus in order to implement TVWS regulations of different operating regions; it has to be flexible. The incumbent user service acting as primary user (PU) in TVWS band consists of digital terrestrial television (DTT) and program making & special event (PMSE) users such as wireless microphones etc. A wireless space device (WSD), also known as TV band device (TVBD), acts as a secondary user (SU). Working on the principle of interference avoidance, a WSD must have exact knowledge about operating parameters of licensed service, which it gets from centralized, secured and verified yet regulated GDB. Hence most of the regulatory authorities prefer this approach. Therefore, the regulatory implementation of GDB is indispensable to the proper working of IEEE 802.11af. Two main approaches that govern the regulatory implementation of GDB are open-loop GDD and closed-loop GDD [40].

i. **Open-loop GDD:** This implementation is regulated by Federal communications commission (FCC) in the US, within 54-698 MHz band using 6 MHz channels. The WSDs are operated in the flexible operating region since they have to follow a 48 hours channel schedule by GDB requiring conservative and fixed transmitted power. This kind of implementation is more suitable for rural areas.

ii. **Closed-loop GDD:** European telecommunication standards institute (ETSI) and United Kingdom regulator (OFCOM) follow this implementation model, within 470-790 MHz using 8 MHz channel. Unlike the open-loop model, WSDs are required to update parameters through GDB, every two hours. These operational parameters are only valid for a specific time period and only applicable to a specific location. Therefore, the transmitted power of WSDs in closed-loop is flexible.

5.4 System Model

In this section, the network model is explained for the better understanding of the SG scenario and communication between entities, followed by formulation of a mathematical model of the JCPA problem in CRSGCN.

5.4.1 Network Model

We consider a rural environment with moderate user density having fixed SUs in a slow-varying radio environment. Thus, the open loop model, described in the previous section, is applicable. The detailed network model is shown in Figure 5-3 & 5-4. The service area is divided into different clusters, termed as NAN cluster, having several smart meters (same as WSDs) with a data concentrator unit (DCU) at the center, as shown in Figure 5-4. DCU is connected to RLSS using 802.22 WRAN and long-term evolution (LTE). Each SM gets its operating parameters such as transmitted power and channel availability from DCU which is controlled by cognitive NAN gateway (CNGW) having RLSS. RLSS server CNGW is merely a base-station with RLSS server, having the name gateway since it is the central entity of NAN side that communicates with control centre (CC) through base-station of WAN, called cognitive WAN gateway (CWGW). RLSS is connected to GDB via the internet, which is the primary regulatory storage for all operating parameters for WSDs (SMs in our case). A single SM can only communicate with a single DCU or in other words; SM can only be registered in one cluster.

Communication inside the NAN cluster is shown in Figure 5-4. A single DCU can communicate with all the smart meters (SMs) within 1Km radius using hybrid spectrum management (HSM) using IEEE 802.11af and LTE. The LTE technology is used for time-critical data and IEEE 802.11af for delay-tolerant data. A DCU plays a similar role as an access point (AP) or GDD-enabling station (ES) and SMs as GDD-dependent station (DS), as described in section III. Both GDD-ES and GDD-DS are fixed in a slow varying radio environment where both location and duration of vacant channels remain same during channel assignment.

The number of WSDs (SMs) is higher than a number of holes since not every channel is available for all the SMs and there can be cognitive users (CUs) other than SMs. On the other hand, according to open loop regulatory model, the maximum effective isotropic radiated power (EIRP) for a fixed WSD/SM is 4W (36dBm) and 100mW (20dBm) for portables WSDs. It is desirable to keep transmitted power to a lower level and still able to reach the receiver for energy efficiency. Transmitted power of each SM affects SNR at DCU, directly related to user reward (explained in a later section) thus joint power and channel allocation (JPCA) is mandatory to avoid serious quality of service (QoS) constraints. Both PA and CA are implemented through DCU as it manages all SMs within a NAN cluster.

There are two interference constraints that are needed to be addressed for smooth operation within a NAN cluster. First one is interference between SUs (SMs) and PUs (DTT or PMSE) and the other is Inter-SU interference. To cater the first constraint, we adopt the interference avoidance approach where the channels occupied by PUs are never used by SUs, but only unused channels are available within a NAN cluster. Moreover, the channel adjacent to the one assigned to PUs, cannot be assigned to SUs. Similarly, each SM is assigned a unique channel, or in other words, none of the holes is reused within a NAN cluster thus evading any inter-SU interference. However, more than one channel can be allocated to an SM provided channel is available and not assigned to any other SM.

We assume that each SM is equipped with a directional antenna and the transmit power is kept to the minimum allowable level so as to reach the DCU at required threshold SNR level to not only increase the overall energy efficiency but also to reduce co-channel interference. Further, it can be assumed that DCUs of neighboring NAN clusters have an inter-cluster link to facilitate the smooth channel assignment, specifically for the SMs at boundary edges since a single SM can only be a registered in only one NAN cluster.

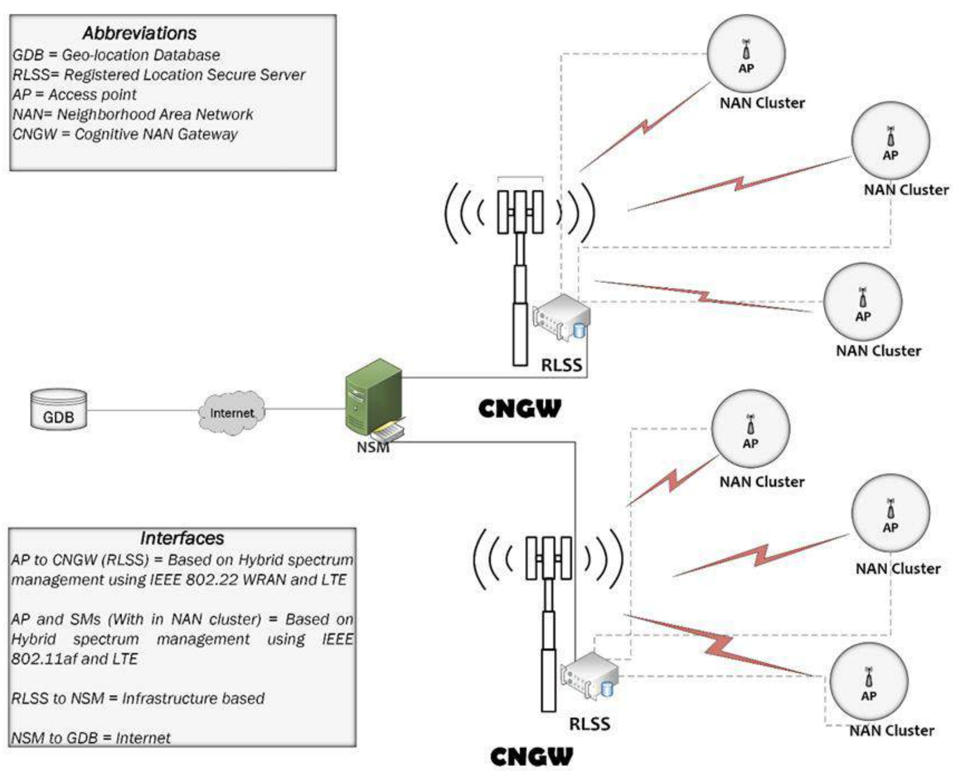

Figure 5-3: Network model for overall NAN communication in context of IEEE 802.11af network architecture

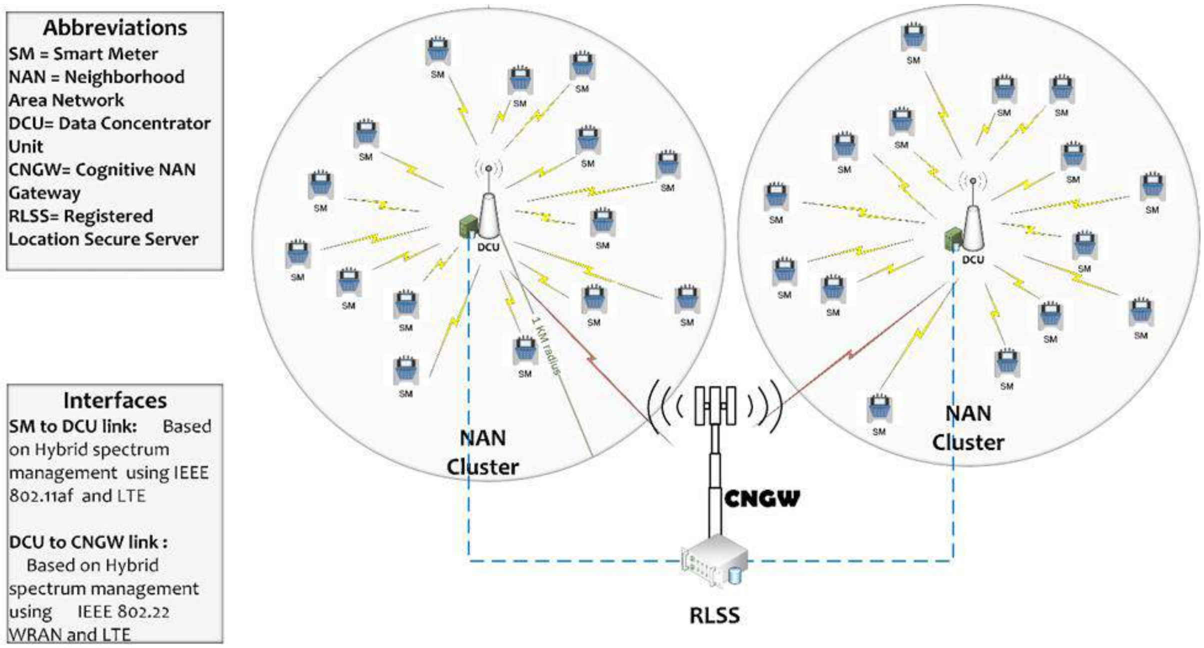

Figure 5-4: Network model showing communication inside the NAN cluster

5.4.2 Mathematical Model

Consider total S number of SMs in a service area, divided into total C disjunct clusters, each having a single DCU/AP at center as shown in Figure 5-4. Let ***S*** denote set of SMs in a service area, ***S*** = {1, 2... S}, ***C*** denotes set of disjunct clusters, ***C*** = {1, 2… C}. The clustering constraints C1 & C2 can be written as C1: $\cup_{i=1}^{C} C_i = \boldsymbol{S}$ and C2: $\cap_{i=1}^{C} C_i = \emptyset$. Let N represents a number of available holes, ***N*** = {1,2,3……N}, and there are K number of SMs (users) in a single cluster connected to a single DCU. Let d^k be the distance of k^{th} SM from AP, transmitting with a power p^k, then the respective signal to noise ratio (SNR) Γ^k, at AP is given by:

$$\Gamma^k = \frac{p^k \|g^k\|^2}{p_{noise}} \tag{12}$$

In (12), $p_{noise}$is the noise power, $\| g^k \|^2 = \| g_1 \|^2 . {}^{1}/_{L(d^k)}$ is the channel gain [113] between k[th] user and DCU including large scale path loss $L(d^k)$ shown in (13) and g_1 is account for Rician fading [114].

$$L(d^k) = \begin{cases} 20 \log\left(\frac{4\pi\lambda}{d^k}\right) = L(d_0) & for\ d^k \leq d_0 \\ L(d_0) + 10 * \varepsilon * \log\left(\frac{d^k}{d_0}\right) + X_g & for\ d^k > d_0 \end{cases} \tag{13}$$

Where, λ is the wavelength of transmission frequency, d_0 is reference distance, ε is path loss exponent and X_g is account for shadowing.

Next, we describe the following key components essential to our mathematical model:

Distance Matrix, $\mathcal{D}$: The distance matrix is defined as $\mathcal{D} = \{d^k\}_{Kx1}$, where $d_{min} \leq d^k \leq d_{max}$ is the distance of the k[th] user from DCU and d_{min} , d_{max} define the upper and lower limit. Each SM must be located within these boundary values.

