# ENERGY EFFICIENT MULTI CHANNEL PACKET FORWARDING MECHANISM FOR WIRELESS SENSOR NETWORKS IN SMART GRID APPLICATIONS

MUHAMMAD FAHEEM

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Computing
Faculty of Engineering
Universiti Teknologi Malaysia

NOVEMBER 2021

# DEDICATION

Dedicated to beloved prophet MUHAMMAD (PBUH), and my family, Thank you for their immense love, precious, supports and for all that you have done for me. Especially to my beloved late father RAHIM DIN and mother MALKAN BIBI. May Allah SWT be pleased with them and grant them Al Jannah (Aameen).

# ACKNOWLEDGEMENT

First and Foremost praise is to ALLAH, the Almighty, the greatest of all, on whom ultimately we depend for sustenance and guidance. I would like to thank Almighty Allah for giving me opportunity, determination and strength to do my research.

Firstly, I wish to express my sincere gratitude to my supervisor **Prof. Dr. Md. Asri Bin Ngadi** for the continuous support and valuable guidance throughout my Ph.D study and related research. It would be very difficult to complete this research successfully without his suggestions, advise and thoughts. I would like to thank him for personal kindness and patience. Besides my supervisor, I would like to thank and express my deepest appreciation to my co-supervisor Prof. Dr. Vehbi Cagri Gungor for his technical support, proper guidance in exploration of this research, insightful comments and encouragement.

I must express my sincerest and heartiest thanks to my beloved Wife for her continuous support and prayers during my Ph.D research. Also, I would like to say special thanks to my brothers and sister for their support all the time that moves me towards my goals. I am also grateful to Abdullah Gul University, Kayseri, Turkey, for the support and cooperation. I would also like to express my sincere thanks and deepest appreciation to all my friends and research fellows especially Dr. Basit Raza, Dr. Muhammad Waqar Ashraf and Dr. Rizwan Aslam Butt for their motivation and technical support.

# ABSTRACT

Multichannel Wireless Sensor Networks (MWSNs) paradigm provides an opportunity for the Power Grid (PG) to be upgraded into an intelligent power grid known as the Smart Grid (SG) for efficiently managing the continuously growing energy demand of the 21st century. However, the nature of the intelligent grid environments is affected by the equipment noise, electromagnetic interference, and multipath effects, which pose significant challenges in existing schemes to find optimal vacant channels for MWSNs-based SG applications. This research proposed three schemes to address these issues. The first scheme was an Energy Efficient Routing (ERM) scheme to select the best-optimized route to increase the network performance between the source and the sink in the MWSNs. Secondly, an Efficient Channel Detection (ECD) scheme to detect vacant channels for the Primary Users (PUs) with improved channel detection probability and low probability of missed detection and false alarms in the MWSNs. Finally, a Dynamic Channel Assignment (DCA) scheme that dealt with channel scarcities by dynamically switching between different channels that provided higher data rate channels with longer idle probability to Secondary Users (SUs) at extremely low interference in the MWSNs. These three schemes were integrated as the Energy Efficient Multichannel Packet Forwarding Mechanism (CARP) for Wireless Sensor Networks in Smart Grid Applications. The extensive simulation studies were carried through an EstiNet software version 9.0. The obtained experimental simulation facts exhibited that the proposed schemes in the CARP mechanism achieved improved network performance in terms of packets delivery ratio (26%), congestion management (15%), throughput (23%), probability of channel detection (21%), reduces packet error rate (22%), end-to-end delay (25%), probability of channel missed-detection (25%), probability of false alarms (23.3%), and energy consumption (17%); as compared to the relevant schemes in both EQSHC and G-RPL mechanisms. To conclude, the proposed mechanism significantly improves the Quality of Service (QoS) data delivery performance for MWSNs in SG.

