APPLICATION OF COGNITIVE RADIO BASED SENSOR NETWORK IN SMART GRIDS FOR EFFICIENT, HOLISTIC MONITORING AND CONTROL

By

Ogbodo, Emmanuel Utochukwu

Discipline of Electrical/Electronic and Computer Engineering
UNIVERSITY OF KWAZULU-NATAL

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Supervisor: Professor David G. Dorrell
Co-supervisor: Dr. Adnan M. Abu-Mahfouz

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Abstract

This thesis is directed towards the application of cognitive radio based sensor network (CRSN) in smart grid (SG) for efficient, holistic monitoring and control. The work involves enabling of sensor network and wireless communication devices for spectra utilization via the capability of Dynamic Spectrum Access (DSA) of a cognitive radio (CR) as well as end to end communication access technology for unified monitoring and control in smart grids.

Smart Grid (SG) is a new power grid paradigm that can provide predictive information and recommendations to utilities, including their suppliers, and their customers on how best to manage power delivery and consumption. SG can greatly reduce air pollution from our surrounding by renewable power sources such as wind energy, solar plants and huge hydro stations. SG also reduces electricity blackouts and surges. Communication network is the foundation for modern SG. Implementing an improved communication solution will help in addressing the problems of the existing SG. Hence, this study proposed and implemented improved CRSN model which will help to ultimately evade the inherent problems of communication network in the SG such as: energy inefficiency, interference, spectrum inefficiencies, poor quality of service (QoS), latency and throughput.
To overcome these problems, the existing approach which is more predominant is the use of wireless sensor network (WSNs) for communication needs in SG. However, WSNs have low battery power, low computational complexity, low bandwidth support, and high latency or delay due to multihop transmission in existing WSN topology. Consequently, solving these problems by addressing energy efficiency, bandwidth or throughput, and latency have not been fully realized due to the limitations in the WSN and the existing network topology. Therefore, existing approach has not fully addressed the communication needs in SG.

SG can be fully realized by integrating communication network technologies infrastructures into the power grid. Cognitive Radio-based Sensor Network (CRSN) is considered a feasible solution to enhance various aspects of the electric power grid such as communication with end and remote devices in real-time manner for efficient monitoring and to realize maximum benefits of a smart grid system. CRSN in SG is aimed at addressing the problem of spectrum inefficiency and interference which wireless sensor network (WSN) could not.

However, numerous challenges for CRSNs are due to the harsh environmental wireless condition in a smart grid system. As a result, latency, throughput and reliability become critical issues. To overcome these challenges, lots of approaches can be adopted ranging from integration of CRSNs into SGs; proper implementation design model for SG; reliable communication access devices for SG; key immunity requirements for communication infrastructure in SG; up to communication network protocol optimization and so on.

To this end, this study utilized the National Institute of Standard (NIST) framework for SG interoperability in the design of unified communication network architecture including implementation model for guaranteed quality of service (QoS) of smart grid applications. This involves virtualized network in form of multi-homing comprising low power wide area network (LPWAN) devices such as LTE CAT1/LTE-M, and TV white space band device (TVBD). Simulation and analysis show that the performance of the developed modules architecture outperforms the legacy wireless systems in terms of latency, blocking probability, and throughput in SG harsh environmental condition.

In addition, the problem of multi correlation fading channels due to multi antenna channels of the sensor nodes in CRSN based SG has been addressed by the performance analysis of a moment generating function (MGF) based M-QAM error probability over Nakagami-q dual correlated fading channels with maximum ratio combiner (MRC) receiver technique which includes derivation and novel algorithmic approach. The results of the MATLAB simulation are provided as a guide for sensor node deployment in order to avoid the problem of multi correlation in CRSN based SGs.

SGs application requires reliable and efficient communication with low latency in timely manner as well as adequate topology of sensor nodes deployment for guaranteed QoS. Another important requirement is the need for an optimized protocol/algorithms for energy efficiency and cross layer spectrum aware made possible for opportunistic spectrum access in the CRSN nodes. Consequently, an optimized cross layer interaction of the physical and MAC layer protocols using various novel algorithms and techniques was developed. This includes a novel energy efficient distributed heterogeneous clustered spectrum aware (EDHC- SA) multichannel sensing signal model with novel algorithm called Equilateral triangulation algorithm for guaranteed network connectivity in CRSN based SG. The simulation results further obtained confirm that EDHC-SA CRSN model outperforms conventional ZigBee WSN in terms of bit error rate (BER), end-to-end delay (latency) and energy consumption. This no doubt validates the suitability of the developed model in SG.

Dedication

To God Almighty and my family.

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My gratitude goes to the number of friends who in one way or the other assisted in making this work a beneficial one.

Declaration 1 - Plagiarism

I, **Ogbodo, Emmanuel Utochukwu,** declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons 'data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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SIGNED: D Dorrell .... NAME Prof D. G. Dorrell DATE: 02/03/2020

As the candidate 's Co-supervisor, I agree to the submission of this thesis.

SIGNED: .... NAME: DR. ADNAN M. ABU-MAHFOUZ DATE: 02/03/2020 ....

Declaration 2 - Publications

The following are details of publications emanating from this research which include published papers, accepted, revised, under review, and submitted to accredited journals:

(1) **E. U. Ogbodo,** D. G. Dorrell and A. M. Abu-Mahfouz, “Cognitive Radio based Sensor Network in Smart Grid: Architectures, Applications and Communication Technologies," published in IEEE Access, vol. 5, no. 9, pp.19084-19098, Sep 2017. Impact factor, IF = 3.557

(2) **E. U. Ogbodo,** D. G. Dorrell and A. M. Abu-Mahfouz, “Performance analysis of correlated multi-channels in cognitive radio sensor network based smart grid," in IEEE Explore AFRICON 2017 Conference Proceeding, Cape Town, 18 Sep 2017, pp. 1599-1604.

(3) **E. U. Ogbodo,** D. G. Dorrell and A. M. Abu-Mahfouz, “Communication Access Technologies Performance Measurements and Improved CRSN Model for Smart Grid Communication," published in Transactions on Emerging Telecommunications and Technologies, June, 2019. Impact factor, IF = 1.6.

(4) **E. U. Ogbodo,** D. G. Dorrell and A. M. Abu-Mahfouz, “Improved Resource Allocation and Network Connectivity in CRSN Based Smart Grid for Efficient Grid Automation" in IEEE ICTAS (ICT and Society) 2019 Conference held on 6 - 8 March 2019 in Durban, South Africa.

(5) **E. U. Ogbodo,** D. G. Dorrell and A. M. Abu-Mahfouz, “Energy Efficient Distributed Heterogeneous Clustered Spectrum Aware Network Model for Guaranteed QoS in CRSN based Smart Grid," submitted to an accredited journal (revised) for publication.

(6) **E. U. Ogbodo,** D. G. Dorrell and A. M. Abu-Mahfouz, “Radio Resource Allocation improvements in CRSNs based Smart Grid: A Survey," submitted to an accredited journal (revised) for publication.

All the sections of the aforementioned publications are the original work of Mr. Emmanuel Ogbodo. Prof. David Dorrell and Dr. Adnan Abu-Mahfouz provided adequate guidance in various sections of the work which brings the research publications to fruition.

Lists of Acronyms/Symbols/Terms

Acronyms/Terms/Symbols	**Descriptions**
1xEV-DO	1 times radio transmission (Evolution-Data Optimized)
A	Required area of sensing coverage
AC	Available channels
ADSL	Asynchronous digital subscriber line
AMI	Automatic metering infrastructure
AWGN	Additive white Gaussian noise
BAN	Building area network
BE	Backoff exponent
BER	Bit error rate
BLE	Bluetooth low energy
BPL	Broadband over power line
BST	Base station transceiver
BTS	Base transceiver station
BU-CH	Back up cluster head
CAN	Commercial area network
CBC	This is the common backup channel and serves as channel for communication when the available channels are in use by the PU
CH	Cluster head
C_N	Number of cluster
Control Algorithm	Algorithm with mechanism for data/control signals
COV_{Pr}	probability of coverage
CR	Cognitive radio
CRAHNs	Cognitive radio ad-hoc networks
CRN	Cognitive radio network
CRSN	Cognitive Radio Sensor Network
CSMA/CA	Carrier sense multiple access and collision avoidance

Acronyms/Terms/Symbols	**Descriptions**
DA	Distribution automation
DER	Distributed Energy Resources
DES	Discrete event simulation
DHC	Distributed heterogeneous cluster
DL	Down link
DLL	Data link layer
DoS	Denial of service attack
DR	Demand response
DRM	Demand response management
DSA	Dynamic Spectrum Access
DSAC	Distributed spectrum aware clustering
DSL	Digital subscriber line
DSM	Demand-side management
DSSS	Direct Sequence Spread Spectrum
$E_{CONNECTED}$	CRSN nodes connection with available channel
E_{CBC}	CRSN nodes connection with CBC
EDD	Event driven data
EDD_{S_N}	Event driven data sensor nodes
EDHC-SA	Energy efficient distributed heterogeneous clustered spectrum-Aware
$E_{pldintra}$	Is the energy dissipation in the radio frequency (RF) amplifier within a C_N due to pathloss
$E_{mpdshinter}$	Is the energy dissipation in the RF amp in single hop inter C_N due to multipath fading
$E_{shadmhinter}$	Is the energy dissipation in the RF amp in multi hop inter C_N due to shadowing
EPS	Electric power system
ETA	Equilateral triangulation algorithm
FDD	Frequency division duplex
FDMA	Frequency division multiple access
FFD	Full function device
GMSK	Gaussian minimum-shift keying
GPRS	General packet radio service
GSM	Global system for mobile communication
GUI	Graphical user interface
HAN	Home Area Network
H-DSA	Hybrid dynamic spectrum access
HEMS	Home energy management system
HGC	Hybrid guard channel

Acronyms/Terms/Symbols	**Descriptions**
HGW	Home gate way
IAN	Industrial area network
IED	Intelligent electronic device
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ISM	Industrial scientific and medical
LOS	Line of sight
LPWAN	Low power wide area network
L	Length of the sensing area
LTE-CAT1	Long time evolution category 1
LTE-M	Long time evolution category M1
LV	Low voltage
MAC	Medium access control
MDMS	Meter data management system
MAN	Metropolitan area network
MATLAB	Matrix laboratory
MGF	Moment generating function
MQAM	M-ary quadrature amplitude modulation
MRC	Maximum ratio combiner
MSC	Mobile switching centre
NAN	Neighborhood area network
NC	Network coverage
NIST	National Institute of Standards and Technology
NETSIM	Network simulator
NIST	National Institute of Standards and Technology
NLOS	Non line of sight
OFDM	Orthogonal frequency division multiplexing
OpenWRT	Linux operating system for embedded system and devices
Optimal available channel	Available channels with guaranteed link
OSA	Opportunistic spectrum access
PHY	Physical layer
PLC	Power line communication
PMU	Phasor management unit
PS	Periodical sensing
PHY	Physical layer
Point p	This is any point within the area where the phenomenon to be sensed or covered is situated
PU	Primary user

Acronyms/Terms/Symbols	**Descriptions**
QoS	Quality of Service
RBAC	Role-based access control
RRA	Radio resource allocation
R_{min}	This is the minimum communication range
R_{max}	This is the maximum communication range
R_{ils}	S_i least sensing range
R_{ifs}	S_i farthest sensing range
R_{us}	The sensing range of S_u
RS	Random search
SBC	Single board computer
SCADA	Supervisory control and data acquisition
SCSN	Spectrum aware and cognitive sensor network
SG	Smart Grid
SIMO	Single-input-multiple-output
SINR	Signal-interference-noise-ratio
SNR	Signal-noise-ratio
SN	Sensor network
SO	Superframe structure Order
SS	Serial search
SU	Secondary user
SG	Smart Grid
S_i	RFD CRSN node
S_u	FFD CRSN node
S_N	The number of both RFD and FFD CRSN nodes that make a cluster or clusters
$S_{1,1}$, $S_{2,2}$....S_N	The number of both RFD and FFD CRSN nodes up to the last CRSN node in a cluster
S_{Ns}	Sensor nodes
SO	Superframe structure Order
SU	Secondary user
TCP	Transmission control protocol
TDD	Time driven data
TV	Television
TVBD	TV white space band device
TDD_{S_N}	Time driven data sensor nodes
TS	Total number of CRSN nodes required for full coverage in an area.
UDP	User datagram protocol
UE	User equipment

Acronyms/Terms/Symbols	**Descriptions**
UHF	Ultra high frequency
UL	Uplink
VR	Variator
VHF	Very high frequency
WAN	Wide area network
WAMR	Wireless automatic meter reading
WASA	Wide area situational awareness
WIFI	Wireless fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless local area network
WSN	Wireless Sensor Network
XML	eXtensible markup language

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Chapter 1

Introduction

1.1 Background

The Smart Grid (SG) is replacing traditional power grids and is intended to be the next generation of electric power system operation. SGs will integrate diversified renewable energy resources in addition to primarily supporting power systems. Control centers equipped with smart communication network infrastructures will utilize modern communication technologies in order to monitor and control remote smart electric devices in real time. Currently, traditional power grids use a top-down layer approach where the communication flow is only in one direction from the utility to the consumers. A SG has a bidirectional communication flow between utility and consumers.

By definition, according to Cisco, the SG is a data communications network integrated with the power grid that collects and analyzes data, captured in near real-time, about power transmission, distribution, and consumption [1]. Based on this data, SG technology then provides predictive information and recommendations to utilities, their suppliers, and their customers on how best to manage power delivery and consumption. Smart Grids can be fully realized by integrating communication network technologies infrastructures.

Integration of CRSNs which is a combination of CR and WSNs in Smart Grids enables power generation, transmission, distribution, utilities and customers to transfer, monitor, predict, control and manage energy usage effectively and in cost efficient manner. A Smart Grid CRSN can communicate with its end and remote devices in a real-time approach which can lead to efficient monitoring of the following Smart Grids applications: load management and control, wireless automatic meter reading (WAMR), fault diagnostic and detection, remote power line monitoring, and automated distribution. SG has enormous advantages which include:

- Financial benefit: Through smart metering, utilities can provide demand response programs, which are designed for customers or energy users in cutting back/adjusting power usage during peak/off-peak periods by reducing high demand periods on the grid. Hence, one can schedule the most energy-intensive activities for low-demand periods when paying less. Consequently, one is in control of electric usage/utilization, thereby saving money.

- Energy reliability: Smart meters enable utilities to provide more reliable power electricity service which decreases the number of power outages. Smart meters can automatically report the location of an outage before a person will ever have to notify their utility companies. This makes restoration faster and status notification to individuals very easy.

- Environmental friendly: SG can drastically reduce air pollution from our surrounding by renewable power sources such as wind energy, solar plants and mega hydro stations.

- SG meets increasing demand through Demand Response Management (DRM): with the advancement of technology and the use more electronic devices than ever, the demand for power continues to grow rapidly; DRM enables customers to make choices in order to reduce their energy consumption. It is imperative to the operations of electric utility in order to assess peak load management, for economic purpose and power distribution operations; the traditional grid will be unable to meet the challenges of the future.

- Reduces blackouts and surges: power surge can damage TVs, audio equipment, and computers and other electronic gadgets whenever it occurs. Smart grid applications smooth the flow of power, and when abnormalities do occur, they are immediately and easily dealt with. Also, the question of blackouts is greatly reduced or almost eliminated.

- It simplifies real-time troubleshooting: when there is fault in today 's electrical system or traditional grid, a utility worker must get to the location of the problem to collect data before solution can be provided. Smart grid change system events into real-time-retrievable digital information, so that problem solving can be executed immediately [2].

- Reduces high cost to energy producers: to meet up with spikes due to high energy consumption, traditional grid depends on the building and maintenance of expensive standby or redundant plants which is idle except during critical high demand periods. Smart grid allows bidirectional communication with customer equipment to reduce consumption during these peak periods, thereby lowering the need for costly standby power plants.

- Feasibility of renewable power: SG systems are needed in order to strategically manage the distributed and geographically located renewable power sources such as solar plants, wind energy farms, and hydro stations including micro-grids. SG will ensure that this energy sources are stored safely and distributed wherever and whenever they are needed.

The Cognitive Radio based Sensor Network (CRSN) is considered a feasible solution in enhancing various aspects of the electric power grid and in realizing a smart grid [3]. CRSN in SG is aimed at addressing the problems of spectrum inefficiency and interference which WSN would not. Hence, CRSN has numerous advantages than WSN and CRN as shown in Table 1.1, which emphasizes the comparative framework that characterizes WSN, CRSN, and CRN based on some features or metrics. However, numerous challenges in CRSNs are caused by the harsh environmental wireless condition in smart grids. As a result, latency, throughput and reliability become critical issues. To overcome these inherent challenges, lots of approaches can be proposed and adopted ranging from the integration of cognitive radio sensor capability into SG; consideration of key immunity requirements for communication infrastructure deployment in SG; proper implementation design model for SG; reliable communication network architecture in SG and to communication network protocol optimization and so on.

1.2 Statement of Research Problem, Research Questions, and Motivation

1.2.1 Research Problem Statement

CRSN is a component of communication network infrastructure. Hence, reliable communication systems are key in achieving the benefits of smart grids [4].There are challenges associated with communication network infrastructure in a smart grid system which, if not addressed, will lead to poor performances and power quality issues. These issues include: transmission losses, which invariably will lead to poor utilization and lack of full benefits or advantages of smart grid which have been highlighted. The problems shall be delved into in turns as this thesis proceeds. Firstly, the current WSN operates in the unlicensed frequency band, which is shared by many other wireless technologies such as IEEE 802.11a/b/g/n (WIFI devices) and other branded devices like microwave and others, thus leading to the problem of interference. Research has shown that the interference can degrade the performance of the WSN [5].

However, according to [6] CR technology has been proposed as the key technology for future wireless communication that exploits dynamic spectrum access strategies. [7]

Secondly, the existing WSN communication protocols and algorithm are not spectrum

Table 1.1: Comparative framework for WSN, CRSN, and CRN

Features/Metric	**WSN**	**CRSN**	**CRN**
Channel access	Fixed channel access	Multiple/dynamic	Multiple/dynamic
Organizing and Self-healing	Moderate	Very high	Very high
Interference avoidance	Low	High	High
Network topologies	Star, Cluster-tree, and Mesh	Star, Cluster, Hierarchical, Mobile Ad Hoc, Distributed Heterogeneous Clustered (DHC)	Star, Mesh, Hierarchical, Mobile Ad Hoc (MANET)
Communication Protocol stack	Physical, Data link, Network, and application layer	Physical, Data link, Network, Transport, and application layer	Physical, Data link, Network, Transport, and application layer
Data centricity and unification	Highly supported	Highly supported	Less supported
Energy conservation and harvesting	High	High	Medium
Efficient energy consumption	Low (More energy waste)	High (energy efficiently used)	High (energy efficiently used)
Application specific driven	Highly Supported	Highly supported	Less supported
scalability	Large scale (supports thousands of nodes)	Large scale (supports thousands of nodes)	Medium scale (supports hundreds of nodes)
Coverage range	Short range	Short to medium range	Long range
Environment sensing	Sense any target phenomenon	Sense any target phenomenon and radio properties	Sense mainly radio properties (spectrum channels, modulation, power control)
Computational complexity	Low	Medium	High

aware, hence there is a problem of integrating protocols/algorithm in the communication layers for DSA in CRSN in smart grid. Research in this area is still at infancy [7].

Thirdly, the wireless sensor node is a resource constraint device with limited energy and memory; this poses a challenge of energy efficiency issue and processing capability to operate effectively and efficiently in CRSN in smart grid. Another challenge is the lack of efficient energy harvesting mechanism to support the limited energy storage of a sensor.

Lastly, CRSN in smart grid has variant Quality of Service (QoS) requirement with respect to specific smart grid application; thus, there is a tradeoff between QoS support and energy efficiency. Hence QoS requirement of smart grid applications is an interesting research problem [4] to be solved.

1.2.2 Research Questions

The following research questions will systematically be addressed in the advancement of this thesis:
(1) How to design sensing and management techniques that can address the problem of interference vis-a-vis DSA in CRSN in smart grid?
(2) How to design and optimize algorithms/protocols that will support DSA capabilities in the communication layers of wireless sensors nodes in CRSN driven smart grid?
(3) How will the energy efficiency be used to increase the sensor node life?
(4) How to design a CRSN model that can address the issue of trade-offs between QoS requirement and energy efficiency in smart grid system?

1.2.3 Motivation

In order to realize the full benefits of SG, it is important to mitigate the associated challenges of communication network infrastructure solution in SG. This, has however necessitated this research interest in the application of CRSN in SG for holistic, efficient monitoring and control. Also, the research motivation includes the aspect of mechanism in addressing challenges in CRSN based SG.
Hence, the scope of this research is limited to smart communication infrastructure solution comprising cognitive radio sensor network in SG. The work involves design of communication network architecture and implementation model. It includes design, consideration and optimization of protocols/algorithms of CRSN for SGs. This study makes use of simulation testbed in MATLAB simulation environment including graphical user interface (GUI) simulations program.

1.3 Aim and Objectives

The aim of this research is to develop smart communication network infrastructure solutions which comprise the Cognitive Radio Wireless Sensor Networks (CRSNs) for holistic, efficient monitoring and control in smart grids. To address specific aspects related to this aim, then the following objectives have been identified:

(1) To design a CRSN based smart grid communication architecture and implementation model for guaranteed QoS of smart grid data delivery.

(2) To design an energy efficient and spectrum aware CRSN algorithms for guaranteed QoS of smart grid applications and data delivery.

(3) Consideration and optimization of protocols/algorithm in the physical layer of CRSN for smart grid for efficient delivery of smart grid sensed data

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(4) Consideration and optimization of protocols/algorithm for DSA in the Medium Access Control (MAC) layer for CRSN in smart grids.

1.4 Significance of the Research

The importance of this research includes the improvements of the following in the communication system domain of SG:
(1) Improved throughput
(2) Low end-to-end delay
(3) Low latency
(4) Improved link reliability
(5) Improved Quality of Service (QoS) guaranteed
(6) Energy efficient spectrum aware protocols

1.4.1 Overall Expectation of this Research

This research will invariably lead to the overall Smart Grid benefits with respect to the contribution of specific aspect of power grid utilization as elucidated:
(1) Improved Reliability and Performance- Indeed, there will be improved reliability and performance leading to the reduction of the cost of interruptions and power quality issues and reducing the tendency and consequences of widespread power outages. This will be achieved with the help of improved link reliability already highlighted.
(2) Efficiency- There will be reduction in the cost of production, transmission, distribution and consumption of electricity. This will be achieved with the help of improved throughput, and the QoS guaranteed; hence there will be no communication failure of smart grid application thereby eliminating unnecessary cost that would been incurred in the event of failure.
(3) Good Economics of Scale- The downward keeping of the prices of electricity vis- à-vis the reduction on the amount paid by consumers as compared to the conventional grid, and creation of new jobs through Distributed Energy Resources (DER) will definitely enhance

the economics of scale. The low-end-to-end delay will improve demand response (customer side management) application real-time monitoring.
(4) Green Environment- Actually, there will be improved environmental condition due to the reduction in emissions when compared to conventional grid. This involves the enabling of larger penetration of renewable energy and improving efficiency of generation, transmission, distribution and consumption. This will be achieved with the help renewable energy integration.
(5) Improved Safety- Obviously, the issues of injuries and loss of life from grid related activities will be drastically reduced due to the aid of efficient sensing and monitoring system. The QoS guaranteed will support efficient monitoring of all applications including safety operations and application.
(6) Improved Security- It will help in addressing the issues and consequences of Denial of Service (DoS) attacks and natural disasters. The QoS guaranteed will also support the efficient monitoring of security applications.
(7) Improved Spectra Efficiency- the design of spectrum sensing and management will help in achieving this as the study focuses on the development of communication network infrastructure solution in the context of Cognitive Radio based Sensor Network (CRSN) for smart grid improvement.

1.5 Thesis Contributions

The contributions of this research from each chapter together with the publication outcomes are described in the following subsections:

1.5.1 Cognitive Radio based Sensor Network in Smart Grid: Architectures, Applications and Communication Technologies

A reliable SG communication network architecture is required for transferring information which is needed by the SG applications, alongside the monitoring and control by the cognitive radio based sensor network (CRSN). Hence this section briefly describes chapter two of this thesis. The work investigates and explores the CRSN conceptual framework, and SG communication architecture with its applications; vis-a-vis the communication access technologies including implementation design with quality of service (QoS) support. Consequently, various research gaps such as implementation design model, utilization of LPWAN for CRSN based SG deployment and so on were highlighted. This includes discussion on the future direction for various aspects of the CRSN in SG. In addressing these research gaps, a smart unified communication solution to improve the efficiency of the SG and mitigate various associated challenges was introduced. Technical contributions of this work so described was published in IEEE ACCESS journal publication.

1.5.2 Radio Resource Allocation Improvement in CRSN based Smart Grid

This section gives brief description of chapter three. It reviews literature surrounding various aspects of radio resource allocation in CRSN based SG. CRSN is a new paradigm for modern SG which is totally different from the traditional power grid also different from the conventional SG that uses static resource allocation technique to allocate resources to sensor nodes and communication devices in the SG network.

Due to the challenges associated with competitive sensor nodes and communication devices in accessing and utilizing radio resources, the need for dynamic radio resource allocation has been envisioned as a promising solution in allocating radio resource to sensor nodes in CRSN based smart grid ecosystem (network). These challenges include: energy/power constraints, poor quality of service (QoS), interference, delay, spectrum efficiency issue, and excessive spectrum handoffs. Hence, optimization of resource allocation criteria such as energy efficiency, throughput maximization, QoS guarantee, fairness, priority, interference mitigation/avoidance, and so on will go a long way in addressing these problems of radio resource allocation in CRSN based SG.

Consequently, this work explores radio resource allocation in CRSN based SG. The overview, unique characteristics and functionalities of CRSN are highlighted. Also, the various resource allocation schemes vis-a-vis radio resource allocation architecture in a CRSN SG environment are presented. Finally, future research direction in contributing to knowledge such as energy efficiency and hybrid energy harvesting schemes for perpetual power supply to the battery power constraints sensor node have also been highlighted. Technical contributions of this work were published in IEEE ICTAS 2019 Conference Proceedings; as well as submitted as manuscript (revised) for an accredited journal publication.

1.5.3 Performance Analysis of Correlated Multi-Channels in Cognitive Radio Sensor Network based Smart Grid

This section provides brief description of chapter four of this thesis. It addresses the problem of radio resource allocation in multi correlated fading channels in CRSN based SG. Recently, CRSN has been introduced into Smart Grids (SG) in order to address the problems of spectrum inefficiency and interferences. CRSN has the capability of opportunistic spectrum access (OSA) to dynamically allocate radio resources to the sensor nodes. However, one of the CRSN challenges is the problem of multi correlation fading channels due to multi antenna channels of the sensor nodes as well as very close spacing of sensor nodes deployment in a SG environment. This correlation can lead to degradation of the signals as well as co-channels interference.

In addition, the signal-interference-noise-ratio (SINR), multipath fading, and shadowing peculiar to SG harsh environmental condition including interference from SG equipment also pose great challenges to CRSN based SG. All these problems have attracted research attentions; however, research regarding the problem of correlated signals in SG has not been considered.

Hence, this work addresses the problem of correlation in multi fading channels. Consequently, an MGF based performance analysis of M-QAM error probability over Nakagami-q dual correlated fading channels with maximum ratio combiner (MRC) receiver technique has been derived using analytical method of trapezoidal numerical integration. An algorithmic approach which is based on a proposed transformation technique has been introduced. The error probability performance analysis is then carried out in MATLAB simulation, the simulations result agrees with the analytical or theoretical result with overlapping curves. Finally, the produced results show that dual correlated channels degrade the signal performance. The technical contribution of this work has been published in Proceeding of the 2017 International Conference of IEEE AFRICON.

1.5.4 Performance Measurements of Communication Access Technologies and Improved CRSN Model for Smart Grid Communication

This section briefly describes chapter five of this thesis. It presents a novel communication architecture in CRSN based SG. Traditional power grid has unidirectional flows of power and information transfer which limits its capacity for scalability, efficiency and renewable energy integration. Smart Grid (SG) has been envisioned as a more intelligent power grid with bidirectional flows of power and information inter exchange. A reliable communication network is required in order to actualize some important SG features, such as renewable energy integration, distributed energy resources, scalability, self-healing and efficient holistic monitoring and control capability. However, this communication network needs to comply with critical requirements.

Cognitive Radio (CR) has been projected to address the problems common in the conventional wireless systems such as spectrum scarcity and interference. CR access greater range of spectra via dynamic spectrum access capability. Consequently, this work focuses on communication network architecture of a cognitive radio sensor network (CRSN) based SG. The work employs the National Institute of Standard framework for SG interoperability, virtualized network in form of multi-homing comprising low power wide area network (LPWAN) devices such as LTE CAT1/LTE-M, and TV white space band device (TVBD). Simulation analysis results show that the performance of the proposed modules architecture outperforms the legacy cellular such as CDMA 1x-EVDO and legacy Wi-Fi in terms of latency and throughput in SG harsh environmental condition. The technical contribution of work of this chapter has been published in Transactions on Emerging Telecommunications

Technologies Journal.

1.5.5 Energy Efficient Distributed Heterogeneous Clustered Spectrum Aware Network Model for Guaranteed QoS in CRSN based Smart Grid

This section briefly describes chapter six of this thesis. The development of modern electric power grid has triggered the need for enormous scale monitoring and communication in smart grids (SGs) for efficient grid automation. This has activated the era of cognitive radio sensor networks (CRSNs) integration in SGs development. CRSNs are the combination of cognitive radios (CRs) and wireless sensor networks (WSNs). It has the benefits of overcoming spectrum limitations and interference challenge.

The implementation of dense CRSNs based on specific topology in SGs is one of the critical issues for guaranteed quality of service (QoS) and a reliable message delivery transmission through the communication network. In this chapter, various topologies of ZigBee CRSNs were investigated while suitable topology with energy efficient spectrum aware algorithms of ZigBee CRSNs in SGs was proposed. The performance of the proposed ZigBee CRNSs topology with control algorithm were analyzed and compared with conventional ZigBee sensor network topology scenario for implementations in SG environments.

The QoS metrics used for evaluating the performance are end-to-end delay, bit error rate (BER) and energy consumption. The simulation results confirm that the proposed topology model with control algorithms is preferred in sensor network deployment in SGs based on reduced BER, end-to-end delay (Latency), and energy consumption. Owing to the fact that SGs application requires reliable and efficient communication with low latency in timely manner, the proposed topology with model is thus suitable for efficient grid automation in CRSNs based SGs. The technical contribution of work in this chapter has resulted in:
(1) Part of the work has been presented in IEEE ICTAS 2019 conference paper, and published in IEEE Explore.
(2) Submitted manuscript (revised) for an accredited journal publication.

1.6 Thesis Outline/Organization

Beyond the contribution of various chapters of this thesis as elucidated in section 1.5, the rest of the thesis is organized as follows: chapter 2 presents Cognitive Radio based Sensor Network in Smart Grid: Architectures, Applications and Communications Technologies which includes survey of related work within the context of CRSN paradigm in SG, and recommendation for adequate monitoring and control in SG system. Chapter 3 presents Radio Resource Allocation improvements in CRSNs based Smart Grid. It explores radio resource allocation in CRSN based SG. Various resource allocation schemes are presented. Also, performance analysis of a throughput radio resource was investigated in order to establish appropriate spectrum channel operation in CRSN SG implementation. Chapter 4 presents Performance Analysis of Correlated Multi-Channels in CRSNs based Smart Grid which includes a novel implementation of CRSN in SG under correlated channels conditions. While chapter 5 proposes a novel Communication Network Architecture in CRSNs Based Smart Grid which contains design of a CRSN based SG Implementation model for QoS guaranteed of smart grid applications. Chapter 6 proposes Energy Efficient Distributed Heterogeneous Clustered Spectrum Aware Network Model for Guaranteed QoS in CRSNs based Smart Grid. Various topologies of ZigBee CRSNs were investigated while suitable topology with energy efficient spectrum aware algorithms of ZigBee CRSNs in SGs was proposed. Finally, chapter 7 presents conclusion and relevant future works.

Chapter 2

CRSNs in Smart Grid: Architectures, Applications and Communication Technologies

2.1 Introduction

The CRSNs is envisioned as a strong driver in the development of modern power system SGs. This can address the spectrum limitation in the sensor nodes due to interference caused by other wireless devices operating on the same unlicensed frequency in the industrial, scientific and medical bands. These sensor nodes are used for monitoring and control purposes in various components of a SG, ranging from generation, transmission, and distribution, and down to the consumers, including monitoring of utility network assets. A reliable SG communication network architecture is required for transferring information which is needed by the SG applications, alongside the monitoring and control by the CRSNs. Hence, this chapter investigates and surveys the CRSN conceptual framework, and SG communication architecture with its applications; vis-à-vis the communication access technologies including implementation design with quality of service (QoS) support.

Smart Grids can be fully realized by integrating communication network technologies infrastructures. Integration of CRSNs which is the combination of CRs and WSNs in smart grids, enables power generation, transmission, distribution, utilities and end users to transfer, monitor, predict, control and manage energy usage effectively and in cost efficient manner. A Smart Grid CRSN can communicate with its end and remote devices in a real-time manner which can lead to efficient monitoring of the following smart grids applications: load management and control, wireless automatic meter reading (WAMR), fault diagnostic and detection, remote power line monitoring, and automated distribution. However, there are constraints in WSNs such as limitations of the battery supply life, processing capability, operating frequency and memory. Because of these, researchers are seeking ways to increase the lifetime of this resource-constrained wireless sensor node. The question of resource constraints have been highlighted in [8]–[11]. In addition, SG applications require a guaranteed quality of service (QoS) as part of its network parameters. Hence, it is challenging to meet QoS requirements in a SG due to the varying characteristics of the network parameters [12]. [13].

In addition, distributed renewable energy generators(DGs) in a SG can have an adverse impact on a power system causing imbalance in the power system if appropriate stability and and control are not considered [14]. This imbalance between the DGs and the area load demand usually leads to mismatches in frequency and scheduled power interchanges. Based on this, frequency regulation of source-grid-load systems is an essential consideration in CRSN SG. Hence, Wen et al. [15] proposed a compound control strategy for frequency regulation of source-grid-load systems whereby power source, the grids and loads are all participating in the process. Similarly, Fu et al. [16] proposed an approximate model for frequency dynamic process so as to address the problem of distributed frequency regulation in SG. In general, there is a need to design an effective monitoring and control system with control strategy for frequency regulation to efficiently delivers SG sensed data in a reliable and timely manner.

Numerous works have been reported in the literature and this study presents a survey that focuses jointly on the CRSN and SG. Only very few studies jointly cover CRSNs and DGs and the application of a CRSN into a SG. Bhatti [17] presented a review on possible design opportunities with cognitive radio ad-hoc networks (CRAHNs) and cross-layer considerations for implementing viable CRSN routing solutions. A survey article was presented in [18], and in this work a comprehensive survey of the physical architecture of a CRSN, including cognitive capability and the spectrum sensing method was conducted. In [19], a survey was carried out on the recent advances in radio resource allocation in CRSNs. This survey indicated that radio resource allocation schemes in CRSNs can be classified into three main categories: centralized, cluster based, and distributed.

[20] presented a survey paper on CRSNs; in this work, current scenario protocols are examined together with the prerequisites for a CRSN. These can mutually eliminate the difficulties that are encountered in the CRSN scenario. In [5], a survey entitled “CRSN: Applications, Challenges and Research Trends" was presented. This describes the advantages of cognitive radio wireless sensor networks including the differences between ad hoc cognitive radio networks, wireless sensor networks, and CRSN networks and the potential application areas of CRSN. Challenges and research trends in CRSN are also presented. [21] presented an overview article on the design principles,potential advantages, application areas, and network architectures of CRSNs. Existing communication protocols and algorithms devised for CRSNs were discussed.

Another survey on CRSNs was presented in [22]. It puts forward a high-level review on how cognitive radio primarily forms dynamic spectrum access support for emerging applications such as SGs, public safety and broadband cellular, and medical applications. Despite the benefits that cognitive radio would bring, some challenges are yet to be resolved. Surveys on SGs that do not involve CRSNs include the work presented by Kuzlu et al.[23]; they presented information about the different communication network requirements for a range of SG applications, cutting across those used in a home area network (HAN), neighborhood area network (NAN) and wide-area network (WAN). Emmanuel and Rayudu [24] conducted a review on the integral components of the emerging grid and communication infrastructures enabling the six SG applications. In addition, they summarized the communication and networking requirements such as payload (size and frequency), physical (PHY) and media access control (MAC) layer latency based on the IEEE Guide for Smart Grid Interoperability and National Institute of Standards and Technology frameworks.

[25] presented an overview and discussion of some of the major communication technologies which included: IEEE specified ZigBee, WiMAX and Wireless LAN (Wi-Fi) technologies, GSM 3G/4G Cellular, DASH7, and PLC (Power Line Communications), with special focus on their applications in SGs. Also, [26] conducted a review of communication and networking technologies in SGs. This included communication and networking architecture, different communication technologies that would be employed in this architecture, consideration of the quality of service (QoS), optimization of assets utilization, control, and management. An additional survey of the SG is given in [27] where a survey of the enabling technologies for the SG is put forward. This survey also explored three major systems, comprising the smart infrastructure system, the smart management system, and the smart protection system.

Survey works that jointly involve CRSN and SG are few; one of such contribution is [28]. In which a systematic investigation was detailed were it addressed the novel idea of applying the next generation wireless technology and cognitive radio network to the SG. It considered the system architecture and algorithms, including the study of a hardware test bed. The work in [29] also reported on how Cognitive Radio, as a means of communication, can be utilized in an end-to-end SG, ranging from a home area network to power generation. The authors also considered how Cognitive Radio can be mapped to integrate the different possible communication networks within large scale SG deployment. In addition, information security issues were discussed in terms of the use of cognitive radio in a SG environment at different levels and layers, and possible mitigation techniques.

The study in [30] provided a comprehensive survey on the CRN communication standard in SGs, including discussion on system architecture, communication network compositions, applications, and cognitive radio based communication technologies. It highlighted potential applications of cognitive radio based SG systems including a survey of cognitive radio based spectrum sensing approaches with their major classifications. [31] presented a survey on the spectrum utilization in Malaysia, explicitly in the UHF/VHF bands, cellular (GSM) 900, GSM 1800 and 3G), and WiMAX, ISM and LTE band. The goal was to determine the potential spectrum that can be exploited by cognitive radio users in the SG network. In [13], a case study for the implementation of SG network using CRSN specifically in the remote areas of Pakistan was presented.

For clarity, a tabulated survey works with respect to SG communication network architectures and SG implementation design is presented in Table 2.1.

Table 2.1: Comparison of Survey Work in SG Communication Network Architecture and Implementation Design

References for SG Architecture	Conventional SG	SG Implementation	CRSN/CRN Approach in SG
Gao et al.[25]	Yes	No	No
Qiu et al.[27]	No	No	Yes
Shuaib et al.[28]	No	No	Yes
Wang et al.[21]	Yes	No	No
Gungor et al.[31]	Yes	No	No
Rayudu et al.[23]	Yes	No	No
Rehmani et al.[29]	No	No	Yes
Khan et al.[12]	No	No	Yes

From the discussion, it can be seen that some of the surveys mainly focused on the CRSN while some was directed to the integration of the CRSN into the SG. However, this thesis complements and extends the surveys which involve the integration of CRSN in SG. While a few of these surveys have presented overviews of SG communication architecture, communication technologies, and SG applications (including their motivations and challenges in SG), none has considered the full implementation design with QoS support in the entire CRSN based SG. Also, none has contemplated the suitability and utilization of Low Power Wide Area Networks (LPWANs) as the communication access technology in a CRSN based SG for delivering SG applications.

So far, the existing survey is on cognitive radio network (CRN) context whereas the focus of this survey is on cognitive radio sensor network (CRSN). The attention is to explore in the context of the CRSN based SG, SG communication architecture, SG applications, and their communication access technologies. It included SG Implementation designs with QoS support; thus leading to the following contributions of this chapter:

- An extensive survey of communication network architecture for the CRSN based SG is provided.
- Also included is a survey of SG applications and their communication access technologies in CRSN based SG.
- The potential for an implementable design with QoS support in a CRSN based SG is identified.
- The potential for suitability and utilization of LPWAN in a CRSN based SG is discussed.
- Challenges, recommendations and future research in CRSN based SGs are highlighted.