Availability Matrix, $\mathcal{L}$: It is a binary matrix that defines the availability of a channel for each SM, in a single cluster. Mathematically, $\{l_n^k | \ l_n^k \ \in \{0,1\}\}_{K \times N}$, where l_n^k means that n[th] channel is available for k[th] SM or not. $l_n^k = 1$ means the channel is available, $l_n^k = 0$ means otherwise.

Reward Matrix, β: The reward matrix $\boldsymbol{\beta} = \{\beta_n^k\}_{K \times N}$ is the reward or weight associated with each channel available to the user at a particular location, where β_n^k is the weight of the n[th] channel available to k[th] SM. A channel is given a weight only if it is available for a particular user in other words $\beta_n^k = 0$ if $l_n^k = 0$.

Channel reward $\boldsymbol{\beta}$ is very important and crucial parameter for calculating overall user rewards or utilization of resources. In literature, $\boldsymbol{\beta}$ is often taken in terms of coverage area or bandwidth or throughput [90]. Channel reward for our problem is given by:

$$\beta_n^k = w_n^k log_2(1 + \eta^k) \tag{14}$$

Where, w_n^k is the bandwidth of nth channel assigned to kth user and η^k is the respective signal to noise ratio (SNR).

Channel Interference Matrix, $\mathcal{F}$: In order to avoid inter-SU interference, the necessary condition is that a single channel cannot be re-used with in a NAN cluster. To ensure this, we define a matrix $\mathcal{F} = \{ f_n^{k,m} | f_n^{k,m} \in \{1,0\} \}_{KxKxN}$, where $f_n^{k,m} = 1$ means that nth channel is assigned to kth and mth SM in a same cluster at the same time and $f_n^{k,m} = 0$ must be true for any channel assignment.

Channel assignment Matrix, $\mathcal{A}$: It is binary matrix $\mathcal{A} = \{ \alpha_n^k | \ \alpha_n^k \in \{0,1\}\}$ showing channel assignment for all the SMs in a cluster, subject to availability matrix, where $a_n^k = 1$ means that nth channel is assigned to kth SM, otherwise $\alpha_n^k = 0$. A conflict free allocation requires that α_n^k x $\alpha_m^k = 0, where\ m, k \in C\ and\ n \in$ **N.** It means that a channel may be available for more than one SM at a particular time but it can only be allocated to just one SM.

Max channel assignment, α_{max}: A single channel can only be assigned to single SM, but theoretically a SM can be assigned more than one channel, subject to interference and availability condition, thus better utilization of resources. The channel assigned to the kth

user is given by: $\rho^k = \sum \alpha^k$. This $\boldsymbol{\alpha_{max}}$ defines the upper limit to how much channels can be assigned to a single user.

User reward Matrix, $\mathcal{R}$: Reward of a k^th^ SM in a cluster is given by:

$$\gamma^k = \sum_{n=1}^{N} \alpha_n^k \beta_n^k \tag{15}$$

Where $a_n^k \in \{0,1\}$ and β_n^k is reward of k^{th} SM having allocated an n^{th} channel. Thus, matrix $\boldsymbol{\mathcal{R}}$ represents user rewards of every SM in the cluster i.e., $\boldsymbol{\mathcal{R}} = \{\gamma^k\}_{Kx1}$, where $\gamma^k$is the reward of k^{th} SM. It is clear from (4) that more assignments per user leads to greater reward, however, it may degrade fairness.

User History Matrix, $\mathcal{H}$: History matrix $\boldsymbol{\mathcal{H}} = \{h_t^k\}_{Kx1}$ is essential in implementing overall fairness. The term h_t^krepresents the reward history of the k^{th} SM after t^{th} round. Following equation is used to update user rewards and channel allocations per user:

$$h_t^k = \gamma_{t-1}^k + \gamma_t^k \tag{16}$$

Where, γ_t^k is the reward of k^{th} SM in t^{th} round and γ_{t-1}^k is the reward of k^{th} SM in the previous round.

Fairness: To measure fairness among users, one may calculate Jain's fairness index (J.F.I) or counting number of allocations per user, given by:

$$J.F.I = \frac{\left(\sum_{k=1}^{K} \sum_{n=1}^{N} \alpha_n^k \beta_n^k\right)^2}{K \sum_{k=1}^{K} \left(\sum_{n=1}^{N} \alpha_n^k \beta_n^k\right)^2} \tag{17}$$

$$\rho^k = \sum_{n=1}^{N} \alpha_n^k \tag{18}$$

Max-Sum Reward (MSR) is a measure of how the overall sum reward is increasing, given by:

$$U_{sum} = \sum_{k=1}^{K} \sum_{n=1}^{N} \alpha_n^k \, \beta_n^k \tag{19}$$

The primary objective of our problem under consideration is to optimize the power and channel allocation to maximize utilization factor.

$\boldsymbol{Utilization\, Factor}\ \boldsymbol{U}(\boldsymbol{\mathcal{R}})$:The utilization factor is the same as objective function, depending on the problem under consideration. We have two different objectives for two different allocation requirements, therefore we use different $\boldsymbol{U}(\boldsymbol{\mathcal{R}})$ to tackle each case (described in later a section). To maximize the utilization factor $\boldsymbol{U}(\boldsymbol{\mathcal{R}})$, we have to optimize the channel assignment $\boldsymbol{\mathcal{A}}$ meeting multiple constraints, which can be written as:

$$\boldsymbol{\mathcal{A}}^* = \max_{\boldsymbol{C},\boldsymbol{f},\boldsymbol{l},\boldsymbol{p},\boldsymbol{\Gamma},\boldsymbol{\beta},\boldsymbol{\rho}} \boldsymbol{U}(\boldsymbol{\mathcal{R}}) \tag{20}$$

$s.t$ C1: $\cup_{i=1}^{C} C_i = \mathbf{S}$, where $C_i \subseteq \mathbf{S}$

C2: $\cap_{i=1}^{C} C_i = \emptyset$, where $C_i \subseteq \mathbf{S}$

C3: $p_{min} \leq p^k \leq p_{max}$

C4: $\eta_{th}^{min} \geq \eta^k \geq \eta_{th}^{max}$

C5: $l_n^k \text{ x } l_n^p = 0, where\ p, k \in C\ and\ n \in \mathbf{N}$

C6: $f_{k,m}^n = 0, \forall\ k \neq m\ where\ k, m \in \mathbf{K}\ and\ n \in \mathbf{N}$

C7: $\rho^k \leq \alpha_{max}$

C8: $\beta_n^k \in [0,1]\ and\ \beta_n^k = 0\ if\ \alpha_n^k = 0$

C1 and C2 require that all clusters are disjunct and disjoint. C3 ensures that transmit power of each SM remains within allowable limits and C4 guarantees sufficient QoS by keeping SNR of each SMs signal in between allowable thresholds. C5 is the PU constraint that SUs can only be assigned channels left vacant by PUs and channels adjacent to the one used by PUs cannot be used by SMs. C6 dictates that no channel is re-used in a single round. C7 puts an upper limit of maximum allocations to any SM and C8 is intuitive.

5.5 Proposed Solution

In this section, we propose two algorithms, first for optimized power allocation in terms of energy efficiency and then channel allocation scheme based on the cuckoo search algorithm.

5.5.1 Power Allocation Algorithm (PAA)

Our objective in this proposed algorithm is to increase energy efficiency by allocating less transmit power but still fulfilling the QoS criteria of threshold SNR. All clusters are disjoint and disjunct and independent of each other; thus, our power allocation scheme is applicable in each cluster at the same time. We assume that the approximate distances of each SM from the central DCU are known. Then power is allocated in such a way that SM closest to the DCU transmits with the least power and the SM at the farthest location has the max transmitting power. This distance-wise power is shown in Figure 5-5.

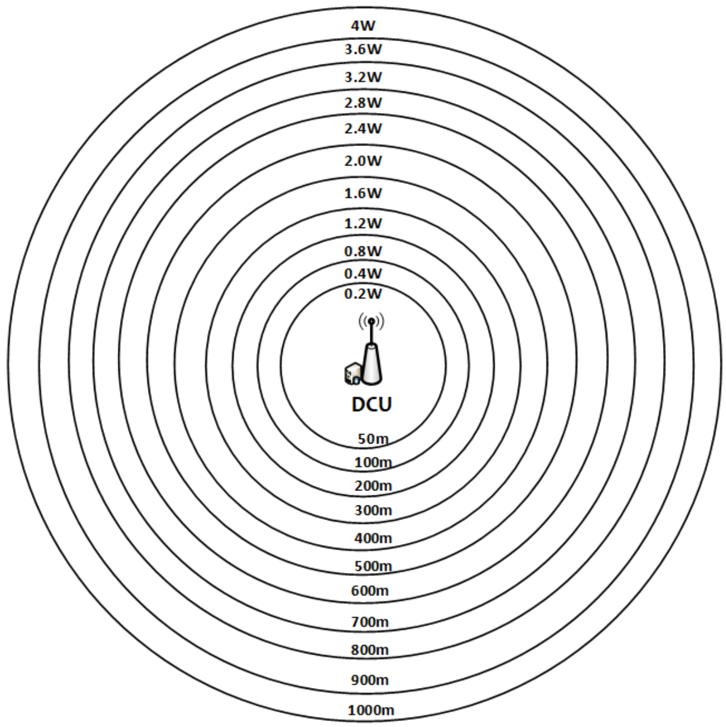

Figure 5-5: Power allocation on the basis of the distance from central DCU

SNR for each SMs transmission is calculated through (12) using this allocated power. Each SNR is then compared with upper and lower SNR thresholds. If the SNR is within the threshold range, then this power is approved otherwise a fractional power (Δp) is added/subtracted to allocated power until the desired SNR is achieved. The flow chart of the algorithm is presented in figure5-6, while this algorithm is detailed step by step in Figure 5-7. The transmitted power allocated to each SM is used to calculate respective SNR at the central DCU which is used in (14) for channel reward and finally contributes towards user reward in (15).

5.5.2 Channel Allocation Algorithm (CAA) based on Cuckoo Search Optimization

First, we brief the cuckoo search algorithm in this section, and then we discuss our proposed CA algorithm for a scenario under consideration.

Cuckoo Search Algorithm (CSA), inspired by the aggressive breeding behavior of Cuckoos, was first introduced by Xin-She and Suash Deb in 2009. It was first proposed as a numerical function optimization tool for continuous problems and performed better on some well-known benchmarks compared to GA and PSO [115]. Since then it has been applied in many domains such as engineering optimization, image processing, classification, scheduling and other real-world applications for both continuous and discrete problems.