# ABSTRAK

Paradigma Rangkaian Sensor Tanpa Wayar Pelbagai Saluran (MWSN) memberi peluang kepada Grid Kuasa (PG) untuk dinaik taraf menjadi grid kuasa pintar yang dikenali sebagai Grid Pintar (SG) untuk pengurusan yang lebih efektif terhadap permintaan penggunaan tenaga yang terus meningkat pada abad ke-21. Walau bagaimanapun, sifat persekitaran grid pintar dipengaruhi oleh kebisingan peralatan, gangguan elektromagnetik dan kesan pelbagai laluan, yang menimbulkan cabaran besar dalam skema sedia ada untuk mencari saluran tidak terpakai yang optimum untuk aplikasi SG berasaskan MWSN. Penyelidikan ini mencadangkan tiga skema untuk menangani isu-isu ini. Skema pertama ialah skema Penghalaan Cekap Tenaga (ERM) untuk memilih laluan yang paling optimum untuk meningkatkan prestasi rangkaian antara sumber dan sink di MWSN. Kedua, skema Pengesanan Cekap Saluran (ECD) untuk mencari saluran tidak terpakai untuk Pengguna Utama (PU) dengan kebarangkalian pengesanan saluran yang cekap dan kebarangkalian rendah pengesanan yang tidak terjawab dan penggera palsu dalam MWSN. Terakhir, skema Penetapan Saluran Dinamik (DCA) yang menangani kekurangan saluran dengan cara penukaran dinamik antara saluran yang berbeza yang menawarkan saluran kadar data yang lebih tinggi dengan kebarangkalian melahu yang lebih lama kepada Pengguna Sekunder (SU) pada gangguan yang sangat rendah dalam MWSN. Ketiga-tiga skema ini disatukan sebagai Mekanisme Penghantaran Paket Cekap Tenaga Pelbagai Saluran (CARP) untuk Rangkaian Sensor Tanpa Wayar dalam Aplikasi Grid Pintar. Kajian simulasi yang meluas telah dilakukan menggunakan perisian EstiNet versi 9.0. Fakta eksperimen simulasi yang diperoleh menunjukkan bahawa skema yang dicadangkan dalam mekanisme CARP mencapai peningkatan prestasi rangkaian dari segi nisbah penghantaran paket (26%), pengurusan kesesakan (15%), daya tampung (23%), kebarangkalian pengesanan saluran (21%), pengurangan kadar kesalahan paket (22%), kelewatan hujung ke hujung (25%), kebarangkalian pengesanan saluran terlewat (25%), kebarangkalian penggera palsu (23.3%), dan penggunaan tenaga (17%) berbanding dengan skema yang berkaitan dalam kedua-dua mekanisme EQSHC dan G-RPL. Sebagai kesimpulan, mekanisme yang dicadangkan dapat meningkatkan prestasi Kualiti Perkhidmatan (QoS) penghantaran data untuk MWSN dalam SG.

## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| CAA | - | Channel Assignment Algorithm |
| CPSs | - | Cyber-physical Systems |
| CSMA/CA | - | Carrier Sense Multiple Access/Collision Avoidance |
| DCA | - | Dynamic Channel Assignment |
| ECD | - | Efficient Channel Detection |
| EEVD | - | Energy Efficient Virtual Distance |
| EMS | - | Energy Management System |
| ERM | - | Energy Efficient Packet Forwarding |
| ESHC | - | Energy Efficient Spectral Clustering |
| HAN | - | Home Area Network |
| IAN | - | Industrial Area Network |
| IEDs | - | Intelligent Electrical Devices |
| IoS | - | Internet of Services |
| IoT | - | Internet of Things |
| LAN | - | Local Area Network |
| MWSN | - | Multichannel Wireless Sensor Networks |
| NAN | - | Neighborhood Area Network |
| PTDs | - | Power Transmission and Distribution systems |
| PU | - | Primary User |
| QCA | - | Quality-aware Channel Assignment |
| SCADA | - | Control and Data Acquisition |
| SG | - | Smart Grid |
| SGEs | - | Smart Grid Environments |
| SU | - | Secondary User |
| WAN | - | Wide Area Network |
| WSN | - | Wireless Sensor Networks |