The remainder of this chapter is structured as follows: Descriptions of the conceptual framework of the CRSN in a SG; discussion on the challenges of the CRSN based SG; SG communication network architecture and CRSN based SG applications with respect to communication access technologies; Recommendations and future research work are discussed; and chapter summary.

2.2 Concept and overview of CRSN in Smart Grids

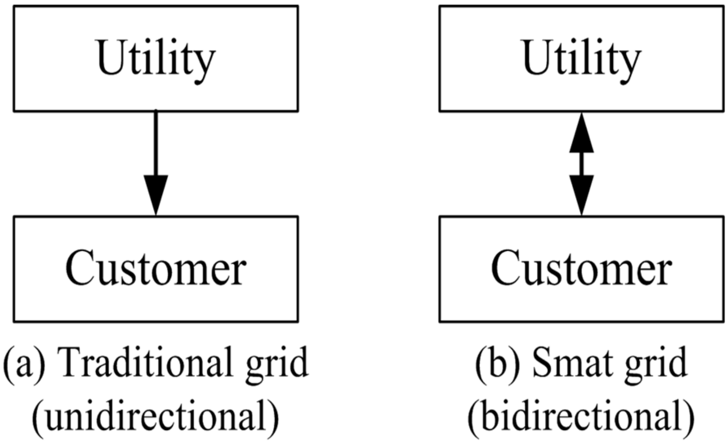
2.2.1 Smart Grid

The SG is replacing traditional power grids and is intended to be the next generation of electric power system operation. SGs will integrate diversified renewable energy resources in addition to primarily supporting power systems. Control centers equipped with smart communication network infrastructure will utilize modern communication technologies to monitor and control remote smart electric devices in real time. Currently, traditional power grids use a top-down layer approach where the communication flow is only in one direction from the utility to the consumers as depicted in Fig 2.1. A SG has a bidirectional communication flow between utility and consumer as shown in Fig. 2.1.

According to Cisco [1], SG technology provides predictive information and recommendations to utilities, their suppliers, and their customers on how best to manage power delivery and consumption.
The SG has functional areas comprising:
(1) power system layer - this is made up of power generation, transmission, and distribution by utilities, with power supplied to the customers (consumers);
(2) power control layer, which enables SG monitoring, control, and management functions;
(3) communication network layer - which allows two-way communications in a SG environment;

(4) security layer- which provides data confidentiality, integrity, authentication and availability;
(5) application layer - which delivers various SG applications to customers and utilities based on an existing information infrastructure [30].

The communication layer domain is one of the most critical domains that enables SG applications. In the SG scenario, the consumer can benefit from real-time energy management and pricing through demand response management, thereby enabling energy conservation and cost-effectiveness [32]- [37].



(a) Traditional grid (unidirectional)

(b) Smat grid (bidirectional)

Figure 2.1: Evolving grid communications

2.2.2 Cognitive radio based sensor network (CRSN)

Traditionally, wireless networks are regulated by a spectrum assignment and management policy which makes fixed assignments of the spectrum to license holders for a long time within large geographical regions. This fixed assignment under-utilizes spectrum with utilization levels that ranges from 15 percent to 85 percent [38]. Cognitive Radio which has the capability of Dynamic Spectrum Access (DSA) is a promising option to solve these spectrum inefficiencies. A cognitive radio sensor network (CRSN) is a network comprising of Cognitive Radio and Sensor nodes that are equipped with cognitive capability and reconfigurability, and can change their transceiver parameters based on interactions with the environmental circumstance in which they operate [39].

In a CRSN, there are two types of users: primary and secondary. Primary users (PUs) are the licensed or authorized users, which have the license to operate in an assigned spectrum band accessing the primary base station. Secondary users (SUs) also called the Cognitive Radio users (CRs) are unlicensed users without a spectrum license. CRs use the existing spectrum through opportunistic access without causing interference to the primary or licensed users. CRs look for the available portion of the spectrum known as spectrum hole

or TV white space. The optimal available channel is then used by the secondary or CR users if there are no licensed users operating in the licensed bands [39]. These CR users need additional functionalities to share the licensed spectrum band. Such functionalities include: (1) Spectrum Sensing- this is the means of detecting unused spectrum called spectrum holes or white spaces and the presence of the PUs [40].
(2) Spectrum Management- this involves the selection of the best available channels with respect to the received signal strength, transmission power, number of users, interference, energy efficiency and QoS requirements. This process also includes spectrum sharing process for best channel and power allocation, and some of the functionalities are related to the main functionalities of medium access control (MAC) layer protocols. Hence, it can be incorporated into the MAC layer. However, there are challenges associated with efficient spectrum sharing which include time synchronization and distributed power allocation
(3) Spectrum mobility- implies the maintenance of seamless communication and ability to vacate the channel whenever the PU arrives CRs [38], [41]. A typical block diagram

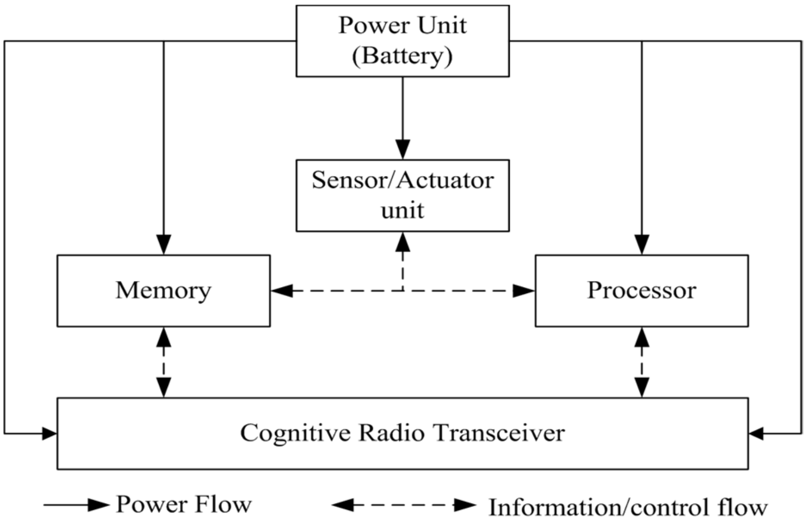


Figure 2.2: CRSN node structure

structure of a node of a CRSN is shown in Fig. 2.2 . A sensor or sensing unit is used for sensing data.The processor processes and commands the activities of various units. The transceiver with CR capability is used for transmitting sensed data. The battery or power unit supplies the necessary power to the rest of the units. A group of CRSN nodes can be deployed in a cluster based architecture as illustrated in Fig. 2.3. This deployment can be accomplished in a SG environment for monitoring and control activities, thus resulting in CRSN based SG. A designated node,also called the Cluster Head(CH), controls a group of sensor nodes for opportunistic spectrum access to a licensed or primary network in SG environment.

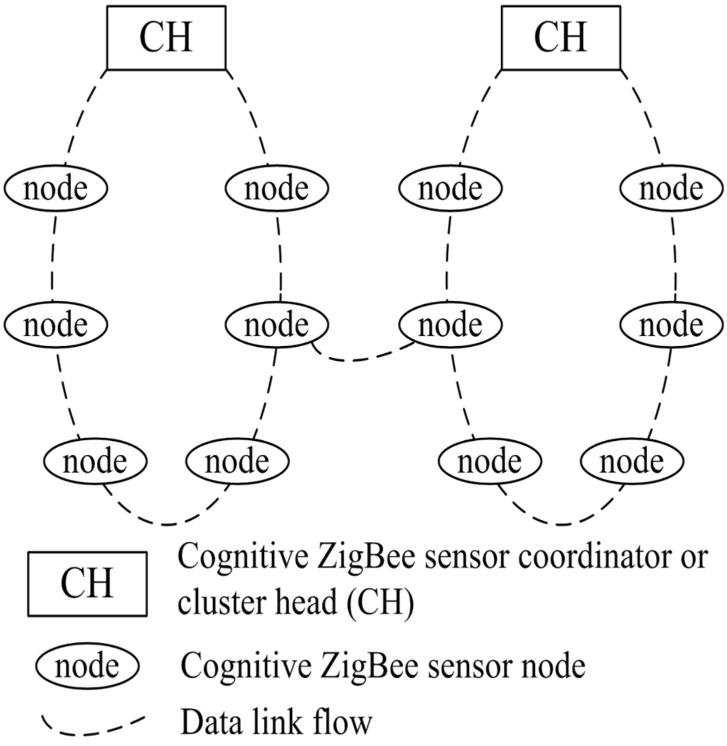


Figure 2.3: Cluster based CRSN architecture

2.3 Challenges of CRSN Based Smart Grid

The communication required for SG applications are associated with some challenges including problem of severe wireless signal propagation conditions which is common in communication in the SG environment, for example through high power disturbances [42]. In addition, many SG applications require guaranteed communications QoS, such as demand response applications [41], [43] which require reliable and timely communication. Hence, the key design challenge is to reliably and timely deliver the sensed data using the wireless sensor devices that are installed at various locations for efficient decision making [44]. These challenges of SG communications have necessitated the development of CR communications mechanisms that are designed for the SG. The SG encompasses a wide range of settings from inside individual homes to outdoor neighborhood areas, and from electrical power distribution stations and up to generation and transmission substations. These settings are associated with challenging wireless communication conditions.

A major challenge in wireless communication is the area of electrical power equipment that usually contains coils. Electrical wiring loops in coils can behave like antennas which radiate electromagnetic waves that can cause interference with wireless communication [45]. Also, impulse noise and high power transients from switching power electronic components can adversely affect 59 wireless communications [16], [45], [46]–[51]. Furthermore, wireless communications from indoor appliances to outdoor smart meters do suffer from high path losses [49]–[54]. SG application requires reliable and low-delay communication. Many key SG applications require high communications QoS [55]-[57]. For example, the demand response application [41] controls and adjusts the operation of electrical appliances in homes and businesses to lessen demands on the power grid. Reliable bi-directional communication between homes and the utility control is required for efficient functioning of the load management [58]-[59]. Again, monitoring and control of the power grid depend on low-delay delivery of real-time data [59]-[60]. Also, there exists a problem of interoperability due to multiple interconnection communication technologies in different parts of the SG; thus, ensuring interoperability within heterogeneity in the SG.

The communication network structure is envisioned to address this challenge . Therefore, when building a workable SG communication infrastructure, it is required to address the interoperability issue. To address these challenges, a reliable CRSN SG communication network architecture design can be implemented for realizing satisfactory data delivery for a SG application. In parallel to the issue of interoperability, the American National Institute of Standards and Technology (NIST) [61] proposed a Framework and NIST Smart Grid Architectural Interoperability Standards Road-map. The conceptual SG architecture standard is composed of seven domains as illustrated in Fig. 2.4 . These describe the functional areas and scope of the SG infrastructure. Table 2.2 gives the descriptions of the NIST Framework architectural model.

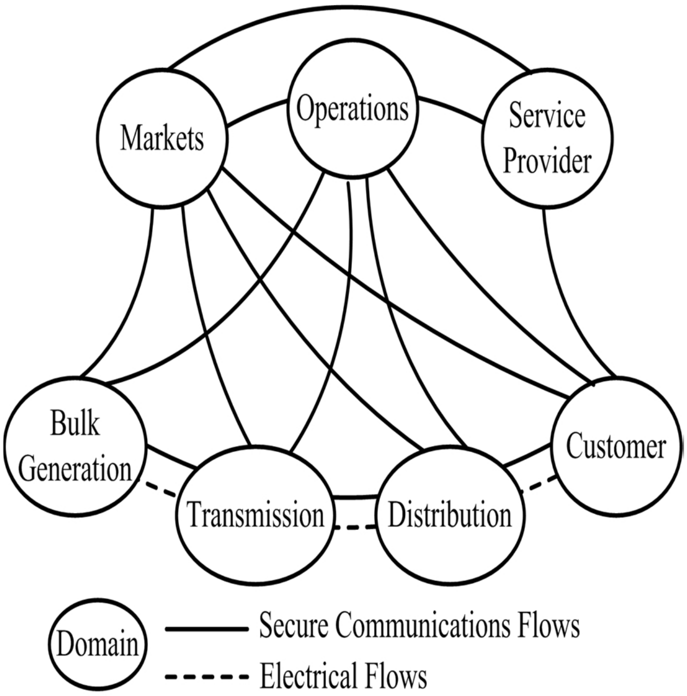


Figure 2.4: The NIST Smart Grid Conceptual Reference Model [60]

Table 2.2: Domains and Actors in the NIST Smart Grid Conceptual Reference Model

Domain	Actors in Domain
Customers	The end users of electricity. May also generate, store, and manage the use of energy.
Markets	The operators and participants in electricity markets.
Service Providers	The organizations providing services to electrical customers and utilities.
Operations	The managers of the movement of electricity.
Bulk Generation	The generators of electricity in bulk quantities. May also store energy for later distribution.
Transmission	The carriers of bulk electricity over long distances. May also store and generate electricity.
Distribution	The distributors of electricity to and from customers. May also store and generate electricity.

2.4 CRSN based Smart Grid Communication Network Architecture

In this section, work on SG communication architecture is described. Several requirements such as latency, delay, QoS, reliability, and so on, must be met in the communication network infrastructure [62]. To successfully achieve these communication requirements, some open research issues need to be addressed. Much works [35], [63], [44], [65] have been conducted in this area. Many SG architectures have been proposed. For example, NIST proposed the SG reference model in the NIST Framework and Roadmap for Smart Grid Interoperability Standards [61]. Cisco proposed an architecture that is totally different because it argues that the whole system would use an independent “network of networks" [66]. Cisco also maintained that the best standard suite of protocols for the SG is the Internet Protocol (IP) [1]. Since IP has already achieved great success in the current internet in terms of flexibility, security, and interoperability. Cisco therefore asserted that the interoperability standards of the SG should use IP architecture as a reference [1].

Many other researchers have proposed SG architectures with certain features added to the system for modification. A wireless SG architecture that has the capability to remotely sense power delivery was proposed in [66]. Gadze [67] presented a hierarchical architecture for the SG, which is a multilevel decentralized platform that handles the potential impacts of harsh power environments. Other presented the SG architectures [68]–[70] that are focused on one part of the whole system in some way and are intended to deal with specific requirements that are worthwhile addressing. SG architectures must address the following critical issues [71]:

- transmitting data over multiple heterogeneous media;

- collecting and analyzing massive amounts of data rapidly;
- changing and growing with the industry;
- connecting large numbers of devices;
- maintaining reliability;
- connecting multiple types of systems;
- ensuring security; and
- bring returns on investments.

After consideration of these proposed architectures, it can be deduced that NIST 's model is the most fully described SG architecture proposed. It contains nearly every scope brought up by various organizations, from bulk generation to end users. Also, it provides a means to evaluate cases, to identify communication network interfaces for which interoperability standards are needed, and to aid the development of a cyber-security strategy [61]. Therefore, a communication network architecture based on the improvement of this model as the basic framework is envisioned. Consequently, various communication network architectures which can connect to the SG for distribution automation, that reflects the NIST framework, have been proposed.

Communication Networks can be represented by a hierarchical layer architecture in a CRSN based SG environment, which can be classified by data rate and coverage range. Hence, SG communication layer architecture comprises:
(1) Home Area Network (HAN); Building Area Network (BAN); Industrial Area Network (IAN); Commercial Area Network (CAN).
(2) Neighborhood Area Networks (NAN); Field Area Network (FAN).
(3) Wide Area Network (WAN). Communication network parameters such as latency, delay, QoS and reliability must be met for any successful SG communication architecture.

In addition, it will be better for the architecture to cut across the seven domains of the NIST Framework. A lot of works did not simultaneously fulfill these requirements. However, it will be advantageous for the NIST Framework architecture on the SG road-map for interoperability and CISCO SG Reference model to be complementary. Consequently, research is needed for SG communication network architecture that includes an implementation design model for guaranteed QoS of SG applications. Such envisioned SG architecture should cut across the seven domains of the NIST Framework while simultaneously addressing the network parameter issues in the SG for efficient monitoring and control. Table 2.3 shows a comparison that reflects either or both the NIST Framework for SG architecture and the implementation design model. A look at a typical smart grid communication network in

Table 2.3: A Comparisons of Proposed or Existing Works in SG Communication Network Architecture and Implementation Design Model Including NIST Framework

References for SG Architecture	Based on NIST SG Domains	Implementation with QoS	CRN/CRSN Approach in SG
Gao et al. [25]	Yes	No	No
Shaban et al. [72]	No	No	No
Barka et al. [73]	No	No	Yes
Wang et al. [64]	No	No	No
Kuzlu et al. [22]	No	No	No
Budka et al. [71]	No	No	No
Rehmani et al. [26]	No	No	Yes
Shuaib et al. [28]	Yes	No	Yes

the subsequent sections may be necessary.

The SG communication architecture presented by the work in [26] utilizes the NIST Framework, though not in the context of the CRSN approach for the SG. Implementation design model for guaranteed QoS in SG architecture was not considered.

The work in [23] presented a SG communication architecture covering some aspects of the NIST SG Framework; although not in the context of the CRSN approach in the SG. However, their work details typical communication implementation scenarios in various sections of the SG, although not with specific implementation designs.

Another study in [72] describes an implementation design without consideration of the NIST Framework in the SG communication architecture. In SG implementation illustration of the study, the authors investigated the employment of multi-homed wireless transceivers; multi- homing over heterogeneous wireless networks which is expected to increase the available data rate, and reduce the data transfer latency common with delay sensitive applications such as multimedia video monitoring for wide area situational awareness. However, their work is still not in the context of CRSN in a SG.

The study in [73] highlighted the NIST framework without any specific proposed SG communication architecture. However, they showed a typical network topology architecture in various segments of a CRSN based SG. They also showed implementation design specifically for information security in CRSN based SG using Role-Based Access Control (RBAC). Their implementation design was not an overall SG implementation design, rather it was specifically an information security implementation design. A communication network architecture and design procedure for the SG was presented in [74] which proposed a communication network architecture that reflects some aspect of the NIST Framework. They highlighted network topologies and a logical connection model for the

SG and integrating legacy applications in the SG.
To the extent of exploration of this thesis, no work has been carried out in relation to a CRSN in a SG that has a communication network architecture that cuts across the entire 7 domains of NIST Framework for SG interoperability standard. This includes the CRSN based SG implementation design. Table 2.3

2.5 CRSNs Based Smart Grid Applications Vis-a-Vis Communication Access Technologies

2.5.1 Advanced Metering Infrastructure (AMI)

The AMI is a collection of inter-related systems that allow utilities and service providers to collect, measure and analyze energy usage data from advanced devices such as electricity meters through a heterogeneous communication network on demand for billing and power grid management. It extends over the communication network layer (Wide Area Network (WAN), Neighborhood Area Network (NAN), Field Area Network (FAN) and Home Area Network (HAN)) of the SG.

AMI in the WAN provides the backbone or core communication for all distributed area networks that exist at different area of the grid. AMI in the NAN is implemented within the distribution system for pricing provision messages, monitoring and controlling power delivery to the various end users or customers, and determines the grid efficiency [74]. In general, it collects all the energy usage data from various HANs and sends to the Utility core/backbone through its gateways. AMI in the HAN consists of the smart meter that interconnect various home appliances, sensors, in-home display, gas meter, water meter [73], photovoltaic panel and home energy management system (HEMS) [74]-[77]. Table 2.4 summarizes the layer architecture with their respective coverage area, data rates and possible communication access technologies.

Generally, the AMI comprises of communication networks, smart meters, local data aggregators, back-haul networks, utility provider data centers, Meter Data Management Systems (MDMSs) and software application platforms [63], [78]. The heterogeneous characteristics that exist within the various components of the AMI make interoperability a major challenge, without open standards put in place [79]. Hence, to have a reliable, scalable and successful integration of an AMI architecture, there is a need for power system and communication technologies interoperability to be taken into full consideration during the design stage.

The communications access technologies for the AMI must employ open bi-directional communication standards [63] to provide seamless connection between the utility, cus-

Table 2.4: Three Tiers of Smart Grid Architecture[74]

Network Type	Coverage	Data rate	Standard
Home Area Network (HAN)	1-10 m	1-100 kbps	ZigBee, Wifi Z-wave, PLC
Neighborhood Area Network (NAN)	10 m-10 km	100 - 1000 kbps	Wifi, RF Mesh, WiMAX, cellular stds (3G,4G,LTE) Wired—Ethernet,PLC, DOCIS
Wide Area Network (WAN)	10-100 km	10-100 Mbps	Wifi, Mesh, WiMAX, cellular stds (3G,4G, LTE) Wired—DSL

tomer and the controllable electrical load. Various communication access technologies are deployed in the AMI architecture, depending on bandwidth requirements, reliability, cost effectiveness, future expansion and ease of installation [62]. Examples are:

- Power Line Communication (PLC);
- Copper or Fiber Optic;
- Broadband over Power Lines (BPL);
- WIFI and Low Power WIFI;
- Cellular/LTE/GSM;
- WiMax;
- Bluetooth and BLE (Bluetooth low energy);
- General Packet Radio Service (GPRS);
- Internet;
- Satellite;
- Zigbee;
- 6LoPWPAN- IP Version 6 Low Power Wireless Personal Area Network;

- Z-Wave; and
- Wireless Hart.

Also, though not mentioned in the literature is the Low Power Wide Area Network (LPWAN), such as: LoRa, Sigfox, RPMA, NB-IoT, LTE Cat-1, and LTE-M1. The LPWAN is a promising access technology for a wide area network for delivering SG application data and control, smart cities, and Internet of things (IoT) applications [80].

The information flow in an AMI system architecture is bi-directional; data is collected from a group of smart meters in the customer premises network local concentrator (CPN), and then transmitted via a back-haul link to the utility core backbone servers, where all the data collected are analyzed by various applications for management and billing [62]. Reliable communication access technologies or network media are required for successful information flows in the AMI system. Gobena et al in [33] presented an AMI architecture service and their communication requirements as a middle-ware solution, it supports the capability of handling the huge amount of smart meter data in terms of scalability, flexibility and performance adherence. Also, the communication access technologies for AMI applications must have sufficient bandwidth (2-5 Mbps), be security proven [81]-[82], and be able to support current and future technologies [83], [84].

Due to the interference issue caused by other devices using the spectrum free band, CRSN technology is the only suitable solution as the communication access between the consumers and the utility control centers (as the AMI communication back-haul system) and provides dynamic and opportunistic spectrum access for improved data communication performance [57].

2.5.2 Home Energy Management Systems (HEMS)

This application is specifically for the HANs. It provides home automation and control for household appliances that communicate with smart meters and in-home displays. HEMS can minimize energy costs through adaptive control such as load balancing [85]. HEMS can be used by commercial and industrial customers for building automation, heating, ventilation, and air conditioning (HVAC) control [77], including industrial energy management applications. A CRSN based communication infrastructure and software with internet connection installed in the HAN enables HEMS to track and record the flows of electricity in the home. Customers can connect and interact with it through an HEMS app or interface device. HEMS require real-time information transmission for reliable and efficient operation. Consequently, the communication access technologies for this application should be QoS guaranteed with an appreciable bandwidth for better throughput. A CRSN is beneficial for the real-time information sharing among HEMS [23], [54].

2.5.3 Demand Response Management (DRM)

This is also called Demand-side management (DSM), it operates within the customer premises and interacts with the utility providers, markets and operational regions. Demand response (DR) applications are designed to alter the energy consumption pattern of the customers in response to price and other forms of incentives to better utilize the utility capacity so that the capacity does not have to be expanded [79], [85]. Reliable bidirectional communication between consumers and utility is needed for effective DRM [59]. Smart meters installed at the customer premises provides a two-way communication between the utility provider and customer, this enables the utility to shape customer load profile in an automated and comfortable manner [86]. DRM helps users to turn selected devices on or off by sending communication signal commands to a load controller installed at customer premises [23], [54].

However, a successful DRM scheme requires reliable and efficient communication access technologies for real-time DR applications. Communication access technologies for DR applications are IEEE 802.15.4, IEEE 802.11 or power-line communication (PLC) which connects user appliances to smart meters installed within the home, building and industrial area networks [87]. The work in [88] analyzed the use of long-term evolution (LTE) as the communication link between the aggregator and customer premises. This provided low latency and packet drop for DR.

Furthermore, DRM helps utility to enhance operations and to efficiently maximize and optimize the use of Distributed Energy Resources (DER) including renewable energy. It also helps the customer to make more informed choices about how and when to use power. Above all, DRM is a vital component in smart grid. However, there exist an open issue to be addressed in the DRM especially in a situation of SG network having many utility companies and customers where each entity is concerned with taking full advantage of its own benefit. Hence, Maharjan et al. [36] proposed a Stackelberg game between utility companies and end-users to maximize the revenue of each utility company as well as the payoff of each customer. They developed a distributed algorithm which unites to the equilibrium with only local information available for both utility companies and customers. In addition, they also proposed a scheme based on the concept of shared reserve power to enhance the grid reliability and ensure its dependability so as to mitigate the attempts of an attacker trying to manipulate information of the price from the utility.

2.5.4 Distributed Energy Resource (DER)

DERs have renewable and non-renewable energy resources with the following functions: electric power generation, conversion, storage, and interconnection to the area electric power system (EPS). They are made up of photo-voltaic arrays, micro turbines, wind turbines, fuel cells, traditional diesel and natural gas reciprocating engines, and energy storage such as batteries technologies and other energy storage techniques [64]. The power flow between the energy sources into the grid is bidirectional since there is storage, unlike the traditional unidirectional power flow paradigm. DERs form a micro-grid by integrating controllable loads and power storage devices [37]. These are usually deployed as alternate sources of power to meet local needs of consumers. These needs are typically lightings, elevators and security surveillance in case of utility blackouts [89]. Also, SG functionalities are geared towards the decentralization of power generation to enable bidirectional flow of electricity from DERs and power storage devices [90].

Therefore, reliable and efficient communication technologies linking DERs and distribution system operators (DSO) remain a critical issue [91]. DERs are connected to the grid using communication access technologies and intelligent electronic devices (IEDs) for control, monitoring and islanding [92]. Consequently, DER applications require reliable communication links for efficient control and monitoring. In addition, DER integration into the grid requires low latency. Hence reliable and scalable communication access technologies with stringent latency requirements between 12 and 20 ms are required for correct integration, [83], [92]. [93] proposed using GPRS and existing power line communication (PLC) for connecting photovoltaic (PV) cells to a low voltage (LV) data concentrator. A case study with a SG demonstration project (known as the Future Renewable Electric Energy Delivery and Management (FREEDM) system) which had PV and storage as part of the power resource system, was presented in [65]. Kanabar et al. [94] presented studies using different communication technologies. An IEC 61850 based 69 kV/11 kV distribution substation IED, and DER IED for Generic Object Oriented Substation Event (GOOSE) messages, were studied within the context of transfer trip and islanding operations using wire line and wireless (IEEE 802.11) communication access technologies. Wire line gave a higher throughput and less latency which makes it suitable for a densely populated urban region; while for spatially distributed DERs, wireless would be a better communication access technology option for economic and technical reasons.

However, wireless networking faces several challenges, such as network congestion, noise, obstructions, and interference due to overcrowding in the ISM free band. One possible approach to address these issues is to improve the spectrum utilization and wireless communication performance through the opportunistic spectrum access of CR communications [41]. Wi-Fi and ZigBee communication access technologies can be deployed for real-time pricing data, while in continuous carrier and smart meter reading systems, and for islanding prevention, PLC is mostly used in [95].

2.5.5 Wide-Area Situational Awareness (WASA)

WASA involves real-time data monitoring, protection and control of the power system across large geographic areas using intelligent electronic devices (IEDs) and Phasor Measuring Units (PMUs). WASA application provides automatic self-healing with local control and faster response than manual control by a control center. It can fully and automatically protect power systems against extensive blackouts or unexpected events [23], [54]. Sanchez-Ayala et al. in [90] presented the use of PMUs for distribution, dynamic monitoring, protection, harmonic estimation, load modeling, parameter estimation, and fault location and detection. WASA also retrieves information about components, e.g., transformers, capacitor banks, and network protection devices. Many communication access technologies can be used for these purposes.

However, the choice of appropriate communications access technologies for handling huge amount of data provided by the WASA system remains a critical issue for a high voltage network [90]. Joshi et al in [79] presented a performance analysis of the communication system between the PMUs and phasor data collector (PDC) over a WiMAX network. PMU traffic has a stringent traffic requirement ranging from 20 to 200 ms. Amidst the various communication access technologies for networking synchrophasors, fiber optic is a preferred choice due to its robustness and insusceptibility to electromagnetic disturbances or capacity constraints [96]. But due to the high cost of implementation of fiber optic for WASA over a wide geographic area, wireless may be appropriate option for wide area monitoring, control, and protection.

However, wireless suffers from interference due to competition in the ISM free band. Reference [5] describes how CRSN is suitable for real-time surveillance applications which have a minimum communication delay requirement. These are applications such as traffic monitoring, biodiversity mapping, habitat monitoring, environmental monitoring, environmental conditions monitoring that affect crops and livestock, irrigation, underwater WSNs, vehicle tracking, inventory tracking, and disaster relief operations. They also show the suitability of CRSN for indoor and outdoor monitoring. Hence CRSNs, with their opportunistic spectrum access, are a promising alternative for wide area monitoring, control, and protection [41].

2.5.6 Distribution Automation (DA)

Distribution Automation (DA) monitors, controls and manages the distribution grid. DA provides real-time operational information concerning distribution-level devices, such as capacitor bank controllers, fault detectors, switches, and voltage regulators. This information is distributed to other intelligent field devices such as IEDs and integrates them with transmission systems and customer operations [90]. The communication access technology requirement for DA varies between utility providers. The CRSN appears to be a promising technology in terms of successfully fulfilling the DA requirements of a given utility [23].

From the described SG applications and their communication access technologies, it can be seen that access technologies such as WIFI, Z-wave, PLC, 3G, 4G, LTE, DSL, and others are recommended media for delivering SG application data, control and information [33], [90]. Table 2.4 tabulates the communication access technologies in various SG segments. However, it is worth noting that LPWAN could be considered as the most promising access technology for a wide area network in terms of delivering SG application data, control and information due to its features, which are:

- Long range
- Low/Medium data rate
- Low power consumption, and
- High receiver sensitivity

Only few works have highlighted LPWAN for SG and smart metering applications as seen in [80], [97]–[100], though not in the perspective of CRSN. Andreadou *et al.* in [97] provided a study of European SG projects including the technological solutions with a focus on smart metering low voltage (LV) applications. In [98], Abbasi *et al.* presents LPWAN suitability in handling large-scale SG applications. Li *et al.* [99] highlights that LPWAN technologies is a new solution for current SG communications due to their excellent features. Ferrari *et al.* [100] Demonstrates with an experimental result that LPWAN technology such as LoRaWAN is a potential wireless communication solution for Vehicle to Grid communication (V2G).

Table 2.5 summarized the studies discussed in this review regarding communication access technologies with respect to the discussion on the suitability of LPWAN for CRSN based SG applications delivery. Furthermore, different SG applications require different communication access technologies to meet the QoS requirements. The communication access technologies at the various levels of a network layered architecture (WAN, FAN, NAN and HAN) are considered. From the discussions put forward, it is believed that LPWAN is a good enabler for various components in the CRSN SG communication access system.

2.6 Featured CRSN Integration in SMART GRID

A typical cognitive radio based sensor network integration in SG should have the potential of possessing a smart unified communication solution that can holistically and efficiently

Table 2.5: Comparisons Table for Access Technologies with respect to LPWAN Consideration in SG

Comm.Access Technologies References	Approach in Conventional SG	LPWAN Consideration	CRSN Approach in SG
Lu et al. [56]	Yes	No	No
Gobena et al. [32]	Yes	No	No
Gungor et al. [40]	No	No	Yes
Vuran et al. [37]	No	No	Yes
Khan et al. [97]	Yes	No	No
Ergul et al. [38]	Yes	No	Yes
Laverty et al. [94]	Yes	No	No
Andreadou et al. [98]	Yes	Yes	No
Whitaker et al. [96]	Yes	No	No
Kanabar et al. [95]	Yes	No	No
Sood et al. [84]	Yes	No	No
Roy et al. [89]	Yes	No	No
Akyildiz et al. [127]	No	No	Yes

monitor and control power and renewable energy generation systems, power transmission and distribution automation, utilities, distributed energy resources at the customer side, security and privacy systems, smart meters, customer load, and demand response management. To accomplish these tasks of monitoring and control of the entire SG systems, the following are required:

(1) Implementation design consideration of CRSN in SG.
(2) Utilization of cognitive radio wireless multimedia sensor and actuator network (WMSAN) [101], [102], [13].
(3) Utilization of LPWAN as communication access technology for CRSN in SG.
(4) Consideration of security strategy [29], [102]-[103], [28].
(5) Consideration of energy efficient cross layer framework of the CRSN nodes in SG [104], [105].
(6) Consideration of energy efficient control strategy/optimization in radio resource allocation and spectrum sensing [103], [106], [107].
(7) Consideration of energy efficient optimization of communication protocols/algorithms [103], [108], [41], [28].
(8) Perpetual energy harvesting for the CRSN nodes in SG.

Considerations of the requirements for featured CRSN integration in SG when implementing SG will indeed lead to full benefits of SG. It will certainly help in addressing the enumerated challenges in SG as highlighted in the earlier section such as interference, impulse noise, and path lose, delay, interoperability within heterogeneity in SG, and so on.

An example of CRSN based SG is that of a case study in Pakistan in which Khan et al. [13] proposed the utilization of CRSN in SG infrastructure. In their work, they enumerated the benefits of deploying CRSN in SG such as helping in sustainable production of renewal energy and minimization of power theft. They also pointed out that network communications aspect in SG can be accomplished by cognitive radio technology using the software defined radio (SDR). However, their study is specifically for Pakistan environment by considering the broadband and cellular available in Pakistan as the communication access technologies for the CRSN in SG. Hence, it was not a generalized consideration such as the unified smart CRSN communications solution in SG that have been highlighted in this thesis.

A typical illustration of communication network in SG is depicted in Fig. 2.5 and Fig. 2.6. The CRSN architecture shown in Fig. 2.3 can be deployed in strategic locations of the various SG segment (generation, transmission, distribution, control canter/utility, and customer premises). Putting the requirement earlier stated into consideration, will help in the formation of smart unified communication solution using CRSN alongside with communication access technologies such as LPWAN. This unified communication solution can then be integrated into SG to yield holistic efficient monitoring and control in the entire SG ecosystems.

Furthermore, regarding the works on utilization of cognitive radio (CR) paradigm and sensor network (SN), most of the works surveyed CR paradigm in SG [6]. Their focus is majorly on cognitive radio network (CRN) in SG but not on cognitive radio based sensor network (CRSN), which is the intersection of CR and SN in SG. Obviously, no survey work has been done in the context of the intersection of CR and SN in SG, except the work presented by Khan et al. [13] which is somewhat related to a survey, though is basically a case study of CRSN in SG at Pakistan. It is mainly a case study peculiar to the Pakistan environment and not a generalized example solution. For clarity, Table 2.6 helps to showcase various survey works on CR paradigm indicating the focus area and whether they are in the context of CRSN in SG or CRN in SG. It also showcases whether the survey work considers unified smart communication solution for holistic efficient monitoring and control in SG.

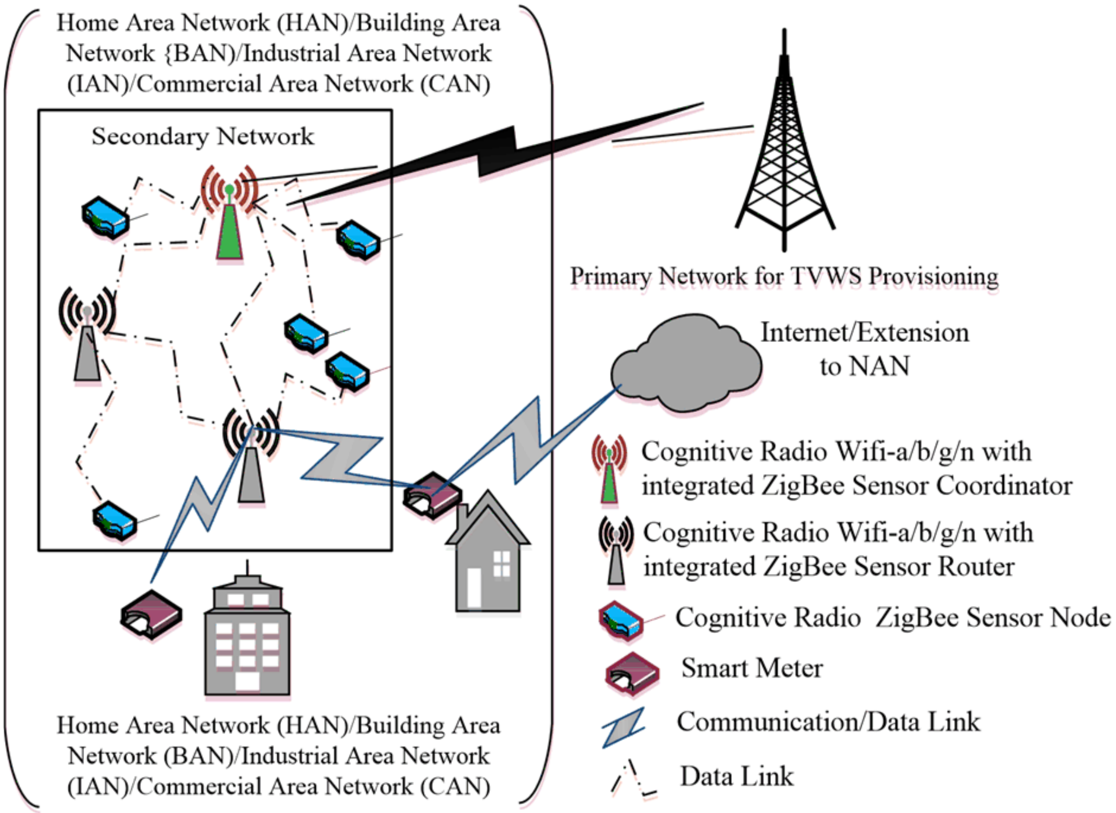


Figure 2.5: Typical SG communication in customer premise (HAN/BAN/IAN/CAN)

2.7 Recommendations and Future Work

A SG involves key scientific and technological areas such as (i) power quality; (ii) reliability; (iii) resilience; (iv) widespread integration of distributed renewables energy along with associated large scale storage; (v) widespread deployment of grid sensors; and (vi) secure cyber based communication within the grid. To account for these areas, it will be good for the SG communication architecture to cut across the entire 7 domains of the NIST Framework for Smart Grid Interoperability standards. Based on this, from Table 2.3, it can be deduced that research attention needs to address this issue. Hence, the authors believe that a communication network architecture, which reflects the entire 7 domains of NIST Framework, alongside the implementation of a design model, could yield successful SG integration and deployment.