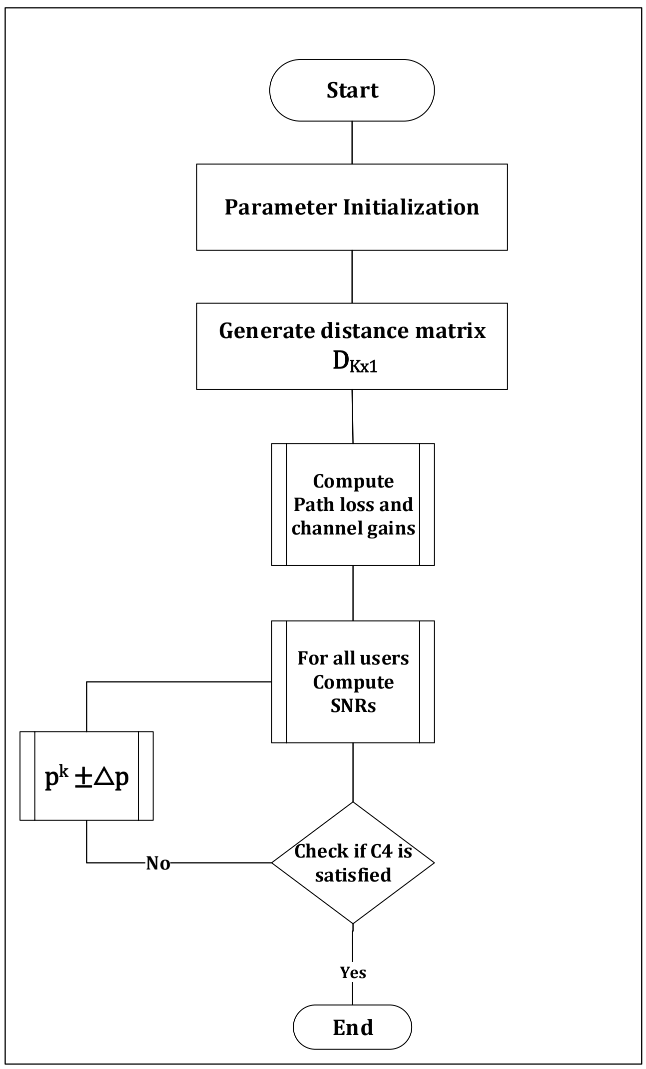

Figure 5-6: Flowchart for power allocation algorithm

Power Allocation Algorithm

1. **Step I: Initialization**
   - Set $p_{max}, p_{min}\ K, N, \eta_{th}^{min}, \eta_{th}^{max}, d_{min}, d_{max}, \Delta p, \lambda, w_n^k, p_{noise}, \varepsilon$ meeting C1, C2

2. **Step II:**
   - Randomly distribute *K* users in the area
   - Generate distance matrix $\boldsymbol{\mathcal{D}}$, containing distance $d_{min} \leq d^k \leq d_{max}$

3. **Step III:**

for all K
   - Calculate path loss using (14) and compute channel gains

end

4. **Step IV:**

for all K
   - Allocate Tx power to each user according to the distance from DCU, meeting constraint C3
   - Compute SNRs using (12)

end

5. **Step V:**

for all K
   - Compare SNRs with threshold values meeting constraint C4

$$\eta_{min}^{th} \geq \eta^k \geq \eta_{max}^{th}$$

If

C4 is satisfied, Terminate

else

Go to the next step

end

3. **Step VI:**
   - C4 is not satisfied, Add or subtract fractional power to allocated power for each user

$$p^k \pm \Delta p$$

   - Compute SNRs
   - Repeat Step V

Figure 5-7: Proposed power allocation algorithm based on SNR threshold

Cuckoos dump their own eggs in the nest of host cuckoos. Each egg in a nest represents a candidate solution whereas cuckoo's egg denotes a new solution. Each cuckoo can lay only one egg at one time, which is then dumped in a host nest chosen randomly. The best solution is identified by comparing the fitness/quality of each nest. In this way, CSA obtains an optimum solution by putting an average solution in a host nest. CSA is based on two operations: Levy flights and alien egg discovery, both are used to evolve better generations in terms of fitness/quality. Levy flights can be implemented (21) and alien egg discovery having discovery probability pr_a using (23) [116].

$$x_i^{t+1} = x_i^t + \delta \frac{\vartheta\mu}{|\nu|^{\frac{1}{\zeta}}} (x_i^t - x_{best}^t) \tag{21}$$

Where, $x_i^{t+1}$is the next solution, $x_i^t$is the previous solution, x_{best}^t is the fittest solution, δ is a constant, μ and ν are normally distributed pseudorandom numbers, ζ is also a constant between (1,2) and

$$\vartheta = \frac{\Gamma(1+\zeta) * \sin(^{\pi\zeta}/_2)}{\Gamma(\left(\frac{1+\zeta}{2}\right) * \zeta * 2^{\frac{\zeta-1}{2}})} \tag{22}$$

$$x_i^{t+1} = x_i^t + \psi\Omega \tag{23}$$

Where Γ is gamma function, ψ is updated coefficient and Ω is a binary coefficient given by:

$$\Omega = \begin{cases} 1 & if\ rand() < pr_a \\ 0 & otherwise \end{cases} \tag{24}$$

CSA can be implemented following the steps, described in Figure 5-8.

For our channel allocation scheme which is based on CSA (described above), we have to deal with two practical cases having conflicting requirements that lead to two different allocation modes.

Cuckoo Search Algorithm (CSA)
1. Step I: Initialization — Set $number\ of\ nest, eggs, pr_a, \zeta,\ \delta, \mu, \nu$ — Generate initial population **2. Step II: Check Fitness** — Check fitness of each egg — Identify global best **3. Step III: Levy flights** ***for all eggs*** — Update eggs using levy flight function in (21) — Check fitness of each updated egg ***end*** **4. Step IV: Survival of the fittest** ***for all eggs*** — Compare fitness of each updated egg with eggs of the initial population — Keep the best eggs and discard the remaining ***end*** **5. Step V: Alien egg discovery** ***for all eggs*** — Update all eggs using (23) — Calculate the fitness of each egg in the new generation ***end*** **6. Step VI: Termination Criteria** ***If*** — Required fitness is achieved, or number of iterations reached then terminate ***else*** — Go to step III

Figure 5-8: Cuckoo search algorithm

Case I: Fairness-based Allocation

First one is a daily routine scenario where all the SMs have scheduled transmission regarding DRM and AMI data towards central AP in a cluster. It necessitates that all the SMs should have an equal share of resources, e.g., same bandwidth or equal user rewards or equal channel allocations per user. Vacant channels are assigned to every SM in a cluster, meeting the constraints (C5-C8). Since the objective here is to maximize the fairness among SUs, only one channel is allocated per user. In other words, for case 1, we set α_{max} = 1. User rewards are computed according to the power allocated by our proposed algorithm (described previously in this section). The objective function in (20) for implementing fairness in user rewards (15) is given by:

$$\gamma_e = ||\gamma^{max} - \gamma^{min}||^2 \tag{25}$$

Where, γ_e is mean square error (MSE) between max. user reward, γ^{max} min user reward γ^{min}. Jain's fairness index (J.F.I) in (17) is another indicator that shows fairness among users. The values of user rewards, channel allocations to each user are stored in history matrix $\mathcal{H}$. Next, the holes are assigned in a way as to maximize the fairness among SMs, again meeting constraints (C5-C8). Values of γ^k, ρ^k are updated in history matrix $\mathcal{H}$ using (16) at the end of each round. After completing the total number of rounds T, all SMs should have almost the same user rewards and equal allocations per user.

Case II: Priority-based allocation

The second case is to implement a typical practical scenario when some user asks to remotely access the power/load profile of his/her home. Therefore, priority is required for such users, although for a comparatively shorter period of time. To deal with such a task, we allocate a significant share of resources to priority users K_{pr} and remaining resources are distributed evenly among standard users K_{sd}. The channel assignments, in each round, are performed meeting the constraints (C5-C8), same as case I. Instead of fairness, here the requirement is to maximize the user reward of priority users and the standard users should have an equal share of remaining resources. Therefore, a priority user can be assigned more than one channel subject to availability condition, provided that the channel is not reused. The objective function in (20), however, is given by:

$$Avg\ \gamma_{pr} = \frac{1}{K_{pr}} \sum_{i=1}^{K_{pr}} \gamma_{pr}^{i} \tag{26}$$

Where, γ_{pr} denotes a priority user reward. The average reward for standard users is given by:

$$Avg\ \gamma_{sd} = \frac{1}{K_{sd}} \sum_{i=1}^{K_{sd}} \gamma_{sd}^{i} \tag{27}$$

Flowchart of the proposed CA algorithm is shown in Figure 5-9 and algorithm is detailed in Figure 5-10.

5.6 Performance Evaluation

In this section, we evaluate the performance of our proposed joint power and channel allocation (JPCA) scheme via intensive computer simulations using MATLAB R2015a. First, we describe the simulation parameters and scenario, followed by analysis and discussion on results for both cases.

5.6.1 Simulation Configuration

The NAN communication scenario is already explained in Section 5.4.1. All clusters are independent of each other. Therefore, our JPCA scheme can be implemented in each cluster at the same time.

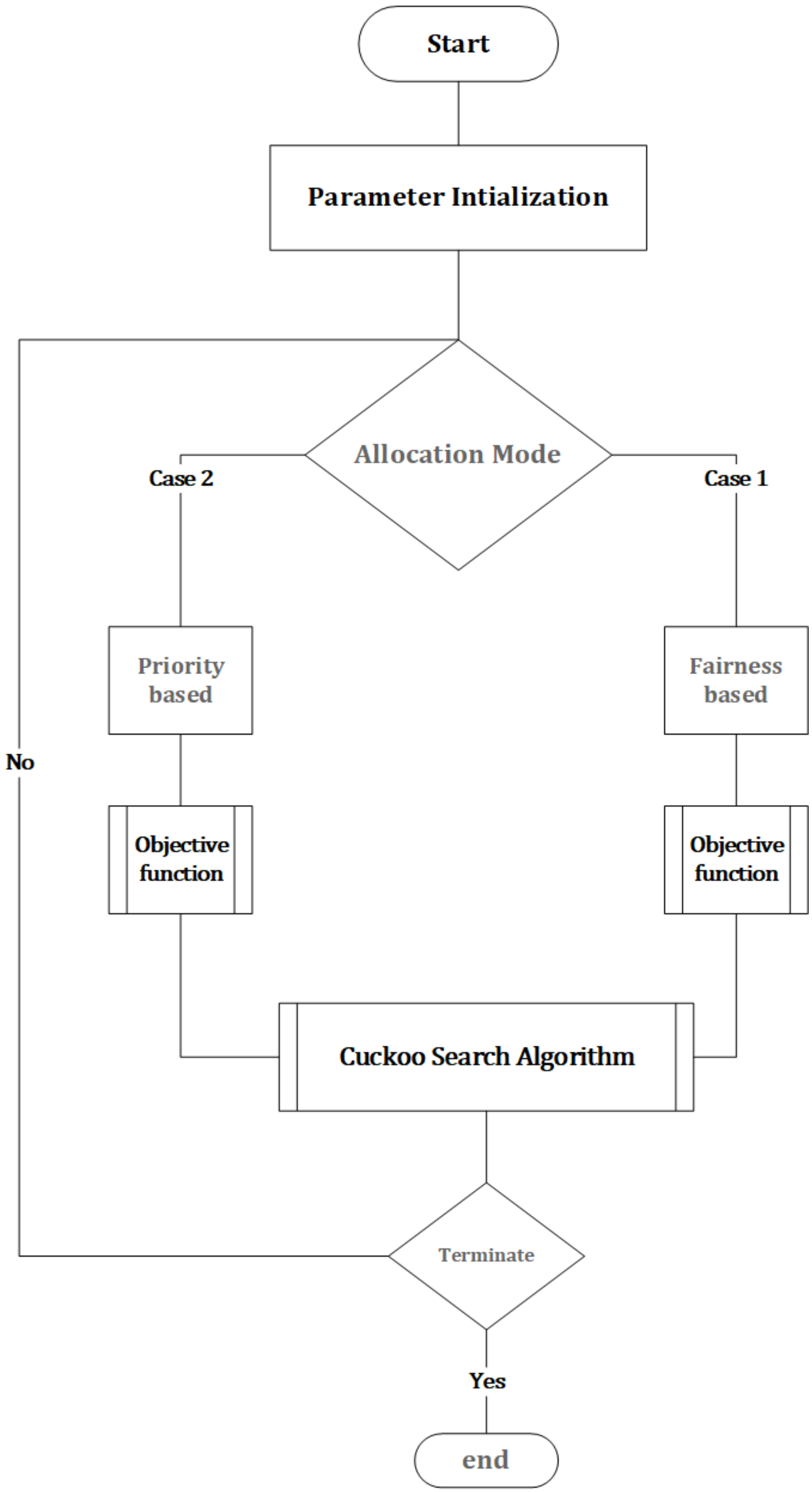

Figure 5-9: Flowchart for CSA based Channel allocation scheme

CSA based Channel Allocation scheme

1. **Step I: Initialization**

— Set $P, K, N, T, K_{pr}, K_{sd}$, α_{max} meeting C5

— Set CSA parameters $number\ of\ nest, number\ of\ eggs, pr_a, \zeta, \delta, \mu, \nu$

2. **Step II: Availability Matrix**

for all K

— Generate availability matrix $\mathcal{L}_{KxN}$ meeting PU constraint C5

end

3. **Step III: Mode Selection**

If

— Case I is selected, go to step IV

else

— Go to step VII

4. **Step IV: *Case1: Fairness-based allocation***

for all K

— Assign channels using CSA with (14) as objective function meeting constraints C6, C7, C8