## LIST OF SYMBOLS

| | | |
|---|---|---|
| $\bar{\mathcal{C}}_{i(\zeta)}$ | - | Average Channel Capacity of the Channel with Random Packet Transmission rate |
| $\mathcal{B}_{\ell_j}$ | - | Bandwidth of the link $\ell_j$ between $\mathcal{SU}_j$ and $\mathcal{PS}_j$ |
| $\mathcal{B}_{of}$ | - | Buffer Overflow |
| $\mathrm{C}_{\mathcal{D}_{elay}}^{sw}$ | - | Channel Switching Delay |
| $\mathrm{E}_{\mathcal{T}(r)}$ | - | Data Packets Receiving Energy Consumption |
| $\mathrm{E}_{\mathcal{T}(x)}$ | - | Data Packets Transmission Energy Consumption |
| $\mathrm{E}_{amp}$ | - | Constant Signal Amplifier Coefficient |
| $\mathcal{F}_{\mathrm{E}(i)}$ | - | Final Level of Energy |
| $\mathcal{H}_{eat}$ | - | Systems and Subsystem Heat in the SG |
| $\mathcal{HM}_{o}$ | - | Human or Mammal Noise |
| $\mathcal{I}_{\mathrm{E}(i)}$ | - | Initial Level of Energy |
| $\mathcal{I}_{ntf}$ | - | Interference |
| $\mathcal{I}_{r}$ | - | Carrier Sense Range, such as Equal to Interference Range |
| $\mathcal{M}_{o}$ | - | Machine or System Noise |
| $\mathcal{R}_{\mathrm{E}}$ | - | Residual Energy |
| $\mathrm{E}_{elec}$ | - | Circuitry Energy Consumption of Receiving or Transmitting Data Packets |
| $\mathrm{E}\mathcal{M}_{s}$ | - | Impact of Electromagnetic Waves |
| $\mathrm{E}\mathcal{S}_{\mathcal{L}}$ | - | Received Signal Energy and the $n$-Sample of the $\mathcal{S}_{\mathcal{L}}$ |
| $\rho_{\mathcal{FAs}}$ | - | Probability of False Alarms |
| $\rho_{\mathcal{M}i\mathcal{D}}$ | - | Probability of Missed-Detection |
| $\rho_{\mathcal{D}e\mathcal{T}}$ | - | Probability of Detection |
| $\rho_{r(c)}$ | - | Probability of Packet Collision in the Network |
| $E_c$ | - | Energy Consumption |
| $\mathcal{C}_{ong}$ | - | Congestion |
| $\mathcal{CR}_c$ | - | Increment in the Credit Counter |
| $\mathcal{CDP}_{sink}$ | - | Corrupted Data Packets Received at the Sink |