Also, Table 2.5 highlights the fact that research attention needs to address the consideration of a LPWAN in a CRSN based SG. Looking at the highlighted SG applications and their communication access technologies, as well as LPWAN consideration, it is believed by the authors that the integration of hybrid and multi-homed communication access infrastructure to operate at different segment of the SG will lead to efficient and seamless communication in the SG network. For example, a CRSN SG design requirement

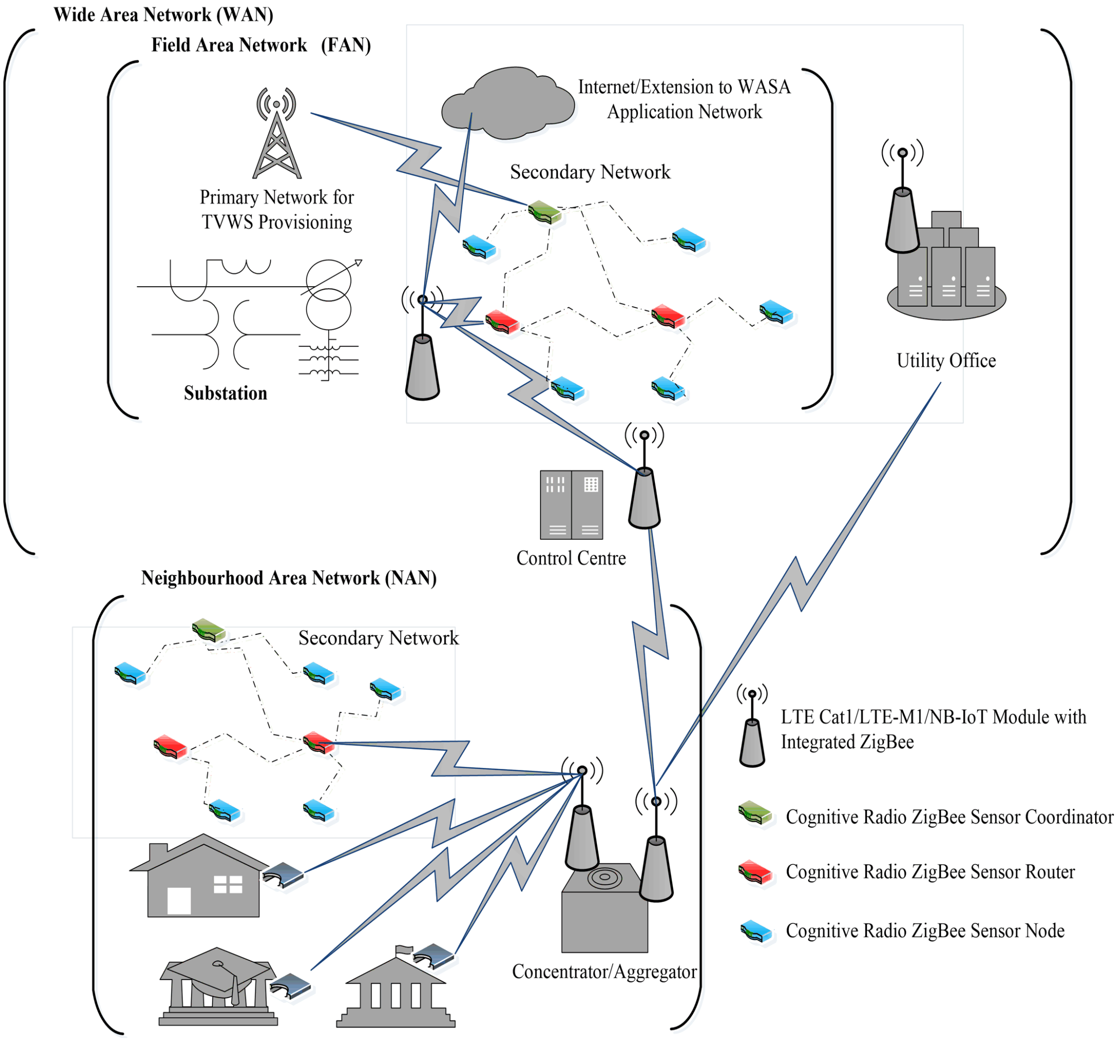


Figure 2.6: A typical Smart grid communication in WAN/NAN/FAN

consideration could consider the network topology that comprises of cognitive radio dual band (5 GHz and 2.4 GHz) WIFI (802.11a/g/n) with integrated ZigBee to operate in the HAN, BAN, IAN and CAN. Also, the topology for WAN, FAN and NAN could comprise of LTE cat1/LTE-M1/NB-IoT (private/dedicated) with integrated ZigBee. In addition, as a further example, the authors also believe that Table 2.7 could help in developing the design requirement for correct CRSN based SG integration and deployment for efficient holistic monitoring and control.

The problems of severe wireless signal propagation conditions [39], including impulse noise, and high power transients and switching power electronics components [109]-[111] that adversely affect wireless communication link in SG environment, can be addressed by:

Table 2.6: Summary of focus area and consideration of Unified Communication by various surveys in SG

References	CRN SG	CRSN SG	Architecture utilizing NIST Framework in the entire SG 7 domains	SG implement design model	LPWAN consideration	Unified Solution for holistic monitoring and control in CRSN SG
Khan et al. [12]	Yes	No	No	No	No	No
Our survey	No	Yes	Yes	Yes	Yes	Yes
Gungor et al. [40]	Yes	No	No	No	No	No
Rehmani et al. [29]	No	Yes	No	No	No	No
Zhang et al. [73]	Yes	No	No	No	No	No
Qiu et al. [27]	Yes	No	No	No	No	No
Ranganathan et al. [104]	Yes	No	No	No	No	No
Gao et al. [25]	No	No	Yes	No	No	No
Le et al. [101]	Yes	No	No	No	No	No
Gungor et al. [31]	No	No	No	No	No	No

- An energy efficient modulation scheme that has an excellent signal to noise ratio (SNR) capability with low complexity detection mechanism and an appreciable bit error rate (BER). This can be integrated in the physical and media access (MAC) layer protocols for enhanced link quality.

- Consideration of link budget analysis in CRSN deployment in a SG for enhanced signal strength and link quality.

Similarly, the issue of interference caused by electrical wiring coil loops that radiate electromagnetic waves can be addressed by a cross layer protocol that will operate jointly at the physical, MAC, and network layer for interference mitigation; thus, yielding to excellent link quality. The interoperability issue in the SG due to the heterogeneous method of communication in the SG environment can be addressed by the development of a workable communication standard for SG infrastructure.

The problems of security in a CRSN based SG can be addressed by 'end-to-end security 'of high bit-rate SG applications. This will involve consideration of security of the air interface and the delivery of the application interface software to the SG infrastructure. Hence, the need for a workable acceptable use policy for improving end-to-end security in a CRSN based SG is recommended.

Future work is required in the utilization of hybrid systems together with a LPWAN

Table 2.7: Smart Grid Deployment Design Requirement Guide

Communication Standard	Data rate	Consumption Power	Deployment Cost	SG Segment	Distance &Latency	SG Application
Power Line Communication (PLC)/BPLC	High	Medium	Medium /Low	HAN/NAN	Long range, Low latency	Distribution Automation, AMI
Optic Fibre	Very high	Medium	High	NAN/WAN	Long range, Low	Core/Backhaul Infrastructure
ADSL/DSL	High	Medium	High	HAN/NAN /WAN	Long range, Low	AMI, SCADA, DA
WIFI	Very high, High	Medium	Low	HAN/NAN	Medium range Low	DA, AMI DER, DRM
Cellular/GSM	Low	Medium	Low	HAN/NAN/ WAN	Long range, High	Distribution Substation
LTE-A	Very high	High	Low	HAN/NAN/ WAN	Long range, Low	SG wireless Surveillance, SCADA , WASA
ZigBee	Low	Low	Low	HAN	Short range, Low	Home Automation AMI, DRM, DER, DA
Bluetooth	Low	low	Low	HAN	Short range, Medium	Home Automation
WIMAX	Very high	High	Medium	HAN/NAN/ WAN	Long range, Medium	Distribution Automation (DA) AMI, DER
Satellite	Very high/high	High	High	HAN/NAN/ WAN	Short range, High	AMI, DA, SCADA
LoRa	Low	Low	Low	HAN/NAN/ WAN	Long range, Low	Home Automation, AMI
Sigfox	Low	Low	Low	HAN/NAN/ WAN	Longt range, Low	Home Automation, DA
RPMA	Medium/low	Low	Low	HAN/NAN/ WAN	Long range, Low	AMI, DRM, DA
NB-IoT	Low	Low	Low	HAN/NAN/ WAN	Long range, Low	AMI, DRM, DA
LTE Cat-1	Medium/Low	low	Low	HAN/NAN/ WAN	Long range, Low	SG Wireless Surveillance, SCADA, DER, DRM, DA
LTE –M1	Low	Low	Low	HAN/NAN/ WAN	Long range, Low	SCADA, DER, DRM, WASA, DA

infrastructure for the design of an CRSN SG. Also, future work is needed in the area of design and optimization of the communication cross layer protocol that will operate on a heterogeneous communication platform in a SG. This is due to the different SG applications. Other future work includes radio resource allocation for dynamic spectrum access (DSA) in the wireless devices and the sensor nodes. Due to the limited battery life of some sensor nodes, reliable energy harvesting remains an open research area.

In addition, research into a unified solution for holistic mitigation of all sort of interferences in the SG environment is urgently needed. Likewise, research on end-to-end security for mitigating security breaches in a CRSN based SG will be an interesting development.

2.8 Chapter Summary

In this chapter, CRSN based SG architecture and applications vis-a-vis communications access technologies are explored, and a conceptual framework for a CRSN in a SG, including challenges of a CRSN based SG, are highlighted. Overall, the CRSN based SG communication network architecture together with implementation of a design model, and associated communication access technologies, are presented. The NIST Framework for SG Interoperability standard is discussed.

Recommendations are made with regards to a CRSN based SG communication network architecture and implementation design model. This includes a discussion on the suitability and utilization of a LPWAN infrastructure for successful SG integration and deployment. Finally, future work is discussed and this includes: utilization of hybrid communication access systems and a LPWAN infrastructure in a CRSN SG, communication network protocols, radio resource allocation, and energy harvesting in a SG. These are presented as open research issues.
Some of the open research problems are addressed in the subsequent chapters in this thesis.

Chapter 3

RRA Improvements in CRSN based Smart Grid

3.1 Introduction

This chapter investigates and surveys the perspective of radio resource allocation (RRA) in CRSNs based SG including the overview and unique characteristics as well as functionalities of CRSNs. Also, the various resource allocation schemes vis-a-vis RRA architecture in a CRSN SG environment are highlighted. The work reported in this chapter, includes performance analysis of RRA based on throughput improvement criteria in CRSNs for SGs. The analysis assists in establishing suitable spectrum band operation of CRSNs in RRA for SGs. Finally, future research direction in contributing to knowledge such as energy efficiency, hybrid energy harvesting schemes for perpetual power supply to the battery power constraints sensor node have also been presented.

Traditional power grids use a top-down layer approach where the communication flow is only in one direction from the utility to the consumers. A SG has a bidirectional communication and information flow between utility and consumers. There are several communication technologies such as wired or wireless technologies which can be used to realize the bidirectional communication in SG. Wireless communication is a good communication technology option to drive SG due to the extensive coverage area required in SG. However, the wireless channels in the wireless communication undergo wide range of impediments such as fading, path losses and interference caused by other wireless devices operating in the same ISM free band. There is also spectrum limitation and spectrum efficiency issues due to the high cost of acquiring a spectrum channel and poor spectrum utilization (only about 15 %) of the allocated spectrum is utilized.
To this end, to address the impairments and spectrum issues, a CRSN which is the combination of CR and WSN is proposed as adequate communication technology in SG which will enable power generation, transmission, distribution, utilities and customers to transfer,

monitor, predict, control and manage energy usage effectively and in cost efficient means.

The realization of CRSNs for smart grid mainly requires efficient radio resource allocation strategies to manage the DSA of cognitive radio sensor nodes in harsh SGs environmental condition. To meet the requirement of data rate and power constraints of the CRSN users, as well as to avoid interference, researchers all over the world are working hard to develop RRA scheme that will effectively manage radio resources. CRSN has the potential advantages of reconfigurability and DSA capabilities; to exploit these potential advantages of CRSN, a dynamic efficient RRA among the sensor nodes is essential.

The RRA has been well studied for various wireless networks, though not in the perspective of SG. Numerous surveys on RRA for different wireless networks such as cellular/LTE networks, cognitive radio networks (CRN), and WSN can be found in literature [112]–[116]. These works are not in the context of SG; they do not involve the integration of the wireless network into SG in their surveys. Only very few studies survey RRA in CRSN perspective. Yet, their emphasis is not on the intersection of CRSN in SG for the RRA. This chapter presents investigative and survey approach that focused on RRA in CRSN application in smart grids.

Surveys on RRA in CRSN for SG environments have been rarely conducted. References [117]–[119] conducted a survey on resource allocation in WSN. The study in [19]] surveyed works on RRA in CRSN. In their work, CRSN resource allocation scheme were categorized some optimization criteria for CRSN highlighted outside the context of SG consideration. Other studies which are not mainly on the survey of resource allocation but on some aspects of resource allocation strategies are found in [21], [120]-[126]. Reference [120] presented a survey of spectrum sensing methodologies for cognitive radio which was centered on spectrum sensing strategy. [121] conducted a research showing that resources in cognitive radio networks (CRNs) should dynamically be allocated according to the sensed radio environment.

Another work by Le and Hossain is in [122], which presented a RRA framework specifically for spectrum underlay in cognitive wireless networks. [123] studied resource allocation in Orthogonal Frequency Division Multiplexing (OFDM)-based cognitive radio network (CRN), under the consideration of many practical limitations such as imperfect spectrum sensing, limited transmission power, different traffic demands of secondary users.
Table 3.1 presents a comparative table on RRA survey in CRN, CRSN and CRSN based SG. It helps to exemplify whether surveys on radio resource allocation have been considered in CRSN based SG

Also, [124] studied the energy efficiency aspect of spectrum sharing including power allocation in heterogeneous cognitive radio networks with femtocells. [125], [117] - [119] presented a generalized survey works on WSNs. Resource allocation was generally dis-

Table 3.1: Comparison table on radio resource allocation in CRSN based SG

Survey References for resource allocation	CRN	CRSN	CRN based SG	CRSN based SG	Resource allocation
Tragos et al. [111]	Yes	No	No	No	Yes
Ahmad et al. [18]	No	Yes	No	No	Yes
Ireyuwa et al. [118]	Yes	No	No	No	No
Xie et al. [122]	Yes	No	No	No	No
Le et al. [101]	Yes	No	No	No	No
Yu et al. [133]	Yes	No	No	No	No
Khan et al. [29]	No	No	Yes	No	No
Akan et al. [20]	No	Yes	No	No	No
Gungor et al. [40]	No	No	Yes	No	No
Faheem et al. [12]	No	No	No	Yes	No

cussed in these works but the survey of resource allocation strategies was not their major target. [21] discussed issues regarding dynamic spectrum management in CRSN which does not provide any survey on resource allocation strategies. The authors in [126], [127] discussed CRN but radio resource allocation was not the main objective of their papers. Works reflecting survey in SG that highlight some aspect of resource allocation are found in [30], [41], [13]. They discussed spectrum sensing, they did not highlight resource allocation extensively such as including spectrum, QoS, fairness, priority, and power allocation scheme, and so on. Also, resource allocation scheme was not their main focus.

Some of the works focused on radio resource allocation in only CRN or CRSN or other aspects of wireless network without intersecting with the SG domain. None surveyed the integration of RRA in CRSN into SG. The studies which involve SG domain discussed some aspects of RRA without delving into full details of resource allocation schemes; and RRA was not the main aim of their studies. This chapter articulates the extension of works on radio resource allocation into SG domain. Hence, the focus here is to explore radio resource allocation in CRSN based SG, thus leading to the following contributions:

- A comprehensive survey of RRA in CRSN based SG is presented.
- The overview, functionalities, unique characteristics and challenges of CRSN in SG are discussed.
- Radio resources optimization criteria in CRSN based SG are also discussed in this chapter.
- Also, RRA scheme in CRSN based SG including its architecture are presented.

Suggestions and future research directions concerning RRA in CRSNs based SG are highlighted. The remainder of this chapter is structured in subsections as follows: Description of the overview, functionalities and unique characteristics of CRSN in a SG; radio resource allocation in CRSN based SG; recommendations and future research direction are discussed. Finally, the chapter is summarized.

3.2 Overview, Functionalities, Unique Characteristics, and Challenges of CRSN in SG

3.2.1 Overview of CRSN

In a CRSN, there are two types of users: primary and secondary. Primary users (PUs) are the licensed (authorized) users, which have the license to operate in an allotted spectrum band so they can access the primary base station. Secondary users (SUs) or the Cognitive Radio users (CRs) are unlicensed users without a spectrum license. CRs use the existing spectrum through opportunistic access without causing harmful interference to the PUs. CRs look for the available portion of the spectrum that are not in use, which are called a spectrum holes or White Spaces. The SUs can share the spectrum channels with the PUs by using one of the two method known as: overlay and underlay method. In overlay method, SUs can opportunistically access the PU 's spectrum channels only if the channels are completely not in use by the PUs. Whereas, in the underlay method, the SUs can simultaneously access the PU 's channels even when the PUs are using the channels, so long as the harmful interference caused to the PUs is below a predetermined threshold value.

However, there are problems associated with the two methods: overlay, and underlay method in CRSNs. For instance, in the overlay method, some wireless services such as TV and cellular network, the PUs channels may be busy predominantly for a long time, resulting to no white space. Hence, the SUs may be unable to opportunistically access the spectrum channels since there is no white space available in the PUs network. On the other hand, the problem in the underlay method involves the inability of the SUs to opportunistically access channels in an area predominantly deployed with PUs. This is because more interferences will be caused to closely located PUs, thereby making it difficult for the SUs to access these channels amidst state of interference. Therefore, it is essential to solve these problems that are associated with the overlay and underlay methods in CRSNs. Consequently, this work employs the overlay method in CRSNs. Throughout this thesis, the overlay method is adopted, in which the SUs use the optimal available channel only if there is no PU operating in the licensed bands [39].

Importantly, the problem of the inability of the SUs to access channels in overlay method has been addressed in chapter five. The work has been published as seen in [128]. In the work, Channel fragmentation strategy (CFS)-based Alamouti space-frequency block coded (SFBC) scheme was used to improve the performance of the SUs network. The details of this scheme is presented in chapter five of this thesis.

3.2.2 Functionalities of CRSN

The CRSN has the following cognitive functionalities to enable the secondary users to have dynamic and opportunistic access to the spectrum holes [129] these functionalities are spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. These four main cognitive radio functionalities are required to determine the accurate communication parameters of SG communication and adjust to the dynamic radio environments [130].

3.2.2.1 Spectrum Sensing

Spectrum sensing is the process of discovering available spectrum bands and detection of spectrum holes in PUs [131]. Spectrum sensing operation is an enormous power-consuming function and poses great challenges to provide seamless communications in large-scale SG deployment. Therefore, some solutions need to be deployed to achieve viable CRSN based SG communications. Minimum hardware, for example using single radio, and less advanced spectrum sensing functionalities can be used to lower the complexity level of sensing operations and reduce energy consumption [41].

Also, reducing the sensing durations to an appreciable level can be a good solution. There are various spectrum sensing techniques, such as energy detection, feature detection, matched filter, and interference temperature [130]. Using one or combination of these methods can be achieved.

Generally, spectrum sensing comes with additional energy consumption. Hence, there is a trade-off between sensing accuracy and energy efficiency. Therefore, an optimized DSA is required in order to address the spectrum accuracy which involves lowering of packet collisions and the ability of switching to the best available channel including less contention delay and enhanced bandwidth.

On the other hand, spectrum sensing faces the challenge of being absolutely sensitive in detection mechanism due to harsh environmental conditions such as multipath fading and environmental noise in a SG environment. However, an optimized DSA will help in addressing this.

3.2.2.2 Spectrum Decision

Spectrum decision process involves two steps, viz: spectrum characterization and spectrum selection, which are the necessary steps to characterize the spectrum band in terms of the received signal strength, interference, power of transmission and energy efficiency, number of communication users, QoS, and security requirements of SG applications [132].

Therefore, providing QoS-aware cognitive communication network is highly essential in choosing the appropriate spectrum band to meet the specific requirements of CRSN based SG communications in spectrum decision process. However, SG system environment has a distributed nature, and interference from radio signal, network density, and channel characteristics vary over a wide geographical area, which limits obtaining optimal knowledge about spectrum availability. Consequently, this problem poses great challenges in making precise spectrum decisions and meeting QoS requirements of CRSN SG applications.

3.2.2.3 Spectrum Sharing

Spectrum sharing process involves the selection of the best channel and power allocation, and some of the functionalities are related to the main functionalities of medium access control (MAC) layer protocols. Hence, it can be incorporated into the MAC layer. However, there are challenges associated with efficient spectrum sharing which include time synchronization and distributed power allocation [133]. For instance, methods of controlling power are essential for spectrum sharing process in large SG deployments so as to adapt to the radio environments and maximize the network life-time [134]. Moreover, precise time measurements and time synchronization are required for some SG applications, such as equipment fault diagnostics and phasor measurement monitoring applications.

An effective spectrum sharing techniques helps to meet QoS requirements in CRSN SG by adaptively allocating communication network resources. The opportunistic dynamic spectrum access capability can be used to adjust the communication transmission parameters to lessen redundant power consumption of CR sensor nodes thereby preventing the performance degradation of CRSN based SG communications.

3.2.2.4 Spectrum Mobility

Spectrum mobility which is also called spectrum handoff is used to mitigate the interference caused by SG communication infrastructure. Spectrum handoff occurs when changing the physical regions of the existing congested communication path or switches the currently used spectrum band [107]. In both cases, the QoS requirements for the current SG communication transmission will be affected. Hence, the choice of the switching activities should be made with respect to the requirements of different SG applications [130]. However, spectrum mobility passes interference to the current communication transmission. Because of this, schemes to prevent buffer overflows and minimized communication contention delay should be developed in order to allow for seamless, reliable and real-time monitoring in CRSN based SG [135].

3.2.3 Unique characteristics of CRSN

CRSN has numerous unique characteristics that differentiate it from the conventional wireless networks such as cellular/LTE, satellite/microwave and Wi-Fi; and since it incorporates the cognitive capabilities of CRN into WSN. It therefore differentiates itself from CRN and WSN. Hence, it has a unique feature (possessing dualized features: CRN and WSN). These unique characteristics of CRSN include:

- Capabilities of sensing the current radio frequency spectrum environment.
- Policy with configuration repository: Policies specifies how the radio is to be operated, while the repository are usually sources used to constrain the operating process of the radio to remain within regulatory or physical limits
- Dynamic Spectrum Access (DSA) capabilities with multiple channels availability
- Spectrum hand-off capabilities
- Adaptive algorithmic mechanism- During radio process, the cognitive radio is sensing its environment, following the constraints of the policy and configuration by exchanging with sensor nodes to best employ the radio spectrum and meet user demands.
- low traffic flow
- Reconfigurability and distributed cooperation capabilities
- limited memory and power constraints.

Due to the presence of these unique features of CRSN, the radio resource allocation schemes that are used for conventional wireless including WSN cannot be directly applied to CRSN due to the dynamic availability of multiple channels in CRSN, and the dynamic spectrum access in the presence of primary user activity. Hence, while designing resource allocation schemes for CRSNs, their unique features should be considered as well as the primary user activity consideration.

3.2.4 Challenges of CRSN in SG

There are challenges associated with a CRSN, which can adversely affect adequate resource allocation within a CRSN in a SG. They are described below:

3.2.4.1 Intermittent channel availability for a SU network

PU activities can cause intermittent channel availability to a SU network. This is because whenever a PU arrives to use the channel, the SU relinquishes it. When this occurs too frequently, it mars the correct communication of the CRSNs for adequate resource allocation.

3.2.4.2 High bit error probability of detection of the PU

When the SU has a high probability of an error in the detection of the presence of a PU, it will lead to false detection which affects the SU network negatively or causes harmful interference in the PU network. Hence, this issue is a research challenge which requires the mitigation of the high probability of an error in detection by the SU.

3.2.4.3 Problem of limited spectrum holes due to PU activities

Frequent PU activities will lead to fewer spectrum holes. There can impact adversely on the performance of the SU network. Creating multiple spectrum channels for the SU will lead to more spectrum holes which will help to avert the problem. Part of this challenge is addressed in Section 4.4, where performance analysis was carried out in order to establish a suitable spectrum band with more white space for CRSNs in a SG.

3.2.4.4 Adequate protocol for CRSN in a SG

Protocols that are suitable for a CRSN in a SG are in their infancy since a CRSN is a new paradigm and its protocol is quite different from that of a conventional wireless system which has higher computational complexity. It is different from a conventional WSN which has lower complexity, but the computational complexity for a CRSN is of medium complexity; hence, it requires protocol that matches its functionalities which will help to realize adequate resource allocation in a SG communication system. Its protocol is unique due to the dynamic multiple channel access, whereas the protocol for conventional wireless has fixed channel access.

There are other problems that affect communication infrastructure including CRSNs in a SG environment. For example, power frequency electromagnetic fields and radio frequency (RF) noise exist in the SG environment due to corona and partial discharges, solid-state and substation switching devices, and circuit breaker switching, including commutating processes [136]. These can result in electromagnetic interference (EMI) issues which are known to cause interference and failure of electronic devices and communication infrastructure [136]. These disturbances and environmental changes negatively impact communications infrastructure and its operation.

Therefore, communications infrastructure needs to be strong enough to operate in harsh SG environments. The International Special Committee on Radio Interference (CISPR) investigated radio noise originating from high voltage (HV) power equipment and provided recommendations for reducing the radio noise generated in SGs [137]. Impulse noise has been investigated in HV substations including its influence on the performance of wireless channels and modulations [138]. EMI impacts on SG wireless communication equipment and this was studied in [139]. Hence, it is necessary to define the appropriate compliance requirements in a SG to ensure reliable performance of the wireless communications infrastructure.

To this end, the International Electrotechnical Commission (IEC) has enacted the following key immunity compliance requirements for use in SGs with regards to the communication network infrastructure:

- IEC 61850-3 - Part 3: General requirements for communication networks and systems for SG utility automation.
- IEEE 16.13-2003 - IEEE standard environmental and testing requirements for communications network infrastructure in SG Substations.
- IEEE 16.13.1-2013 - IEEE standard environmental and testing requirements for communication network infrastructure Installed in SG transmission and distribution facilities.

Consequently, RRA in CRSNs for other applications is different from the RRA in CRSNs for SG applications. That makes this survey quite different from other related surveys on CRSNs. Hence, RRA in CRSN for SG applications should be based on the following considerations:

- Consideration of key immunity compliance requirements for the CRSN in a SG as stated earlier.
- Appropriate resource allocation architecture to cope with the EMI in the SG environment.
- Consideration of appropriate electromagnetic comparability (EMC) for the CRSN to operate effectively in a varying EMI SG environment.

based on the forgoing, the work reported throughout in this thesis is based on the Consideration of key immunity compliance requirements for the CRSN in a SG.

3.3 RRA in CRSN based SG

3.3.1 Radio Resource Optimization Criteria

RRA involves strategies or schemes of allocating radio resources such as frequency bands, channels, and transmit antenna to the channel state information based on some optimization criteria. Optimizing these radio resource criteria will go a long way in improving the overall performance of the CRSN in SG environment. Hence, the aim is to utilize the limited spectrum, constraints power and network infrastructure efficiently. The summary of literature with respect to various resource optimization criteria used in different context of CRSN has been tabulated in Table 3.2. This table highlights each resource optimization criterion used in the different context of CRSN including CRSN based SG. One can infer from the table that the utilization of optimization criteria for RRA in CRSN based SG is limited. In this scenario, resource optimization criteria such as energy efficiency, throughput maximization, and adaptive modulation are yet to be applied in CRSN based SG. Hence, research attention should be drawn in this direction.

Table 3.2: Summary of Resource Optimization Criteria for CRSN based SG

Resource optimization criterion	CRSN	CRN based SG	CRSN based SG	References for various optimization
Energy efficiency	Yes	Yes	No	[41], [39], [147], [140], [73]
QoS guarantee	No	Yes	Yes	[133], [104],[142]
Throughput	Yes	No	No	[143], [142]
Interference mitigation	Yes	Yes	Yes	[142], [144], [145]
Fairness	Yes	No	Yes	[142], [141]
Priority scheduling	Yes	Yes	Yes	[142], [145]
Adaptive modulation	Yes	No	No	[146]
spectrum handoff	Yes	Yes	Yes	[140], [147]

The following optimization criteria are considered:

3.3.1.1 Energy Efficiency

Realizing energy efficiency with power algorithm schemes is usually required to extend the lifetime of the battery power of the sensor node. Energy efficiency criterion is highly necessary for CRSN in SG, because the sensor nodes have limited power battery constraints. However, the schemes used for this criterion are based on energy preservation and power consumption minimization which cannot achieve maximum power performance. Energy/power efficient schemes for CRSN related applications in general and in SG have been widely studied in literature [73], [140]. Since SG applications are mission critical, it is essential to incorporate an energy harvesting scheme in the energy efficiency so as to provide a perpetual lifetime to the sensor node.

3.3.1.2 QoS Guaranteed

SG has various applications with different and stringent QoS requirements. Hence, the design of RRA schemes should put into consideration different QoS support for the SG applications. Resource allocation schemes involving CRSN applications that considered the QoS requirements are found in [141], [104]. [142] considered QoS guarantee for heterogeneous traffic of SG applications such that each traffic type has an associated priority with specific QoS support. QoS support is very imperative especially for SG surveillance and multimedia applications including distribution automation [102].

3.3.1.3 Maximizing throughput scheduling

Giving scheduling priority to data flows in terms of consumed network resources per amount of information transferred will help to maximize total throughput of the CRSN based SG. Scheme utilizing throughput maximization scheduling based criterion in CRSN applications have been investigated in [143], [142].

3.3.1.4 Interference Mitigation and Avoidance

Destructive interference from the external network to the CRSN based SG network should be avoided. Also, co-channel interference within the network as well as interference to the primary networks should be mitigated or cancelled. This interference avoidance and minimization criterion improves both the primary and secondary networks. RRA scheme that utilized this criterion in protecting the links of both the primary users and the secondary network has been well studied in [144], [142]

3.3.1.5 Fairness Scheduling Criterion

Fairness among Secondary Users in opportunistic spectrum access and scheduling and fairness in transmitting power allocation to Secondary Users are essential in the design of RRA schemes for CRSN based SG. Since there is trade-off among QoS guaranteed, maximum throughput and fairness, consideration of fairness among multiple sensor node in prioritizing traffic should be done in such a way that throughput maximization and QoS support must be maintained as well as in the CRSN based SG network. Work that utilized this fairness criteria in SG is in [142] which considered QoS guaranteed for heterogeneous traffic of SG applications such that each traffic type has an associated fairness. RRA strategies that utilized fairness criterion are also found in [142].

3.3.1.6 Priority Scheduling Criterion

The need to prioritize various SG applications traffic is essential in the capability to adapt to varying network conditions in real time [145]. A typical traffic type in smart grid applications is the control commands having small packet size [145]. Hence, prioritizing traffics types per their order of importance, bandwidth/spectrum demand, real time, and power of consumption is highly beneficial in CRSN based SG domain. Prioritizing traffic in CRSN based SG was also considered in [142].

3.3.1.7 Reduced Adaptive Modulation Overhead

The adaptive modulation scheme in CRSN based SG dynamically adapt to other modulation type due to the DSA capability. This leads to overhead as well as supplemental energy consumption, which results from the adaptation or switching to other modulation types

[146] at the sensor node. Hence, there is need to design RRA scheme in CRSN based SG that has reduced complexity of the adaptive modulation mechanism.

3.3.1.8 Reduced Spectrum Hand-offs

Spectrum hand-off occurs too often in CRSN applications. This leads to overhead as well as extra energy consumption at the sensor nodes. Incurred in hand-off, the buffer overflows and results in packet losses which affects the transmission reliability. Studies employing this criterion for RRA in CRSN applications have been well reported in [140], [147]. The authors in [140] presented a reduced handoffs technique using a home gateway (HGW) for home area network in a cognitive radio based SG. Whereas [147] investigated a resource allocation scheme involving reduced spectrum handoff for CRSN applications.

3.3.2 RRA scheme architecture

RRA scheme architecture in CRSN based SG is divided into three groups. They are: centralized architecture, cluster architecture and distributed architecture. The resource optimization criteria which have been highlighted in the preceding section are implemented based on each specific resource allocation scheme architecture. A look at these architectures refers the following:

3.3.2.1 Centralized Architecture

Centralized radio resource allocation scheme consists of the central node or sink node which serves as a base station that is responsible for providing network operation services such as spectrum allocation, power/energy control, node localization, link/modulation adaptation and routing among the sensor nodes. A logical topology for this architectural approach is a star network as illustrated in Fig. 3.1. The centralized scheme can be classified per how the information is processed which include the following: single sink, multi sink (for large coverage area and redundancy), multiple task devices (for auxiliary devises and specific task within the network). Radio resource allocation are made based on selected optimization criteria by the sink node which are then communicated to the sensor node. The selected optimization criteria may be to address more than one or two criteria. Centralized architecture schemes in CRSN related applications have been well investigated in [140], [147]-[148], [149], [142] There are several advantages of centralized schemes, the main advantages includes
(i) simplified energy efficient management.
(ii) conflicts avoidance in the transmission and reception link because the sink node coordinate every sensor node.
However, there are some disadvantages in this architecture. The main disadvantages of these schemes include

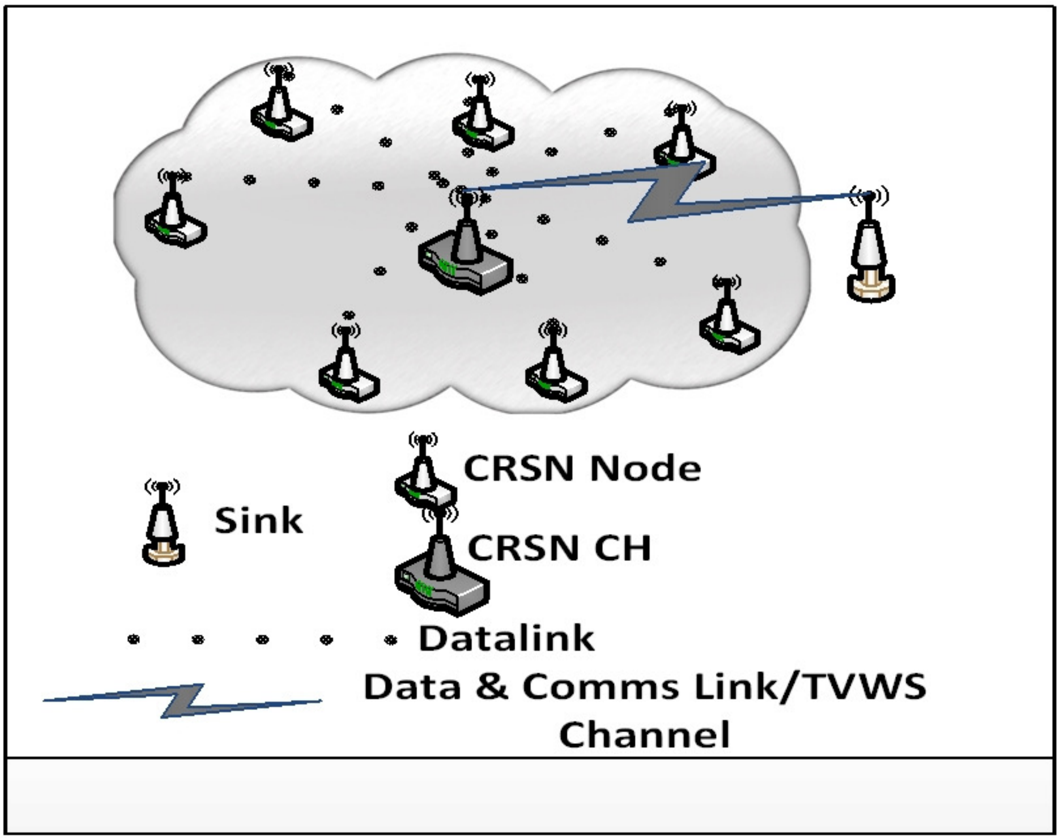


Figure 3.1: Centralized resource allocation architecture for CRSN based SG

(i) the network cannot support large density sensor nodes
(ii) there is high signaling overhead leading to huge consumption of energy

3.3.2.2 Cluster Architecture

On a logical topological level, cluster architecture is accomplished by grouping CRSN nodes within a smaller sub-network transmission area. A designated node usually known as Cluster Head (CH) controls this group of sensor nodes as shown in Fig. 3.2. The CH performs similar role of allocating resources like that of the sink node in centralized scheme. However, the CH has lesser overhead and utilized lesser power for the common control channel in each cluster compared to the sink node in centralized scheme. Hence, this schemes can achieve better spectrum use with the help of the distribution of nodes in several cluster and bandwidth reuse. Cluster schemes have been well studied in [150]. A closer cluster member can perform the role of CH if CH encounter any failure. Since there are small number of cluster members in each cluster, this leads to low signaling overhead at each CH compared to the overhead at the sink node of centralized architecture approach. The main advantages of this scheme are: (i) Information is local since a sensor node keeps the information of its neighboring node within a cluster.

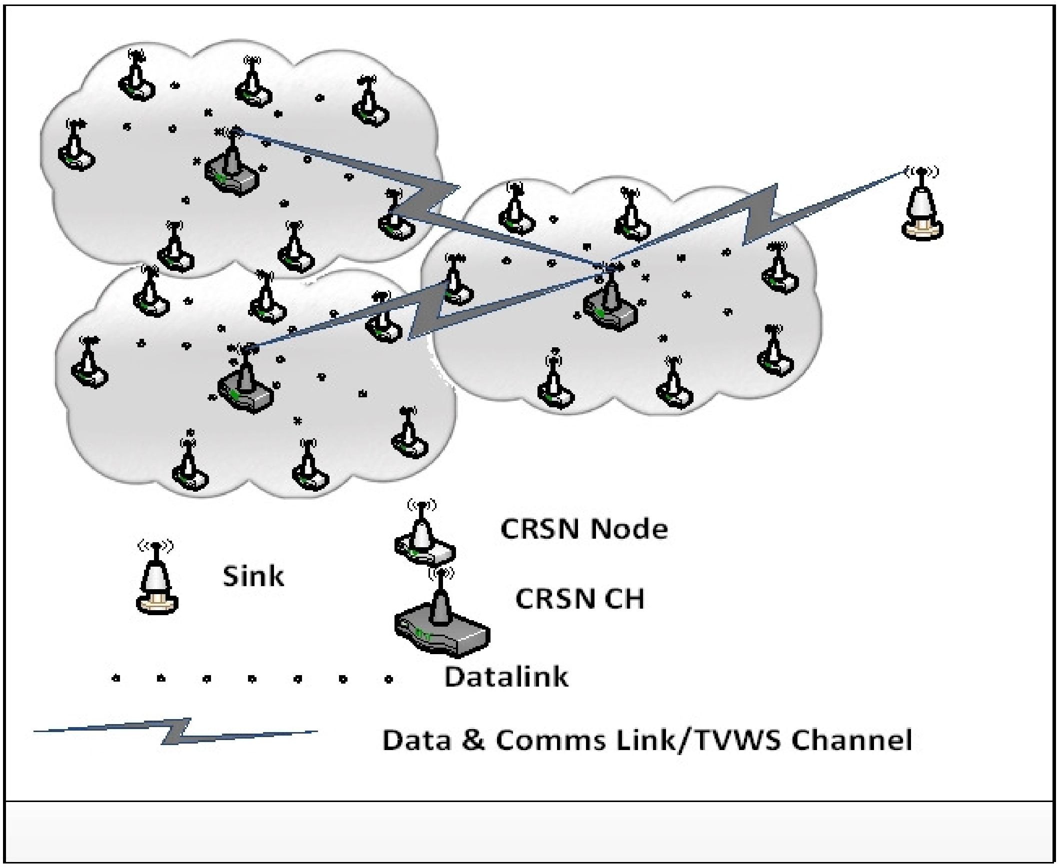


Figure 3.2: Cluster resource allocation architecture for CRSN based SG

(ii) cluster architecture is scalable.
(iii) Reconfiguration is done locally on only the affected part. However, there are some drawback in this architecture, the main drawback is the high number of broadcast which is equal to the number of clusters; thus, leading to broadcast storm in the network.
Another disadvantage of cluster architecture, is the prolonging of PUs activities, which leads to delay in SUs transmission.

3.3.2.3 Distributed Architecture

In distributed architecture, each CRSN node makes its transmission decision in an independent manner. In addition, neighboring sensor nodes can cooperate with each other for transmission decision. There is no central or base station node among the sensor nodes on the cooperation communication, distributed resource allocation schemes can be either cooperative distributed resource allocation or non-cooperative distributed resource allocation. These schemes can quickly adjust to changes, and are robust to time changing wireless environment. For example, if an area of the network is disturbed, only the sensor nodes in the affected area will need to update their transmissions mechanism which is a relatively faster process whereas in the case of centralized architecture the resource allocation for all the sensor nodes will be updated.