— Compute γ^k, J.F.I, ρ^k, γ_e and store in history matrix $\mathcal{H}$

end

5. **Step V:**

for all K

— For the next round, depending upon availability, first allocate channels using CSA to the users with min rewards in previous round from history matrix $\mathcal{H}$ meeting constraints C6, C7, C8

— Compute γ^k J.F.I, ρ^k, γ_e

— Update history matrix $\mathcal{H}$ using (16)

end

6. **Step VI:**

— Repeat V till the completion of a total number of rounds T

7. **Step VII: *Case II: Priority-based allocation***

for all K

— Using CSA with objective function (27), assign 50% channels to K_{pr} and distribute the remaining channels fairly among K_{sd} meeting constraints C5, C6, C8

— Compute $Avg\ \gamma_{pr}, Avg\ \gamma_{sd}$, ρ^k and store in history matrix $\mathcal{H}$

end

8. **Step VIII:**

— Repeat VII until the termination criteria are reached

Figure 5-10: CSA based channel allocation scheme

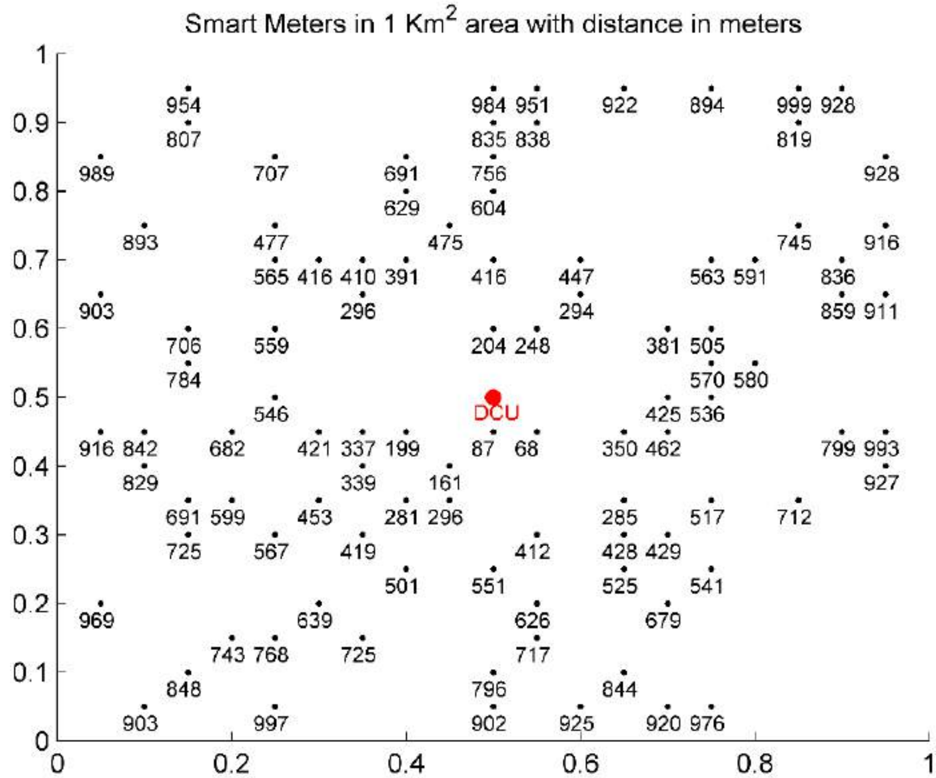

Figure 5-11: Random distribution of SMs around DCU along with their distances

We have only considered cognitive communications between SMs and single DCU for delay-tolerant data (such as AMI and DRM). PUs and SMs are randomly distributed in the 1x1 Km^2 area around a single DCU at the center. The distance of each SM from central DCU is calculated, as shown in Figure 5-11. We have adopted the open-loop regulatory paradigm thus all the parameter values regarding TVWS are in accordance with IEEE 802.11af PHY specifications [116], as described in Table 5-2. We assume that all WSDs (SMs) operate in fixed MODE. Therefore, the max effective isotropic radiated power (EIRP) cannot exceed 4W. It must be noted that for 22 TV channels (14-35) with 4 sub-channels per TV channel gives a maximum of 88 sub-channels. To avoid the confusion, we use channels instead of the word sub-channels. According to the open-loop regulatory paradigm, a TV channel adjacent to incumbent service cannot be utilized. Therefore, a single PU means that 12 channels (4 x 3) at max are occupied. Hence, for our simulations, we have considered 75, 60 and 50 channels for 1, 2 and 3 PUs respectively.

Table 5-2: TVWS parameters

Parameter	***Value***
TV channels	14 – 35
No. of sub-channels per TV channel	4
Total no. of sub-channels (max)	88
Frequency range	470 – 602 MHz
TV channel bandwidth	6 MHz
Sub-channel bandwidth	1.25 MHz
Max Tx Power (EIRP)	4 W
Coverage area	1 x1 Km^2

Table 5-3: Parameter values for Power and channel allocation algorithm

Parameter	***Value***
Max Tx power = $\boldsymbol{p_{max}}$	4 W
Min Tx. Power= $\boldsymbol{p_{min}}$	0.2 W
Fractional power increment = $\boldsymbol{\Delta p}$	0.1 W
Noise power =$\boldsymbol{p_{noise}}$	10^{-13}
Number of SMs, *K*	100, 200, 300
No. of PUs	3, 2, 1
No. of channels, *N*	50, 60, 75
No. of Priority users, $\boldsymbol{K}_{pr}$	0.02* *K*
Max channel assignment, $\boldsymbol{\alpha}_{max}$	$(0.5*N / K_{pr})$
Reference distance = $\boldsymbol{d_0 = d_{min}}$	50 m
Max range= $\boldsymbol{d_{max}}$	1000 m
Min. SNR threshold = $\boldsymbol{\eta_{th}^{min}}$	20dB
Max. SNR threshold = $\boldsymbol{\eta_{th}^{max}}$	40dB
Tx antenna gain = $\boldsymbol{G_{tx}}$	0 dB
Rx antenna gain = $\boldsymbol{G_{rx}}$	12 dB
Channel bandwidth = $\boldsymbol{w_n^k}$	1.25 MHz
Wavelength = $\boldsymbol{\lambda}$	0.6 m
Pathloss exponent = $\boldsymbol{\varepsilon}$	3.5
Shadowing constant = $\boldsymbol{X_g}$	10 dB

Table 5-4: Parameters for CSA

Parameter	***Value***
Number of nests	10
Number of eggs	10
Discovery probability= $\boldsymbol{pr_a}$	0.3
Constant= $\boldsymbol{\zeta}$	[1,2]
Constant= $\boldsymbol{\delta}$	Random distribution
Pseudorandom number = $\boldsymbol{\mu}$	Random distribution
Pseudorandom number = $\boldsymbol{\nu}$	Random distribution
No. of Rounds	50

For power allocation (PA) algorithm and channel allocation (CA), described in section 5.5.2, we use parameters in agreement with IEEE 802.11af standard [39][40], as shown in Table 5-3. A number of vacant channels (holes) available to the SMs have same bandwidth of 1.25 MHz. Transmit powers, allocated to each SMs through PAA, is used to compute user rewards for channel allocation (CA) algorithm. As described in previous Section 5.2, our proposed CSA based CA scheme has to tackle two cases. The parameter values used for CSA are described in Table 5-4.

5.6.2 Results and Analysis

In this sub-section, we analyze the performance of our proposed algorithms for each of the cases explained in the previous section.

5.6.2.1 Case I: Fairness-based allocation

The primary objective of power allocation among SMs is to have better power efficiency, but decreasing the transmit power of SMs, decreases the SNRs which reduces the user reward. Therefore, we compare three power allocation schemes to analyze the performance of our PAA in this trade-off situation. First one is fixed power allocation (FPA), which is mainly for the reference to tell how much power is saved. In FPA, all the SMs operate at max transmit power, i.e., 4W. The second scheme is distance-based power allocation (DPA), with only considering min SNR threshold. The last scheme is SNR-based power allocation scheme (SPA), described in section V-A, having both upper and lower SNR thresholds.

In case I, all SMs have same priority thus the idea is to allocate power to increase power efficiency and user reward. The comparative analysis of the three schemes is shown in Table 5-5, in terms of total power consumed in a NAN-cluster $P_{cluster}$, Average transmitted power allocated to a single SM P_{avg} and over all power consumption with in a NAN-cluster taking FPA as reference.

Table 5-5 summarizes the performance of three PA schemes in terms of power efficiency. FPA just provides a reference point to measure how much power is saved with DPA and SPA. It is observed that increasing the SMs in a cluster, the avg allocated power P_{avg} is also slightly increased thus increasing power consumption a touch. Although there is a significant reduction in overall power consumption in a cluster using DPA and SPA but in comparison, SPA saves ~9.5% more power than DPA.

Next, we evaluate our proposed channel allocation scheme based on CSA for the case I, where the idea is to assign vacant channels in a way as to maximize the fairness in terms of user reward.

Table 5-5: Case I: Comparison of power allocation Schemes

No. of SMs	***PA Scheme***	$P_{cluster}$ ***watts***	P_{avg} ***watts***	***Power consumption***
100	FPA	400	4	100 %
	DPA	263.2	2.63	65.8 %
	SPA	225.27	2.25	56.32 %
200	FPA	800	4	100 %
	DPA	537.8	2.69	67.22 %
	SPA	458.57	2.29	57.32 %
300	FPA	1200	4	100 %
	DPA	824.75	2.75	68.73 %
	SPA	713.4	2.38	59.45 %

Considering the SPA scheme for 200 SMs, we measure fairness on the basis of user rewards at the end of 50 rounds. As described earlier in section 5.2, the two fairness indicators J.F.I (using eq 17) and MSE, γ_e , of max and min user rewards (using eq 25) is plotted against 50 number of rounds in Figure 5-12 and 5-13 respectively. The number of allocations to each SM for 50 rounds is also shown in Figure 5-14.

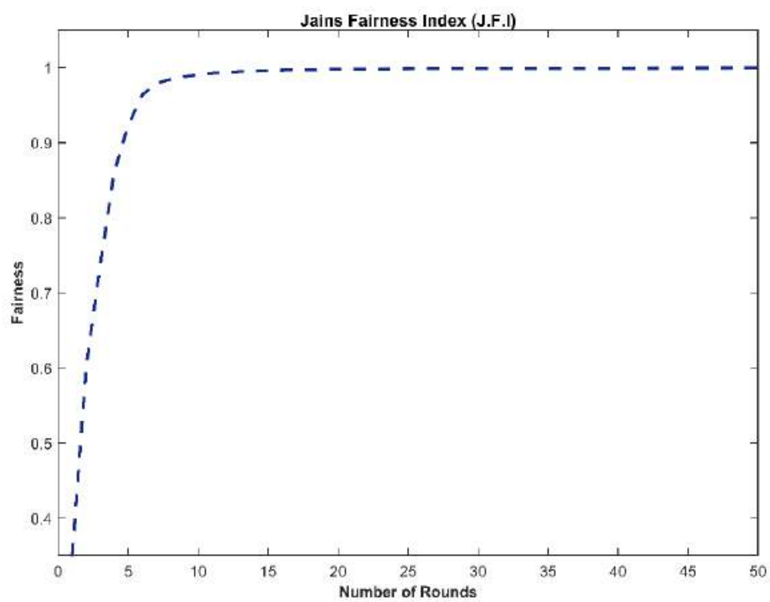

Figure 5-12: Case I: Plot of Jains Fairness Index (JFI) for 50 rounds

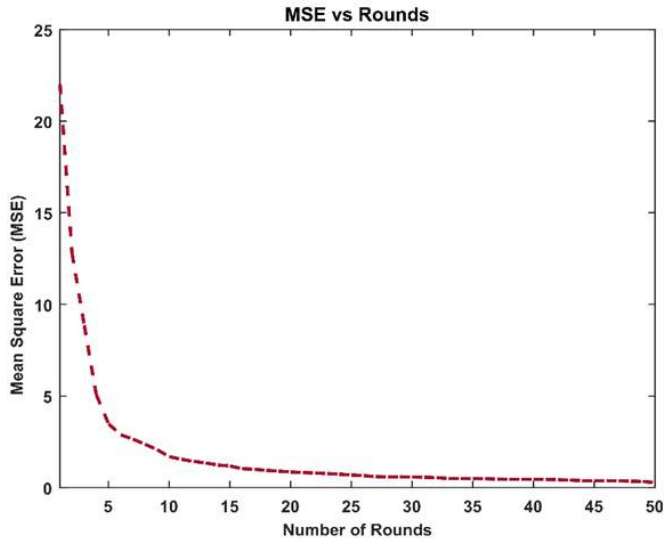

Figure 5-13: Case I: Plot of MSE Vs. Rounds

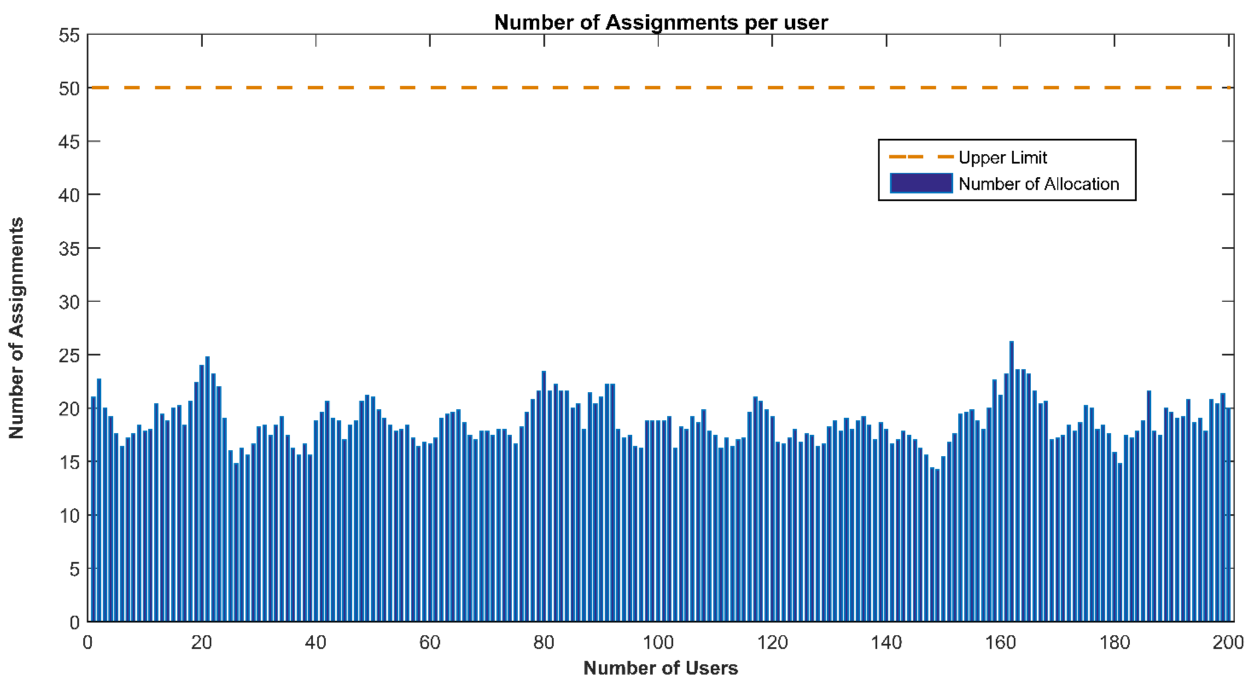

Figure 5-14: Case I: No. of allocation per user for 50 rounds for 200 SMs and 75 channels

As seen in figure 5-12 & 5-13, the fairness indicators are at a very low value at the start. The reason being that the user rewards differs a lot, mainly due to indifferent user SNRs that varies because of diverse locations of users (range: 50 m to 1000m). However, as soon as channels are allocated using our proposed algorithm, there is a drastic improvement in both fairness indicators J.F.I and MSE γ_e. The difference in user rewards starts at almost 22 which is considerably reduced with a number of rounds, even though the user rewards are quite different. This is achieved by controlling assignments per users in a way as to optimize the fairness as seen in Figure 5-14. For the case I, we allowed only one channel to be allocated to a single user per assignment, thus in this case, channels assignments and allocations are same. However, lots of variation is observed in channel assignment per user, as users with poor rewards are allocated comparatively more channels to match the users with better rewards, thus in turn optimizing fairness.

Table 5-6: Case I: Avg user rewards and Max-Sum rewards for different combinations of channels and users

No. of PUs	***No. of Channels***	***Number of SMs***					
		100		***200***		***300***	
		γ_{avg}	U_{sum}	γ_{avg}	U_{sum}	γ_{avg}	U_{sum}
3	50	5.49	594.87	2.68	604.92	1.81	632.39
2	60	6.60	689.27	3.21	698.69	2.17	741.45
1	75	8.29	869.42	4.01	876.34	2.72	918.22

Impact of varying number of channels and number of users.

Table 5-6 is presented to evaluate the impact of varying the different number of users and channel combinations on avg user rewards γ_{avg} and avg Max-Sum reward U_{sum}. It is observed that increasing users from 100 to 300, keeping the channels constant results in decreasing the γ_{avg}, whereas U_{sum} increases but not considerably, comparing to a three-fold increase in users since the available channels are very limited. Similarly, increasing the number of channels from 50 to 75, which has the same impact as reducing the number of PUs, shows a significant increase in both γ_{avg} and U_{sum}, since more resources are available for allocation in each round.

5.6.2.2 Case II: Priority-based allocation

For the same area 1x1 Km^2, the number of priority users $K_{pr}$are taken as 2% of total SMs K and remaining $(K - K_{pr})$ users are normal or standard users K_{sd}. Resources are shared such that 50% of total channels are equally divided among K_{pr} .i.e., the max channel assignment α_{max} is taken as (0.5*N/ K_{pr}) and rest of the channels are fairly distributed among K_{sd} using the same strategy as in case I.

In case 2, the idea is to allocate the power in such a way as to maximize the reward of priority users. Therefore, the priority users transmit with max power, i.e.,P_{pr}= 4W while normal users are allocated power using the same DPA or SPA. The comparative analysis of the three schemes is shown in Table 5-7. Similar observations, as in the case I, indicates the comparatively better behavior of SPA in terms of power saving at almost~9.5% power on average. The slightly increase in overall power consumption compared to the case I, is due to the priority users K_{pr}(2% of total users) are allocated maximum power of 4W.

Figure 5-15 shows the number of assignments for every user for a total of 50 rounds considering 200 users and 75 channels. It must be noted that a number of assignments means how many times a user has a channel assignment in 50 rounds. Typically, as standard users can have one channel per assignment, where priority users have more than one channel per assignment depending upon availability. It can be seen that all the four priority users have been assigned in all 50 rounds compared to standard users with less than 20 assignments at max.

Considering the same combination of 200 SMs ($K_{pr} = 4, K_{sd} = 196$) and 75 channels, the user rewards are plotted against the number of rounds in Figure 5-16. It can be seen that the user rewards of all the priority users are very high as compared to avg. user reward of standard users (shown by the black line). The variation in rewards of priority users is because of different SNRs of each priority user, mainly due to their indifferent location.

Table 5-7: Case II: Comparison of power allocation schemes

No. of SMs	***PA Scheme***	$P_{cluster}$ ***watts***	***Avg*** P_{sd} ***watts***	***Avg*** P_{pr} ***watts***	***Power consumption***
100	FPA	400	4	4	100 %
	DPA	265.1	2.65	4	66.28 %
	SPA	227.85	2.27	4	56.96 %
200	FPA	800	4	4	100 %
	DPA	545.4	2.73	4	68.17 %
	SPA	466.37	2.33	4	58.30 %
300	FPA	1200	4	4	100 %
	DPA	837.10	2.79	4	69.76 %
	SPA	726.2	2.42	4	60.52 %

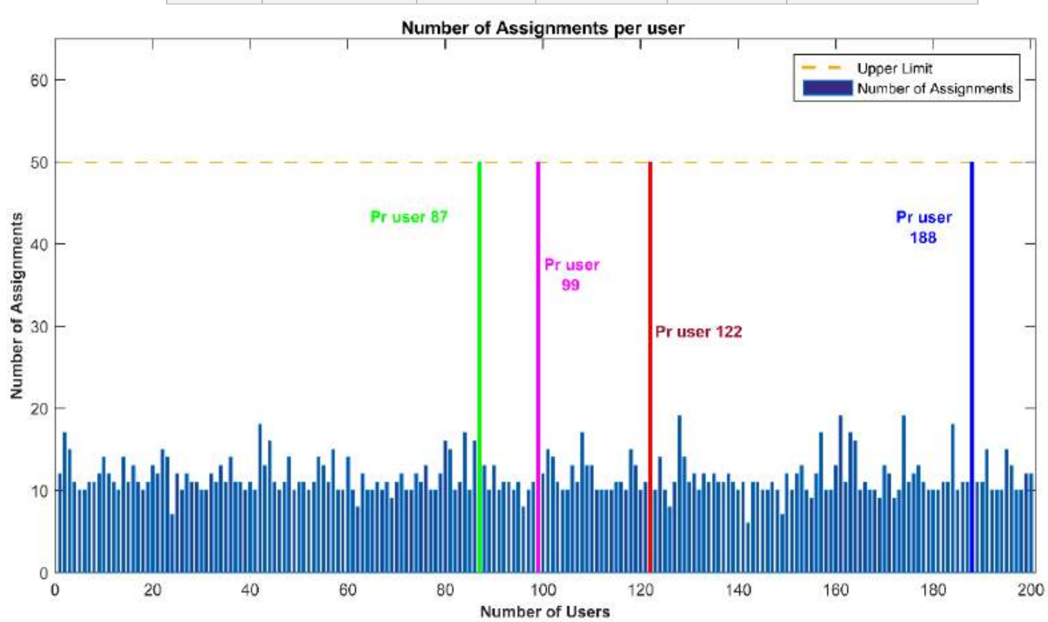

Figure 5-15: Case II: Number of Assignments per user for 200 SMs and 75 channels

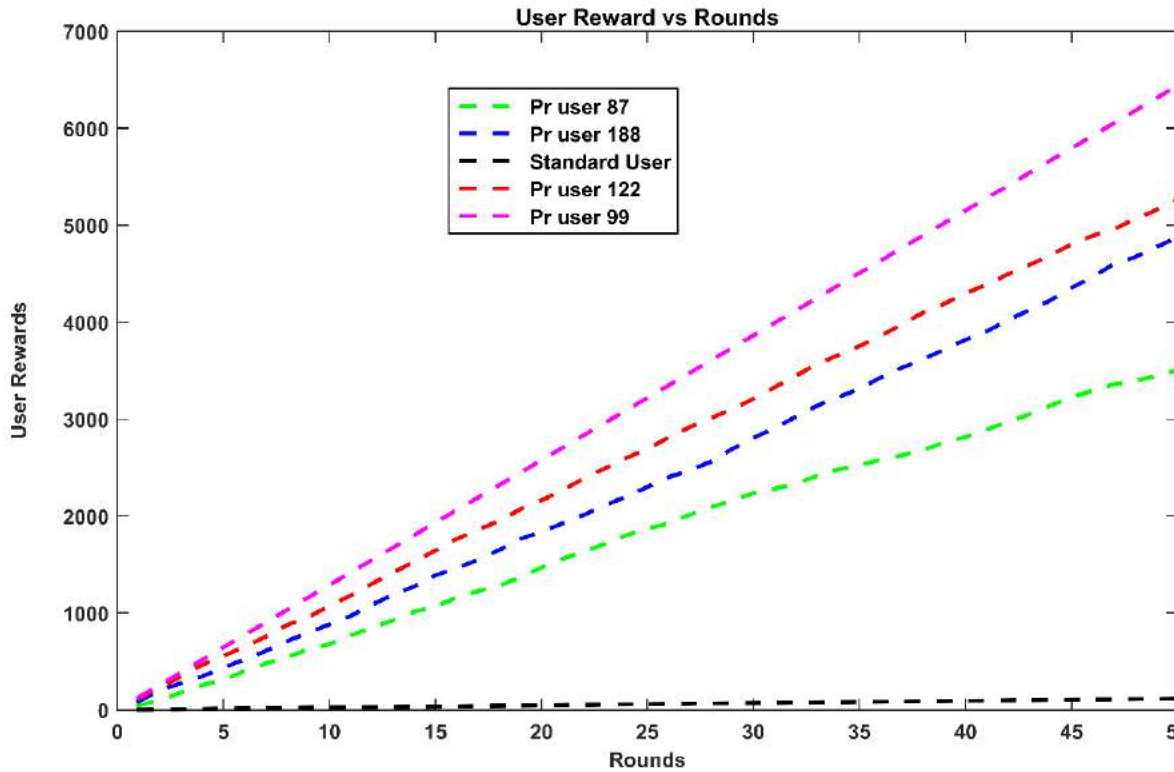

Figure 5-16: Case II: User Rewards vs. No. of Rounds

Table 5-8: Case II: Avg. User and Max-Sum rewards comparison for priority users and standard users for different combinations of users and channels

No. of PUs	***No. of Channels***	***Number of users***								
		$K_{sd} = 100, K_{pr} = 2$			$K_{sd} = 200, K_{pr} = 4$			$K_{sd} = 300, K_{pr} = 6$		
		$Avg\ \gamma_{pr}$	$Avg\ \gamma_{sd}$	U_{sum}	$Avg\ \gamma_{pr}$	$Avg\ \gamma_{sd}$	U_{sum}	$Avg\ \gamma_{pr}$	$Avg\ \gamma_{sd}$	U_{sum}
3	50	111.25	3.08	528.6	58.03	1.58	541.23	44.57	1.08	584.82
2	60	139.75	3.63	635.82	68.38	1.91	648.74	57.13	1.24	706.56
1	75	169.35	4.62	793.6	90.01	2.31	813.55	67.04	1.61	875.7

Table 5-9: Case II: Avg. User and Max-Sum rewards comparison for fixed priority and standard users for different combinations of α_{max} and channels.