In addition, the distributed schemes have lower signaling overhead as well as faster decision process. The advantages of distributed schemes are synonymous to cluster scheme, however, with an additional advantage of reduced power of consumption at every sensor nodes. The major disadvantage is that connectivity cannot be assured since each node makes decisions on local information which may include error or malicious activity spread by the neighboring nodes which renders distributed resource allocation to weak optimal solution. Distributed architecture resource allocation in CRSN related applications has also been studied in [73], [144], [102], [151]. Example of distributed resource allocation architecture for CRSN based SG is shown in Fig. 3.3.
A hybrid scheme, that is, a combination of different architecture is suggested to overcome the drawback of a single architecture. Hence, a Distributed Heterogeneous Cluster (DHC) is proposed in order to overcome the disadvantages of a single architecture. The DHC topology is presented in the subsequent sections. Table 3.3 summarized schemes with

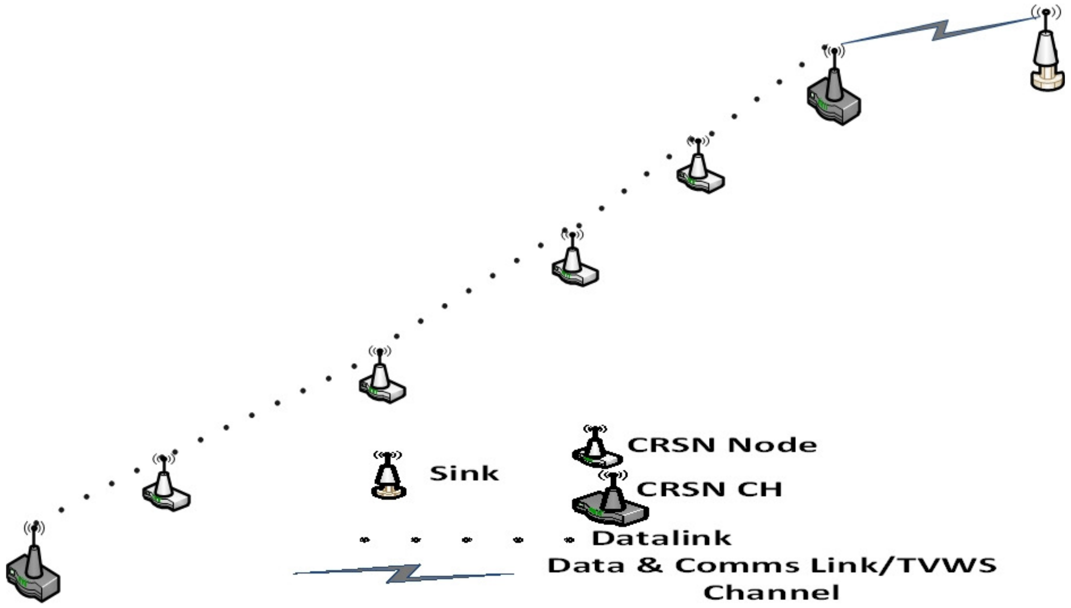


Figure 3.3: Distributed resource allocation architecture for CRSN SG

multiple optimization criteria consideration as well as cross layer framework consideration in different CRSN contexts. From Table 3.3 with respect to the references, it is obvious that a lot of radio resource allocation schemes have been applied to CRSN applications in general. However, the application of RRA schemes in CRSN/CRN based SG is not yet predominant. Also, schemes with multiple optimization criteria, that is, schemes having two or more resource optimization criteria, are very few with regards to CRSN based SG. In addition, only one scheme with cross layer framework is applied to CRSN based SG.

Utilizing cross layer framework in radio resource allocation will improve communication in SG. This is because the protocol stack in the bottom and upper layer of the sensor nodes and wireless device will exchange information seamlessly through a common control channel without delay, and complexity. In general, scheme with multiple optimization criteria and cross layer framework will improve radio resource allocation in CRSN based SG.

Table 3.3: Summary of cross layer framework with respect to various radio resource allocation schemes for CRSN based SG

References for resource allocation schemes	CRSN	CRN based SG	CRSN based SG	Scheme with multiple optimization critaria	Cross layer framework consideration
Yu et al. [137]	No	Yes	No	Yes	Yes
Ayala et al. [141]	Yes	No	No	Yes	No
Naeem et al. [111	Yes	No	No	No	No
Byun et al. [138]	Yes	No	No	Yes	No
Gao et al. [144]	Yes	No	No	No	No
Ahmad et al.[19]	Yes	No	No	No	No
Shah et al. [145]	No	No	Yes	No	Yes
Zhang et al. [142]	No	Yes	No	Yes	No
Phuong et al. [157]	Yes	No	No	Yes	No
Luo et al. [150]	No	No	Yes	No	No
Liu et al. [148]	Yes	No	No	No	No

3.3.2.4 Distributed Heterogeneous Clustered (DHC) Architecture

The DHC architecture has been proposed for RRA in CRSN based SG deployment, which is published in [152]. Details of the DHC scheme are presented in chapter six. The DHC is adopted in order to leverage multiple performance improvement criteria. The architecture consists of heterogeneous CRSN nodes such as normal ZigBee CR nodes, actuator, and multimedia sensor nodes. It is suitable for providing network operation services such as spectrum allocation, energy control, node localization, and link/modulation adaptation among the sensor nodes. A logical topology for this architectural approach is illustrated in Fig. 3.4. The allocation of radio resources here is done in a distributed clustered manner covering an extensive and long range area. This scheme is suitable for a SG application, based on the fact that a SG requires heterogeneous networks in supporting different QoS for the various SG applications. Since this architecture is a newly introduced scheme, only very few schemes utilize this architecture for RRA in a CRSN based SG. The main importance of the DHC architecture is that it circumvents the disadvantages in centralized and distributed architecture while leveraging all the benefits of other architectures. DHC architectures consider the EMC in order to operate optimally in a varying EMI SG environment. These schemes can quickly adjust to changes, and are robust to time varying wireless and EMI environments.

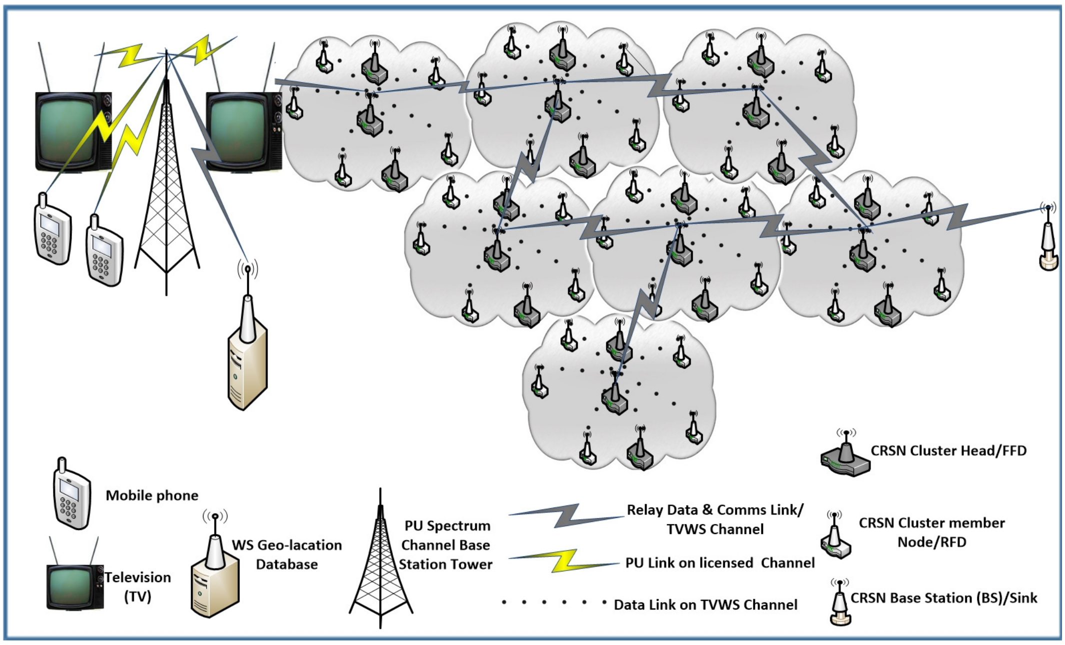


Figure 3.4: CRSN Distributed Heterogeneous Cluster (DHC) Topology

The improvement of the DHC scheme to support energy efficiency, multi-channel sensing coverage model including guaranteed network connectivity in CRSN based SG deployment is presented in chapter six. Notable schemes of DHC architecture for RRA performance improvement are found in [124], [150], [156]. Ref. [124] proposed the energy efficiency aspect of spectrum sharing including power allocation in heterogeneous CRNs using a Stackelberg game with femtocells. Though this scheme is not specifically for the SG environment. Ref. [150] proposed a queuing theoretic model of the important components of a CRSN using the bandwidth of a heterogeneous network, including service rate heterogeneity and proactive priority for primary users. Ref. [156] proposed a probability of detection mechanism using a moment generating function and a maximum ratio combiner (MRC) for performance improvement of radio resources in a multi-channel CRSN based SG.

3.3.3 Performance analysis of RRA based on throughput improvement criteria in CRSN for SG

3.3.3.1 Concepts and simulation experimental setup

PU activities can impact on the performance of the SUs or CRSN users in Overlay method of CRSNs. Frequent and large numbers of PUs activities will lead to fewer spectrum holes. However, making SU to support multiple SU spectrum channels will lead to more spectrum holes or white space. Multiple channels together with high bandwidth is adequate for the enhancement of the throughput of the SUs [157]. Hence, making CRSN users operate at a higher frequency band (UHF: 470-868 MHz or higher) during certain PU activities will create more channels thus improving the throughput performance of the CRSN users. Whereas a lower frequency band (VHF: 54-216 MHz) for the CRSN users, operating with the same conditions as the PU activities, will adversely impact on the throughput performance of the CRSN users due to limited spectrum holes and fewer channels. The methodology of making SU to operate on multiple spectrum channels is presented in chapter five. However, this chapter carries out evaluation of suitable channel bandwidth for SUs network.

An investigation was carried out using NetSim simulation and modelling software for the performance analysis of the SU or CRSN throughput in order to establish a suitable spectrum band for the CRSNs in a SG network. NetSim is a network Discrete Event Simulation (DES) software package for protocol modelling and simulation. It allows for analysis of networks with unmatched depth [158], [159]. Table 3.4 shows the network parameters used for modelling a CRSN base station and CRSN module users in three spectrum bands: 54-80 MHz; 54-216 MHz; and 54-802 MHz respectively. The experiment was modelled with a SG custom application. The SG application is generated from the SG application server via CRSN base station transmitter with a packet size of 1460 bytes. The packet size is then transmitted by broadcast to twenty CRSN modules for the SG data services. Table 3.4 shows the CRSN configuration parameters. And Table 3.5 shows the SG application parameters

Table 3.4: CRSN configuration parameters

CRSN Base station parameters	
Device name	Base Station
Modulation	4 QAM
Pathloss	30 dB
Coding rate	(1/2)
Transmission power	5 mW
Multipath fading	Nakagami-q
Channel Bandwidth	6 MHz
Frequency (varies with each scenario)	54-80 MHz/54-216 MHz/54-802 MHz
Distance	1 KM
CRSN Module parameters	
Device name	CRSN Modules
Transmitter power	5 mW
Modulation	4 QAM
Pathloss	30 dB
Transport Layer protocol	UDP

Table 3.5: SG Application parameters

Device name	SG_Application Server
Application Method	Broadcast
Application Type	Custom
Application Name	DRM
Source ID	SG_Application Server
Destination ID	CRSN Modules
Start Time (s)	0 s
End time (s)	90 s
Packet size (bytes)	1460 bytes

3.3.3.2 Simulation Results and Analysis of Throughput of CRSN in SG

The simulation was conducted in Netsim under the same severe propagation conditions (30 dB) of SG in three different spectrum bands: 54-80 MHz; 54-216 MHz; and 54-802 MHz respectively. The aim of the simulation experiment is to analyze the throughput of the CRSN link in different spectrum bands with severe SG environmental conditions. There are the same PU activities in the three scenarios in order to ascertain a suitable frequency spectrum for an optimal throughput. A data packet of 1460 bytes for the SG application was transmitted to be received by the CRSN nodes. The results of the CRSN link moving average throughput were obtained and are shown in Figures 3.5 to 3.7 Fig. 3.5 shows Scenario 1: a moving average throughput of 0.23 Mbps is obtained at the initial phase of the transmission. This reduces, then levels off up to about 10000 ms. It then reduces to 0.12 Mbps at 17500 ms. It increases again to about 0.15 Mbps at 31000 ms and decreases. It then continues erratically with attainment of below 0.15 Mbps throughput throughout the transmission duration. Fig. 3.6 shows Scenario 2: a moving average throughput of

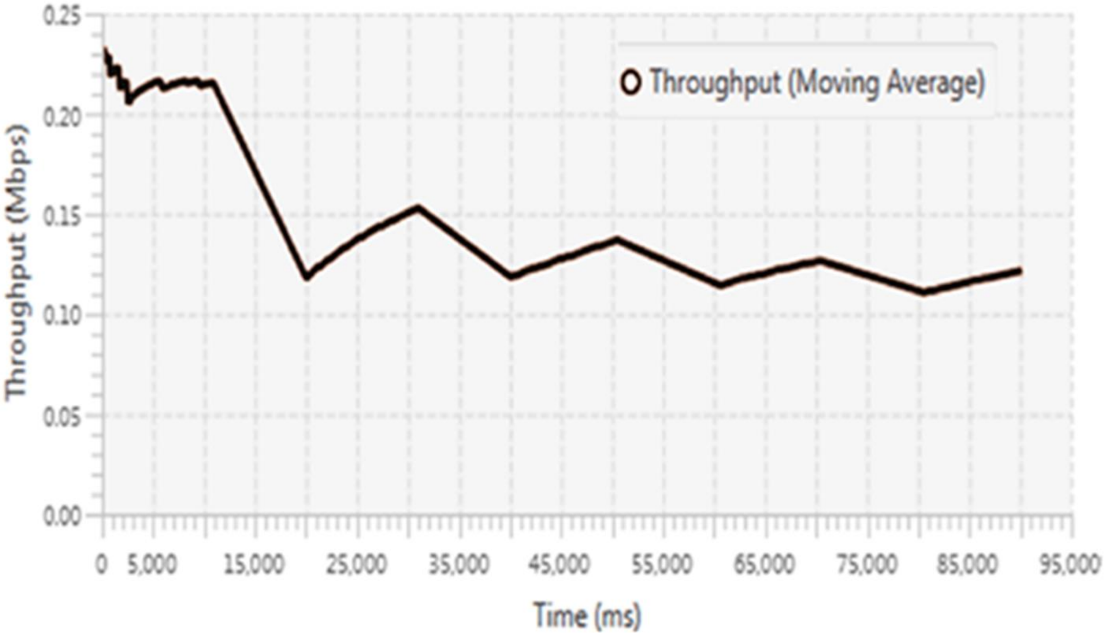


Figure 3.5: Scenario 1: 54 MHz to 88 MHz

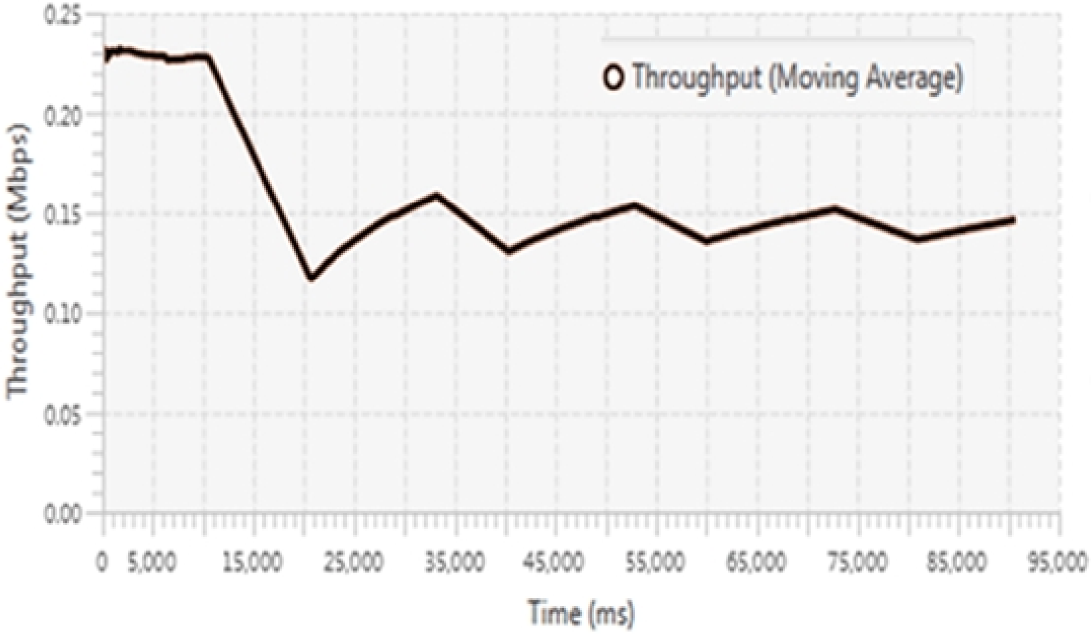


Figure 3.6: Scenario 2: 54 MHz to 216 MHz

0.23 Mbps is initially obtained and this starts reducing at about 10000 ms and resumes at about 20000 ms. A throughput of 0.15 Mbps is attained at 30000 ms. It then starts reducing again at 33000 ms. It continues erratically with an attained throughput that is about 0.15 Mbps throughout the transmission duration.

Fig. 3.7 shows Scenario 3. A moving average throughput attainment of 0.23 Mbps at

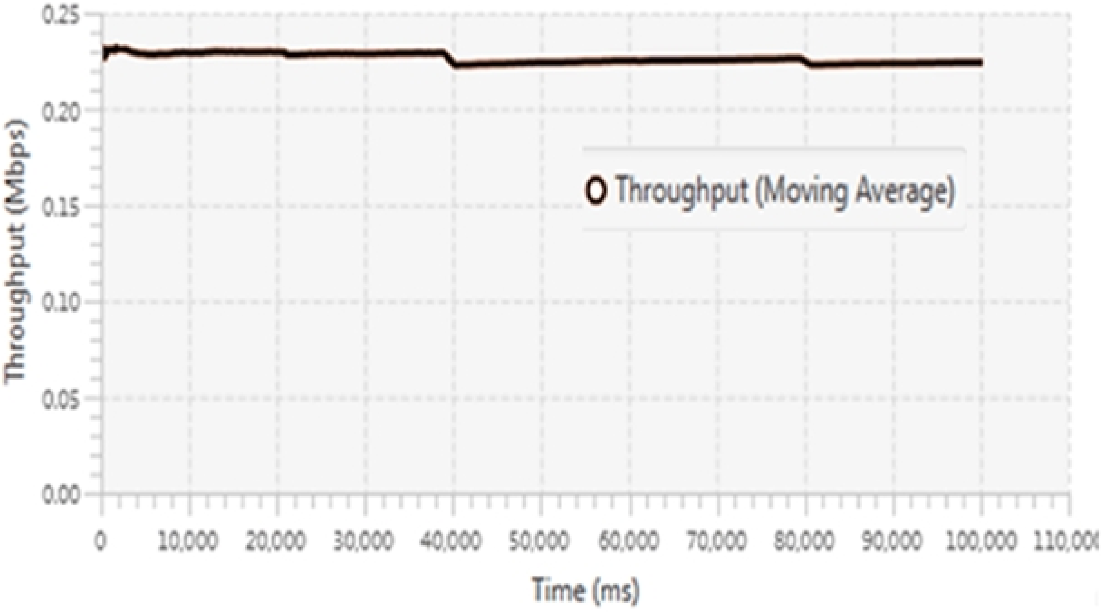


Figure 3.7: Scenario 3: 54 MHz to 802 MHz

the initial phase of the transmission. This continues steadily with negligible throughput fluctuation, and maintains 0.23 Mbps throughout the transmission duration.

Overall, the higher frequency spectrum with more channel availability gives a steady throughput. This gives rise to optimal appreciable throughput of the CRSN in a SG. Because the throughput is necessary for network connectivity in the CRSNs radio resources such as a spectrum channel to be efficiently allocated to CRSN nodes. Whereas, the lower the frequency spectrum, which usually has less available channels, has lower throughput attainment with unsteady conditions. This latter case is not suitable for SG applications that are mission critical. The higher spectrum bands are associated with more channels compared with lower frequency bands which are usually associated with less available channels.

Hence, a CRSN for SG communications should be developed to accommodate higher spectrum bands with multiple available channels of over 800 MHz bands in order to leverage spectrum hole from both digital TV and some 4G/LTE frequency bands.

3.4 Future Research Direction and Suggestions

Smart grid requires reliable and timely delivered sensed data to meet the expectation of various SG applications in satisfactory service delivery. The traditional or conventional SG used probable WSN for monitoring and control in delivering the sensed data. This WSN makes used of static resource allocation to statically allocate resources to the sensor node and communication devices. To this end, the CRSN paradigm makes used of dynamic resource allocation due to the presence of dynamic spectrum access (DSA) capability.

This CRSN paradigm thrives well to dynamically allocates radio resources to sensor nodes and communication devices in a SG ecosystem. Hence, CRSN makes used of dynamic resource allocation schemes to allocate resources optimally among multiple resource competitive sensor nodes. As seen from the preceding section, the dynamic resource allocation schemes improve energy efficiency in the communication devices, for example, it helps to extend the battery power life of sensor nodes. Unfortunately, the energy efficiency schemes in terms radio resource allocation are lacking in CRSN based SG.

Also, looking at Table 3.2, schemes for adaptive modulation and throughput maximization are lacking in CRSN based SG. In addition, schemes that covers multiple resource optimization criteria. To this end, the authors believe that designing a holistic cross layer scheme that accommodates energy efficiency, throughput maximization and adaptive modulation while leveraging optimization criteria such as interference avoidance, hand-offs reduction, fairness, priority, and QoS support will go a long way in yielding optimal results in CRSN based SG monitoring and control.
Many SG applications such as distribution automation, demand response, SCADA, surveillance and multimedia applications including security of automatic metering infrastructure (AMI) are research critical. Hence, a robust and reliable communication that can withstand harsh environmental SG condition are required to meet the demand of these research critical application. Based in this, attention should be drawn to the direction of design and optimization of a cross layer framework for seamless exchange of signaling and control information across the protocol layers of the sensor node and communication device for CRSN based SG.

It is pertinent therefore to also note that research is highly needed in the development of unified solution schemes that accommodate three or overall of resource optimization criteria for CRSN based SG. Specifically, research should be directed towards energy efficient adaptive modulation, energy efficient throughput maximization, energy efficient spectrum access, and hand-offs reduction. In fact, the energy efficiency issue is an open research direction in CRSN based SG domain. A hybrid energy harvesting that utilized radio frequency alongside other mechanisms for harvesting energy perpetually for the power constraints sensor node remains an open research subject in the domain of SG generally.

3.5 Chapter Summary

In this chapter, CRSN based SG as a new paradigm for modern SG which is totally different from the traditional power grid and also different from the conventional grid is introduced. The existing power grid uses static resource allocation technique to allocate resources to sensor nodes and communication devices in the SG network. Radio resource allocation that leverage DSA capability to dynamically allocate radio resources to the sensor nodes and communication devices in CRSN based SG environment is explored. The overview, unique characteristics, functionalities, and challenges of CRSN in SG are discussed.

Also, a proposed DHC architecture is presented in this chapter. Radio resource optimization criteria which is an important consideration for resource allocation in CRSN based SG has been highlighted. The various resource allocation schemes, i.e., RRA architecture in a CRSN based SG, have been presented in this chapter. Performance analysis of RRA based on throughput improvement criteria in CRSN for SG is also reported in this chapter. Suggestions are made in order to improve communication device connectivity and seamless communication among multiple resource competitive sensor node in the CRSN based SG ecosystem. Future research direction which include design and optimization of cross layer framework for radio resource allocation in CRSN SG has been highlighted.

Finally, energy efficiency and hybrid energy harvesting schemes for perpetual power supply to the battery power constraints sensor node are also pointed out as an open research area in CRSN SG.

Chapter 4

Performance Analysis of Correlated Multi-Channels in CRSNs based Smart Grid

4.1 Introduction

Dual/multi antenna channels of the sensor nodes including too close spacing of sensor nodes deployment in a SG environment can lead to the problem of dual/multi correlation fading channels. This correlation can lead to degradation of the signals as well as co-channels interference. In addition, there exist also problem of spectrum inefficiencies, the signal-interference-noise-ratio (SINR), multipath fading, and shadowing peculiar to SG harsh environmental condition including interference from SG equipment which also pose great challenges to CRSN based SG. Hence, performance analysis of the correlated multi-channels will help in the improvements of SG communications. Reliable communication systems are keys to achieving the benefits of Smart Grid (SG) [160].

However, spectrum inefficiencies and interferences including the aforementioned problems are challenges to reliable communication in SG. Consequently, cognitive radio is the preferred solution to the problem of spectrum inefficiencies. Cognitive Radio has the capability of Dynamic Spectrum Access (DSA) to access spectrum opportunistically, hence is the preferred promising option to solve the problem of spectrum inefficiencies. Therefore, integration of CRSNs which is a combination of Cognitive Radios and Wireless Sensor Networks (WSNs) in SG will help to address the spectrum problem. A network of CRSN devices can exploit these licensed bands opportunistically through opportunistic spectrum access (OSA) as secondary users (SUs), whereas the licensed users (legitimate users), or the primary users (PUs), have precedence over the spectrum band.

However, there are some challenges to be overcome in the deployment of this CRSN paradigm in SG [162]-[168], such as link reliability, co-channel interference, bandwidth, and latency [11], [9], [169]-[170]. In addition, irregular channel conditions and electromagnetic signal-to-noise-ratio-interference from the SG equipment caused by harsh environmental conditions of the SG adversely affects the overall network performance [171]. Hence, one of the non-optimal ways to attain a better throughput-received -signal of the sensed data at the sensor nodes is by deploying sensor nodes with multi channels in close ranges. Nevertheless, there exist a multi co-channels in CRSN paradigm due to the closeness of sensor nodes with multi channels deployed in CRSN based SG environment. These result to dual/multi correlated channels including co-channel interference which adversely affects the received signal of the communication network performance. Thus, leading to high symbol error probability (SEP) or high bit error rate (BER) with poor signal to noise ratio (SNR).

Also, other factors such as multipath fading and shadowing do impair the received signal network performances. Consequently, the problems of correlation of signals can typically be addressed by introducing algorithmic transformation approach and reception diversity technique; such that, a performance analysis will be carried out in order to obtain an improved average signal-to-noise-ratio (SNR) by combining two or more desired signal of the multiple channels. This performance improvement by maximization of the average SNR will give rise to interference mitigation and optimal throughput of transfer of the sensed data in the SG network. Before performance improvement is delved into, a look at the approach of related works in literature is necessary.

The rest of this chapter is organized with the following subsections as follows: related works; moment generating function (MGF) based performance analysis of error probability of dual/multi correlated channels in CRSN based SG including the use of algorithmic approach and transformation technique for converting correlated channels into non-identical and independent signal under Nakagami-q distribution; simulation results and chapter summary.

4.2 Related Works

Numerous works that relates to performance improvements in cognitive radio network (CRN)/CRSN based smart grids have been published, [73], [102], [140], [161], [145], [150], [172]. Most of these works are targeted at improving communication in SG without the consideration of neither correlation multipath fading channels nor diversity reception techniques. Few works that considered correlation multipath fading channels in CRN without consideration in CRSN or in CRSN based SG includes the work by Shaikh et al. [173]. They carried out detection performance in correlated multiple antenna elements using linear test statistic which confirmed that the performance is severely degraded due to the correlation among the sensor antennas.

Hence, the authors proposed modest hard decision fusion strategy by exploiting collaborative gains to improve the performance. Another work in CRN was carried out by AlJuboori et al [174] in which a multichannel spectrum sensing was considered and presented as a closed-form expression for average detection probabilities derived while considering dual and triple correlated channels using selection combining (SC) technique under multipath Nakagami-m fading channels with different fading severities. Also, Digham et al. [175] conducted performance evaluation in CRN using selection combining (SC) diversity techniques in independent and identically distributed L-number channel branches under Rayleigh fading distributions.

In addition, Adebola et al. [176] investigated performance on independent but non- identically distributed channel branches over generalized fading environment based on MGF using SC, square-law selection (SLS) and maximal ratio combining (MRC) diversity schemes. Kim et al. [177] carried out sensing performance of energy detector with correlated multiple antennas and verified that the amount of correlation among antenna channels is directly proportional to degradation of performance. Zhang et al. [178] conducted performance investigation in CRN for spectrum underlay single input multiple output multi access channels while considering PUs interference constraints and SUs peak power constraints. In [179] the authors evaluated bit error rate (BER) performance of cognitive radio physical layer under Rayleigh channel using different channel encoding techniques, digital modulation and channel conditions. Furthermore, works that are purely on wireless systems that are neither based on CRN/CRSN nor in SG but involve performance analysis of signals including correlation multiple antenna channels and receiver diversity are found in [180]-[184].

So far, it is obvious from literature that works on performance analysis of multi correlated channels and receiver diversity technique in CRN/CRSN based SG are not prevalent or has not been considered, looking at the fact that SG has severe harsh environmental conditions and electromagnetic interference from the SG equipment. Hence, the focus of this chapter is to conduct performance analysis on CRSN communication signal under dual correlated Nakagami-q fading channels conditions in SG environment.

4.2.1 System Model

CRSN based SG is a typical scenario where channel conditions fluctuate dynamically, hence CRSN systems employs an adaptive modulation schemes so as to take into account the difference in channel conditions. The adaptive modulation adjusts transmission parameters such as power, data rate, modulation technique and so on. Consequently, a CRSN with adaptive modulation can be equipped with M-ary PSK, M-QAM, DSSS and others. However, this study employed M-ary quadrature amplitude modulation (M-QAM) modulation scheme because it is widely used in communication systems due to its high benefits of bandwidth efficiency as well as power efficiency. In this case, during transmission, the SG sensed data is modulated using MQAM under correlated fading channels distribution conditions such that the signals are received at the various sensor nodes. CRSN node with dual-branch single-input multiple-output (SIMO) system as depicted in Fig. 4.1 was considered. The received signal at the CRSN node receiver can be modelled as:

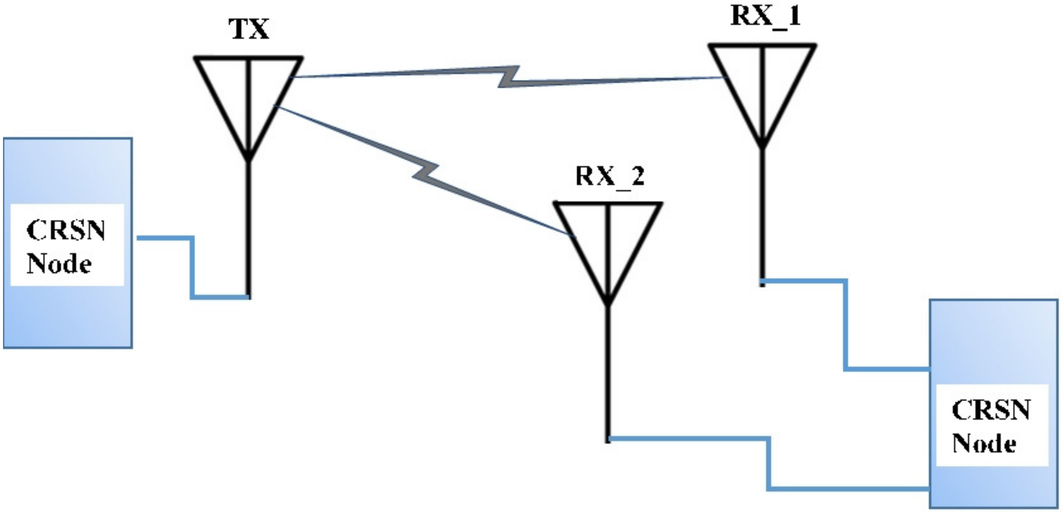


Figure 4.1: SIMO: CRSN node with single input multiple output

$$y_i(t) = \sqrt{E_s}\, h_i(t)x(t) + n_i(t) \tag{4.1}$$

where $y_i(t)$ is the received signal, E_s is the transmit signal power, x is the transmitted symbol (signal), $h_i(t)$ is Nakagami-q fading channels impulse response (suitable channel for harsh environmental condition of SG) i is in range of 1 to 2, i.e (1,2), is the ith number receiving antennas of fading channels for the multi-homed access links, $n_i(t)$ is the noise with complex Gaussian distribution.

$$h_i = h_i^I + jh_i^Q \tag{4.2}$$

But

$$q = \frac{\sigma_y}{\sigma_x} \tag{4.3}$$

where $0 \leq q < 1$

, σ_x, and σ_y are the Gaussian random distributed variables of the shadow and multi-path fading between the transmitter and receiver path respectively; h_i^I is the In-phase or real fading component, and jh_i^Q is the imaginary fading part. Also, based on the assumption that

$$E[(h_i^I)^2] = E[(h_i^Q)^2] = \sigma^2 \tag{4.4}$$

$$Ch_1^I h_2^I = E[h_1^I h_2^I] = \rho\sigma^2 \tag{4.5}$$

where $Ch_1^I h_2^I$ is the correlated fading channels; ρ is the received signal power.

$$Ch_1^Q h_2^Q = E[h_1^Q h_2^Q] = \rho\sigma^2 \tag{4.6}$$

for the noise component , we have:

$$E[n_i h_k^I] = E[n_i h_k^Q] = 0, i = 1,2; k = 1,2 \tag{4.7}$$

where k is the number of fading channel, and E is the energy per bit of the complex Gaussian noise variable and fading channel. We define the instantaneous signal-to-noise ratio (SNR) as:

$$\gamma = E_s/N_0 \tag{4.8}$$

Then the moment generating function (MGF) of the received SNR over Nakagami-q channels can be written as,

$$M_\gamma q(s) = \left(1 - 2s\bar{\gamma} + \frac{(2s\bar{\gamma})^2 q^2}{(1+q^2)^2}\right)^{\frac{-1}{2}} \tag{4.9}$$

where

$$1 \leq q < 1$$

and $\bar{\gamma}$ is the average received SNR for each symbol and is expressed as,

$$\bar{\gamma} = 2\sigma^2 E_s/N_0 \tag{4.10}$$

4.2.2 MGF based Performance Analysis of M-QAM over Single Nakagami-q Fading Channel

In AWGN the symbol error rate probability (SEP) of detection of M-QAM is given by [180]

$$\begin{gathered} \bar{P}_{MQAM} = \frac{a}{n}\left\{\frac{e^{-b\frac{\gamma}{2}}}{2} - \frac{ae^{-b\gamma}}{2} + \right. \\ \left. (1-a)\sum_{i=1}^{n-1} e^{-b\frac{\gamma}{si}} + \sum_{i=n}^{2n-1} e^{-b\frac{\gamma}{si}}\right\} \end{gathered} \tag{4.11}$$

where $\bar{P}_{MQAM}$is the average probability of detection under MQAM modulation,

$$a = 1 - \frac{1}{\sqrt{M}},\ b = \frac{3}{M-1},\ s_i = \frac{2sini\pi}{4n},$$

M is the constellation order which may be 4, 16, 32, etc.; n is the number of iteration.
We can then derive MGF based average error probability by simply retaining the M-QAM SEP given in equation 4.11 under AWGN to be integrated over Nakagami-q fading distribution with this expression,

$$\bar{P_s} = \int_0^{\infty} P_s(\gamma) f_{\gamma_s}(\gamma) d_{\gamma} \tag{4.12}$$

But the MGF of a nonnegative random variable is given by

$$\bar{P_s} = \int_0^{\infty} f_s(\gamma) e^{s\gamma} d_{\gamma} \tag{4.13}$$

Hence, MGF based average error probability is derive thus

$$\bar{P}_{MQAM} = \int_0^{\infty} \frac{a}{n} \left\{ \frac{e^{-b\frac{\gamma}{2}}}{2} - \frac{ae^{-b\gamma}}{2} + (1-a)\sum_{i=1}^{n-1} e^{-b\frac{\gamma}{si}} + \sum_{i=n}^{2n-1} e^{-b\frac{\gamma}{si}} \right\} \left(1 - 2s\bar{\gamma} + \frac{(2s\bar{\gamma})^2 q^2}{(1+q^2)^2}\right)^{\frac{-1}{2}} \tag{4.14}$$

Applying trapezoidal rule, gives:

$$\begin{aligned} \bar{P}_{MQAM} = \frac{a}{n} \Bigg\{ & \frac{1}{2} M_{\gamma} q \left(-\frac{b}{2}\right) - \left(\frac{a}{2}\right) M_{\gamma} q(-b) \\ & + (1-a) \sum_{i-1}^{n-1} M_{\gamma} q \left(\frac{-b}{s_i}\right) + \sum_{i-n}^{2n-1} M_{\gamma} q \left(\frac{-b}{s_i}\right) \Bigg\} \end{aligned} \tag{4.15}$$

Equation (4.15) is the derived MGF based average probability of symbol error rate of M-QAM over single Nakagami-q fading channel.