No. of PUs	***No. of Channels***	***Number of users*** $K_{sd} = 200, K_{pr} = 4,$								
		$\alpha_{max} = 20\%$			$\alpha_{max} = 40\%$			$\alpha_{max} = 60\%$		
		$Avg\ \gamma_{pr}$	$Avg\ \gamma_{sd}$	U_{sum}	$Avg\ \gamma_{pr}$	$Avg\ \gamma_{sd}$	U_{sum}	$Avg\ \gamma_{pr}$	$Avg\ \gamma_{sd}$	U_{sum}
3	50	22.22	2.22	523.48	51.01	1.70	537.83	67.59	1.41	546.87
2	60	33.01	2.55	631.05	61.33	2.04	645.77	86.03	1.60	658.40
1	75	33.91	3.31	783.84	73.52	2.61	805.46	104.20	2.06	820.74

Impact of varying number of channels and number of users

To analyse the impact of varying different combination of users and channels, Table 5-8 compares avg. user reward for both priority users ($Avg\ \gamma_{pr}$) and standard users ($Avg\ \gamma_{sd}$) as well as avg Max-Sum reward (U_{sum})per round. For all combinations, the $Avg\ \gamma_{pr}$ >> $Avg\ \gamma_{sd}$, which was the main objective for case II. By increasing the number of users from 100 to 300, keeping the channels fixed, both $Avg\ \gamma_{pr}$ and $Avg\ \gamma_{sd}$ decreases since the same number of channels are to be shared among more users, whereas U_{sum} increases since more priority users having a larger share of resources contribute better in overall reward. On the other hand, keeping the users fixed and increasing the number of channels, results in increasing all three rewards $Avg\ \gamma_{pr}, Avg\ \gamma_{sd}$ and U_{sum} since more channels contributes towards more reward.

Impact of varying α_{max}

For case II, we reserved 50% of total channels for priority users, i.e., $\alpha_{max} = 0.5 * N/K_{pr}$. To analyze the impact of varying the value of α_{max}, we compare $Avg\ \gamma_{pr}, Avg\ \gamma_{sd}$ and U_{sum} by taking α_{max} as 20%, 40% and 60% of the total channels in Table 5-9. Increasing α_{max} from 20% to 60% for a different set of channels, shows a considerable increase in $Avg\ \gamma_{pr}$ and decrease in $Avg\ \gamma_{sd}$. Also, there is a slight improvement in U_{sum} keeping channels fixed but increasing the channels drastically increases U_{sum}. So, increasing the channel has a more pronounced Impact on user rewards compared to increase in α_{max}.

Comment of scalability

We have considered max up to 300 SMs/SUs for our SG scenario considering a rural environment, but this solution is scalable and practical to have SMs in the range of thousands. Since we are only considering delay-tolerant data, so time-scheduling can be used to provide service to these SUs, other than priority users. The priority users, on the other hand, can be serviced in the same fashion as in case II.

5.7 Summary

In this chapter, we explored the problem of JPCA in CRN applied to neighborhood area network (NAN) in SGCN. First, the detailed network model is presented to depict NAN communication in SG using open loop regulatory framework for TVWS with IEEE 802.11af standard. Then a mathematical model is formulated for the JPCA problem with practical limitations and constraints of SGCN, followed by proposed schemes of QoS based power allocation and channel allocation using cuckoo search optimization. Comparison of proposed power allocation algorithm (DPA and SPA) with baseline FPA for case I and case II, shown in Table 5-5 and Table 5-7, clearly proves the effectiveness of proposed power allocation scheme in terms of considerably reduced power consumption. Similarly, the results in the form of plots in Figures 5-12 to 5-14 (case I), Figures 5-15 to 5-16 (case II) and numerical Tables 5-6, 5-8 and 5-9 manifest that proposed channel allocation algorithms achieve the conflicting objectives of fairness-based and priority-based channel allocation using a heuristic approach, together with reducing power consumption for desired QoS. Moreover, the detailed analysis of the impact of varying number of standard users, priority users, channels and PUs shows the effectiveness of the proposed solution.

This multi-constraint JPCA problem formulation for TVWS with IEEE 802.11af standard using open loop regulatory framework is among the premier works in SG environment. We hope this research work will act as a foundation in the future for the research area under consideration.

Chapter 6

Conclusion and Future Work

The dissertation is summed up in this chapter by concluding remarks on the basis of key contributions of this research work. Some exciting and challenging research directions are also pointed out as a scope of further work in cognitive radio based smart grid communication network.

6.1 Conclusions

Although CR technology is apt to cater to the diverse latency requirements of SG application data, it brings its own problems that have to be addressed for practical implementation. Motivation of our research work presented in this thesis is to solve CR problems in CRSGCN. Among them first one was to know that where in SG, the CR can be used. For this, communication requirements for each segment (HAN, NAN and WAN) of SG, were explored and thus a CR based SGCN was proposed mentioning the communication links, where CR technology can be utilized Also, the most feasible wireless technologies based on IEEE standards are mentioned for each communication link.

Rest of the research work presented in this thesis is focused on resource allocation which is one of the key research areas in CRN domain. A NAN communication scenario in SG considering IEEE 802.11af (CR based) is considered and CA problem among SUs is formulated in a novel fashion for two practical scenarios of fairness-based and priority-based channel allocation. The problem is solved using CSO to meet multiple constraint and diverse objectives of two cases. For the same NAN scenario as mentioned earlier, a joint power and channel allocation (JPCA) is formulated considering open-loop regulatory paradigm for TVWS. An efficient power allocation scheme is introduced to allocate power to each SU in energy-efficient manner and then using these allocated powers the channel allocation based on Cuckoo search algorithm is proposed for fairness and priority-based allocations. The results presented in chapter 4 and 5 in the form of plots and tables manifests the effectiveness of our proposed solutions.

Following are the conclusions drawn from this thesis:

i. CR has its own set of key problems such as resource allocation, which needs to be modeled for CRSGCN considering the practical limitations and boundary values that may differ for different communication scenarios with in SG.

ii. Apparently, the key metrics for identifying where CR technology can be used in SG are data rate and range but the latency requirement for SG application is a major factor to determine whether CR technology can be applied or not. Thus, CR can only be used to carry delay-tolerant data such as AMI, firmware and configuration updates etc.

iii. Resource allocation in CRSGCN requires knowledge about network entities and the parameters necessary for communication such as transmitted power, range and reliability that is governed by the regulatory domain. So, modeling a practical scenario must consider these design constraints.

iv. It is indispensable to restrict number of simultaneous transmissions in any particular service area. Mainly, CR has a simple infrastructure without the requirement of providing seamless coverage to all users but only those SUs that have some latency-tolerant data to transmit.

v. DCU connects to SUs with in its range which depends on the communication technology used. Therefore, resource management techniques like clustering becomes imperative for larger service areas to manage transmissions to ease-off some spectrum congestion.

vi. Number of available channels are less than the SUs/SMs in any service area thus channel assignment is an optimization problem having multiple constraints.

vii. Extending channel allocation problem for CR to SGCN, needs to consider two everyday cases of fairness-based allocation and priority-based allocation.

viii. Extending power allocation problem for CR to SGCN for the objective of power efficiency also needs to consider two everyday cases of fairness-based allocation and priority-based allocation.

This thesis can be a starting point for new researchers in the field of CRSGCN. Also, our work on the channel and power allocation, from problem formulation to proposed solutions, are a cornerstone for future studies in CRSGCN. The CR technology will remain a major player in studies related to smart grid communications in coming years.

6.2 Future Directions for further research

Based on the research presented in this thesis, following are some of the critical challenges that can set some future directions in CRSGCN:

- In this thesis, we have modelled a NAN communication scenario, in which a number of SMs/HGWs are connected to a single DCU using CR based IEEE 802.11af standard. This research work can be extended by incorporating IEEE 802.22WRAN standard. It will give extended range (~30-100Km)[44], but facilitating increased number of users due to large service area would be a challenge. However, different design parameters with different regulatory models have to analyzed before formulating the problem.

- Practical implementation of any CR communication standards requires the involvement of regional regulatory authority. There are at least two regulatory frameworks that are used in literature, i.e., open-loop and closed-loop model[40]. We have used open-loop regulatory framework. It will be interesting to investigate that how closed-loop regulatory constraints will affect this particular communication scenario in SGCN.

- In this thesis, we have considered fixed topology under the slow-varying SG environment with interweave CR network adapting interference avoidance strategy. For future work, it will be an exciting but complex problem to deal with, if one considers a dynamic topology in underlay CR network. Evaluating, the impacts of fast-varying environment for channel availabilities and performance of SUs at boundaries of clusters will also be a challenging task.

- Sum-rate maximization using non-orthogonal multiple access (NOMA) is currently gaining a lot of attention for some practical scenarios. The trade-off situation for fairness and Max-sum reward, for our modeled scenario, can be improved subject to meet QoS constraints using NOMA [117].

- Clustering in CR based SGCN can be done considering many performance metrics such as cluster size, number of nodes, number of channels per cluster, network connectivity, energy efficiency, etc. For SG scenario, this alone is a broad topic requiring extensive time and research.

References

[1] Quang-Dung Ho, Yue Gao, and Tho Le-Ngoc, “Challenges and research opportunities in wireless communication networks for smart grid,” *IEEE Wirel. Commun.*, vol. 20, no. 3, pp. 89–95, 2013.

[2] M. Kuzlu, M. Pipattanasomporn, and S. Rahman, “Communication network requirements for major smart grid applications in HAN, NAN and WAN,” *Comput. Networks*, vol. 67, pp. 74–88, 2014.

[3] S. W. Oh, Y. Ma, E. Peh, and M.-H. Tao, *TV White Space*. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2016.

[4] E. U. Ogbodo, D. Dorrell, and A. M. Abu-Mahfouz, “Cognitive Radio Based Sensor Network in Smart Grid: Architectures, Applications and Communication Technologies,” *IEEE Access*, vol. 5, pp. 19084–19098, 2017.

[5] A. A. Khan, M. H. Rehmani, and M. Reisslein, “Cognitive radio for smart grids: Survey of architectures, spectrum sensing mechanisms, and networking protocols,” *IEEE Commun. Surv. Tutorials*, vol. 18, no. 1, pp. 860–898, 2016.

[6] J. Gao, Y. Xiao, J. Liu, W. Liang, and C. L. P. Chen, “A survey of communication/networking in Smart Grids,” *Futur. Gener. Comput. Syst.*, vol. 28, no. 2, pp. 391–404, 2012.

[7] M. Emmanuel and R. Rayudu, “Communication technologies for smart grid applications: A survey,” *J. Netw. Comput. Appl.*, vol. 74, pp. 133–148, 2016.

[8] N. S. Nafi, K. Ahmed, M. A. Gregory, and M. Datta, “A survey of smart grid

architectures, applications, benefits and standardization," *J. Netw. Comput. Appl.*, vol. 76, pp. 23–36, 2016.

[9] N. S. Nafi, K. Ahmed, M. A. Gregory, and M. Datta, "Software defined neighborhood area network for smart grid applications," *Futur. Gener. Comput. Syst.*, vol. 79, 2018.

[10] D. F. Ramírez and S. Céspedes, "Routing in Neighborhood Area Networks: A survey in the context of AMI communications," *J. Netw. Comput. Appl.*, vol. 55, pp. 68–80, 2015.

[11] R. Ma, H.-H. Chen, and W. Meng, "Dynamic Spectrum Sharing for the Coexistence of Smart Utility Networks and WLANs in Smart Grid Communications," *IEEE Netw.*, vol. 31, no. 1, pp. 88–96, Jan. 2017.

[12] Tigang Jiang, "On-Demand cognitive radio communications for Smart Grid," in *2016 IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 2016, pp. 243–248.

[13] H. Lin and W. Y. Shin, "Non-orthogonal random access in MIMO cognitive radio networks: Beamforming, power allocation, and opportunistic transmission," *PLoS One*, vol. 12, no. 1, 2017.

[14] A. Boustani, M. Jadliwala, H. M. Kwon, and N. Alamatsaz, "Optimal Resource Allocation in Cognitive Smart Grid Networks," *2015 12th Annu. IEEE Consum. Comun. Netw. Conf.*, pp. 499–506, 2015.

[15] S. Bu and F. R. Yu, "Dynamic energy-efficient resource allocation in cognitive

heterogeneous wireless networks with the smart grid," *Glob. Commun. Conf. (GLOBECOM), 2012 IEEE*, pp. 3032–3036, 2012.

[16] Z. Yang, R. Han, Y. Chen, and X. Wang, "Green-RPL: An Energy-Efficient Protocol for Cognitive Radio Enabled AMI Network in Smart Grid," *IEEE Access*, vol. 6, pp. 18335–18344, 2018.

[17] S. N. Islam, A. Mahmud, A. M. T. Oo, C. Yuen, and W. Tushar, "Interference management for cognitive radio enabled smart grid communication," in *2017 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 2017, vol. 6, pp. 1–6.

[18] M. N. Hindia, A. W. Reza, K. A. Noordin, and M. H. R. Chayon, "A Novel LTE Scheduling Algorithm for Green Technology in Smart Grid," *PLoS One*, vol. 10, no. 4, p. e0121901, Apr. 2015.

[19] IEEE Std 2030-2011, *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads*, no. September. 2011.

[20] R. Ma, H. H. Chen, Y. R. Huang, and W. Meng, "Smart grid communication: Its challenges and opportunities," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 36–46, 2013.

[21] a N. Interdisciplinary, *The Future of the Electric Grid*. 2011.

[22] E. Ancillotti, R. Bruno, and M. Conti, "The role of communication systems in smart grids: Architectures, technical solutions and research challenges," *Comput.*

Commun., vol. 36, no. 17–18, pp. 1665–1697, 2013.

[23] NIST, "Department of Energy Communications Requirements," 2010.

[24] M. Daoud and X. Fernando, "On the Communication Requirements for the Smart Grid," *Energy Power Eng.*, vol. 03, no. 01, pp. 53–60, 2011.

[25] IEEE Standard 1646-2004, *IEEE Standard Communication Delivery Time Performance Requirements for Electric Power Substation Automation*, no. February. 2005.

[26] W. Wang, Y. Xu, and M. Khanna, "A survey on the communication architectures in smart grid," *Comput. Networks*, vol. 55, no. 15, pp. 3604–3629, 2011.

[27] D. Niyato, P. Wang, Z. Han, and E. Hossain, "Impact of packet loss on power demand estimation and power supply cost in smart grid," *Wirel. Commun. Netw. Conf. (WCNC), 2011 IEEE*, pp. 2024–2029, 2011.

[28] Nist, N. S. Publication, and National Institute of Standards and Technology, "NIST Special Publication 1108 NIST Framework and Roadmap for Smart Grid Interoperability Standards," *Nist Spec. Publ.*, vol. 0, pp. 1–90, 2010.

[29] H. Khurana, M. Hadley, N. Lu, and D. A. Frincke, "Smart-grid security issues," *IEEE Secur. Priv.*, vol. 8, no. 1, pp. 81–85, 2010.

[30] A. Usman and S. H. Shami, "Evolution of communication technologies for smart grid applications," *Renew. Sustain. Energy Rev.*, vol. 19, pp. 191–199, 2013.

[31] J. Buysse, M. De Leenheer, B. Dhoedt, and C. Develder, "Providing resiliency for optical grids by exploiting relocation: A dimensioning study based on ILP,"

Comput. Commun., vol. 34, no. 12, pp. 1389–1398, 2011.

[32] "IEEE Standard for Testing and Performance for Optical Ground Wire (OPGW) for Use on Electric Utility Power Lines - Redline," *IEEE Std 1138-2009 (Revision IEEE Std 1138-1994) - Redline*, pp. 1–62, 2009.

[33] M. Maier, "Fiber-wireless sensor networks (Fi-WSNs) for smart grids," *Int. Conf. Transparent Opt. Networks*, 2011.

[34] L. Jianming, Z. Bingzhen, and Z. Zichao, "The smart grid multi-utility services platform based on power fiber to the home," *2011 IEEE Int. Conf. Cloud Comput. Intell. Syst.*, pp. 17–22, 2011.

[35] M. Erol-Kantarci and H. T. Mouftah, "Energy-Efficient Information and Communication Infrastructures in the Smart Grid: A Survey on Interactions and Open Issues," *IEEE Commun. Surv. Tutorials*, vol. 17, no. 1, pp. 179–197, 2015.

[36] P. P. Parikh, M. G. Kanabar, and T. S. Sidhu, "Opportunities and challenges of wireless communication technologies for smart grid applications," pp. 1–7, 2010.

[37] "IEEE Recommended Practice for Information technology-Telecommunications and information exchange between systems-Local and metropolitan area networks-Specific requirements Part 15.5: Mesh Topology Capability in Wireless Personal Area Networks (WPANs)," 2009.

[38] Z. S. Organization, "ZigBee Smart Energy Standard ZIGBEE SMART ENERGY," pp. 1–628, 2014.

[39] Jean-Jacques DeLisle, "What's the Difference Between IEEE 802.11af and

802.11ah?,” *Microwaves RF*, 2015.

[40] A. B. Flores, R. E. Guerra, E. W. Knightly, P. Ecclesine, and S. Pandey, “IEEE 802.11af: A standard for TV white space spectrum sharing,” *IEEE Commun. Mag.*, vol. 51, no. 10, pp. 92–100, 2013.

[41] IEEE, “IEEE 802 LAN/MAN Standards Committe 802.22 WG on WRANs,” vol. Jul., no. 802.22.1, 2010.

[42] A. Ghassemi, “Cognitive radio for smart grid communications,” *Smart Grid Commun. (SmartGridComm), 2010 First IEEE Int. Conf.*, pp. 297–302, 2010.

[43] S. Nagaraj and F. Rassam, “Cognitive Radio in TV White Space,” *2014 Natl. Wirel. Res. Collab. Symp.*, pp. 84–89, 2014.

[44] D. Lekomtcev and R. Maršálek, “Comparison of 802.11af and 802.22 standards - physical layer and cognitive functionality,” *ElektroRevue*, vol. 3, no. 2, pp. 12–18, 2012.

[45] C. Eklund, R. B. Marks, K. L. Stanwood, and S. Wang, “IEEE standard 802.16: a technical overview of the WirelessMAN/sup TM/ air interface for broadband wireless access,” *IEEE Commun. Mag.*, vol. 40, no. 6, pp. 98–107, 2002.

[46] “IEEE 802.16m-2011: Air Interface for Broadband Wireless Access Systems Amendment 3 : Advanced Air Interface,” vol. 2011, no. May, 2011.

[47] A. Mahmood, N. Javaid, and S. Razzaq, “A review of wireless communications for smart grid,” *Renew. Sustain. Energy Rev.*, vol. 41, pp. 248–260, 2015.

[48] Jeanette Wannstrom, “LTE-Advanced.” [Online]. Available:

http://www.3gpp.org/technologies/keywords-acronyms/97-lte-advanced.

[49] A. Patel, N. Aparicio, M. Tas, and J. Rosca, “Assessing communications technology options for smart grid applications,” *IEEE Int Smart Grid Commun.*, p. 6, 2011.

[50] V. C. Güngör *et al.*, “Smart grid technologies: Communication technologies and standards,” *IEEE Trans. Ind. Informatics*, vol. 7, no. 4, pp. 529–539, 2011.

[51] Y. Hu and V. O. K. Li, “Satellite-based internet: A tutorial,” *IEEE Commun. Mag.*, vol. 39, no. 3, pp. 154–162, 2001.

[52] A. M. Wyglinski, M. Nekovee, and Y. T. Hou, *Cognitive Radio Communications and Networks: Principles and Practice*. Elsevier, 2009.

[53] H. Wang, Y. Qian, and H. Sharif, “Multimedia communications over cognitive radio networks for smart grid applications,” *IEEE Wirel. Commun.*, vol. 20, no. August, pp. 125–132, 2013.

[54] Y. Zhang, R. Yu, M. Nekovee, Y. Liu, S. Xie, and S. Gjessing, “Cognitive machine-to-machine communications: Visions and potentials for the smart grid,” *IEEE Netw.*, vol. 26, no. 3, pp. 6–13, 2012.

[55] V. C. Gungor, “Cognitive Radio Networks for Smart Grid Applications: A Promising Technology to Overcome Spectrum Inefficiency,” *IEEE Veh. Technol. Mag.*, no. JUNE, pp. 41–46, 2012.

[56] J. Huang, H. Wang, Y. Qian, and C. Wang, “Priority-based traffic scheduling and utility optimization for cognitive radio communication infrastructure-based smart

grid," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 78–86, 2013.

[57] Sekchin Chang, K. Nagothu, B. Kelley, and M. M. Jamshidi, "A Beamforming Approach to Smart Grid Systems Based on Cloud Cognitive Radio," *IEEE Syst. J.*, vol. 8, no. 2, pp. 461–470, 2014.

[58] S. Bu and F. R. Yu, "Green Cognitive Mobile Networks With Small Cells for Multimedia Communications in the Smart Grid Environment," *IEEE Trans. Veh. Technol.*, vol. 63, no. 5, pp. 2115–2126, Jun. 2014.

[59] R. Yu, C. Zhang, X. Zhang, L. Zhou, and K. Yang, "Hybrid Spectrum Access in Cognitive-Radio-Based Smart-Grid Communications Systems," *IEEE Syst. J.*, vol. 8, no. 2, pp. 577–587, 2014.

[60] C. S. Sum, H. Harada, F. Kojima, Z. Lan, and R. Funada, "Smart utility networks in tv white space," *IEEE Commun. Mag.*, vol. 49, no. 7, pp. 132–139, 2011.

[61] IEEE Computer Society, "802.15.4-2011 - IEEE Standard for Local and metropolitan area networks--Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs)," vol. 2011, no. September, 2011.

[62] W. Meng, R. Ma, and H.-H. Chen, "Smart grid neighborhood area networks: a survey," *IEEE Netw.*, vol. 28, no. 1, pp. 24–32, 2014.

[63] "Spectrum Bridge." [Online]. Available: www.spectrumbridge.com.

[64] "Neul." [Online]. Available: www.neul.com.

[65] "British Telecomm." [Online]. Available: www.bt.com.

[66] GTM Research, “Trends in Utility Smart Grid Communications Management,” *Ericsson*, 2013.

[67] T. L. Marzetta, “Massive MIMO: An introduction,” *Bell Labs Tech. J.*, vol. 20, pp. 11–12, 2015.