4.2.3 MGF based Performance Analysis of M-QAM over Dual Correlated Nakagami-q Fading Channel using MRC Diversity Technique

The symbol error rate probability performance analysis is usually being conducted on an independent non-identical fading channel distribution. It is obviously not feasible to conduct performance evaluation on identical dual correlated fading channels. Consequently, a transformation technique was proposed in [183] which is used to transform the identical dual correlated channels into non-identical independent channels. Hence, an algorithmic approach based on the transformation technique was introduced, the algorithmic approach is given as:

$$Cz = \begin{bmatrix} \rho & 1 \\ 1 & \rho \end{bmatrix} \tag{4.16}$$

where Cz is the covariance, obtain by assigning correlated coefficient, ρ, and ρ is $0 \leq \rho \leq 1$.
The transformation technique is given as

$$\bar{\gamma} = (1+\rho)\bar{\gamma} \tag{4.17}$$

$$\bar{\gamma} = (1-\rho)\bar{\gamma} \tag{4.18}$$

Equations (4.17) and (4.18) are used for converting any two-given identical but correlated fading channels with average SNR,$\bar{\gamma} = \bar{\gamma}_1 = \bar{\gamma}_2$ and correlated coefficient, ρ, into non-identical independent channels. Hence, under Nakagami-q fading conditions, the equivalent non-identical independent fading channels, can then be used to obtain an MGF based expression for maximum ratio combiner (MRC) received SNR, γ, as:

$$M_{\gamma qMRC}(s) = M_{\gamma q1}(s)M_{\gamma q2}(s) \tag{4.19}$$

Now an MGF based expression for performance on SEP of MQAM can be derived over Nakagami-q dual correlated fading channels with MRC by substituting equation (4.19) with $M_{\gamma q}$ in equation (4.15), this yield:

$$\begin{aligned} \bar{P}_{MQAMMRC} = \frac{a}{n}\Bigg\{ & \frac{1}{2}M_{\gamma q1}(s)M_{\gamma q2}(s)\left(-\frac{b}{2}\right) - \left(\frac{a}{2}\right)M_{\gamma q1}(s)M_{\gamma q2}(s)(-b) \\ & +(1-a)\sum_{i-1}^{n-1} M_{\gamma q1}(s)M_{\gamma q2}(s)\left(\frac{-b}{s_i}\right) + \sum_{i-n}^{2n-1} M_{\gamma q1}(s)M_{\gamma q2}(s)\left(\frac{-b}{s_i}\right)\Bigg\} \end{aligned} \tag{4.20}$$

4.3 Results and Discussion

Since the transformed independent signals are equivalent to the identical dual correlated signals, we then conduct MGF based MRC diversity receiver technique performance evaluation on the transformed non-identical independent signals. Fig. 4.2 to Fig. 4.6 show how the variation of correlation coefficient, ρ (= 0, 0.3, 0.6, 0.8, and 1) affected the received signals respectively. The simulations were conducted in MATLAB environment and the same number of iteration (n = 10000) of the transmitted signals was used in all the cases of variation of ρ. The simulation parameters for this experiment are shown in

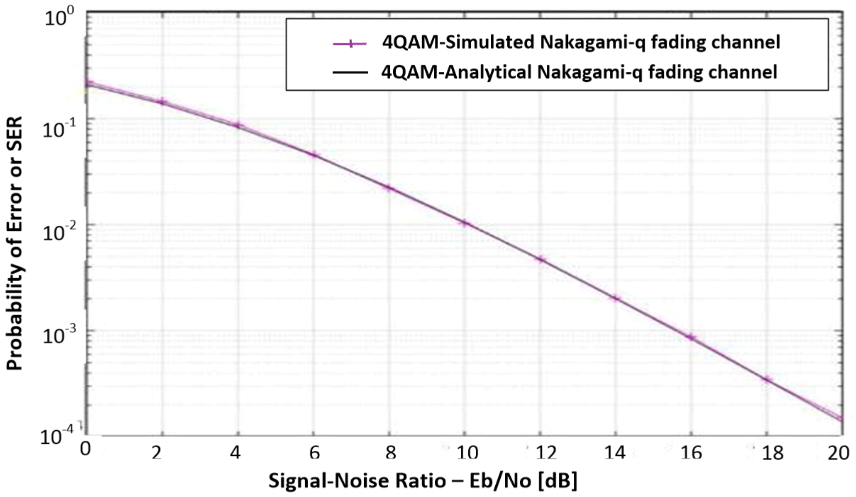


Figure 4.2: MGF based MQAM with ρ =0

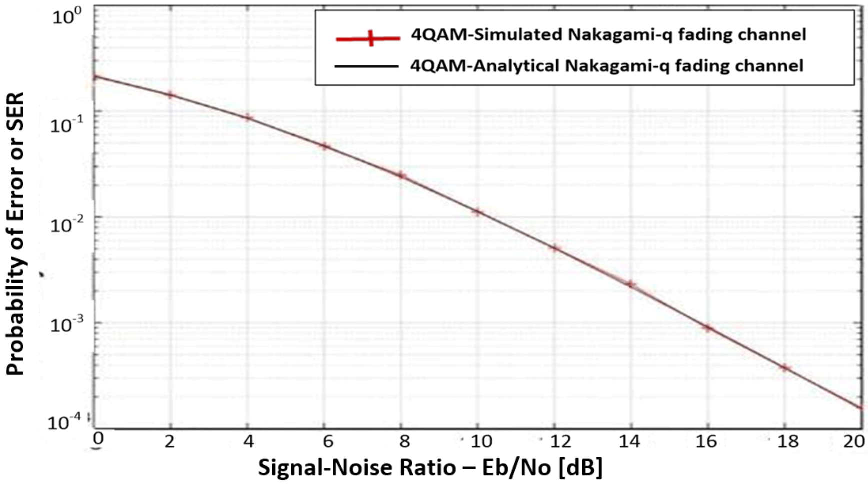


Figure 4.3: MGF based MQAM with ρ =0.3

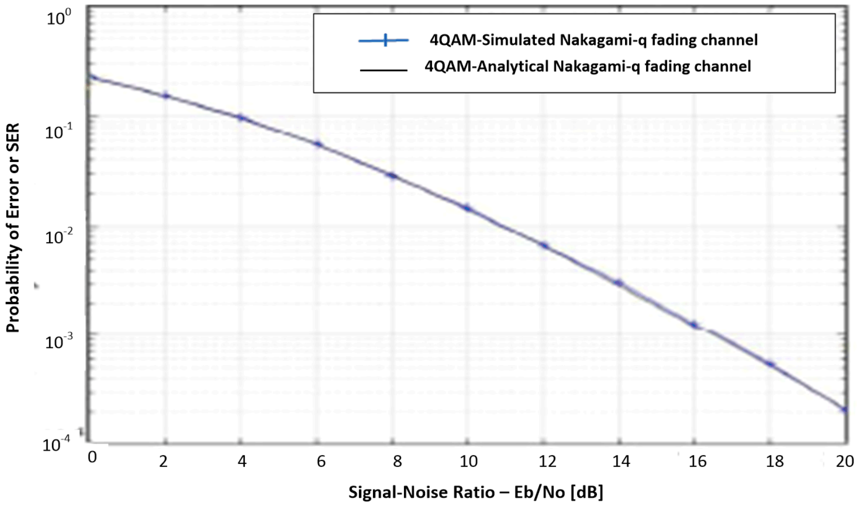


Figure 4.4: MGF based MQAM with ρ =0.6

Table 4.1: Simulation parameters

Parameters	**Values**
Number of correlated channel	2
Simulation runs	10,000
Correlated coefficient (ρ)	0:1
Multipath Fading	Nakagami-q
Shadow Fading	Log-Normal Shadowing
Modulation size	4QAM
SNR	0:20 dB

Table 5.8. Looking at Fig. 4.2 with ρ =0, we can see that when ρ = 0, the simulation result and theoretical or analytical result actually matches which is depicted by the overlapping curves in Fig.4.2. Another important observation here is that the received signal has a

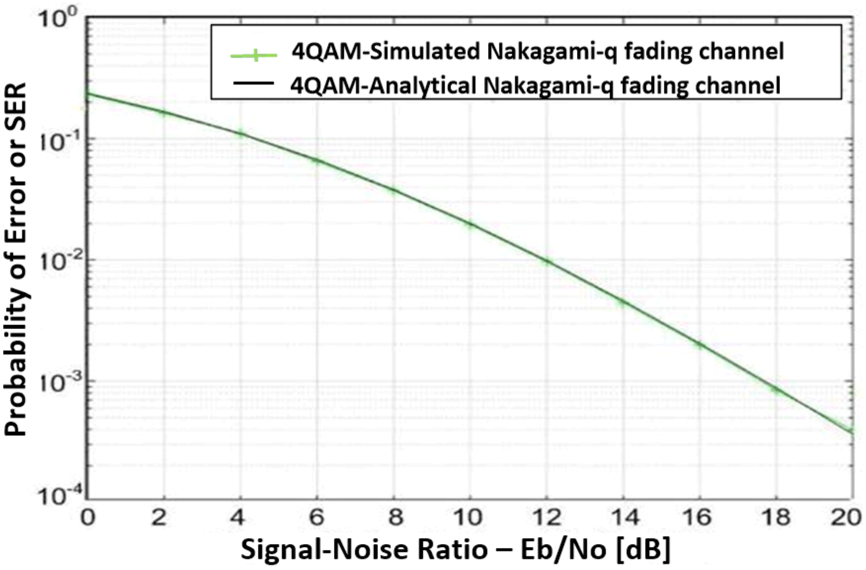


Figure 4.5: MGF based MQAM with ρ =0.8

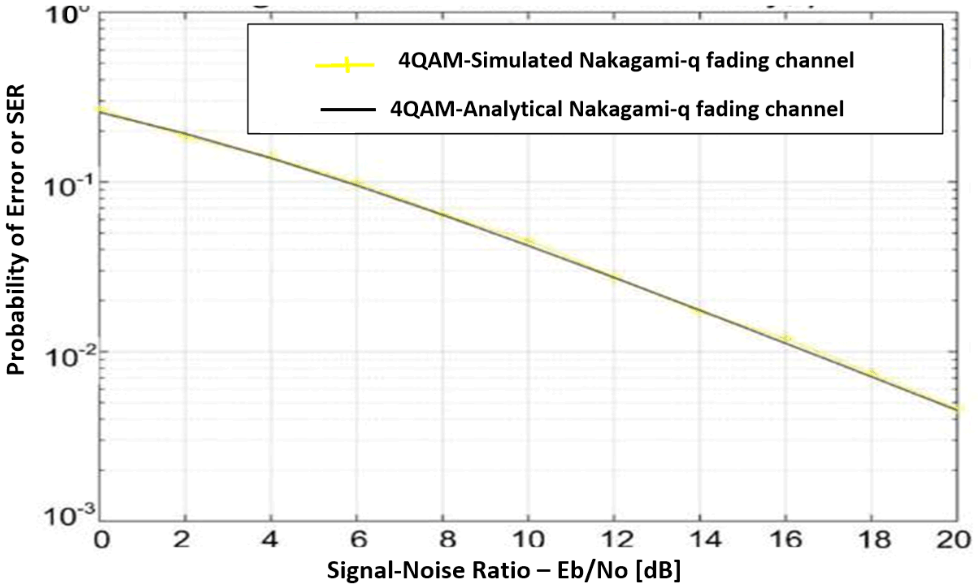


Figure 4.6: MGF based MQAM with ρ = 1

very low symbol error rate, thus, confirming that in a circumstance of un-correlation (when ρ = 0) the received signal will be void of excessive errors. But as the ρ is varied from 0.3 to 1, it is noticed that the symbol error rate increases in the received signal; hence, the presence of excess errors causes degradation of the received signal thereby resulting to poor link reliability in the SG ecosystem. It is also important to note that in each of the graphs the simulated results matches with the analytical numerical integration results as depicted by the overlapping curves shown in Fig.4.2 to Fig.4.6. Also, it is noticed that in each case, the SNR increases as the SEP reduces; which is a clear confirmation that SNR can be maximized by having a reduced SEP. For a better analysis, one can use a particular SNR,that is, the same SNR condition environment in all cases to estimate the approximate error rate of the received signal. Table 4.1 helps to illustrate comparisons of the error rate with respect to various ρ under the same SNR condition environment. Consequently, it is noticed that the error rate increases as the ρ increases, which confirms that correlation of antenna channels degrades the performance of the received signals of the SG sensed data.

4.4 Chapter Summary

In this Chapter, we provide an overview of CRSN based paradigm in SG to illustrate the performance analysis which can be conducted in dual correlated fading channels under Nakagami-q distribution. An expression for (MGF) based performance analysis of error probability of MQAM was derived over single Nakagami-q fading channels using analytical method of trapezoidal numerical integration.
Furthermore, MGF based SEP of MQAM over dual/multi correlated Nakagami-q fading channels with MRC diversity receiver technique was also derived using the same analytical method of trapezoidal numerical integration. A transformation technique was used in converting the dual correlated signals into an independent but non-identical signal. The derived error probability expressions are then used in carrying out performance analysis on these independent signals.

Overall, the simulation results agree with the analytical solution results of the study. These results will enable performance improvement in the deployment of multi-channels sensor nodes in CRSN based SG. Hence, CRSN based SG designer will make sure that the antenna channels in a multi-channels sensor nodes are substantially spaced apart including adequate spacing of sensor nodes deployment in a SG environment to overcome signal degradation due to dual/multi correlations.

Chapter 5

Performance Measurements of Communication Access Technologies and Improved CRSN Model for Smart Grid Communication

5.1 Introduction

This chapter proposes evaluation of communication access technologies performance measurements and improved cognitive radio (CR) model for SG communications, including design and implementation models in CRSN based SGs. The work employs the National Institute of Standard framework for SG interoperability, virtualized network in form of multi-homing comprising low power wide area network (LPWAN) devices such as LTE CAT1/LTE-M, and CR such as TV white space band device (TVBD).

Currently the power grid infrastructure is becoming outdated and prone to power problems such as poor power quality, high transmission losses and low efficiency. Smart Grid (SG) has been projected to overcome these problems. SG technology involves the inclusion of Information and Communication Technology (ICT) into generation, transmission and distribution of electrical power to the consumers. The impression of SG, involves data collection about its processes, electrical power demands by consumer and intelligently provide solution for optimal power delivery across the grid ecosystem. SG has been evolving with various communication architecture proposed by authors in order to address the various problems related with the power grid. The communication network is one of the most critical aspect that enables SG applications as found in reference [185]. In the SG scenario, the consumer can be benefited from real-time energy management and pricing with the help of demand response management (DRM), through this, they conserve energy and save cost, reference [185]–[189]. Hence, an efficient and reliable communication network is the bedrock of smart electrical power grid. Reliable bi-directional communication between the homes and utility control center is required for efficient functioning of the load management [185], [15], [32]. Also, monitoring and control of the electrical power grid actually depend on the low-delay delivery of real-time data [185], [190]-[191]. In addition, the issue of interoperability due to multiple interconnection communication technologies at different parts of the smart grid pose a big challenge, thus a proper communication network architecture is envisioned in ensuring interoperability within heterogeneity in SG.

Moreover, such communication network should be supported by fault tolerance capability in order to meet the needs of mission-critical and real-time systems, such as the SG [192].
WSN is good for monitoring and control capability [192]. Also, it can help to avoid equipment failures, capacity limitation including power outages and disturbances. In this respect, WSN is paramount to the maintenance of safety, reliability, efficiency, and real-time of the SG [12].

But challenges such as spectrum scarcity and interference are associated with wireless communication and WSN. [193] Wireless networks are regulated by a spectrum assignment and management policy which makes fixed assignments of spectrum to license holders for a long time within large geographical regions. This fixed assignment under-utilizes spectrum with utilization levels that ranges from 15 - 85 % [156], [18].Cognitive Radio has the capability in accessing spectrum opportunistically via Dynamic Spectrum Access (DSA). This is a promising option to solve the problems of spectrum inefficiencies and interference [156], [194]– [195]. Hence, integration of CRSNs which involve a combination of CR and WSNs in Smart Grids will help to address the spectrum inefficiencies issue [185].

In CR paradigm, The intermittent relinquishing of the SU can lead to the blocking of the SU connection when the channel is used by the PU, thereby causing blocking probability in the SU transmission. This blocking probability can affect the throughput of the SU signals. Hence, there is a need to mitigate the blocking probability in CR for efficient smart grid communication.

Furthermore, the communication access technologies are technologies devices that can enable communication in the electrical power grid. There are vital aspect of SG network ranging from wired to wireless technologies. However, some access technologies do not have potential for efficient smart grid communication, due to the fact that, they have poor throughput and latencies, especially in tough SG environmental conditions. Hence, there is a need to investigate and evaluate the measurements of access technologies in terms of their capacity throughputs and latency.

5.1.1 Communication challenges in CRSN based SG

The communication challenges affecting CRSN in SG are described in the following:

- Communication Infrastructure: Identifying adequate communication infrastructure that will handle both long range transmission of information and short range sensing/ transfer of sensed data in the entire SG is a vital subject. The current aging communication infrastructure cannot withstand the modern SG [30]. Thus, advance communication infrastructure that supports heterogeneous and varying network topology environment such as a SG is of necessity.

- Communication Architecture: It is challenging to design adequate communication architecture that will integrate and enable network applications to cover the entire SG network such as the HAN, NAN, and WAN. This is due to the heterogeneous nature of the SG network environment.

- Communication requirements for SG Applications: Difficulty in fulfilling the essential communication requirements for the different SG applications is of utmost concern. This is because a particular SG application has specific QoS requirements that are different from other SG applications. These essential requirements include: latency, link reliability, and throughput.

- Design Challenges: Other major problems are design challenges which involve scalability for additional smart devices/technologies [196]; cybersecurity for mitigating vulnerability in SG [197], [198]; and interoperability for communication of different networks and standardization of protocols [197].

- Harsh propagation conditions in the SG environment: Varying network topologies and harmonics from power lines including obstructions hinder efficient communication signals in SG [196].

- Constraints resources: Constraints resources such as limited memory, limited energy of the battery, and high energy consumption due to CR spectrum sensing activity are major predicaments in CRSN communications in a SG [196]. Hence, adequate energy efficiency is essential in addressing the limited energy issue.

- Communication protocol: A CRSN protocol is unique due to the dynamic multiple channel access. Hence, it requires protocol that matches its functional computational complexity.

- Blocking probability in the SU transmission: The problem of blocking probability in the SU transmission is crucial. This is because as soon as the SU vacates the channel to the PU, if there is no available channel, the SU will not be able to transmit signals. This will lead to several packet losses. Hence, it is necessary to avoid this blocking probability by way of adequate channel availability. Blocking probability can be evaluated to analyze the QoS of a CR network for a SG [30],[145].

Hence, the main contribution of this chapter can be summarized as follows:

- Firstly, there is an investigation of the validity of the blocking probability in CRSN based on bit error rate (BER).
- Secondly, it is proposed that a channel fragmentation strategy (CFS) based Alamouti transmit diversity scheme will help to reduce blocking error probability in CRSN for SG.
- Thirdly, the design of communication infrastructure to be in a hierarchical multilayer structure that cut across the whole SG seven domains.
- Fourthly, a model is implemented that addresses some of the challenging issues associated with the SG architecture design. These include interoperability, huge data, varying traffic and quality of service (QoS).
- Also, we introduce a novel design of virtualized network architecture in form of multi-homing comprising LPWAN devices and TVBD device for leveraging heterogeneous network services for the differs SG applications.
- Furthermore, owing to the fact that different SG applications have different QoS requirements because of the varying data and traffic, we make sure that the SG is implemented in such a way that various segments of the hierarchical multi-layer have different transmission bandwidth and latency that suite respective SG applications. This will help for the effective and reliable flow of information over the communication network.
- An improved CR model is implemented to address the problem of blocking probability in the CR scenario.
- An improved CR model which involves a CFS based Alamouti space-frequency block coded (SFBC) scheme has been implemented to address the problem of blocking probability in the CR scenario.
- Further, the performance measurements of access technologies in terms of their capacity throughputs and latency has been carried out for SG communication.

Thus, the rest of this chapter is organized with subsections as follows: related works are highlighted; the proposed CRSNs communication network topology and interaction in SG domain are put forward; improved CR model and module architecture for efficient SG communication are proposed; access technologies implementation models and performance measurements in CRSN based SG are presented; Simulation results and analysis are discussed; future research directions are discussed including recommendations; finally, the chapter is summarized.

5.2 Related Work

As stated earlier, communication access technologies are a vital aspects of SG network ranging from wired to wireless technologies. It is essential to study the performance of various access technologies in order to establish the appropriate ones for a reliable SG network. This then necessitates investigative study on performance measurements of access technologies for SG network. However, most of the works are tilted toward Communication network architecture in SG in order to achieve a reliable SG communication network. Hence, communication network architecture in smart grid have been addressed in one way or the other. A study in [194] proposed three layers-architecture for communication network architecture in the Smart Grid. The first layer represents the wireless local area network (WLAN) by using Wi-Fi to provide communication inside the data centres and link to metering devices and to the next layer. The second layer is the wireless metro network (WMAN) by using WiMAX to provide communication between data centres and transmission substations to the utility. The third layer is the wide area network (WAN) using fibre optic between the data centre and control to the utility. However, it does not consider performance measurements of the access devices used. Also, CRSN and interoperability issues are not considered in its architecture.

Another work suggests a hybrid network architecture by incorporating a wired infrastructure, WSN, and a PLC for the Smart Grid [195]. Their proposed architecture has three subsystems comprising the data acquisition subsystem, communication subsystem, and supervisory control subsystem. However, the work has the following drawbacks such as not adopting the NIST framework model in its architecture and no technology for mitigating interference was also adopted.

The study in [200] proposed communication network architecture alongside software architecture in terms of energy efficiency in the neighborhood area network (NAN) of the smart grid. The drawback of this work is that its architecture is only for NAN and not for the entire SG. Also, the communication network architectures that support most of the smart grid applications, ranging from power generation to distribution as well as automatic metering infrastructures (AMI), are discussed in various research works such as in [201]–[203]. But these studies do not consider implementation models that involve heterogeneity and multihoming in the communication network including performance measurements of the access devices for SG. This is because various SG applications requires different transmission bandwidths and latency.

Obviously, many researchers employed the use of wireless sensors for monitoring in various SG applications. For example, using wireless sensors for smart grid multimedia applications are investigated in [204]. Mirza et al. [205] proposed the use of CR based Wi-Fi for field area network (FAN) in SG. The difference between their work and ours is that their focus is on FAN, and they did not incorporate low power wide area network (LPWAN) technologies and multihoming. Whereas our work considered in detail the entire SG communication network domain.

Another area of work which is of concern to the research community is the issue of blocking probability in CRSN for a SG. For instance, the authors in [150] proposed a non-cooperative channel packing scheme (CPS) to reduce the blocking probability in a heterogeneous CRSN for an SG. Numerical results show that the CPS scheme significantly reduces the blocking probability, and increases the spectrum utilization. However, this work did not consider bit error rate (BER) nor channel fragmentation with a diversity scheme in their investigation. Ref. [206] proposed a new binary exponential backoff (NBEB) algorithm that significantly reduces the blocking/dropping probability, and improves the performance of the communication in CR for SG. Ref. [207] proposed the use of buffer occupancy as an indicator of the sensor node priority to access spectrum in order to mitigate congestion and packet blocking probability in a CRSN for a SG. Ref. [145] investigated blocking probability based on prioritizing traffic in a CR network-based SG. The blocking probability in the SUs of the prioritized system increases very little. Whereas, the blocking probability of SUs in the non-prioritized system increases greatly. In [140], a hybrid dynamic Spectrum Access together with joint WAN/NAN Spectrum Management has been proposed. The scheme actually outperforms the traditional system by significantly decreasing the dropping and blocking probability.

Another study [72] proposed communication network architecture that support high data rate applications with low data transfer latency by using wireless multi-homing of two heterogeneous wireless networks in a SG. The difference between their work and ours is that their work is not on CRSN based SG, there is also no consideration of LPWAN technologies for energy efficiency. The study here involves consideration of performance measurements of access technologies including consideration of improved CR model for SG communication. This is achieved through the use of multihoming in heterogeneous wireless networks utilizing LPWAN technology, such as LTE cat1/LTE-M1, and the use of CR technology in the form of TV band devices (TVBDs), also called super Wi-Fi, for cognitive capability. Hence, the focus here is on performance measurements of access technologies jointly with improved CR model for SG communication that utilizes the technology discussed above with the following considerations:

1) The National Institute of Standard (NIST) Framework for Smart Grid Interoperability

Standards is addressed.
2) Support for various SG application including high data rate is included.
3) The energy efficiency of the technology used is considered.
4) An Improved CR model is also considered.

Based on the studies reported in the available literature related to this work, to the authors' best knowledge, it can be observed that no other research has holistically considered the technologies discussed above, and consideration of performance measurements jointly with improved CR model in a CRSN based SG.

5.3 COMMUNICATION NETWORK TOPOLOGY AND INTERACTIONS IN CRSN BASED SG DOMAIN

The communication network architecture in a CRSN based SG is divided into two:
1) A Block diagram of communication network interactions in the CRSN based SG domain.
2) A communication network topological architecture in the CRSN based SG.

5.3.1 Block diagram of communication network interactions in CRSN SG domain

This architecture is based on the NIST framework for smart grid interoperability standard. It buttresses how various domains interconnect and operate with each other domains. Thus providing inter seamless communication with the entire seven SG domains without the issue of interoperability constraint with the components. We have earlier given the descriptions of the NIST framework for the SG architectural reference model in section 2.4. The block diagram of communication network interaction is adopted from the NIST framework which is depicted in Fig. 5.1.

Basically, Communication Network can be represented by a hierarchical layer architecture in a CRSN based SG; which classifies the data rate and coverage range. Hence, CRSN based SG communication network layer architecture comprises:
1) Premise Area Network which includes Home Area Network (HAN), Building Area Network (BAN), Industrial Area Network (IAN), and Commercial Area Network (CAN)
2) Neighborhood Area Networks (NAN)
3) Field Area Network (FAN)
4) Wide Area Network (WAN)

5.3.2 Communication Network Topological Architecture in CRSN Based SG

The communication network topological architecture is based on the framework for specification of the various communication network components such as nodes and links and their functional organization and arrangement. It represents how communication is carried out by a hierarchical layer architecture in the SG as mentioned in the preceding section. The communication network topological architecture ensures the connection of an enormous number of sensing and actuators devices including communication access devices in order to transmit status, sensed data and control message throughout the entire smart grid domain ecosystem. The architecture is depicted in Fig. 5.2 and Fig. 5.3 for the Premise area network and NAN/FAN/WAN respectively. It is a modification of a typical SG communication in our previous work [185].

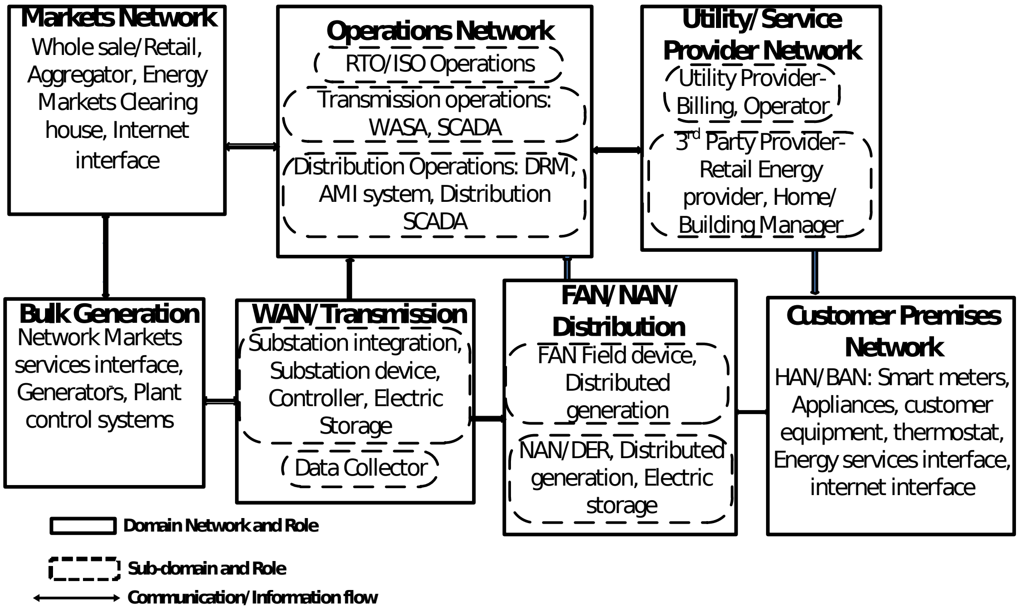


Figure 5.1: Communication network interactions in CRSN based SG domain [61]

There was a modification of communication access module that was initially having a multihoming of dual-band interface comprising 2.4 GHz and 5 GHz Wi-Fi and integrated ZigBee in the premise area network. It is now having a multihoming feature with an LTE-M1 interface and TVBD interface. The communication access module in the NAN/FAN//WAN that was initially LTE Cat1/M1 with integrated ZigBee is modified as module with multihoming support and LTE Cat1/M1 interface and TVBD interface. Here the NAN utilizes the LTECat1/M1 interface and TVBD interface. Here the NAN utilize the LTE cat M1 while the FAN and WAN make use of the LTE cat1 owing to the fact that the FAN/WAN is responsible for huge data rate SG applications such as substation/distribution automation, Supervisory Control and Data Acquisition (SCADA), phasor management units[208], mul-

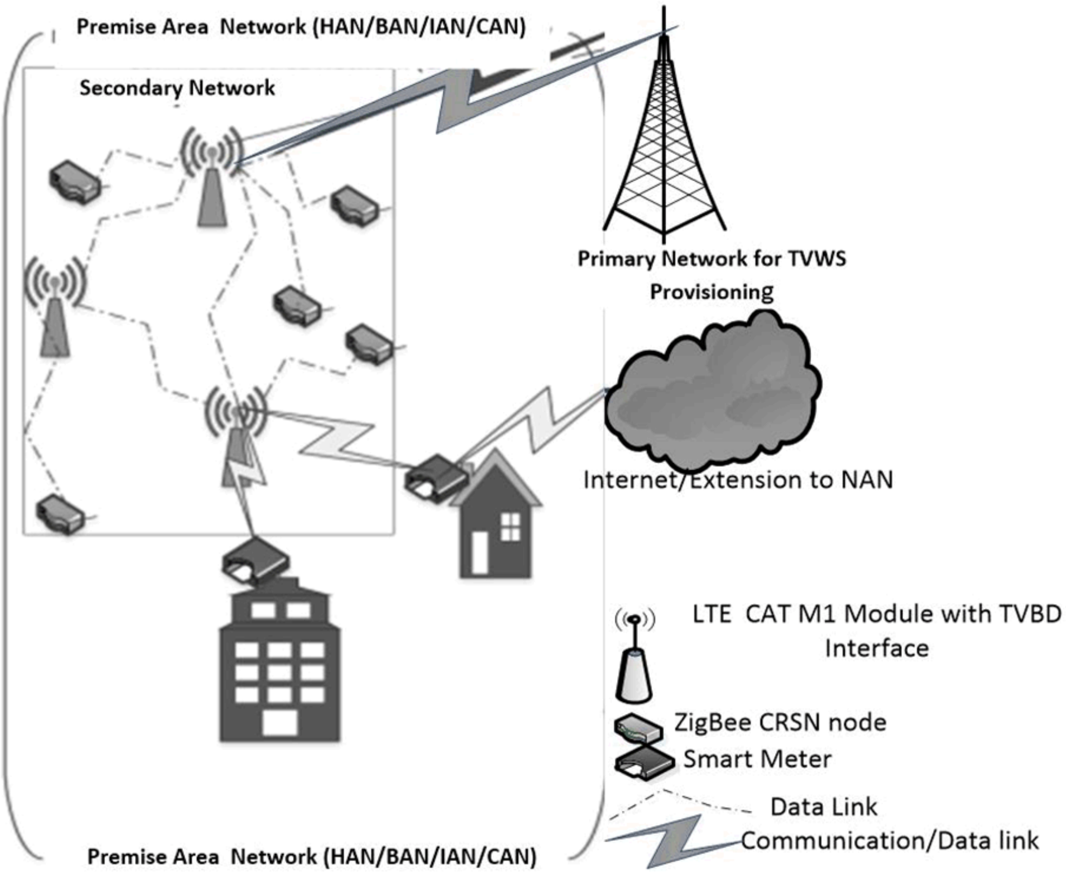


Figure 5.2: SG communication network topology at the customer premise

timedia surveillance and Wide Area Situational Awareness (WASA) including the Phasor data concentrators (PDCs) which are the critical components of WASA in SG [208]. These types of SG applications, require a high throughput of up to 5 Mbps and above with latency below 100 ms. These requirements are well supported by LTE Cat1 which has a throughput of up to 10 Mbps and latency of 10-15 ms.

The architecture specification is structured in such a way that the low power wide area (LPWA) transceivers (LTE Cat1/M1) are responsible for conveying the data and control message while the TVBD transceivers are responsible for accessing TVWS (TV White Space) opportunistically from a TVWS database. And then act as a ZigBee coordinator for the ZigBee clustered sensor network for spectrum allocation via DSA. The ZigBee sensor networks are deployed in clusters at specific locations where the monitoring activities are required. More details of the multihomed module interface are explained in the subsequent sections in this chapter, i.e., access technologies module architecture, and performance measurements of various access technologies.

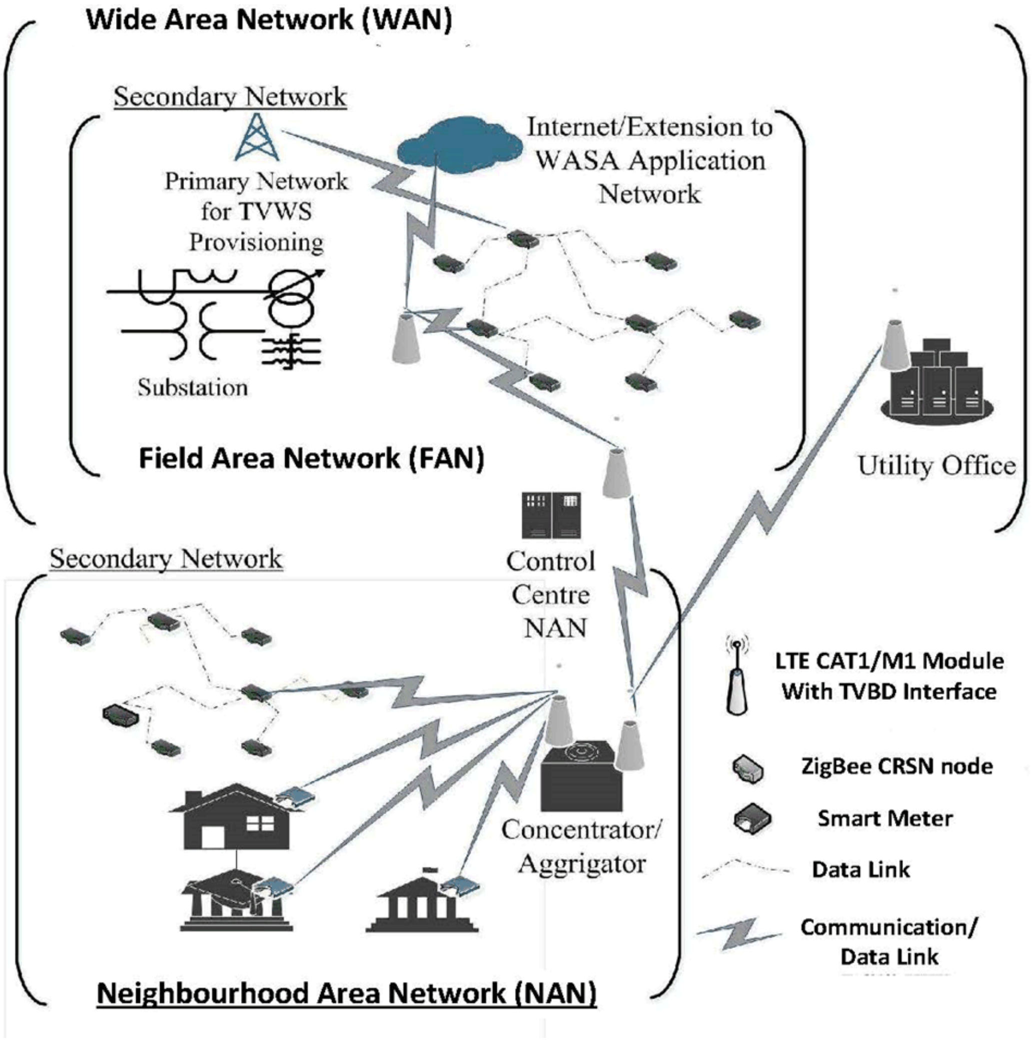


Figure 5.3: SG communication network topology at NAN/FAN/WAN

5.4 IMPROVED CR MODEL AND MODULE ARCHITECTURE FOR EFFICIENT SG COMMUNICATION

5.4.1 Cognitive Radio Technologies Overview

CR has been proposed as new technologies to promote the efficient use of spectrum resources by exploiting unused spectrum or spectrum holes. CR has the capability to sense, quantify, learn, and aware of the constraints related to the radio frequency (RF) channel characteristics. Also, it is aware of the spectrum availability of the operating environment, power, and user operating restrictions requirements and applications including available network devices and nodes.

In CR setting, PUs are the licensed users, which have the license to operate in an assigned spectrum band in order to access the primary base station. SUs or the CRs are unlicensed users without a spectrum license. CRs use the existing spectrum through opportunistic spectrum access (OSA) without causing harmful interference to the PUs or licensed users. CRs look for the available portion of the unused spectrum also called spectrum hole or TV white space (TVWS). The optimal available channel is then used by the CRs if there are no primary users operating in the licensed bands.

However, the major challenge associated with CR is the intermittent relinquishing of the channel by the SU whenever PU arrives. This can lead to the blocking of the SU connectivity when the channel is used by the PU, leading to blocking probability in the SU transmission. The blocking probability can affect the throughput of the SU signals. Hence, an improved CR model has been proposed to address this challenge in the next section.

5.4.2 Improved CR Model for SG communication

The CR signal can be modulated with lower constellation order M, for (M = 4 or 16) of quadrature amplitude modulation (QAM), under Rayleigh fading channel distribution conditions. However, 16 QAM has been employed in the aspect of the performance measurements due to its moderate computational complexity with just sixteen symbols of 4 bits per symbol in supporting an appreciable data rate. This is suitable in CRSN for SG data rate because a CRSN has moderate computational complexity compared with WSN and conventional massive MIMO wireless systems which have a lower and higher computational complexity respectively. Hence, the average received SNR ($\bar{\gamma}$) signal for each channel, can be expressed as

$$\bar{\gamma} = E_s/N_0 \tag{5.1}$$

where E_s denotes the instantaneous transmit power and N_0 denotes the noise power spectral density of a channel. To obtain an appreciable or higher received average SNR the error or blocking probability should be minimal. Hence, the blocking probability is inversely proportional to the average SNR expressed as:

$$\text{blocking probability, } P_b = \frac{K_{delay}}{\bar{\gamma}} \tag{5.2}$$

where K_{delay} is the delay resulted from blocking of SU transmission, and re-transmission delay. Channel fragmentation is employed to the signal in order to obtain an appreciable average SNR ($\bar{\gamma}$) with minimal blocking probability. Channel fragmentation and bonding have been specified to be supported in some wireless networking standards, such as IEEE 802.11ac and IEEE 802.22 wireless regional area network (WRAN) [209]-[210]. However, the CR device such as the TVBD considered in this work is based on IEEE 802.22 WRAN standard. Channel fragmentation is a method of allocating a portion of a spectrum band by splitting the channel such that each subdivision has the same replica of the same channel bandwidth. For example, if a channel has a bandwidth of 6 MHz, channel fragmentation enables allocation of a portion of the spectrum band corresponding to two contiguous spectrum bands of 3 MHz bandwidth to a user. Further, the proposed CFS is implemented on Alomouti transmit diversity scheme using two transmission antennas and one receiver antenna [211]. This will help in creating a spectrum holes for the CR users, such that when the PU channel is in use, the alternate available channel will be used by the SU.

A two-branch transmission antenna and one receiver antenna system has been adopted in this thesis. According to Alamouti, it follows that the transmission sequence and encoding are done in space and time as well as in space-frequency coding [211]. The figures and tables illustrating this scheme are given in Ref. [211].

5.4.3 Network Assumptions for Channel Fragmentation Strategy (CFS) based Alamouti Scheme

The CFS is represented in Fig. 5.4. A 6 MHz channel bandwidth with a frequency range below 3 GHz has been considered. When CFS is applied to the 6 MHz channel bandwidth, a dual replica of the 3 MHz sub-channel bandwidth is produced as shown in the line segments of CD and DE. Initially, there are 8 channels in the 6 MHz channel bandwidth with two unoccupied spectrum hole channels. The CFS reproduces an additional 8 unoccupied spectrum hole sub-channels as shown in Fig. 5.4. Without the CFS, when two new PUs arrive and occupy the unoccupied spectrum holes, there will be no vacant channel for the SU. This will block the SU from the transmission, thus leading to a high delay as well as errors due to frequent re-transmission attempts. However, with the application of CFS, the arrival of two new PUs to occupy the unoccupied spectrum holes will not result in blocking of the SU transmission. This is because adjacent sub-channels are available which the SU can use for transmission. Hence, there will be no error due to blocking that may be encountered during the SU transmission using the CFS. The CFS can be applied using an Alamouti transmission diversity scheme for optimal performance of the CRSN communication in the SG. The CFS yields alternative available channels that can guarantee implementation when using an Alamouti space-frequency block coded (SFBC) scheme. However, with a non-CFS, there would be no alternative available channels that can guarantee implementation on Alamouti SFBC scheme. Hence, a CFS based Alamouti scheme will greatly reduce error probability due to alternative channel availability.

In the Alamouti SFBC scheme, there are two transmission antennas and one reception antenna. Hence, the sub-channel carrier is denoted by $(2S_C)^{th}$. In the $(2S_C)^{th}$ sub-channel carrier, $X_1(2S_C)$ and $X_2(2S_C)$ are transmitted simultaneously at antenna 1 and antenna 2 respectively. In the adjacent sub-channel carrier $(2S_C+1)^{th}$, $-X_2^*(2S_C)$ and $X_1^*(2S_C)$ are transmitted simultaneously at antenna 1 and antenna 2 respectively. The fading channel of the sub-channel carriers $(2S_C)^{th}$ and $(2SC+1)^{th}$ from the antenna 1 transmission to the reception antenna are denoted as $h_1(2S_C)$ and $h_1(2S_C+1)$ respectively; similarly, the fading channel of the $(2S_C)^{th}$ and $(2S_C+1)^{th}$ sub-channel carriers from antenna 2

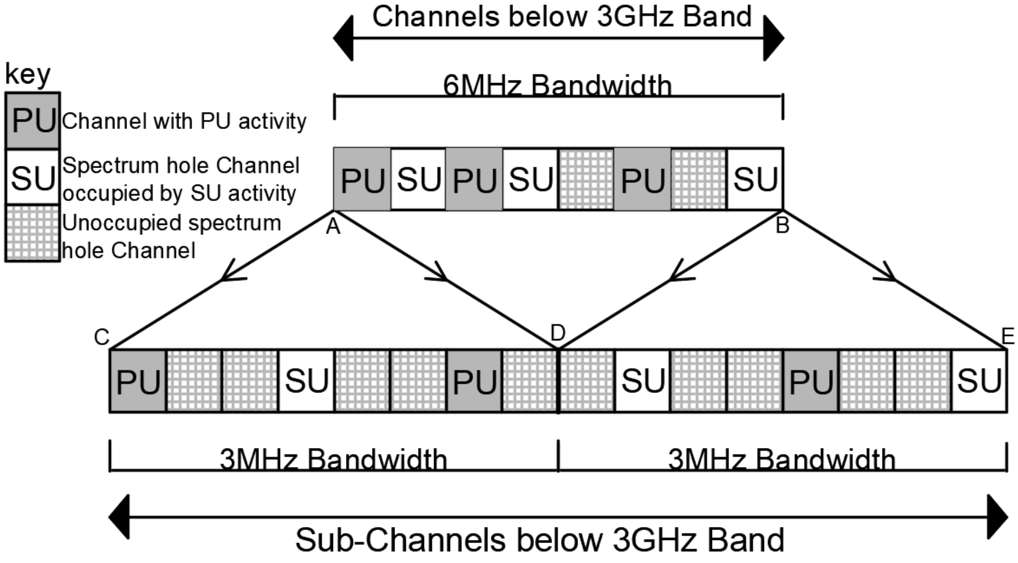


Figure 5.4: Channel Fragmentation Strategy (CFS)

transmission to the reception antenna are denoted as $h_2(2S_C)$ and $h_2(2S_C+1)$ respectively. The received signals of the $(2S_C)^{th}$ and $(2S_C+1)^{th}$ sub-channel carriers at the reception antenna can be obtained as:

$$\begin{aligned} Y_{(2S_C)} =& h_1(2S_C)X_1(2S_C) + h_2(2S_C)X_2(2S_C) \\ & + n_1(2S_C) \end{aligned} \tag{5.3}$$

$$\begin{aligned} Y_{(2S_C+1)} =& -h_1(2S_C+1){X_2}^*(2S_C)+ \\ & h_2(2S_C+1){X_1}^*(2S_C) \\ & + n_2(2S_C+1) \end{aligned} \tag{5.4}$$

where n_1 and n_2 are the noise components in the $(2S_C)^{th}$ and $(2S_C+1)^{th}$ sub-channel carriers respectively. The combined received signals of the two branch transmit diversity Alamouti scheme at the reception antenna is equivalent to that of a two-branch antenna maximum ratio combiner (MRC).

Thus, the blocking probability P_b of the transmit diversity signal is based on probability density function (PDF) of MQAM transmit signal under Rayleigh fading channel; which is derived as follows:

$$P_{b_{QAM}} = \int_0^{\infty} P_{E_{QAM}}((\bar{\gamma}|\gamma))f_{\gamma_{cs}}(\gamma_{cs})\mathrm{d}\gamma_{cs} \tag{5.5}$$

where γ_{cs} is the resulting SNR of the combined signals from the two branch transmit diversity order with one receiver which is equal to that of two-branch antennas maximum ratio combiners (MRC). Hence, the PDF of γ_{cs} under Rayleigh fading is given by

$$f_{\gamma_{cs}}(\gamma_{cs}) = \frac{\gamma_{cs}^{N_{ra}-1}}{\bar{\gamma}^{N_{ra}}(N_{ra}-1)!} exp\left(\frac{-\gamma_{cs}}{\bar{\gamma}}\right) \tag{5.6}$$

But the error or blocking probability of MQAM signal under Additive White Gaussians Noise (AWGN) is given by:

$$\bar{P}_{bQAM} = \int_0^\infty \frac{a}{n} \left\{ \begin{array}{l} \frac{\exp\left(-b\frac{\gamma}{2}\right)}{2} - \frac{a\exp\left(-b\gamma\right)}{2} \\ +(1-a)\sum\limits_{i=1}^{n-1} \exp\left(-b\frac{\gamma}{s_i}\right) \\ +\sum\limits_{i=n}^{2n-1} \exp\left(-b\frac{\gamma}{s_i}\right) \end{array} \right\} \mathrm{d}\gamma \tag{5.7}$$

where

$$a = 1 - \frac{1}{\sqrt{M}},\ b = \frac{3}{M-1},\ s_i = \frac{2\sin(i\pi)}{4n},$$

n is the number of iterations, N_{ra} is the number of receiving antennas.
Then under Rayleigh fading distribution:

$$\begin{aligned} \bar{P}_{bQAM} = \int_0^\infty \frac{a}{n} & \left\{ \begin{array}{l} \frac{\exp\left(-b\frac{\gamma_{cs}}{2}\right)}{2} - \frac{a\exp\left(-b\gamma_{cs}\right)}{2} \\ +(1-a)\sum\limits_{i=1}^{n-1} \exp\left(-b\frac{\gamma_{cs}}{s_i}\right) \\ +\sum\limits_{i=n}^{2n-1} \exp\left(-b\frac{\gamma_{cs}}{s_i}\right) \end{array} \right\} \\ & \times \frac{\gamma_{cs}^{N_{ra}-1}}{\bar{\gamma}^{N_{ra}}(N_{ra}-1)!} exp\left(\frac{-\gamma_{cs}}{\bar{\gamma}}\right) \mathrm{d}\gamma_{cs} \end{aligned} \tag{5.8}$$

Simplifying further using trapezoidal rule, yields the average blocking probability $\bar{P}_b$ as:

$$\bar{P}_b = \frac{a}{n} \left\{ \begin{array}{l} \left(\frac{1}{b\bar{\gamma}+2}\right)^{N_{ra}} - \frac{a}{2}\left(\frac{1}{\bar{\gamma}+1}\right)^{N_{ra}} \\ +(1-a)\sum\limits_{i=1}^{n-1} \left(\frac{s_i}{b\bar{\gamma}+s_i}\right)^{N_{ra}} \\ +\sum\limits_{i=n}^{2n-1} \left(\frac{s_i}{b\bar{\gamma}+s_i}\right)^{N_{ra}} \end{array} \right\} \tag{5.9}$$

Moreover, the result of the implementation of the proposed CR improved model is presented in section VI using NetSim and MATLAB simulation environment to validate enhanced throughput, and reduced blocking probability respectively.

5.4.4 Access Technologies Module Architecture

This section gives the architecture of the proposed communication access technology module.

The communication access technology module is made up of a single board computer (SBC) or routerboard running an OpenWRT,multihomed interface comprising LTE-Cat1/M1 transceiver and a TVBD (super WiFi) transceiver. This also includes an eNodeB which serves as the base station for the user equipment (UE) transceivers and the TVWS database, for the provision of unused spectrum for the TVBD through a TVBD base station, and the incumbent. Alix routerboard [212] can be used to represent the SBC for the design of the virtualized module architecture.

The TVBD and LTE-Cat1/M1 which are represented with antennas are connected to the SCB as depicted in Fig. 5.5. The deployment of this virtualized module architecture is shown in Fig. 5.2 and Fig. 5.3.

The TVBD carries out two functions. First, it acts as a ZigBee coordinator or Clustered Head (CH) for the ZigBee CR sensor nodes via the active link path as depicted in Fig. 5.5 The second function is as a redundant link in case of failure of the LTE Cat1/M1 transceiver for data transfer. The LTE Cat1/M1 operates at 1900/800 MHz while the TVBD operates at the 650 to 890 MHz TV band.

Due to the heterogeneous-mixed of the network interfaces, the proposed module architecture adopted multihomed scheduler at the multihomed layer [213] and Multipath routing at the network layer protocol stack [214] for feasible data transmission. Multihomed scheduler has a priori knowledge of the heterogeneous link, thus, it schedules the appropriate flow of traffic at the respective interface. The multipath routing helps in route discovery and link reliability. It enables traffic to switch to TVBD redundant path in the event of failure of LTE Cat1/M1 path.

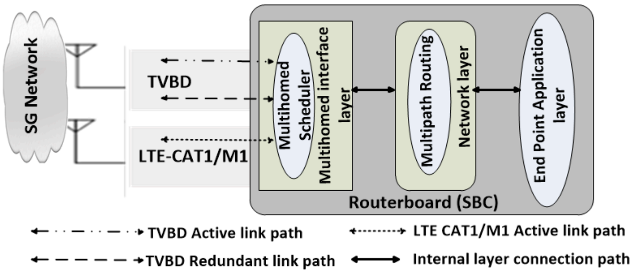


Figure 5.5: Virtualized Multihomed Network Module Architecture

5.5 ACCESS TECHNOLOGIES IMPLEMENTATION MODEL AND PERFORMANCE MEASUREMENTS

The communication access technology implementation is carried out in line with the proposed architecture in Figs. 5.2 and 5.3. It was modeled before carrying out the physical implementation in order to have satisfactory and seamless communication in the SG ecosystem. The simulation and modeling tool used here is the NetSim modeling software and well suited for network lab experimentation [158], [214]–[216].

5.5.1 System Model

The received signal at the receiver of the access technologies to be implemented can be modeled as:

$$y_i(t) = \sqrt{E_s}\,h_i(t)x(t) + n_i(t) \tag{5.10}$$

where $y_i(t)$ is the received signal, E_s is the transmit signal power, x is the transmitted symbol (signal), $h_i(t)$ is Nakagami-q fading channels impulse response (suitable channel for harsh environmental condition of SG) i is in range of 1 to 2, i.e [1,2], is the ith number receiving antennas of fading channels for the multi-homed access links, $n_i(t)$ is the noise with complex Gaussian distribution.

Also, the link feasibility at the receiver or the received signal power P_y can be determined by the expression:

$$P_y = P_x + A_y + A_x - L_y - L_x - L_p \tag{5.11}$$

where P_y is the received signal power in dBm, P_x is the transmit power in dBm, A_x and A_y are the transmit antenna and receiver antenna gain respectively, in dBi, L_x and L_y are the losses in dB due to transmitting and receiving access devices respectively such as mismatch, access device kit and cable connectors, and L_p is the free space path loss in dB. In free space without other impairment such as attenuation, obstruction and disturbances, the path loss propagation model can be expressed as:

$$L_p = 10\log\left(\frac{P_x}{P_y}\right) = -10\log\left[A_x A_y\left(\frac{c}{4\pi d f}\right)^2\right] \tag{5.12}$$

This expression can also be referred to as link budget Where c is the speed of light, d is the distance between transmitting and receiving access devices, and f is the operating frequency. The path loss models in an environment where there are obstructions, attenuation and disturbances include Hata- Okumura, Modified Erceg-SUI, COST231-Hata, WINNER II, ITU-R M.2135-1, and Log-Normal shadowing path loss, etc. NIST has recommended a large-scale outdoor path loss model for last-mile wireless communication in various segments of an SG (WAN, NAN, FAN, and AMI), and in the utilities [217]. This is due to the varying propagation conditions in a SG environment. However, the Log-Normal shadowing path loss model has been the most widely employed in SGs and in IoT-based SG [218]–[220]. Hence, the Log-Normal shadowing path loss (LNP_L) can be expressed as:

$$LNP_L = P_L(d0) + 10n\log\left(\frac{d}{d0}\right) + X_\sigma \tag{5.13}$$

where $P_L(d0)$ is the path loss initially present due to a reference distance ($d0$) of 1 m; n is the path loss exponent which varies with the environmental conditions, and adjusts the rate at which the power degrades with distance and d is the entire covered distance of propagation path. The last term X_σ is the zero-mean Gaussian random distributed variable, which models the shadowing and multi-path environments, while the parameter

σ denotes the variation of the standard deviation of distribution around the mean.

Consequently, the Log Normal Shadowing path loss as shown in equation (5.13) is the SG factor to be considered as the key immunity compliance requirements in a CRSN deployment for SG.

The link feasibility can be estimated in the area of deployment of the wireless communication for a SG, by considering the signal power and receiver sensitivity.

However, we can estimate the difference between the received signal power and the receiver sensitivity. This is called the fade margin, expressed as:

$$F_m = P_y - y_s \tag{5.14}$$

where F_m is the fade margin in dB, y_s is the receiver sensitivity in dBm. Hence, adequate received signal power will result in an appreciable fade margin. The fade margin will account for the impairment or losses caused by multi-path fading, shadowing, attenuation and other obstruction. Fade margin is maximized in order to get a desired received signal [221]. Based on field experience, and link budget analysis, it has been discovered that increasing the fade margin can lead to outage-free links [222]-[223]. Thus, is suggested that the fade margin should be increased to a level of at least twice the total antenna gain of the transceiver access devices in a CRSN based SG implementation. This is due to the fact that SG has harsh environmental conditions.

5.5.2 Network implementation setup

All the experiments were modeled with the same SG application configuration parameters alongside their respective device parameters. Eight nodes of the respective access devices are used. The nodes are placed in the varying distances with locations of (X, Y) coordinates; e.g., the location of UED and UEK in Fig. 5.6 are (115m,390m) and (890m,390m). Similarly, other access devices node placement follows the same trend of placements. In this thesis, since the investigation is of a prototype, 8 nodes are used with 1000m maximum horizontal range for the LTE Cat1/M1 and CDMA EVDO-1x access devices, and 400m maximum horizontal range for TVBD and Wifi (IEEE 802.11b) access devices.

However, this prototype is scalable, hence, larger scale deployment can be carried out based on the stipulated parameters with many nodes randomly placed at the various coordinates within long range. Regarding the transmission path, the dotted lines are the link path from the base station to each node. The green and pink lines are the paths for the transfer of SG application data to the nodes. Each SG application is transmitted independently using a unicast mode to differentiate each application transfer from the other.

5.5.3 Modeling LTE CAT1/M1

In this section, we modeled LTE CAT1/M1 and compare it with legacy cellular such as CDMA EV-DO which is 3G wireless technology and suited for data transmission. Table

5.1 shows network parameters for LTE CAT1/M1 base station (eNB). Table 5.2 shows the network parameters used for modeling LTE CAT1 and LTE M1 user equipment modules respectively; while Fig. 5.6 depicts the simulation experimental testbed for LTE CAT1/M1.

The experiment is modeled with six smart grid applications such as: Automatic Metering infrastructure (AMI), Demand Response Management (DRM), Distributed Energy Resources (DER), Home Energy Management System (HEMS), Wide Area Situational Awareness (WASA) and Distribution Automation (DA). The SG applications are generated from the SG application server with a packet size of 1460 bytes, which are then used by the LPWA communication access devices for various SG data services. Table 5.3 shows the SG application parameters.We also modeled legacy cellular such as CDMA EVDO to compare it with our LPWA (LTE CAT1/M1) model. Table 5.4 shows the EVDO base station and module parameters. Fig. 5.7 depicts the simulation experimental testbed.

5.5.4 Modeling TVBD

Since the communication access technologies is based on multi-homing, we modelled TVBD which is the other interface, that is responsible for making use of TVWS as well as a redundant link in case of primary link failure. Table 5.5 shows the TVBD configuration parameters, and the simulation experimental testbed is shown in Fig. 5.8.

We also modeled legacy Wi-Fi (802.11b) to compare it with our TVBD model.
Table 5.5 shows the Wi-Fi base station and module parameters. Fig. 5.9 depicts the simulation experimental testbed.

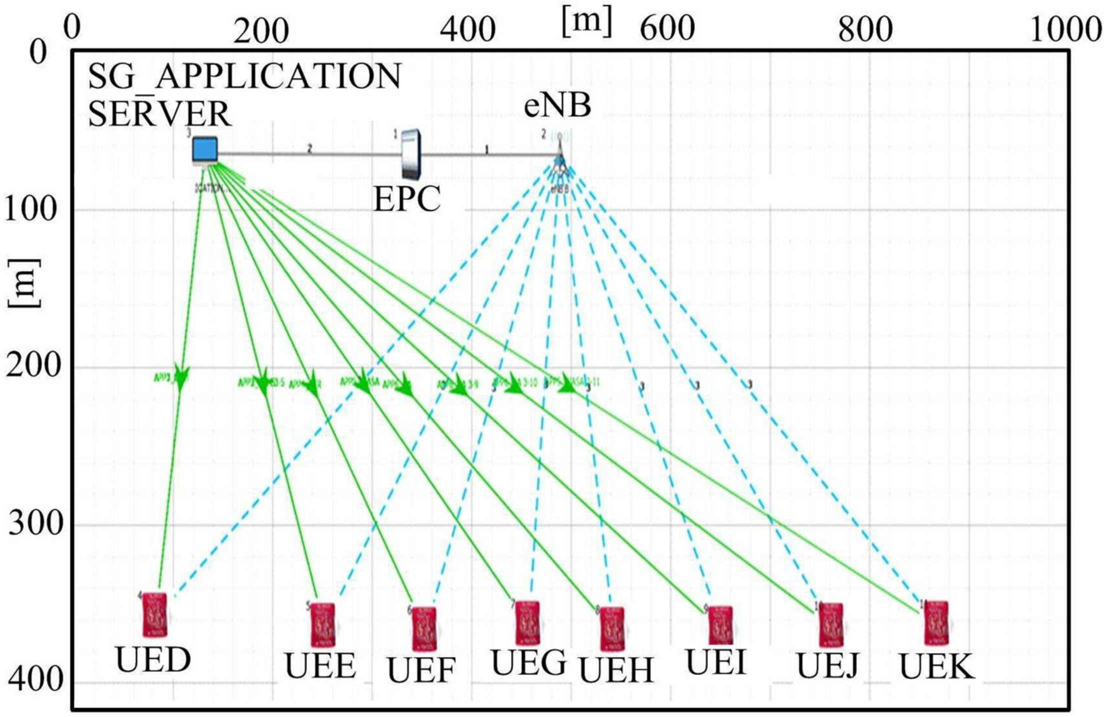


Figure 5.6: LTE CAT1/M1 Simulation Experimental testbed

5.6 RESULTS AND DISCUSSION

For a proper understanding of the results in terms of throughput, the throughput of the access technologies devices is shown in Table 5.6. Also, regarding the application delay of the devices, as a guide, the threshold required for the application delay metrics of each of the various access devices is 600 ms. This threshold requirement is suitable for SG environment based on the fact that most of the SG applications are mission-critical and cannot tolerate higher delays. A full analysis of the results is given in the subsequent sections. The following terms are also useful in this study:

Throughput: Throughput is the rate of successfully transmitted data packets per second.

Instantaneous throughput: Instantaneous throughput of a link is the throughput at any point in time for the link within the overall transmission or simulation time.

Moving average throughput: Moving average throughput is the average of the instantaneous throughput for the link for a given period of time.

Based on the above terms, regarding the instantaneous throughput, if you take a point on the link, and then check what happens over time you would see that there is a packet or there is no packet. Hence, the instantaneous throughput would either be one packet or zero packet. Hence, moving average throughput is used throughout the simulation experiments

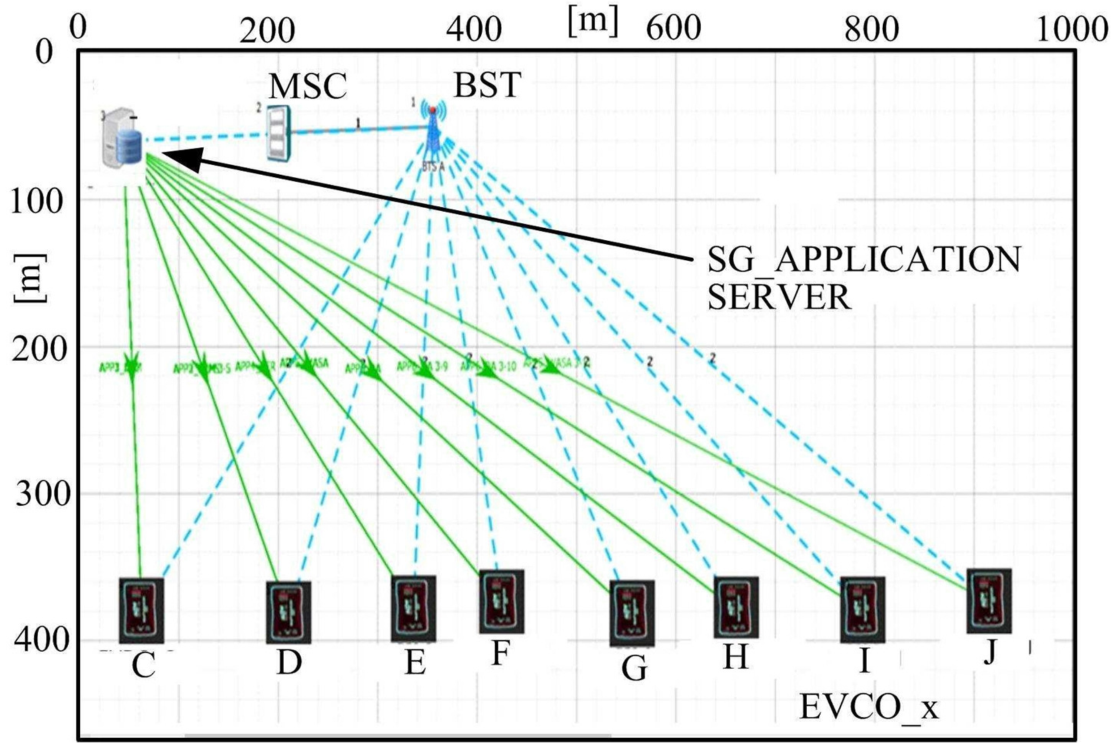


Figure 5.7: CDMA EVDO Simulation Experimental testbed

5.6.1 Results and analysis of the CR-TVBD network model

The simulation is conducted in Netsim under two different scenarios. Scenario 1 is CR-TVBD improved model; scenario 2 is a conventional CR network. In each scenario, eight nodes are induced by the same SG applications under 650-860 Mhz frequency range. The result of the application moving average throughput was obtained in NetSim, and then plotted in Matlab as shown in Table 5.7 and Fig.5.10 and Fig. 5.11 respectively.
The aim of the simulation experiment is to analyze the throughput of the various applications in both scenarios Further, a simulation experiment was also conducted in Matlab in order to investigate the performance of the improved CR model based on Alamouti diversity scheme under Rayleigh fading channel. 10,000 iterations of 4 QAM Rayleigh fading channel were used for both the improved CR model and conventional CR network. The simulation parameters for this experiment are shown in Table 5.8

The result of the Matlab graphical plot for blocking or error probability with respect to SNR, showing comparisons of the improved CR model and conventional CR network is depicted in Fig. 5.11.

5.6.1.1 Analysis of the CR throughput and blocking probability

A data packet of 1460 bytes of each of the SG applications is transmitted to be received by the CR nodes. looking at Fig. 5.10, considering the improved CR model, one can see that a

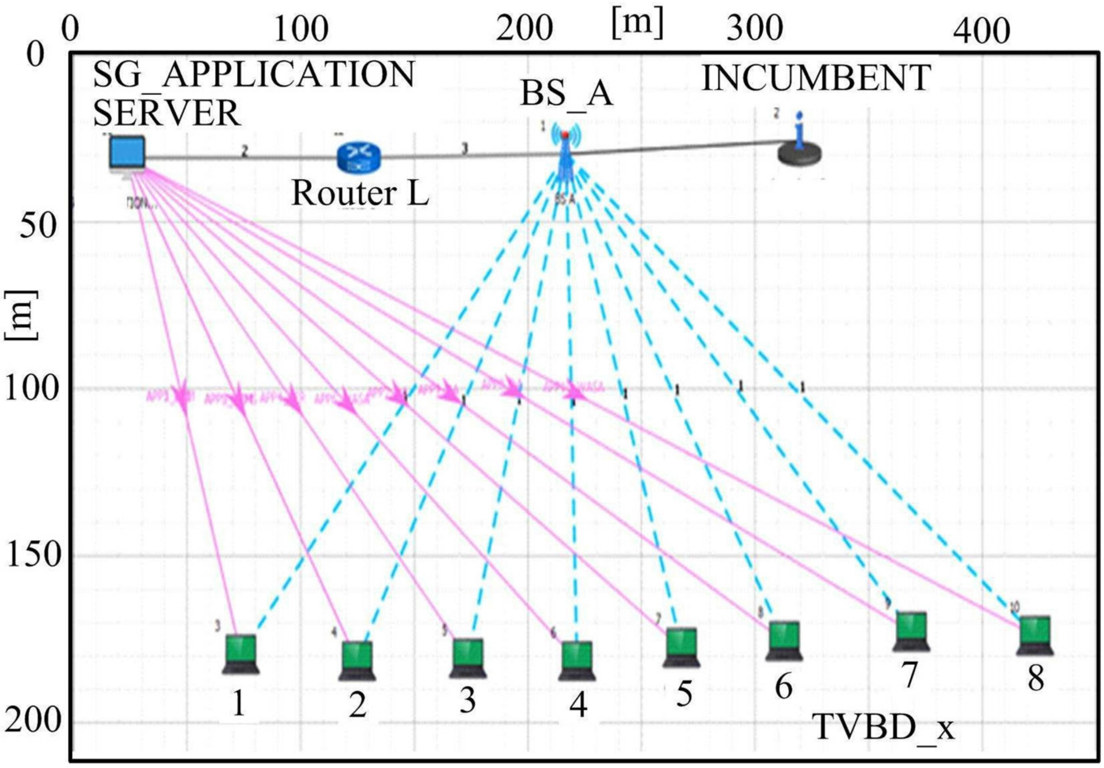


Figure 5.8: TVBD Simulation Experimental testbed

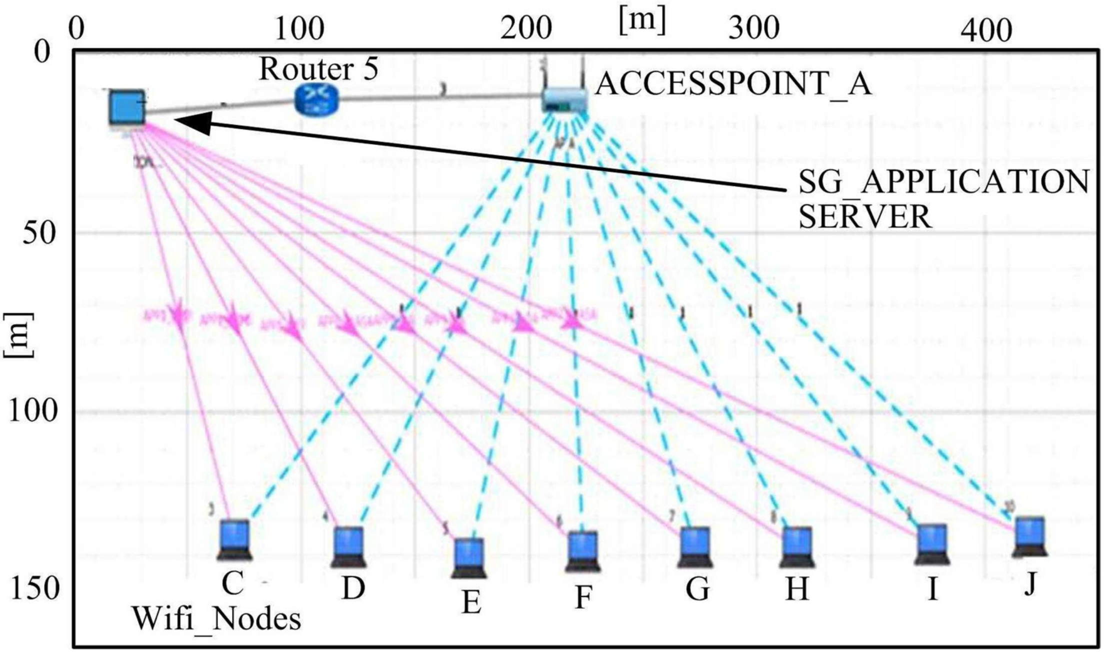


Figure 5.9: Wifi Simulation Experimental testbed

Table 5.1: LTE CAT1/M1 Base station (eNB) major configuration parameters

LTE CAT1 Base Station (eNB) parameters	
Device name	eNB
Transmitter power	30 mW
Modulation	16 QAM
Pathloss	30 dB
Transmission mode	2
Carrier Aggregation (CA)	Intra Band Contiguous CA
CA configuration	CA_1C (LTE CAT1)
MIN/MAX UL Frequency	1920/1980 MHz
MIN/MAX DL Frequency	2110/2170 MHz
Channel Bandwidth	20 MHz
Scheduling Type	Round Robin
Duplex scheme	FDD
LTE CATM1 Base station (eNB) parameters	
Device name	eNB
Transmitter power	20 mW
Modulation	16 QAM
Pathloss	30 dB
Transmission mode	1
Carrier Aggregation (CA)	Intra Band Contiguous CA
CA configuration	CA_27B (LTE M1)
MIN/MAX UL Frequency	807/824 MHz
MIN/MAX DL Frequency	852/869 MHz
Channel Bandwidth	1.4-3 MHz
Scheduling Type	Round Robin
Duplex scheme	FDD

minimum of 0.12 Mbps throughput and maximum of 0.13Mbps throughput are attained by the SG applications. Whereas for the conventional CR, the attained throughput of the SG applications was between 0.06Mbps and 0.07Mbps. Hence, it can be deduced that the improved CR model throughput is ten times better than conventional CR network.
This is because the improved CR model has been optimized to create additional channel using CFS based- Alamouti diversity scheme. Thus, CR device will use the additional channel for transmission even when there is no available channel by the incumbent or PU. This will lead to an appreciable throughput since there is low or no loss of packets during transmission.

However, for the conventional CR, if there is no available channel by the PU, the CR will not transmit due to high blocking probability since the PU is using the channel. This will affect the transmission leading to loss of packets as well as poor throughputs.

Looking at Fig. 5.11, it can be seen that the blocking or error probability at a given SNR in improved CR model is lower than the blocking probability in the conventional CR network.

Table 5.2: LTE CAT1/M1 UE Module major configurations parameters

LTE CAT1 UE Module parameters	
Device name	UE Module
Transmitter power	30 mW
Pathloss	30 dB
Transmission mode	2
Transport Layer Protocol	UDP
Segment size (Bytes)	1472 Bytes
Distance	1 km
Mobility Model	Random way point
LTE CATM1 UE Module parameters	
Device name	UE Module
Transmitter power	10 mW
Pathloss	30 dB
Transmission mode	1
Transport Layer Protocol	UDP
Segment size (Bytes)	1472 Bytes
Distance	1 km
Mobility Model	Random way point

Table 5.3: SG Application server parameters

Device name	SG_Application Server
Application Method	Unicast
Application Type	Custom
Application Name	AMI/DER/DRM/HEMS/WASA/DA
Source ID	SG_Application Server
Destination ID	UE Modules
Start Time (s)	0 s
End time (s)	90 s
Packet size (bytes)	1460 bytes
Inter Arrival time (usec)	20000us

For example, CR model exhibit a minimum error probability of approximately 10^{-6} at SNR of 27 dB and maximum error probability of approximately 10^{-1} at SNR of 0 dB, whereas the conventional CR network exhibit a minimum error probability of approximately 10^{-2} at SNR of 27 dB and maximum error probability of approximately 10^{0} at SNR of 0 dB. This means that the conventional CR network encounters more errors in excess of 100 % at a given SNR than the improved CR model.

The improved CR model has performed better than the conventional CR in terms of error probability because the optimized CR model creates additional channel based on channel fragmentation/bonding and Alamouti diversity scheme.

The error probability encountered by the optimized CR model is only that of the period of switching from a channel to available channel during the arrival of PU. That was why a minimal error rate is exhibited by the optimized CR model. Whereas the error rate

Table 5.4: CDMA EVDO major parameters

CDMA EVDO Base station parameters	
Device Name	BTS (Base Transmission System)
Device Type	BS (Base Station)
Standard	1x-EV-DO
Distance (BTS Range)	1 km
Channel Bandwidth	1.25 MHz
Modulation	GMSK
Mobility Model	Random way point
Transmission Power	20 mW
CDMA EVDO Module parameters	
Device Name	EVDO Module
Mobility Model	Random
Modulation	GMSK

Table 5.5: TVBD/WI-FI major configuration parameters

TVBD Base station parameters	
Device Name	Base Station
Min/Max Frequency	650/862
Coding rate	(1/2)
Distance (Range)	1 km
Channel Bandwidth	6 MHz
Modulation	16 QAM
Pathloss	30 dB
Transmission Power	5 mW
TVBD Module parameters	
Device Name	TVBD Module
Transport Layer protocol	UDP
Pathloss	30 dB
Transmitter power	5 mW
Wi-Fi Base station parameters	
Device Name	AP (Access Point)
Frequency	2.4 GHz
Standard	IEEE 802.11b
Distance (Range)	1 km
Channel Bandwidth	20 MHz
Modulation	DSSS
Pathloss	30 dB
Transmission Power	100 mW
Wi-Fi Module parameters	
Device Name	Wireless Node
Transport Layer protocol	UDP
Pathloss	30 dB
Transmitter power	50 mW

encountered by the conventional CR during arrival of PU includes errors encountered both in the period of switching to available channel and the period when there is no available

Table 5.6: Throughput of Access Technologies Devices

Communication Access Technologies	Theoretical link throughput	Link throughput threshold required	Link throughput obtained
LTE Cat1	10.0Mbps	5.0Mbps	6.0Mbps
LTE CatM1	1.0Mbps	0.5Mbps	0.65Mbps
CDMA-EVDO	2.4Mbps	1.2Mbps	1.0Mbps

Table 5.7: SG applications for both scenarios

SG Applications	Improved CR Model Throughput (Mbps)	Conventional CR Throughput (Mbps)
AMI	0.12257	0.06509
HEMS	0.122619	0.065077
DRM1	0.122581	0.065104
DRM2	0.1226	0.065104
DER	0.122581	0.065109
WASA1	0.1226	0.064918
WASA2	0.122543	0.064918
DA1	0.122562	0.064877
DA2	0.1326	0.065918
DA3	0.122643	0.074877

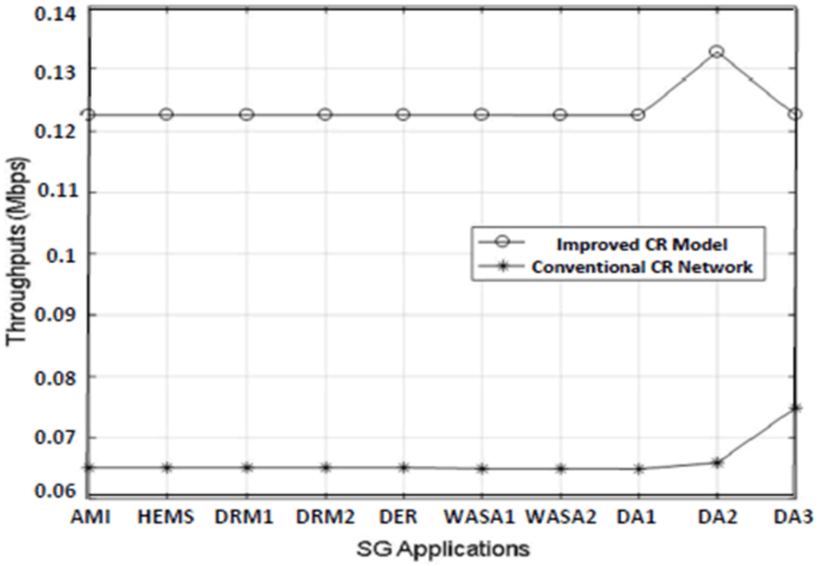


Figure 5.10: SG Applications throughput of CR

channel since no additional channel creating mechanism in this case.

Table 5.8: Simulation parameters

Parameters	**Values**
Number of available channel	6
Simulation runs	10,000
Multipath Fading	Rayleigh
Shadow Fading	Log-Normal Shadowing
Modulation size	4QAM
SNR	0:30 dB

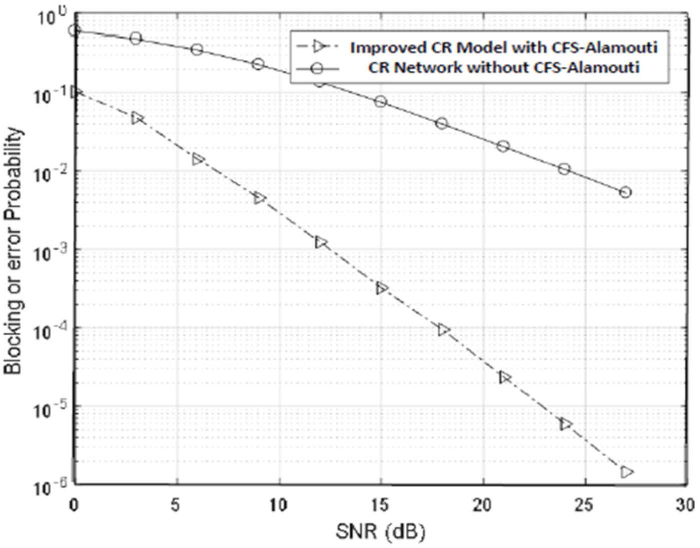


Figure 5.11: Comparisons of CR Blocking Probability

5.6.2 Results and analysis of access technologies performance measurements

The communication access technologies are modeled with various SG applications to determine the performance measurements of the access devices. All the experiments were modeled with the same SG application configuration parameters alongside their respective device parameters.

The simulations run is set to 90 s in all experimental scenarios.This is to enable one see what the performance response of the system will be within a short time frame. Earliest response of the system during initial micro seconds may not be seen if longer simulation duration is used.

5.6.2.1 Analysis of Link Throughput of LTE CAT1/M1 AND EVDO

Looking at Fig. 5.12 for the LTE CAT1, the link could support about 5 Mbps data rate at 0s when the application data commenced and progress to 6 Mbps and maintained this rate throughout the duration of the application transfer data. An LTE CAT1 theoretically support link capacity (bandwidth) of maximum of 10 Mbps. The attainment of 6 Mbps throughput obviously indicates that an appreciable amount of throughput is delivered within a very short time with very low end-to-end delay depicted from the application delay metrics in Table 5.9. This means that LTE CAT1 can withstand varying EMI conditions in a SG environment. Hence, a better throughput is obtained. Since all the experiments are modelled under 1 km range with 30 dB pathloss, shadowing and multipath, in order to align with SG environmental harsh condition; this led to loss of some bandwidth of the full link capacity.

However, the good thing here is that LTE CAT1 could attain up to 60 percent throughput of the link capacity in a harsh rugged environmental condition with non-line of sight (NLOS). Similarly, Fig. 5.13 for the LTE M1 supported throughput from about 0.1 Mbps to 0.65 and maintained that throughout the link delivery. LTE M1 has maximum of 1 mbps bandwidth, and was able support data rate of over 0.65 Mbps confirming over 65 percent throughput of the link capacity in a rugged environmental condition with non-line of sight (NLOS). The application delay metric is also very low as shown in Table 5.9.

Regarding the CDMA 1x-EVDO throughput which is depicted in Fig. 5.14, it has 2.4 maximum link capacity but only about a maximum of 1.1 Mbps throughput could be supported by the link. Just about 45 percent of the link capacity is utilized. This means that in a SG harsh environmental condition, where there are high multi-path fading including NLOS, EVDO will not thrive very well owing to also the high delay. Summarily, LTE CAT1 and LTE M1 outperform CDMA 1X-EVDO in terms of throughput as well as delay.

5.6.3 Analysis of Application Delay Metrics

Applications delay metrics as well as the average delay metrics with respect to the access technologies used is shown in Table 5.9. Graph of the delay metrics is shown in Fig. 5.15. Observation of the application delay metrics in Table 5.9 together with the delay metrics graph of the various access technologies shows that the LPWA devices such as the LTE CAT1 and LTE M1 outperform legacy cellular such as CDMA 1x-EVDO in terms delay. This confirms the suitability of these LPWA devices for SG deployment. Also, TVBD outperform legacy Wi-Fi in terms in terms of delay as depicted from the average application delay metrics graph in Fig. 5.15.

Hence, LTE CAT1/M1 and TVBD have very low latency when compared with EVDO and legacy Wi-Fi. Obviously, Wi-Fi would have had a low latency as well but because the experiment is modelled in rugged condition of high pathloss, multipath, shadowing and NLOS, it could not thrive well in this condition. It is also susceptible to interference due to its frequency of 2.4GHz which many devices operating under this frequency are using and are ubiquitous. Wi-Fi flourishes in less multipath fading and good line of sight (LOS) environment. The super Wi-Fi device could withstand the rugged owing to the fact that it

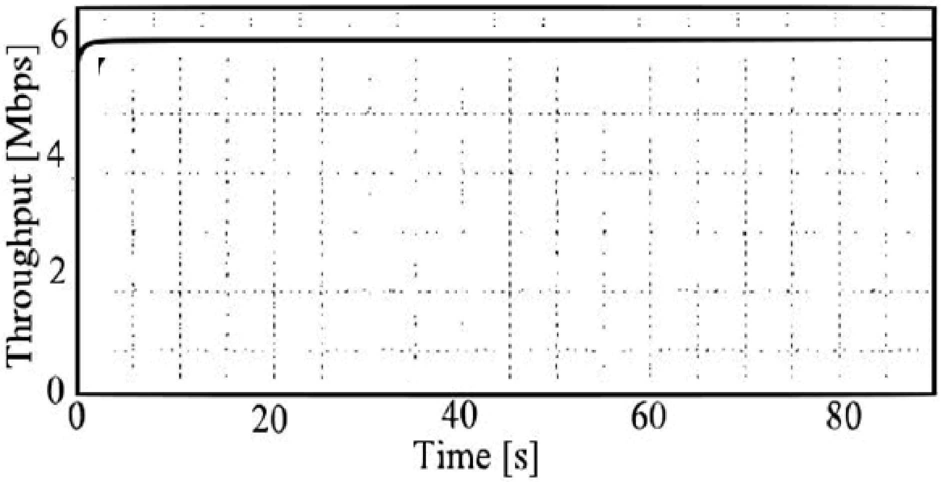


Figure 5.12: LTE CAT1 Link Throughput Graph

is using TV frequency in the range of 650-862 MHz.