[68] H. Miao, “A heuristic best-fit clustering approach for remote metering smart grid networks,” *APSCOM, IEEE*. 2015.

[69] et al. Alam, “Dynamic resource allocation for cognitive radio based smart grid communication networks,” *Int. J. Adv. Appl. Sci.*, vol. 4, no. 10, pp. 76–83, Oct. 2017.

[70] W. Huixin, M. Duo, and L. He, “Analysis and Simulation of the Dynamic Spectrum Allocation Based on Parallel Immune Optimization in Cognitive Wireless Networks,” *Sci. World J.*, vol. 2014, pp. 1–8, 2014.

[71] J. Elhachmi and Z. Guennoun, “Cognitive radio spectrum allocation using genetic algorithm,” *Eurasip J. Wirel. Commun. Netw.*, vol. 2016, no. 1, 2016.

[72] J. Elhachmi and Z. Guennoun, “Evolutionary Algorithm for Dynamic Spectrum Allocation in Cognitive Radio System,” *2016 4th IEEE Int. Colloq. Inf. Sci. Technol.*, pp. 702–706, 2016.

[73] et al. Latif, “Channel assignment using differential evolution algorithm in cognitive radio networks,” *Int. J. Adv. Appl. Sci.*, vol. 4, no. 8, pp. 160–166, Aug. 2017.

[74] E. Fadel *et al.*, “Spectrum-aware bio-inspired routing in cognitive radio sensor

networks for smart grid applications," *Comput. Commun.*, vol. 101, pp. 106–120, 2017.

[75] K. L. A. Yau, N. Ramli, W. Hashim, and H. Mohamad, "Clustering algorithms for Cognitive Radio networks: A survey," *J. Netw. Comput. Appl.*, vol. 45, pp. 79–95, 2014.

[76] D. Brettschneider, D. Hölker, P. Roer, and R. Tönjes, "Cluster-based distributed algorithm for energy management in smart grids," *Comput. Sci. - Res. Dev.*, 2014.

[77] O. Y. Al-Jarrah, Y. Al-Hammadi, P. D. Yoo, and S. Muhaidat, "Multi-Layered Clustering for Power Consumption Profiling in Smart Grids," *IEEE Access*, vol. 5, no. 00, pp. 18459–18468, 2017.

[78] Y. Lu, T. Zhang, and Z. Zeng, "Adaptive weighted fuzzy clustering algorithm for load profiling of smart grid customers," *2016 IEEE/CIC Int. Conf. Commun. China, ICCC 2016*, 2016.

[79] A. Maurya, A. S. Akyurek, B. Aksanli, and T. S. Rosing, "Time-series clustering for data analysis in Smart Grid," in *2016 IEEE International Conference on Smart Grid Communications (SmartGridComm)*, 2016, pp. 606–611.

[80] Xishuang Dong, Lijun Qian, and Lei Huang, "Short-term load forecasting in smart grid: A combined CNN and K-means clustering approach," in *2017 IEEE International Conference on Big Data and Smart Computing (BigComp)*, 2017, pp. 119–125.

[81] L. Vrbský, M. S. Da Silva, D. L. Cardoso, and C. R. L. Francês, "Clustering

techniques for data network planning in Smart Grids," *Proc. 2017 IEEE 14th Int. Conf. Networking, Sens. Control. ICNSC 2017*, pp. 7–12, 2017.

[82] W. He, K. Li, Q. Zhou, and S. Li, "A CR spectrum allocation algorithm in smart grid wireless sensor network," *Algorithms*, vol. 7, no. 4, pp. 510–522, 2014.

[83] S. Yang, J. Wang, Y. Han, and Q. Zhao, "Dynamic spectrum allocation algorithm based on fairness for smart grid communication networks," in *2016 35th Chinese Control Conference (CCC)*, 2016, pp. 6873–6877.

[84] H. Miao, G. Chen, and Z. Dong, "Enhanced evolutionary heuristic approaches for remote metering smart grid networks," *IET Networks*, vol. 5, no. 6, pp. 153–161, 2016.

[85] C. K. Huynh and W. C. Lee, "An efficient channel selection and power allocation scheme for TVWS based on interference analysis in smart metering infrastructure," *J. Commun. Networks*, vol. 18, no. 1, pp. 50–64, Feb. 2016.

[86] C. K. Huynh, T. M. N. Hoang, and W. C. Lee, "Interference avoidance for TVWS smart metering system by optimization assignment problem," *2015 7th Int. Conf. New Technol. Mobil. Secur. - Proc. NTMS 2015 Conf. Work.*, 2015.

[87] M. El Tanab and W. Hamouda, "Resource Allocation for Underlay Cognitive Radio Networks: A Survey," *IEEE Commun. Surv. Tutorials*, vol. 19, no. 2, pp. 1249–1276, 2017.

[88] J. Dai and S. Wang, "Clustering-Based Spectrum Sharing Strategy for Cognitive Radio Networks," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 1, pp. 228–237, 2017.

[89] H. Zhang, D. Jiang, F. Li, K. Liu, H. Song, and H. Dai, "Cluster-based resource allocation for spectrum-sharing femtocell networks," *IEEE Access*, vol. 4, pp. 8643–8656, 2016.

[90] C. Peng, H. Zheng, and B. Y. Zhao, "Utilization and fairness in spectrum assignment for opportunistic spectrum access," *Mob. Networks Appl.*, vol. 11, no. 4, pp. 555–576, 2006.

[91] H. M. Elsayed, M. M. Khairy, and R. M. Eletreby, "Optimal spectrum assignment for cognitive radio sensor networks under coverage constraint," *IET Commun.*, vol. 8, no. 18, pp. 3318–3325, 2014.

[92] Z. Tabakovic and M. Grgic, "Cognitive radio frequency assignment with interference weighting and categorization," *Eurasip J. Wirel. Commun. Netw.*, vol. 2016, no. 1, pp. 1–24, 2016.

[93] M. Hawa, D. I. Abu-Al-Nadi, O. M. K. Alsmadi, and I. F. Jafar, "On Using Spectrum History to Manage Opportunistic Access in Cognitive Radio Networks," *IEEE Access*, vol. 4, pp. 5293–5308, 2016.

[94] S.-C. Chu, P. Tsai, and J.-S. Pan, "Cat Swarm Optimization," *PRICAI 2006 Trends Artif. Intell. PRICAI 2006. Lect. Notes Comput. Sci. vol 4099*, pp. 854–858, 2006.

[95] A. Bouzidi and M. E. Riffi, "Cat swarm optimization to solve flow shop scheduling problem," *J. Theor. Appl. Inf. Technol.*, vol. 72, no. 2, 2015.

[96] A. S. Cacciapuoti, M. Caleffi, F. Marino, and L. Paura, "Mobile smart grids: Exploiting the TV white space in urban scenarios," *IEEE Access*, vol. 4, pp. 7199–

7211, 2016.

[97] H. Hu, D. Kaleshi, A. Doufexi, and L. Li, “Performance analysis of IEEE 802.11af standard based neighbourhood area network for smart grid applications,” *IEEE Veh. Technol. Conf.*, vol. 2015, 2015.

[98] N. Ul Hassan, C. Yuen, and M. Bershgal Atique, “Exploiting QoS flexibility for smart grid and IoT applications using TV white spaces,” *IEEE Int. Conf. Commun.*, 2017.

[99] O. S. Penaherrera, J. L. Delgado, L. F. Guerrero, and J. P. Inga, “TV White Spaces. A case study in Ecuador,” *Proc. 2017 IEEE Russ. Sect. Young Res. Electr. Electron. Eng. Conf. ElConRus 2017*, pp. 198–203, 2017.

[100] N. U. Hassan, W. Tushar, C. Yuen, S. G. Kerk, and S. W. Oh, “Guaranteeing QoS Using Unlicensed TV White Spaces for Smart Grid Applications,” *IEEE Wirel. Commun.*, vol. 24, no. 2, pp. 18–25, 2017.

[101] L. Xu, A. Nallanathan, J. Yang, and W. Liao, “Power and Bandwidth Allocation for Cognitive Heterogeneous Multi-Homing Networks,” *IEEE Trans. Commun.*, vol. 66, no. 1, pp. 394–403, 2018.

[102] Y. Lin and Q. Zhu, “Joint Power and Channel Allocation Based on Fair Sharing in Cognitive Radio System,” in *2009 5th International Conference on Wireless Communications, Networking and Mobile Computing*, 2009, no. 60772062, pp. 1–4.

[103] X. Gong, S. A. Vorobyov, and C. Tellambura, “Joint bandwidth and power

allocation in cognitive radio networks under fading channels," *2011 IEEE Int. Conf. Acoust. Speech Signal Process.*, pp. 2976–2979, 2011.

[104] S. Guo, C. Dang, and X. Liao, "Joint opportunistic power and rate allocation for wireless ad hoc networks: An adaptive particle swarm optimization approach," *J. Netw. Comput. Appl.*, vol. 34, no. 4, 2011.

[105] J. Zou, Q. Wu, H. Xiong, and C. W. Chen, "Dynamic Spectrum Access and Power Allocation for Cooperative Cognitive Radio Networks," *IEEE Trans. Signal Process.*, vol. 63, no. 21, pp. 5637–5649, Nov. 2015.

[106] G. I. Tsiropoulos, O. A. Dobre, M. H. Ahmed, and K. E. Baddour, "Joint channel assignment and power allocation in cognitive radio networks," *2014 IEEE Glob. Commun. Conf. GLOBECOM 2014*, pp. 876–881, 2014.

[107] Q. Song, Z. Ning, Y. Huang, L. Guo, and X. Lu, "Joint power control and spectrum access in cognitive radio networks," *J. Netw. Comput. Appl.*, vol. 41, no. 1, pp. 379–388, 2014.

[108] S. S. Kalamkar, J. P. Jeyaraj, A. Banerjee, and K. Rajawat, "Resource Allocation and Fairness in Wireless Powered Cooperative Cognitive Radio Networks," *IEEE Trans. Commun.*, vol. 64, no. 8, 2016.

[109] X. Pei, "A novel dynamic spectrum allocation and power control algorithm with fairness for multi-hop cognitive radio networks," in *2015 IEEE 5th International Conference on Electronics Information and Emergency Communication*, 2015, no. 61461006, pp. 440–443.

[110] M. El Tanab and W. Hamouda, "Resource Allocation for Underlay Cognitive Radio Networks: A Survey," *IEEE Commun. Surv. Tutorials*, vol. 19, no. 2, pp. 1249–1276, 2017.

[111] S. Alam, A. N. Malik, I. M. Qureshi, S. A. Ghauri, and M. Sarfraz, "Clustering-Based Channel Allocation Scheme for Neighborhood Area Network in a Cognitive Radio Based Smart Grid Communication," *IEEE Access*, vol. 6, no. c, pp. 25773–25784, 2018.

[112] IEEE Computer Society, *IEEE Standard for Information technology: Telecomm. and Information Exchange Between Systems Local and Metropolitan Area Networks - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 5: TVWS Operation*. 2014.

[113] Y. Liu, Z. Ding, M. Elkashlan, and J. Yuan, "Nonorthogonal Multiple Access in Large-Scale Underlay Cognitive Radio Networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 12, pp. 10152–10157, 2016.

[114] A. F. Molisch, L. J. Greenstein, and M. Shafi, "Propagation Issues for Cognitive Radio," *Proc. IEEE*, vol. 97, no. 5, pp. 787–804, May 2009.

[115] I. Fister, X. S. Yang, D. Fister, and I. Fister, "Cuckoo Search: A Brief Literature Review," *Stud. Comput. Intell.*, vol. 516, pp. 49–62, 2014.

[116] Y. Sun, "A New Cuckoo Search and Its Application of Spread Spectrum Radar Polly Phase Code Design," *Proc. - 2016 3rd Int. Conf. Inf. Sci. Control Eng. ICISCE 2016*, pp. 67–71, 2016.

[117] M. F. Sohail, C. Y. Leow, and S. Won, "Non-Orthogonal Multiple Access for Unmanned Aerial Vehicle Assisted Communication," *IEEE Access*, vol. 6, pp. 22716–22727, 2018.