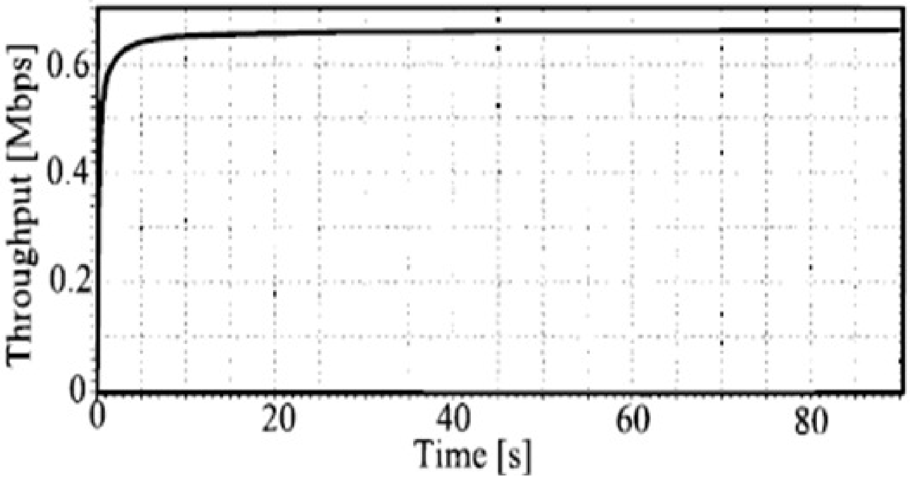


Figure 5.13: LTE CATM1 Link Throughput Graph

5.7 Future Research and Recommendation

The experiments were carried out using basic protocols with improved architectural approach of virtualized network module and multihoming. Configurations were based on the existing device protocols of some devices, however, optimization of protocols based on Alamouti diversity scheme were carried out for the CR model for improved performance. The suitability of access devices based on performance measurements as well as improved CR for improved SG communications was the focus of this study. Obviously, optimization

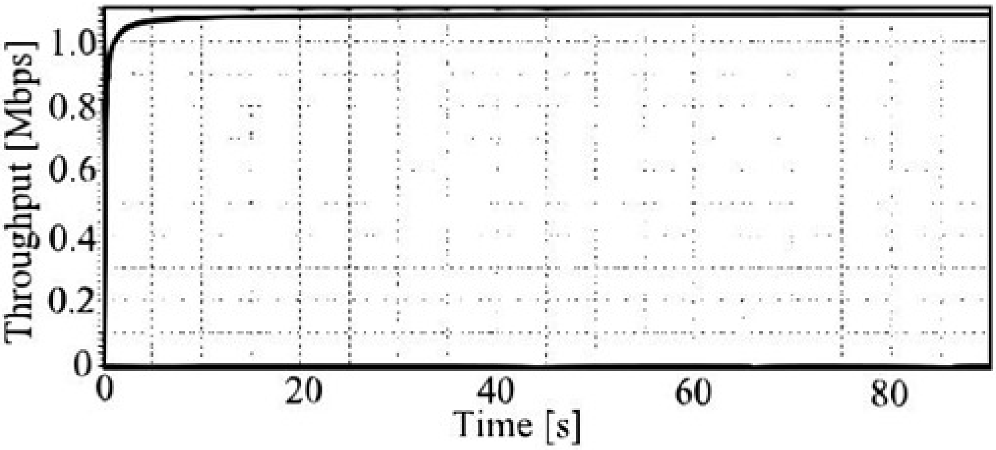


Figure 5.14: CDMA EVDO Link Throughput Graph

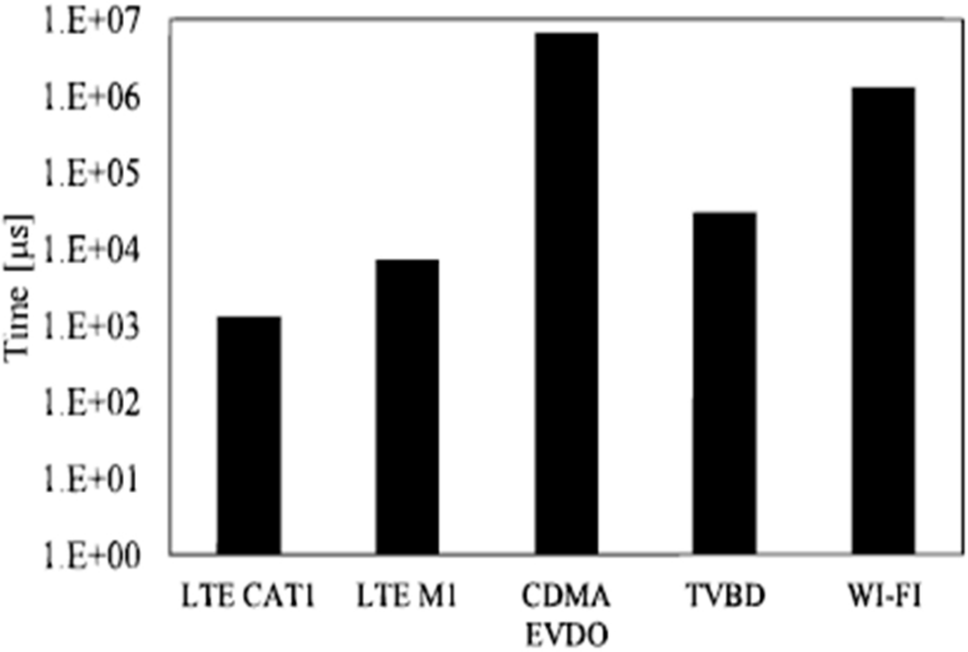


Figure 5.15: Average Application delay metrics comparisons

or modification of protocols at the physical layer, media access layer and network layer will greatly enhance the device capability. Hence, it will be a good research direction, to carry out the following on LTE CAT1/M1 and TVBD:

- Development of energy efficient cross layer communication protocols
- Optimization of the communication network layer protocols

Table 5.9: Application Delay Metric in (ms) of LTE CAT1/M1, EVDO, TVBD & WI-FI

Access Technologies	AMI	HEMS	DRM1	DRM2	DER	WASA1	WASA2	DA1	DA2	DA3	Average Application Delay
LTE CAT1	1.01	1.00	1.01	1.00	1.00	1.00	1.01	2.00	2.01	2.03	1.30
LTE M1	6.06	6.07	8.70	8.70	6.70	5.96	5.82	7.47	7.48	7.47	6.98
CDMA EVDO	6714.3	6719.9	6725.0	6720.20	6717.90	6726.30	6729.8	6735.2	6740.60	6746.0	6727.0
TVBD	4.92	55.78	11.12	15.88	22.62	26.32	33.95	37.07	45.29	48.94	30.19
WI-FI	1268.77	1270.54	1272.92	1274.41	1276.55	1278.47	1280.16	1280.47	1271.09	1083.97	1255.73

- Investigating and appropriating link budget for link feasibility in CRSN based SG deployment

- Optimizing Quality of Service (QoS) algorithms including algorithms for virtualized network flow/admission control will help in throughput enhancement in CRSN based SG.

- Integration of link adaptation algorithms for appreciable throughput in SG harder environment condition.

Finally, the aforementioned recommendation will help to add to the improvement of the throughput with low delay latency of the LTE CAT1/M1 and TVBD communication access devices. This enhancement will help to increase the link full capacity as well to a greater extent. Hence, there will be seamless communication and satisfactory delivery of SG sensed data in timely manner in CRSN based SG ecosystem.

5.8 Chapter Summary

In this chapter, A CRSN alongside communication access technologies for SG communication was x-rayed. An improved CR model which involves CFS based- Alamouti scheme has been developed for reliable SG communication. Performance measurements of communication access devices for SG network were conducted. The use of a single routerboard module can be used to support multiple interfaces through virtualized network in the form of multihoming capability features. We carried out an implementation model of the access technologies through experimentation using simulation testbed.

The results of the modeling and simulation confirm that LPWA devices such as the proposed LTE CAT1/M1 outperform the legacy cellular such as CDMA 1x-EVDO in terms of throughput and latency. Also, the other interface link which serves as redundant link as well as TV band frequency provisioning to the CRSN outperforms the legacy Wi-Fi (IEEE 802.11b) in terms of latency in SG tough environmental condition.

In addition, the improved CR model outperforms conventional CR network in terms of blocking probability and throughput for SG communications. Furthermore, we provided future research direction and recommendations for communication access technologies enhancement in CRSN based SG paradigm.

Chapter 6

Energy Efficient Distributed Heterogeneous Clustered Spectrum Aware Network Model for Guaranteed QoS in CRSN based Smart Grid

6.1 Introduction

In this chapter, we investigate various topologies of ZigBee CRSNs and proposed suitable topology with energy-efficient spectrum-aware algorithms of ZigBee CRSNs in SGs. The performance of the proposed ZigBee CRNSs topology with a control algorithm are analyzed and compared with conventional ZigBee sensor network topology scenario for implementations in SG environments. The QoS metrics used for evaluating the performance are end-to-end delay, bit error rate (BER) and energy consumption.

Cognitive Radio Sensor Networks (CRSNs) have recently been envisioned for SG applications to improve monitoring and control, and overall communication network in the SGs network. So as to have reliable and efficient electric power services. [185], [13]. CR can help to mitigate excessive collisions in the network [224].
Generally, the topologies of CRSNs involve deployments of few to several hundred CR sensors within areas where monitoring activities are required.

Each CR sensor node can connect to one or more CR sensor nodes in order to transmit data. Obviously, CR sensor nodes deployment for full sensing coverage plays a very vital role to allow reliable transmission through SG communication network. Basically, the sensor node including CR sensor node has energy and resource constraints issues [193]. The limitation of the energy or the battery life can adversely affect the overall sensor network lifetime. Thus, adequate topology will go a long way in addressing energy consumption of a CRSNs as well as minimal end-to-end delay and appreciable throughput of the CR sensor nodes. In addition, efficient MAC protocols that will enable the coexistence of CRSNs with existing wireless infrastructure are essential [226].

While the conventional ZigBee WSNs make use of fixed channel access, CRSNs make use of multiple channel access from the available spectrum opportunistically through dynamic spectrum access (DSA). The fixed channel for conventional ZigBee can be easily chocked during access allocation and as a result causes excess energy consumption, overhead and interference. Other features that illustrate the differences between ZigBee WSN and ZigBee CRSNs are depicted in Table 6.1. From the table, it can be seen that there are topological differences between ZigBee WSNs and ZigBee CRSNs. In details, the topologies of CRSNs in the subsequent section are clear.

Table 6.1: Comparisons of ZigBee WSNs and ZigBee CRSNs

Features	**ZigBee WSNs**	**ZigBee CRSNs**
Channel Access	Fixed channel access	Multiple and dynamic channel access
Organizing and self-healing	Moderate self-healing	Very high self-healing
Interference Avoidance	Low	High
Network Topologies	Star, Cluster-tree, and Mesh	Star, Peer-to-Peer/Mesh, Cluster, Heterogeneous and Hierarchical, Mobile Ad Hoc, and Distributed Heterogeneous Clustered (Proposed)
Communication protocol stack	Physical, Data link, Network, and application layer	Physical, Data link, Network, Transport, and application layer

6.1.1 Compliance requirements for communication infrastructure and CRSNs Integration in SG

CRSNs for other applications are different from the CRSNs for SG applications due to the following compliance requirements:

- CRSNs deployment in SG should be supported by the key immunity compliance requirements which have been enacted by the International electrotechnical commission (IEC) [136]. CRSNs for other applications are deficient of the key immunity compliance requirements in SGs.

- CRSNs in SGs must be able to overcome electromagnetic interference (EMI) impacts in SG. It has been established that EMI and environmental changes negatively impact wireless communication infrastructure in SG [136], [138].

- Appropriate electromagnetic comparability (EMC) must be considered for implementation of CRSNs in SG. The International Special Committee on Radio Interference (CISPR) investigated radio noise originating from high voltage (HV) power equipment and provided recommendations for reducing the radio noise generated in SGs [137].

Hence, existing works on CRSNs which are meant for other applications suffer from EMI impact in SG. However, this paper considers the key immunity compliance requirements for CRSNs deployment in SG.

6.1.2 ZigBee CRSN Features

ZigBee CRSN has numerous unique features that differentiate it from the conventional ZigBee WSN. Since it incorporates the cognitive capabilities of CR into WSN, it therefore, differentiates itself from CRN and WSN. Hence, it has a unique feature (possessing dual features: CRN and WSN). We have already elaborated on the unique characteristics of CRSN in chapter 3.

Some of the unique features are based on the cognitive cycle functionalities to enable the secondary users to have dynamic and opportunistic access to the unused channels. These functionalities are spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility. These four main DSA management functionalities of the CR are required to determine the accurate communication parameters of SG communication and adjusts to the dynamic radio environments. Details of the DSA management functionalities are found in [18] In addition, due to the presence of these unique features of CRSN, optimization of the protocol stacks in order to achieve improved QoS performance that is used for conventional ZigBee WSN which cannot be directly applied to CRSN. Also, the existing protocols of conventional WSN cannot be applied to CRSN because of its dynamic availability of multiple channels, and the dynamic spectrum access in the presence of primary user activity.

Hence, while designing resource allocation schemes for CRSNs, their unique features should be considered as well as the primary user activity consideration. Consequently, this work put into consideration these unique characteristics when designing the algorithms for QoS enhancement.

6.1.3 CRSN Topologies

The CRSNs have different network topologies, that are based on the application requirement. Hence each topology is suitable for a particular application. Thus, the following network topologies have been identified:

6.1.3.1 Star Topology

This is the simplest topology suitable for very small scale sensor network. This topology has a central base station infrastructure which handles spectrum sensing and resource allocation to the connected node as depicted in Fig. 6.1 (a).

6.1.3.2 Peer-to-Peer Topology

In this topology, the CR sensor nodes communicate with each other in peer-to-peer as well as in multi-hop manner and directly to the sink node. This topology has no base station infrastructure. Hence, spectrum sensing, resource allocation and sharing are done by each node separately or by cooperative communication. Large scale deployment of this topology can lead to a mesh network with several multi-hops as depicted in Fig. 6.1 (b). This topology has no high computational complexity and overheads. However, there will be a high latency delay due to so many hops count in the mesh network.

6.1.3.3 Clustered based Topology

This is a form of star topology with more sophisticated features suitable for large scale sensor network deployment. The clustered based topology involves selection of cluster-heads or coordinator which will be apportioned to carry out critical tasks such as spectrum sensing for channel availability, and allocation of radio resources to other CR sensor nodes. This topology is depicted in Fig. 6.1 (c). Consequently, cluster heads selection and cluster network formation technique is essential in this topology for improved data communication network in application deployment.

6.1.3.4 Heterogeneous-Hierarchical Topology

This topology involves combination superior sensor nodes such as the actuator and multimedia CR sensor nodes, and the normal CR sensor nodes. The deployment of these mixed CR sensor nodes of various technologies is done in a hierarchical mesh network manner. Hence, this topology comprises a heterogeneous CRSN nodes in a hierarchical mesh network as shown in Fig. 6.1 (d).

6.1.3.5 Distributed Heterogeneous Clustered (DHC) Topology

This topology consists of heterogeneous CRSN nodes such as normal ZigBee CR nodes, actuator, and multimedia sensor nodes. Unlike heterogeneous-hierarchical topology, the deployment here is done in a distributed clustered manner covering an extensive and long-range area. The DHC topology has been presented in chapter three which is depicted in Fig. 3.4. This is the proposed CRSNs topology for SG application, owing to the fact that SG requires heterogeneous networks in supporting different QoS for the various applications. This topology is distributed in that, many inter-clustered are linked with

Table 6.2: Different topologies of ZigBee CRSN with their characteristics

Topology Type	Latency	Computational complexity	Distance covered	Scale of applications	Number of hops
Star	Low	Low	Short	Low scale	Very low
Peer-Peer/Mesh	High	Medium	Long	Large scale	High
Cluster	Medium	Medium	Long	Large scale	low
Heterogeneous hierarchical	High	High	Long	Large scale	High
Distributed Heterogeneous Cluster	Medium	Medium	Very long	Very large scale	Medium
Mobile Ad Hoc	High	Medium	Very long	Very large scale	High

relay CRSN nodes for extensive range coverage. This will help in reducing a number of multi-hops with minimal latency delay, unlike the heterogeneous-hierarchical topology that has several hops with high latency delay.

6.1.3.6 Mobile Ad Hoc Topology

This topology is somewhat similar to the peer-to-peer topology except that mobility is integrated into the CRSN node to cover the deployment area. Some of the CRSN nodes are made to be mobile. For example, mobile Ad Hoc CRSNs can be deployed with environmental, proximity and light monitoring CR sensors.

For clarity, Table 6.2 shows different topologies and their characteristics.

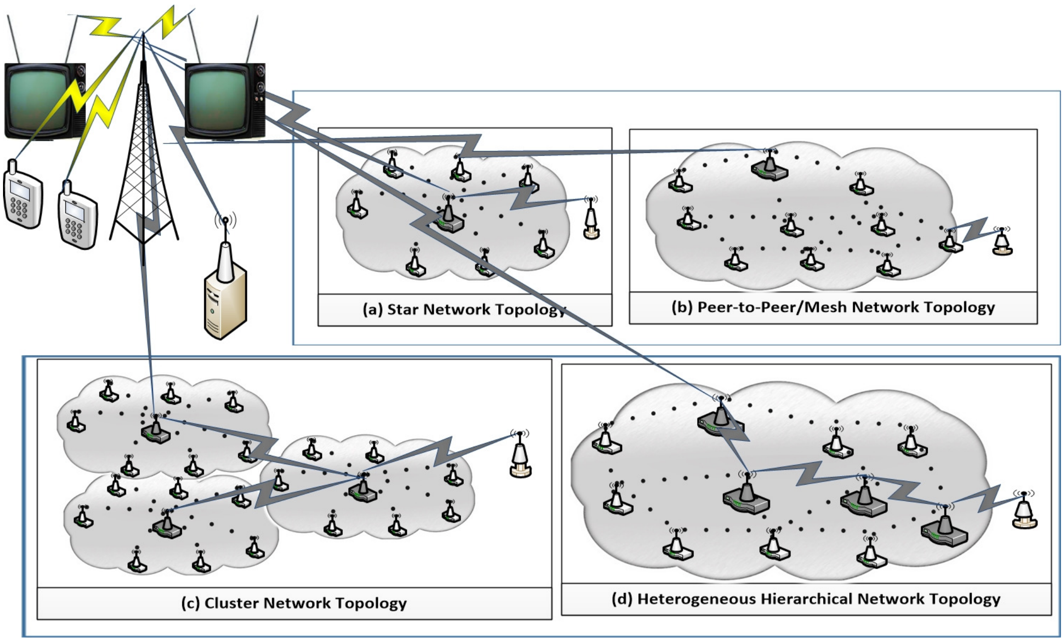


Figure 6.1: CRSN Topologies

6.1.4 Communication Protocols in ZigBee CRSN

In this section, communication layer protocols in ZigBee CRSN were investigated. Obviously, the communication layer protocols have a direct relationship and cooperation with DSA management functionalities highlighted in the previous section. The protocols and cooperation with DSA functionalities as shown in Fig. 6.2 will jointly enhance the communication in ZigBee CRSN nodes. The protocol in each layer of the communication layer protocol must adapt to the spectrum channel operating parameters. Once the spectrum channel is established, the upper layer protocols will adaptively reconfigure their communication protocols accordingly to the application requirements. This is achieved with the help of the inter-layer interaction between the communication protocols and DSA management functionalities as depicted in Fig. 6.2 The communication layer protocols are elucidated below:

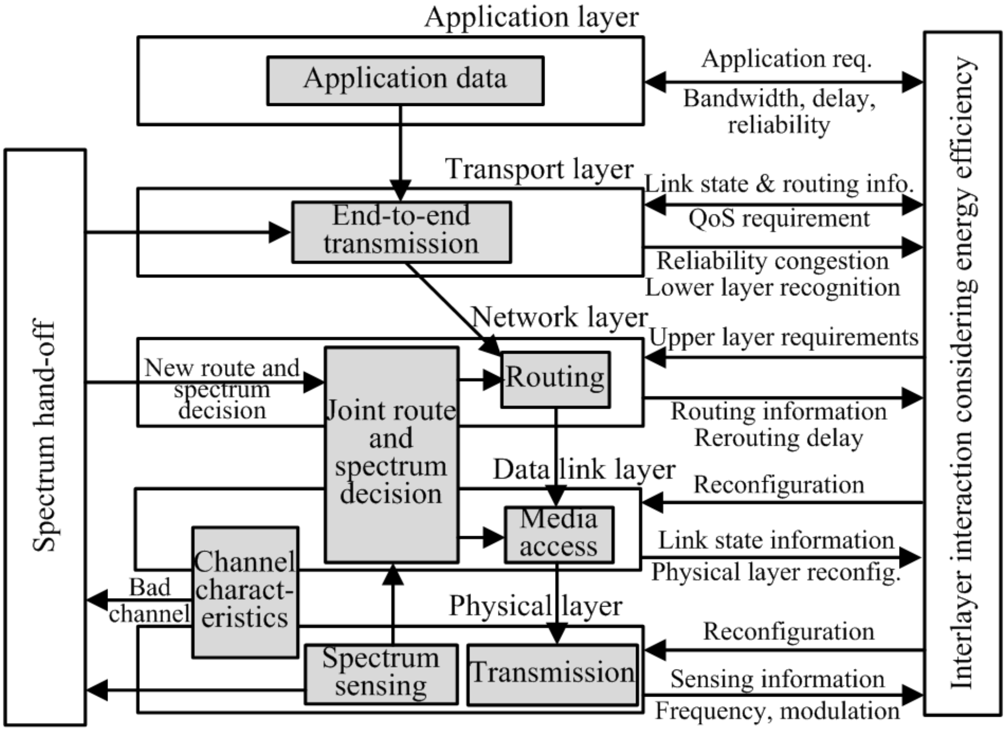


Figure 6.2: Interaction between the communication protocols and DSA management functionalities[130]

- Physical (PHY) Layer;
- media access control (MAC) layer;
- Network Layer;
- Transport Layer; and
- Application Layer.

6.1.4.1 Physical (PHY) Layer

The physical layer in a CRSN node is composed of software defined radio (SDR) based transceiver with configurability capability of its operating frequency, modulation, transmission power and channel coding. This reconfiguration to adjust to the radio environment is done at the software level without any hardware replacement. CRSN node is a resource constrained device. Hence, there is a trade-off between energy efficiency and spectrum sensing detection probability. Performance improvement of CRSN nodes deployment with respect to detection probability was discussed in the earlier work of [156].

6.1.4.2 Data Link Layer (DLL)

DLL consist of the upper sub-layer refers to as logical link control (LLC) layer and the lower sub-layer refers to as media access control (MAC) layer. The LLC layer interact with the network layer for data link connectivity and flow control. The MAC layer handles the spectrum/channel access and allocation. The MAC interacts with the PHY layer for channel access. MAC sub-layer protocol functionalities are sub divided into two, viz:
(i) It interacts with the PHY layer for proper transmission and reception of frame between the CRSN nodes.
(ii) It handles collision/error control function. The MAC protocols handle the spectrum allocation to the CRSN nodes and determines which of the CRSN nodes gets access to the channel and when appropriate. The MAC protocols in CRSNs can be either random access or time-slotted, or both (Hybrid). The Random Access protocols are based on the carrier sense multiple access/collision avoidance (CSMA/CA) standard whereby a CRSN node or secondary user senses the spectrum band to detect the presence of any transmission from neighboring secondary users in order to transmit after an idle period for a random duration. This will help to reduce collisions that would have been caused by simultaneous transmissions. Whereas, the time-slotted MAC protocols are based on network-wide synchronization which is operated by dividing time into distinct slots for data transmission and control channel [18], there are numerous existing and proposed MAC protocols for CRSNs. This work focuses on optimizing the MAC protocols for CRSNs which employ energy efficient with spectrum aware in distributed heterogeneous clustered topology formation and data transmission in CRSNs based SG.

6.1.4.3 Network Layer

The routing protocols take place in the network layer. It is responsible for route or network path discovery for data transfer form one network to the other. For example, the transfer of data from one cluster to another clustered network. Existing conventional routing protocols are not appropriate for CRSNs due to its network unique characteristics such as changes in network topology and varying spectrum channel availability which results to intermittent disconnections.

6.1.4.4 Transport Layer

The transport layer protocols interact with the application layer for delivery of data and pass the request from the application layer protocols down to the network layer. With respect to the existence of PU behavioral activities, varying spectrum availability and channel switching delays in CRSNs environmental condition, conventional transport layer protocols such as transmission control protocols (TCP) performance may considerably degrade and cannot withstand such conditions. Some transport layer protocols have been proposed for reliable transmission in CR environment to address the problems. Though research in the area transport layer protocols for CRSNs is still in its infancy. Hence, we recommend an energy efficient cross layer-spectrum aware transport protocol to circumvent the inherent problems of TCP in CRSNs based SG.

6.1.4.5 Application Layer

The application layer protocols in ZigBee CRSNs are responsible for the control and management of applications with the overall device management tasks. It determines the device type in a network, such as an end device, router, or coordinator. It extracts information of the monitoring events signal. Owing to the unique nature of CRSN characteristics, the existing application layer protocols cannot thrive well with such conditions. Hence, there is a need for suitable application layer protocols for a CRSNs based SG. The contribution of this chapter can therefore be summarized as follows:

- Investigating the potential differences, with particular emphasizes to Network topologies, between ZigBee WSNs and ZigBee CRSNs for SG applications.

- The proposal of a novel network topology called Distributed Heterogeneous Clustered (DHC) of CRSNs suitable for application in SG, industrial networks and Internet of Things (IoT) applications.

- Energy efficient proposal of distributed heterogeneous clustered spectrum aware (EDHC-SA) network connectivity formation and coordination for CRSNs deployment in SG.

- EDHC-SA multichannel sensing signal model based on cross layer algorithm has also been proposed.

Hence, the rest of this chapter is organized in the subsections as follows: related works are highlighted; ZigBee CRSN features; and presentation of proposed DHC of CRSNs in SG; Simulation, results and analysis are provided alongside chapter summary.

6.2 Related Works

Generally, CRSNs implementation for QoS improvement in several perspectives has been investigated by some researchers. The authors of [146] presented a joint life-time maximization and adaptive modulation framework for realizing high power efficiency in CRSNs. The framework to improve energy consumption of the sensor nodes is only on protocol optimization and not based on network topology. Naeem et al. [114] investigated energy efficient power allocation including the maximization of ratio of throughput to power for CRSNs. Their work does not consider network topology for sensor nodes deployment and is not centered on SG.

Aslam et al. [227] proposed a scheme that selects the optimal number of sensor nodes and efficient channel allocation mechanism which improves the performance of clustered topology based CRSNs. The work focuses on efficient channel allocation in CRSNs without considering integration in SG environment. Zhang et al. [228] presented a centralized spectrum-aware clustering algorithm and a distributed spectrum-aware clustering (DSAC) protocol which maintained scalability and stability as well as low complexity with quick convergence in dynamic spectrum variation. The authors did not consider BER in their work. It is also not in the context of SG.

Another work in [104] has been developed in which the authors present differentiation of traffic flows into different priority classes queues according to their QoS requirements. The work did not consider QoS metric in terms of BER and energy consumption.

Other works addressed energy efficiency in sensor network for monitoring applications using hierarchical clustering topology approach. For instance, Heinzelman, et. al. in [229] proposed Low Energy Adaptive Clustering Hierarchy (LEACH) algorithm. The LEACH algorithm involves cluster heads (CHs) which are randomly selected in order to increase the sensor network lifetime. Ref. [230] proposed a Stable Election Protocol (SEP) for clustered heterogeneous WSN. SEP involves a heterogeneous-aware protocol to prolong the time interval before the death sensor node in order to conserve energy.
Ref. [231] proposed a Hybrid Energy-Efficient Distributed (HEED) clustering protocol. HEED periodically selects CHs based on the hybrid of the node residual energy and a node proximity to its neighbors. Ref. [232] proposed Threshold Distributed Energy Efficient Clustering (TDEEC) protocol. TDEEC improves energy of cluster heads by adjusting the threshold value of a node in heterogeneous wireless sensor networks.
Ref. [233] proposed energy-efficient LEACH (EE-LEACH) Protocol for data gathering in WSN. EE-LEACH helps to provide optimal packet delivery ratio with lesser energy consumption. Ref. [234] proposed Cognitive LEACH (CogLEACH), which is a spectrum-aware extension of the LEACH protocol. CogLEACH is a fast, decentralized, and spectrum-aware

including energy efficient clustering protocol for CRSNs.

The major drawback of the mentioned literature for energy-efficient hierarchical clustering topology approach in sensor network is that they lack consideration of compliance requirements for sensor network integration in SG. However, the energy efficiency model in this thesis considers the compliance requirements for sensor network integration in SG. Another area of research attention is the sensing coverage problem in the sensor networks. Numerous researchers have addressed sensing coverage problem based on deterministic sensing models [235]–[237]. Some researchers have investigated sensing coverage problem based on the probability coverage model [238]–[240]. Other researchers explored sensing coverage problems based on the environmental impact such as path loss, multi-path and shadowing fading [241]–[244]. Most of these sensing coverage models ignored the consideration of compliance requirements for sensor network integration in SG. They did not consider multichannel sensing coverage of CRSNs in their works. Also, they did not consider coverage probability with respect to BER and latency in their models. However, this work considers multichannel sensing coverage of CRSNs, and coverage probability with respect to BER and latency for CRSNs based SG communication.

Implementation of CRSNs for enhanced QoS in the SG perspective is found in few literatures. For instance, Shah et al. [142] proposed a cross-layer design that ensures the QoS requirement for CRSN based smart grids. The authors handled the issues of heterogeneous traffics in CRSN based SG by defining different classes of traffic with different priority levels. This classification is significant for separating the traffic with respect to the services and their network requirements, e.g. latency, link reliability, and data rate. However, they did not consider network topology for CRSNs deployment; also, they did not consider BER and energy consumption in their work.

Moreover, Markov chain modeling of CRSN in SG has been presented in [150] with the study aiming at reducing transition delay during handoffs. Though improvement based on network topology, it is also not considered in this work.

However, even though there are few improvements for QoS in the implementation of CRSNs in SG as highlighted, the implementation of CRSNs for guaranteed QoS in the context of network topology of the CR sensor nodes deployments in SG, including the evaluation of QoS metric in terms of BER have been rarely investigated. Hence, our focus here, is on performance improvement of CRSNs based SG which is achieved by utilizing a proposed CRSNs topology for guaranteed QoS based on metric such as reduced BER, low end to end delay, and reduced energy consumption in SG. This will help seamless delivery of sensed data in the SG ecosystem.

6.3 Distributed Heterogeneous Cluster (DHC) Topology of CRSNs in SG

In this section, DHC beginning with the description of the composition of the system as well as the topology was proposed. EDHC-SA network connectivity formation model and EDHC-SA multichannel sensing coverage model were presented.
The investigation work reported in this chapter is conducted for the SUs network.

6.3.1 DHC System Model

A distributed heterogeneous clustered (DHC) ZigBee CRSNs topology was proposed. The system is composed of heterogeneous devices which consists of fully function devices (FFDs) such as ZigBee Pro and multimedia sensors; and reduced function devices (RFDs) such as ZigBee and actuators. In this system model, different tasks are assigned to the different sensor devices such that ZigBee sensors and actuators are responsible for sensing activities within expected coverage and ZigBee Pro which also acts as the cluster head (CH) is for communication channels sensing and allocation to RFDs. It also acts as the coordinator for the RFDs including transmission of collected sensed data as well as relay of the collected data to the base station or sink. The multimedia sensors are responsible for video signals and surveillance activities. Each sector is designed to have two FFDs, primary and redundant or backup coordinators so as to alleviate energy consumption and increase network lifetime. A number of clusters are meant to cover specific areas. The clusters are extended via ZigBee Pro in a distributed relay manner for long range coverage area. The DHC topology has been presented in chapter three as depicted in Fig. 3.4

6.3.2 Energy Efficient Distributed Heterogeneous Clustered Spectrum Aware (EDHC-SA) Network Model

In order to guarantee network coverage and connectivity, the deployment scheme of the heterogeneous ZigBee CRSNs are here presented:

6.3.2.1 Deployment scheme for the EDHC-SA Model

There are two main sensor deployment schemes, which are
(1) structured or deterministic sensor deployment, and
(2) unstructured or random sensor deployment. The latter is suitable for application deployed in remote and inaccessible areas. The deterministic sensor network deployment for SG applications is deployed because it provides sufficient sensing coverage and guaranteed connectivity. This is because SG applications are mission critical applications [99] and requires guaranteed transmission of sensed data in real time manner. Whereas the random deployment is susceptible to sensor coverage holes or possessing some areas that are not being covered in the target field, hence, it is not suitable for SG applications.

A square field area has been considered. And the phenomenon (target) to be sensed or covered is situated within the area. Hence the area can be expressed as A = L x L where L is the length of the sensing area A. The heterogeneous sensors are non-identical and are denoted by S_i, S_u which are deployed clustered by clustered in the sensing area A. where S_i and S_u represent RFD and FFD respectively. The number of CRSN nodes which is denoted as S_{Ns} can be written as $S_{1,1}$, $S_{2,2}$ ...... S_N. They make up a cluster, and are deployed in the target area A. Similarly, the number of clusters which is denoted as C_N can be written as C_1, C_2.....C_N. They make up the total number of clusters in the entire coverage area, and are deployed strategically as well. Let the distance from any point p within the sensing area to a sensor node S_i in the clustered network be denoted as the minimum communication range, R_{min} and the distance from any point p to a sensor node S_u in the clustered network be denoted as the maximum communication range, R_{max}.

The sensing range is based on coverage sensing disk. S_i has least sensing range denoted by R_{ils} and farthest sensing range denoted by R_{ifs}. The sensing range of S_u is denoted by R_us. Hence the following conditional property in a heterogeneous sensor networks are introduced to initialize network coverage (NC) at any given point p in a sensing field area, which is given by equation (6.1) as:

$$NC = \begin{cases} R_{ils} \geq R_{min}(i,p) < R_{ifs} \\ R_{max}(u,p) \leq R_{us} \\ R_{ifs} = R_{us} \\ R_{min}(i,p) < R_{max}(u,p) \end{cases} \tag{6.1}$$

However, due to the excessive number of points on the sensing area, it will be cumbersome to estimate the minimum and maximum communication range at any given point in order to establish if a network coverage will be fully covered. Hence, Voronoi diagram [245],[246] are employed to address this challenge.

The Voronoi diagram partitions the required area A into a set of regular polygons, such that each polygon has a corresponding sensor node; and for any point in the regular polygon, there is a minimum Euclidean distance or minimum communication range to the SN.

The following three regular shapes are used with the Voronoi diagram, viz., square, hexagon, and equilateral triangle. However, the method of the equilateral triangle as depicted in Fig. 6.3 is adopted due to the fact that it gives minimal number of sensors with no errors or coverage hole in an ideal deployment scenario [247]. Since SG is prone to harsh environmental condition and multi-path fading, there may exist a coverage hole; hence, a multichannel fading sensing coverage model is integrated into the Voronoi equilateral triangle to address this challenge. The details of this sensing coverage model is provided in the subsequent sections.

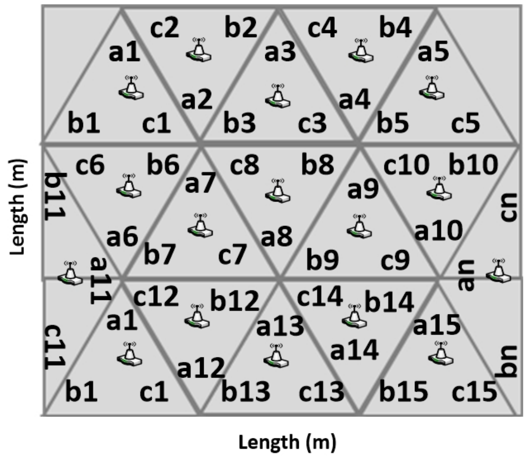


Figure 6.3: Equilateral Triangulation pattern deployment strategy in a square field

6.3.2.2 EDHC-SA Network Connectivity Model

The EDHC-SA network connectivity is modeled by a equilateral triangulation pattern graph, denoted as G = (V, E), as shown in Fig. 6.3, where V represents the vertices of the triangle and E the edges which is the communication links or line segments between the vertices. Hence, the following properties for network coverage and connectivity to be maintained are introduced viz:

- A S_N in any corresponding triangle can communicate with another S_N if any of the vertices of the associated S_N triangle is connected with the other vertices of the associated S_N triangle.

- If all vertices in a triangle are connected, then the triangle is covered by the associated sensor node; hence, the total triangles are covered, resulting into the full coverage and connectivity of the whole area

- Coverage and connectivity can be maintained if and only if the minimum Euclidean distance or minimum communication range, $R_{min}\ (i,p) < R_{ifs}$ as well as the conditional property in equation (6.1), this can be estimated for the edge of any triangle, E to be expressed as:
$$E = R_{ifs}\sqrt{3} \tag{6.2}$$

- Probability of coverage of the equilateral triangulation pattern field is the sensing area of the triangle as depicted in Fig. 6, and it is expressed as:
$$COV_{Pr} = \frac{3(R_{ifs})^2\sqrt{3}}{4} \tag{6.3}$$

- The total number of CRSN nodes that is required for full coverage and connectivity in the total area of the equilateral triangulation pattern field excluding the cut-off edges of the square field, can be obtained with the expression total CRSN nodes,

  $$TS = \frac{A}{COV_{Pr}} \tag{6.4}$$

  $$TS = \frac{4L^2}{3(R_{ifs})^2\sqrt{3}} \tag{6.5}$$

  Since the TS are uniformly distributed, then the total field area A is covered.

- Any point p is said to be connected to the clustered head (CH) if the Euclidean distance is within the sensing range of R_{ifs} or R_{us}.

- The total number of clusters, C_{Ns} is estimated as

  $$C_{Ns} = \sqrt{TS} \tag{6.6}$$

However, there are two CHs in each cluster, the main CH and the backup CH (BU-CH) for energy efficiency and longer network life time. During the formation of cluster network, the primary CH and backup CH will advertise their self as the CH and their header id via the MAC protocol so that SNs within the proximity of the Euclidean distance can be associated with them for data frame exchange. However, immediately after this advertisement, the backup CH will go to idle state until a certain threshold is met for it to become the primary CH and resume association with the S_{Ns}.

Furthermore, the CH coordinates the opportunistic channel access from the primary users 'network via dynamic spectrum access (DSA). It allocates the available unused channels to the CR sensor nodes at the MAC protocol layer through the CSMA/CA. Up to six channels in the 650-860 frequency band can be made available when is not in used by the PU. The SU or CRSNs nodes automatically relinquishes the channels as soon as the authorize users arrives. This intermittent arrival and relinquishes of the channels, especially when the available channels (AC) are all occupied by the PU can cause unnecessary delay to the sensor network which is not suitable for mission critical applications like SG. To address this, we introduce common backup channel (CBC) and equilateral triangulation algorithm (ETA), shown in Algorithm 1, for guaranteed connectivity of the EDHC-SA network in the presence of dynamic multi-channels use. The CBC serves as the control channel and handles the control signaling of the SU and as channel for communication when the available channels are in use by the PU.

The Algorithm 1 involves the equilateral triangulation pattern graph. It begins with the six available channels AC. The seventh channel is the common back up channel (CBC); and the vertices are represented as a1, b_1, c_1, a_2, b_2, c2, ... a_n, b_n, c_n, which indicate connections with channels. It then connects with any available channels. Once connected with a channel, then the edges are connected. Otherwise connect with CBC if there is no

Table 6.3: Algorithm 1: ETA Algorithm for guaranteed S_{Ns} network connectivity

```
BEGIN
1. G = {V, E};
2. AC = [1, 2, 3, 4, 5, 6];
3. CBC = [7];
4. V = {a1, b1, c1, a2, b2, c2,..... an, bn, cn};
5. E = {a1,b1; a1,c1; b1,c1; a2,b2; a2,c2;
       b2,c2; ..... an,bn; an,cn; bn,cn};
6. if AC = 1||2||3||4||5||6;
7.     $E_{CONNECTED}$ = AC (an,bn; an,cn; bn,cn);
8. else if AC = 7;
9.     $E_{CBC}$ = CBC ( an,bn; an,cn; bn,cn);
10. while E = $E_{CONNECTED}$;
11.     Send msg via AC
12. else
13.     send control signal and msg via CBC ; end if;
14.     end
15.       End
```

available channel. Send message via AC while connection is with any channel else send control signal and message if connection is with CBC, if not end, and begin again. Based on the earlier statement of the conditional properties that if all vertices in a triangle are connected, then the triangle is covered by the associated SN. With respect to this, relating to the ETA algorithm line 7 and 8, the vertices are connected by the available channels or backup channel. Hence, the associated SN or CH in the triangle can communicate and exchange messages or sensed data.

6.3.2.3 EDHC-SA Energy Model

In this section, the energy consumption that is involved in the entire process of cluster network formation and the data communication or transmission phase is discussed. The energy expended in the CRSN node during transmission and reception is depicted in the following equations:

$$E_{TX}(z,d) = \begin{cases} zE_C + zE_{pl}d_{intra}, & d \leq d_{intra} \\ zE_C + zE_{mp}d_{shinter}, & d \geq d_{shinter} \\ zE_C + zE_{sha}d_{mhinter}, & d \geq d_{mhinter} \end{cases} \tag{6.7}$$

$$E_{RX}(z) = zE_C \tag{6.8}$$

During transmission, a data frame of size z is transmitted by the transmitter over a distance d, denoted by E_{TX} (z,d), and energy is expended in the S_N device circuit denoted by E_C and in the radio frequency (RF) amplifier. Hence, during transmission there is a device circuit power loss and RF amp power loss. The RF amp power can be adjusted based on a certain distance threshold with respect to distance covered. If distance is within a cluster the RF amp power loss encounters a path loss energy dissipation, denoted by $E_{pl}\ d_{intra}$, if distance is on inter cluster with single hop the RF amp power encounters a multipath energy dissipation, denoted by E_{mp}, and distance as $d_{shinter}$, and if the distance is on inter cluster with multiple hop it encounters shadowing energy dissipation, denoted by E_{sha} with distance as $d_{mhinter}$. At the receiver, the energy expended in receiving a data frame of size z denoted by E_{RX} (z) is the energy dissipated in the S_N device circuit.

Some S_Ns are meant to monitor event-driven data such as object detection and real-time data delivery. Other S_Ns are meant to monitor time–driven data that are scheduled for periodic data reporting. In order to save energy and network lifetime, the S_Ns for the event-driven data and time-driven data are alternated based on their effective energy. During sensing activities, the SN uses priori available channel in the MAC protocol for the sensing. An optimized CSMA/CA algorithm for the alternation of the SNs based on adaptation of the backoff exponent (BE) parameter is employed. In the CSMA/CA algorithm, the BE state is adjusted based on the threshold of the effective energy of the SN device circuit. There is a low duration channel sensing in the CRSN nodes since each SN obtains the available channels with the help of the CH CSMA/CA algorithm with beacon enable mode. Also both the CH and cluster member SN do not wait for channel in the event of non-available channel since there is CBC, thereby eliminating period of waiting for available channel which is crucial to real-time delivery data. The SN effective energy is expressed as follows:

$$E_{Eff} = \frac{E_{current}}{E_{res}} \tag{6.9}$$

where E_{Eff} is the initial effective energy of the CRSN node circuit, $E_{current}$ is the energy currently dissipated in the S_N circuit and E_{res} is the residual or remaining energy of the circuit. The primary CH and the BU-CH follow the technique of S_Ns alternation of equation (6.9), however the effective energy threshold for the primary CH and BU-CH is different from the cluster member SNs. Furthermore, the cluster member S_Ns for both time-driven data and event-driven data are meant to be delivering data to the CH. Energy is dissipated in the cluster member in transmitting data frame to the CH within the cluster, and it is expressed as:

$$E_{CM} = zE_C + zE_{pl}d_{intra} \tag{6.10}$$

where E_{CM} is the energy expended in each of the cluster member and z$E_{pl}\ d_{intra}$ is the distance from the cluster member to the CH. Similarly, the CH expends energy in receiving data frame from the cluster member, aggregates the data frame, and finally transmit the aggregated data frame to the sink or base station (BS); and is expressed as:

$$\begin{gathered} E_{CH-BU} = zE_C\left[\left(\frac{TS}{C_N}\right)-2\right] \\ +zE_{(DFA)}\left(\frac{TS}{C_N}\right)+zE_C+zE_{mp}d_{shinter} \end{gathered} \tag{6.11}$$

$$\begin{aligned} E_{CH-BU} &= zE_C\left[\left(\frac{TS}{C_N}\right)-2\right] \\ &+zE_{(DFA)}\left(\frac{TS}{C_N}\right)+zE_C+zE_{sha}d_{mhinter} \end{aligned} \tag{6.12}$$

where E_{CH-BU} is the energy expended in either the CH or in the BU-CH, $\left[\left(\frac{TS}{C_N}\right)-2\right]$ is the number of cluster member nodes in the cluster without the CH and the BU-CH, E_{DFA} is energy expended during data frame aggregation, E_{mp} with $d_{shinter}$ is the energy expended with distance from the CH to the BS if it is only a single hop to the BS, and E_{sha} with $d_{mhinter}$ is the energy expended when the distance to the BS is with multi-hops. Equation (6.11) and (6.12) above is for CH to transmit a single complete frame of the aggregated data frame for event-driven data. This is because event-driven data are mission critical and requires real-time data delivery.

The CH aggregates and transmits up to five complete frames to the BS for time-driven data. This is because time-driven data requires a periodic data delivery. However, if there is any available aggregated complete frame of the event-driven data, the CH will transmit both the event-driven and time driven data, even if the time-driven data has less than five frames. Hence, the expression for transmitting time-driven data or both set of data frame to the BS is as follows:

$$E_{CHTE} = \sum_{f=1}^{n} E_{CH-BU} \tag{6.13}$$

where E_{CHTE} is the energy expended in the CH for both time-driven and event driven data frame, f represent the frame starting from frame 1 to frame 5, hence, $1 \leq n \leq 5$.

Furthermore, algorithm 2 illustrates the alternation of S_N data frame transmission. It involves the initialization of the Beacon Period (BP), broadcasting available sensed channels and CH/BU-CH identity. Both the event driven data and time driven data are in either active or inactive state. The backoff exponent (BE) is in the range of 0 to 5, while the effective energy is in the range of 5 to 10 Joules. The superframe structure Order (SO) activates if channel 1 to 6 are available. However, if channel is not equal to 0 and less than or equal to 6, the SO changes with the BE decremented by 1. While effective energy is between 5 and 10 inclusive, BE should be decremented by 1and be incremented by 1 if effective energy is less than 5J. If BE is 0 or 1, EDDSN should be triggered to active state and then send message otherwise it should remain in inactive state and ends to initialize again. If BE is between 2 and 5 inclusive, TDDSN is set to active state and then send message, else is in inactive state ends, to initialize again in order to begin the process and then ends finally.

Table 6.4: Algorithm 2:CSMA/CA Algorithms for Alternation of S_N data frame transmission

```
initialize →BP
$EDD_{SN}$ = {Active state || Inactive state};
$TDD_{SN}$ = {Active state || Inactive state};
BE = 0 : 5;
$E_{Eff}$ = 5 : 10;
if AC = 1 : 6;
    activate superframe structure Order (SO);
else
    while AC $\neq$ 0 &&<=6;
        SO changes with →BE -1;
    while $E_{Eff}$ >=5 && <=10;
        → BE ■ -1;
else if E_Eff<5;
        → BE ■ +1;
if BE = 0 ||1;
    $EDD_{SN}$ = Active state;
else
    $EDD_{SN}$ = Inactive state;
if $EDD_{SN}$= Active state;
    send msg; end if;
if BE >=2 &&<=5;
    $TDD_{SN}$ = Active state;
else
    $TDD_{SN}$ = Inactive state;
if $EDD_{SN}$ = Active state;
    send msg; end if;
    end;
end; end; end;
```

6.3.3 EDHC-SA Multichannel Sensing coverage Model

6.3.3.1 Signal Model

CRSN based SG is an example of a situation where channel conditions fluctuate dynamically, consequently, ZigBee CRSN systems use an adaptive modulation schemes so as to take into account the difference in channel conditions [156]. The adaptive modulation varies transmission parameters such as power, data rate, modulation technique and so on. Hence, adaptive cognitive radio (CR) technologies will help to achieve interference-free network as well as spectral efficiency [248],[249] during data frame transmission. The SG sensed data is modulated using MQAM under single fading channel from the available multiple fading channels distribution conditions via DSA. The received signal at the various CRSN nodes can be modelled as:

$$y_i(t) = \sqrt{E_s}\, h_i(t) x_i(t) + n_i(t) \qquad 1 \le i \le 6 \tag{6.14}$$

where $y_i(t)$ is the received signal, E_s is the transmit signal power, x_i is the transmitted signal, $h_i(t)$ is Nakagami-q multipath fading channels expressed as:

$$h_i = h_i^I + jh_i^Q$$

and has a zero mean with complex Gaussian variables denoted as (0,σ_x^2) and (0,σ_y^2), i $\in (1,2,3,4,5,6)$ which is the ith- number of available fading channels, $n_i(t)$ is the noise with complex Gaussian distribution CN (0,N_0), N_0 denotes the noise power spectral density of a single channel. But, q= $\frac{\sigma_y}{\sigma_x}$, where $0 \leq q < 1$, γ= α^2, $\frac{E}{N_o}$ and $\bar{\gamma}$ =2σ^2 $\frac{E_s}{N_o}$, where γ is the received SNR, and $\bar{\gamma}$ is the average received SNR for each channel, and σ denotes the shadowing distribution, E is the signal power, and E_s is the instantaneous transmit power. Hence, the average SNR is obtained by:

$$\bar{\gamma} = E_s/N_0 \tag{6.15}$$

The higher the transmit power (E_s) the higher the energy expended in the CRSN node, leading to a corresponding high SNR. However, the higher the average SNR the lower the BER. Hence, the BER is inversely proportional to the average SNR which is given by:

$$BER = \frac{K_{delay}}{\bar{\gamma}} \tag{6.16}$$

where K_{delay} is the delay resulted from latency, media access delay and retransmission delay and others. Hence, in order to save energy, it is good to avoid a high expended energy in the CRSN node resulting from high SNR. Therefore, it is needful to device a mechanism that will reduce the BER at a given SNR, so as to maintained less errors as well as energy efficient at an appreciable SNR. Consequently, a channel variator VR to the fading channel components which will help to reduce the transmit power without noise amplification for energy efficiency was introduced. Recall that:

$$h_i = 0, \sigma_x^2 + 0, \sigma_y^2 \tag{6.17}$$

hence, the channel implementation given by:

$$h_{VRi} = V_R[0, \sigma_x^2 + 0, \sigma_y^2] \tag{6.18}$$

where

$$1 \leq V_R < N_R$$

and N_R is the maximum number of available channels; hence, $N_R \in [1,2,3,4,5,6]$. V_R adjust to the number of available channels without amplification of the noise component; and then transmits based on number of antennas of the CRSN node. In this case, it transmits on only a single channel since the CRSN node has only one antenna. The V_R factor varies to release only a single channel for transmission and reception via DSA. This help with a moderate transmit power without noise amplification, thereby expending moderate energy for energy efficiency.

6.3.3.2 Coverage probability of sensing signal

Various sensing model such as circular disk sensing model, deterministic model and random deployment model cannot give absolute sensing coverage. This is due to the fact that they do not put into account the error probability mechanism. Hence, error probability of sensing signal was implemented on our Voronoi equilateral triangulation model. Employing probability density function (PDF) using moment generating function based on average bit error probability of MQAM over single Nakagami-q fading channel which have being derived in earlier work in [156] is essential, and it is given by:

$$\begin{aligned}\bar{P}_{MQAM} = \frac{a}{n}\left\{\frac{1}{2}M_{\gamma}q\left(-\frac{b}{2}\right)-\left(\frac{a}{2}\right)M_{\gamma}q(-b)\right.\\ \left.+(1-a)\sum_{i-1}^{n-1}M_{\gamma}q\left(\frac{-b}{s_i}\right)+\sum_{i-n}^{2n-1}M_{\gamma}q\left(\frac{-b}{s_i}\right)\right\}\end{aligned} \tag{6.19}$$

where $\bar{P}_{MQAM}$is the average probability of detection under MQAM modulation,

$$a = 1-\frac{1}{\sqrt{M}},\ b = \frac{3}{M-1},\ s_i = \frac{2sini\pi}{4n},\ M_{\gamma}q$$

is the MGF of the received SNR over Nakagami-q channels which is expressed as

$$M_{\gamma}q(s) = \left(1-2s\bar{\gamma}+\frac{(2s2s\bar{\gamma})^2q^2}{(1+q^2)^2}\right)^{\frac{-1}{2}} \tag{6.20}$$

Furthermore, in order to estimate the coverage probability of detection of the sensing signal, the sensing range RS of the CRSN node is taken into consideration. The RS depends on the transmit power of the sensing signal, sensing received power which is also the received signal strength (power) denoted as ρ, and the propagation path effect such as path loss, shadowing and multipath fading. Hence, the received signal power ρ, is given by

$$\rho = E_s * \eta\left(\frac{R_o}{R_s}\right)^{\gamma} \tag{6.21}$$

where E_S is the sensing transmit power, η is the path loss component, R_0 is the sensing reference distance which is equal to 1 in outdoor CRSN, γ is the SNR which is a function of shadowing and multipath fading effect. The sensing range R_S is not the same for all the CRSN nodes due to the propagation effects. However, applying the error detection probability will account for the error caused by the propagation effects. Hence, the coverage probability of sensing signal of a CRSN node within a sensing range RS to a target over MQAM Nakagami-q fading channel based on equilateral triangulation algorithm is written as:

$$\begin{aligned}\bar{P}_{C_{ETA}} = \int_{0}^{R_{ifs}}\frac{a}{n}\left\{\frac{1}{2}M_{\gamma}q\left(-\frac{b}{2}\right)-\left(\frac{a}{2}\right)M_{\gamma}q(-b)\right.\\ \left.+(1-a)\sum_{i-1}^{n-1}M_{\gamma}q\left(\frac{-b}{s_i}\right)+\sum_{i-n}^{2n-1}M_{\gamma}q\left(\frac{-b}{s_i}\right)\right\}\left(\frac{3R_{ifs}^2\sqrt{3}}{4}\right)dR_S\end{aligned} \tag{6.22}$$

where $0 \leq R_S \leq R_{ifs}$ Scaling the coverage probability of sensing signal for the total sensing field area A gives:

$$\begin{aligned}\bar{P}_{C_{AETA}} = \frac{1}{A}\int_{0}^{R_{ifs}} \frac{a}{n}\left\{\frac{1}{2}M_{\gamma}q\left(-\frac{b}{2}\right) - \left(\frac{a}{2}\right)M_{\gamma}q(-b)\right. \\ \left. +(1-a)\sum_{i-1}^{n-1} M_{\gamma}q\left(\frac{-b}{s_i}\right) + \sum_{i-n}^{2n-1} M_{\gamma}q\left(\frac{-b}{s_i}\right)\right\}\left(\frac{3R_{ifs}^{2}\sqrt{3}}{4}\right)dR_S\end{aligned} \tag{6.23}$$

Hence, integrating between limit gives:

$$\begin{aligned}\bar{P}_{C_{AETA}} = \frac{aR_{ifs}^{3}\sqrt{3}}{4An}\left\{\frac{1}{2}M_{\gamma}q\left(-\frac{b}{2}\right) - \left(\frac{a}{2}\right)M_{\gamma}q(-b)\right. \\ \left. +(1-a)\sum_{i-1}^{n-1} M_{\gamma}q\left(\frac{-b}{s_i}\right) + \sum_{i-n}^{2n-1} M_{\gamma}q\left(\frac{-b}{s_i}\right)\right\}\end{aligned} \tag{6.24}$$

6.4 Simulation, Results, and Analysis

In this section, the EDHC-SA energy model and EDHC-SA multi-channel sensing coverage model have been implemented and evaluated in Matlab. The EDHC-SA energy model is experimented and compared with stable energy protocol (SEP), and LEACH protocol. The performance efficiency of the proposed energy model is evaluated based on average residual or remaining energy of the sensor nodes. The efficiency of the EDHC-SA multi-channel sensing coverage model is experimented and compared with existing ZigBee sensor network model. The proposed multi-channel sensing coverage model is evaluated based on the following metrics: Coverage error probability or bit error rate (BER), SNR, and Latency. Table 6.5 presents simulations parameters for the models.

Fig. 6.4 shows the energy consumption analysis based on average residual energy per round of the EDHC-SA energy model compared with the existing SEP and LEACH Protocol. From the result, it confirms that the EDHC-SA energy model can effectively do the data aggregation from the sensor nodes sources to the sink with minimal energy consumption. This is depicted in Fig. 6.4 which shows higher average residual energy than the existing SEP and LEACH energy protocols. For the EDHC-SA multi-channel sensing coverage model, the results in terms of BER with respect to SNR are obtained in two different scenarios. Scenario 1 represents Fig. 6.5, and Scenario 2 represents Fig. 6.5. Scenario 1 is where all the six channels priori are available in the EDHC-SA CRSN model, which is in comparisons with the conventional ZigBee WSN in order to obtain the BER and SNR. Looking at Fig. 6.5 it can be seen that the error rate at a given SNR in EDHC-SA CRSN model is lower than the error rate in the conventional ZigBee WSN. For example, EDHC-SA CRSN model exhibit a minimum error rate of approximately 10^{-4} at SNR of 18 dB and maximum error rate of approximately 10^{-2} at SNR of 0 dB whereas the conventional ZigBee WSN exhibits a minimum error rate of approximately 10^{-2} at SNR of 18 dB and maximum error rate of approximately 10^{-1} at SNR of 0 dB.

Table 6.5: Simulation parameters

EDHC-SA Energy model parameters	
Parameters	**Values**
Network field size	200 x 200 M^2
Total number of nodes	200
Initial effective energy of CH member	2 J
Initial effective energy of CH	5 J
Number of Clusters	14
Location of Sink (BS)	(250, 200) M
Data packet size	4000 Bits
EDHC-SA Multi-channel sensing coverage parameters	
Number of available channel	6
Simulation runs	10,000
Total Area of Coverage	200 x 200 M^2
Multipath Fading	Nakagami-q
Shadow Fading	Log-Normal Shadowing
Modulation size	4QAM
SNR	0:18
V_R	1:6

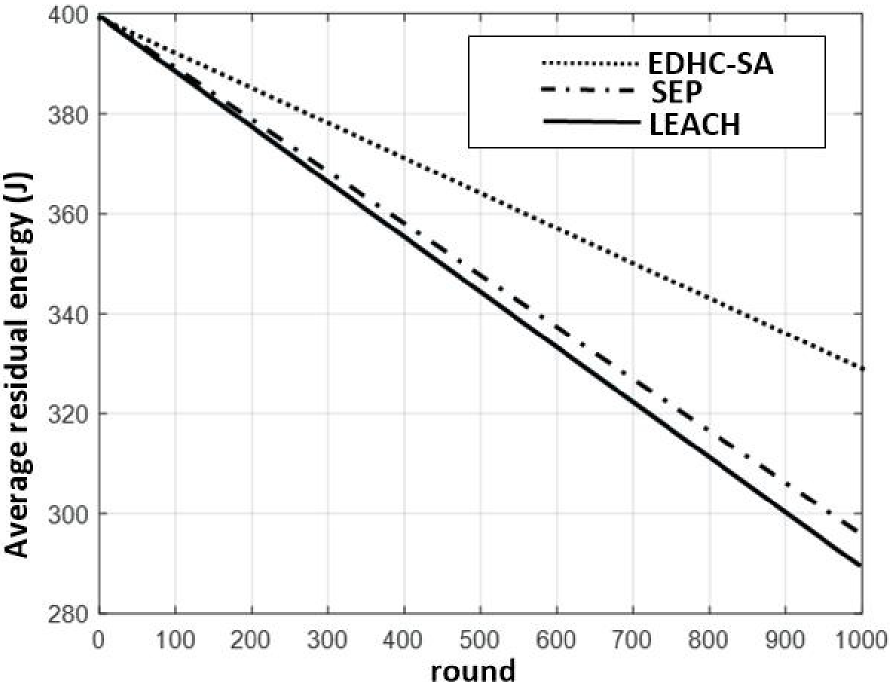


Figure 6.4: Average residual energy per round for EDHC-SA compared with the existing SEP and LEACH Protocol

This means that the conventional ZigBee WSN encounters more errors in excess of over 100% at a given SNR than the EDHC-SA CRSN model. Also, at a given BER, the EDHC-SA

CRSN model experience a lower energy per bit to noise ratio (Eb/No) than the conventional ZigBee WSN. For example, at BER of 10^{-2}, the EDHC-SA CRSN model has SNR of 4 dB whereas the conventional ZigBee WSN has over 18 dB for the same BER of 10^{-2}. This means that a less energy is expended at a given BER in the EDHC-SA CRSN, whereas more energy is consumed in the conventional ZigBee WSN. Consequently, it is obvious that it will take a lower energy to accomplish greater sensing coverage and data frame transmission with minimal BER in the EDHC-SA CRSN than in the conventional ZigBee WSN.

In addition, we further simulate EDHC-SA CRSN model with $V_R = 2$ and $V_R = 4$ respectively in order to validate the behavior of the EDHC-SA CRSN model with respect to changes in the available channels. it is observed that as the available channels increases the BER reduces leading to the improvement of the network with increase in available channels.

Also, as the available channels reduces, the BER increases. However, in all cases, the performance of the EDHC-SA CRSN with opportunistic multi-channels access is better than the performance of the conventional ZigBee WSN in terms of BER and energy per bit to noise ratio as depicted in Fig. 6.6. Therefore, it is easier to reduce the energy consumption of data frame transmission in the EDHC-SA CRSN model by using a lower SNR while simultaneously satisfying a certain minimal BER.

Furthermore, from the simulation results in Fig. 6.5, equation (6.16) was implemented at a given SNR in order to obtained a relationship of BER with respect to delay as depicted Fig. 6.7 for the EDHC-SA CRSN model. From Fig. 6.7, it is obvious that both the SNR and latency reduces as the BER reduces. For example, with the SNR of 18 dB,12 dB,and 6 dB it has a maximum latency of 0.44 seconds, 0.29 seconds, and 0.14 seconds respectively. This means that at any given SNR, there is a corresponding decrease in the latency or delay as the BER reduces; and corresponding increase in the latency as the BER increases. Hence, an optimal data frame transmission can be made at a given SNR with minimal error rate and low latency. Therefore, EDHC-SA CRSN model satisfies both energy efficiency and latency issues.

Moreover, from Fig. 6.8, the BER and the latency take the same trend as that of Fig. 6.7, but however, with a higher error rate and latency at a given SNR. This means that conventional ZigBee WSN exhibits high latency and is not energy efficient when compared with the EDHC-SA CRSN model.

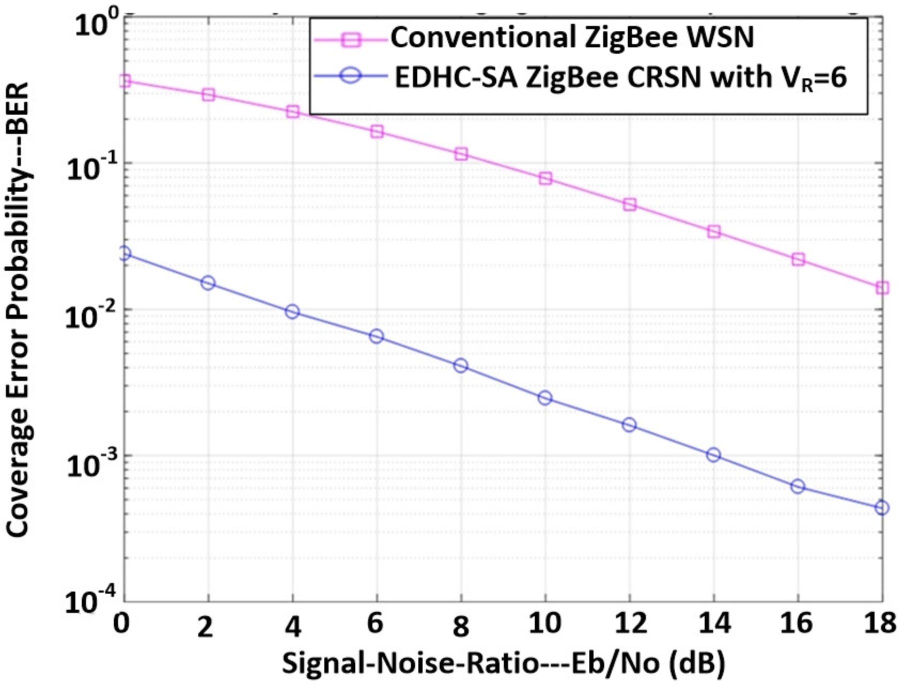


Figure 6.5: Scenario1: Error Probability comparisons of Conventional ZigBee WSN and EDHC-SA CRSN

6.5 Chapter Summary

In this chapter, a DHC topology for ZigBee CRSN in SG was proposed. Potential difference of various topologies between conventional ZigBee WSN and ZigBee CRSN suitable for SG application was evaluated. Further, energy efficient distributed heterogeneous clustered spectrum aware (EDHC-SA) model was proposed. The model was supported by providing a novel algorithm called Equilateral triangulation algorithm for guaranteed network connectivity in CRSN based SG were presented. CSMA/CA MAC protocol algorithm for alternation of data frame transmission of both event driven and data driven CRSN nodes were incorporated in order to save the network life time.

Then was the introduction of a variator mechanism for varying the opportunistic multichannel access with single data frame transmission. The mechanism was implemented with a derived coverage probability of sensing signal under multipath fading conditions.

Finally, the simulations results obtained confirms that EDHC-SA CRSN model outperforms conventional ZigBee WSN in terms of bit error rate, end-to-end delay (latency), and energy consumption. Hence, the EDHC-SA CRSN model is suitable for SG harsh environ- mental condition, due to the fact that SG applications are mission critical applications that require low latency for real-time satisfactory sensed data delivery.

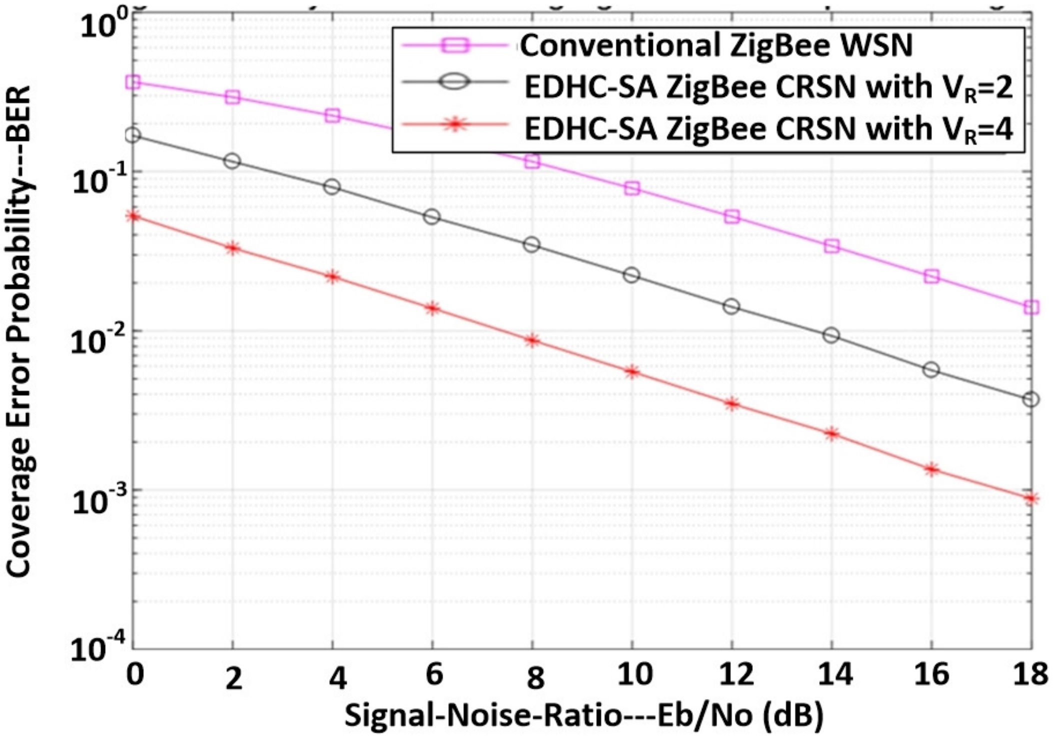


Figure 6.6: Scenario2: Error Probability comparisons of Conventional ZigBee WSN and EDHC-SA CRSN with further channel changes

The spectrum aware cross-layer algorithm framework in the EDHC-SA is mainly based on lower layer communication protocols. Spectrum aware cross-layer algorithm in the upper communication layer protocols (transport and application layer) of CRSN for SG will be an interesting future research area.

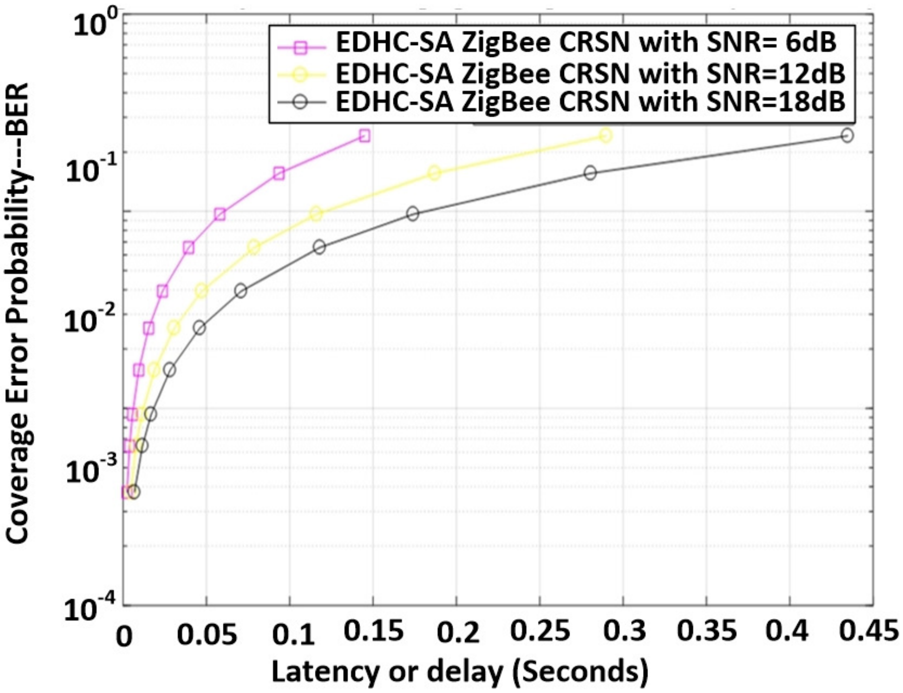


Figure 6.7: BER relationship with Latency at three different SNR values for EDHC-SA CRSN model

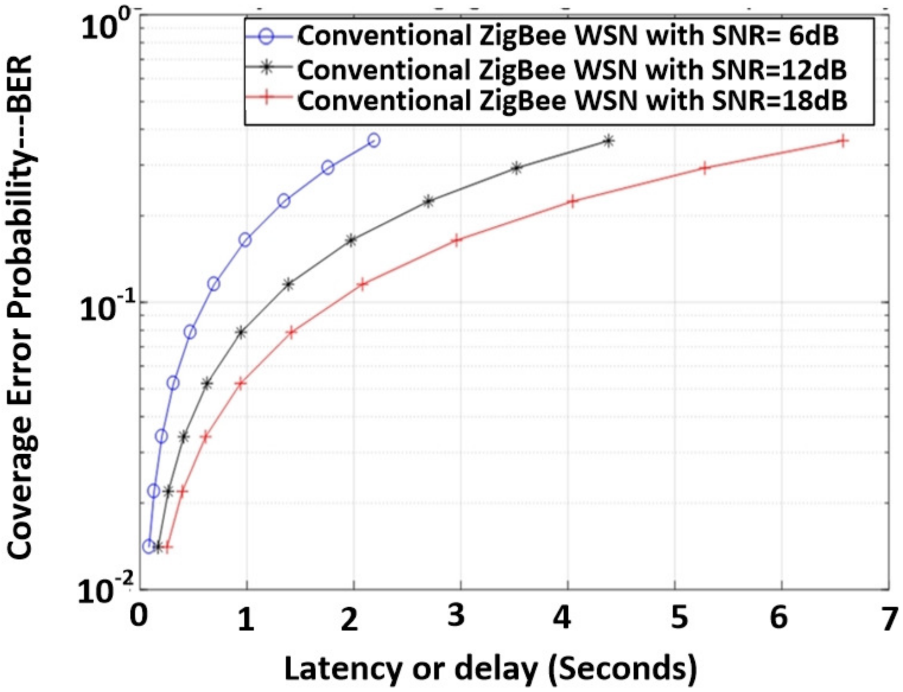


Figure 6.8: BER relationship with Latency at three different SNR values for conventional ZigBee WSN

Chapter 7

Conclusion and Future Works

7.1 Conclusion

In this chapter, the overview of the research work together with all relevant contributions have been presented. The importance and benefits of SG in chapter one were elaborated. Reliable communication systems are keys to achieving maximal benefits of smart grids. However, the conventional communications systems are associated with problem of spectrum inefficiencies and interferences which will affect the reliability of communication in SG. Consequently, cognitive radio technology has been proposed as a new paradigm to solve the spectrum inefficiencies and interferences problems.

To this end, this new paradigm (a combination of cognitive radios with WSNs) leading to CRSNs, are applied to SG for reliable communication and adequate monitoring and control. Furthermore, there exists some problems in the CRSN itself, such as limited energy life span of the sensor node, low complexity in handling huge/varying SG data traffics including problem of existing protocols which are not spectrum aware for DSA support. In order to address these problems, an organized approach was systematically adopted in the chapters.

Chapter two investigated and explored the CRSN conceptual framework including survey of literature of related works, involving SG communication architecture with its applications as well as the communication access technologies. Further, implementation design with quality of service (QoS) support and unified communication solution for SG was introduced and incorporated. Overall, various research gaps including integration of LPWAN for CRSN based SG deployment were highlighted.

Consequent upon the challenges associated with competitive sensor nodes and communication devices in accessing and utilizing radio resources, the need for dynamic radio resource allocation has been projected as a capable solution in allocating radio resource to sensor nodes in CRSN based smart grid ecosystem. These challenges include: energy or power

constraints, poor quality of service (QoS), interference, delay, spectrum inefficiency, and excessive spectrum handoffs.
Accordingly, in chapter three, an investigation and survey in terms of optimization criteria such as energy efficiency, throughput improvement, QoS guarantee, fairness, priority, interference mitigation, etc., for RRA were conducted in order to address the aforementioned problems in CRSN based SG.

The problem of multi fading channels due to multi antenna correlation channels of the sensor nodes as well as very close spacing of sensor nodes deployment in a SG environment has been a big issue. This correlation can lead to degradation of the signals as well as co-channels interference. In addition, the signal-interference-noise-ratio (SINR), multipath fading, and shadowing peculiar to SG harsh environmental condition including interference from SG equipment also pose great challenges leading to degradation of communication link in CRSN based SG.
In order to mitigate these dual correlation challenges, chapter four presents a performance analysis of an MGF based M-QAM error probability over Nakagami-q dual correlated fading channels with maximum ratio combiner (MRC) receiver technique including derivation and a novel algorithmic approach. The results from the MATLAB simulation experiments are provided as a guide for sensor node deployment to avoid problem of multi correlation in CRSN based SG.

A reliable communication network is required in order to actualize some important SG features, such as renewable energy integration, distributed energy resources, scalability, self-healing and efficient holistic monitoring and control capability. However, this communication network needs to comply with critical requirements. In order to achieve this, chapter five presents a novel communication architecture in CRSN based SG. The objective here is the design of a CRSN based smart grid communication architecture and implementation model for guaranteed QoS of smart grid data delivery. The work involves virtualized network in the form of multi-homing comprising low power wide area network (LPWAN) devices such as LTE CAT1/LTE-M, and TV white space band device (TVBD). Simulation analysis show that the performance of the proposed modules architecture outperforms the legacy wireless systems in terms of latency and throughput in SG harsh environmental condition.

SGs application requires reliable and efficient communication with low latency in timely manner as well as adequate topology of sensor nodes deployment for guaranteed QoS. Also, an optimized protocol/algorithms are required for energy efficiency and cross layer spectrum aware for opportunistic spectrum access in the CRSN nodes. To this end, chapter six presents a novel energy efficient distributed heterogeneous clustered spectrum aware (EDHC-SA) model including a novel topology. In addition, novel algorithm called Equilateral triangulation algorithm for guaranteed network connectivity in CRSN based SG was provided.

Finally, the work also presents a novel CSMA/CA MAC protocol algorithm for alternation of data frame transmission of both event driven and data driven CRSN nodes due to varying SG applications in order to save the network life time. The simulation results obtained confirm that EDHC-SA CRSN model outperforms conventional ZigBee WSN in terms of bit error rate, end-to-end delay (latency), and energy consumption. This thus validates the suitability of the model in SG harsh environmental condition.

7.2 Future Works

- In chapter two, an investigation and survey on cognitive radio based sensor network in SG has been carried out. Specifically, the work jointly considers the intersection of cognitive radio and sensor network in SG. Recommendations for future work were pointed out, which include unified communication solution that utilizes LPWAN. Consequently, chapter five adopted this unified communication solution with the state of the art virtualized network architecture, such that both the communication access technologies and sensor network are jointly considered with the integration of LPWAN and TVBD respectively for all-inclusive communication solution. However, research in this area may consider integration of LPWAN in a different perspective for unified solution.

  The integration of optimized physical and media access (MAC) layer protocols including energy efficient modulation schemes with an appreciable bit error rate (BER) for efficient communication is a new direction to follow. The achievement in chapter four was where an MGF based symbol error probability of MQAM over dual correlated Nakagami-q fading channels was implemented with MRC diversity receiver technique. This technique involves investigation and optimization of the physical layer protocols which resulted in the outcome of the conducted performance analysis. However, some other methods of receiver diversity combiner technique including physical layer protocol optimization may be studied for future research. It was found to be an aspect of interesting future research.

- In chapter three, an investigation and survey on RRA improvements in CRSN based SG environment was conducted. Interesting areas of future research incursion includes the need to develop a unified solution schemes that will accommodate the three or overall resource optimization criteria for CRSN based SG which were achieved in chapters five and six with the help of virtualized network and distributed heterogeneous clustered (DHC) ZigBee CRSNs topology respectively.

Multiple optimization criteria such as guaranteed QoS low latency, improved BER, energy efficiency as well as spectrum aware cross layer interaction have been validated in the overall results of this study However, different approach in developing a unified solution scheme that will leverage multiple resource optimizations requirements is a welcome development for future research in addition to the integration of adaptive modulation schemes for efficient communication in SG. Chapters four and chapter six achieved MQAM modulation technique used with a variator that varies based on available channels leading to varying channel conditions in harsh SG environment. Some techniques other than MQAM can be used for the adaptive modulation integration. This is an interesting future research area as well.

- Another possible future research area is energy efficient-spectrum aware cross layer framework for routing protocols in CRSN based SG as well as in Internet of Things (IoT). Also currently, is an interested future research area. Other upper layers (transport and application layers) protocols optimization that integrate energy efficient and spectrum aware in CRSN based SG or IoT is a welcome development in future research direction.

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