| | | |
|---|---|---|
| $\mathcal{CO}_{error(j)}(\mathcal{DP}_i)$ | - | Probability of Communication Error |
| $\mathcal{C}_{u\ell}$ | - | Channel Usage List |
| $\mathcal{C}_{w(\alpha)}$ | - | Minimum Contention Window with Constant α |
| $\mathcal{D}_{elay}$ | - | Delay |
| $\mathcal{DRe}_{\mathcal{SN}_j}$ | - | Destination Relay Sensor |
| $\mathcal{DP}_{\ell oss}$ | - | Data Packets Loss |
| $\mathcal{DP}_{\mathcal{SN}_n}$ | - | Ratio of Generated Packets by the Sensors |
| $\mathcal{DP}_{sink}$ | - | Received Data Packets at the Sink |
| $\mathcal{G}_{(\mathcal{C}_i)^{\ell_j}}$ | - | Channel Gain of a link $\ell_j$ between $\mathcal{PU}_i$ and $\mathcal{PS}_j$ |
| $\mathcal{G}_\sigma$ | - | Zero-Mean Gaussian Random Variable with Standard Deviation |
| $\mathcal{N}_\sigma$ | - | Noise in the Smart Grid |
| $\mathcal{N}_c$ | - | Total Number of Collisions |
| $\mathcal{P}_{\mathcal{C}_\mathrm{i}(h)}$ | - | Primary User's Channel History |
| $\mathcal{P}_{er}$ | - | Packet Error Rate |
| $\mathcal{P}_\ell(d_0)$ | - | Path Loss at Reference a Distance $d_0$, |
| $\mathcal{PS}_j$ | - | Primary or Secondary User |
| $\mathcal{P}_{dr}$ | - | Packet Delivery Ratio |
| $\mathcal{P}_{noise}$ | - | Noise Power Measured in dBm. |
| $\mathcal{P}_{t(\mathrm{i})}$ | - | Transmission Power of the Sensors along a Routing Path $\mathcal{RP}_{(\mathrm{i})}$ |
| $\mathcal{P}_t$ | - | Transmit Power in dBm |
| $\mathcal{Q}_{\mathcal{D}_{elay}}^{mem}$ | - | Queuing Delay due to the Limited Memory ($mem$) Size |
| $\mathcal{S}_\mathcal{L}$ | - | $\mathcal{L}_s$ is the Sum of the Length of $n$ Samples Over an Interval |
| $\mathcal{SRe}_{\mathcal{SN}_i}$ | - | Source Relay Node |
| $\mathcal{SN}_i$ | - | Sensor Node |
| $\mathcal{SU}_{\mathcal{C}_i}$ | - | Secondary User |
| $\mathcal{S}_{pd}$ | - | Power Spectral Density |
| $\mathcal{T}_{\mathcal{D}_{elay}}$ | - | Transmission Delay |
| $\mathcal{T}_\mathcal{P}$ | - | Throughput |

| | | |
|---|---|---|
| $\mathcal{T}d_r$ | - | Transmission Distance between the Transmitter and the receiver |
| $n_{bits}$ | - | Number of Bits |
| $p_{iter}$ | - | Previous Iterations |
| $t_s[\ell]$ | - | Average Length of the Slot Time $t_s$ |
| $\mathcal{FA}s$ | - | False Alarms |
| $\mathcal{M}i\mathcal{D}$ | - | Missed-Detection |
| $\gamma(d)$ | - | Signal to Noise Ratio over Distance $d$ |
| Η | - | Path-Loss Exponent for Wireless Propagation |
| Σ | - | Shadowing Deviation |
| $\mathcal{CDP}$ | - | Corrupted Data Packet |
| $\mathcal{DP}_s$ | - | Data Packet |
| $\mathcal{D}e\mathcal{T}$ | - | Channel Detection |
| $\mathcal{PU}$ | - | Primary User |
| $\mathcal{SU}$ | - | Secondary User |
| $\mathcal{UT}_{\mathcal{C}_i}$ | - | Vacant Channel Usage Time |

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

The electricity industry is now on the verge of a new era-an era that promises to meet the 21st century energy requirements through the evolution of the existing electrical grids to smart grids. The smart grid is a next-generation power grid in which the electricity distribution and management are upgraded by incorporating advanced two-way communications and pervasive computing capabilities for improved control, efficiency, reliability, and safety (Liu *et al.*, 2020). The smart grid, by employing two-way digital technologies, intelligently enhances the efficiency of legacy power generation, transmission and distribution systems to provide quality electricity between suppliers and consumers. Generally, a smart grid covers from a few hundred to thousands of traditional central generators and/or emerging renewal distributed generators through transmission network and distribution systems to industrial consumers with their intelligent appliances (Wood, 2020). In these systems, the two-way information flow creates an automated information delivery network to enable the near-instantaneous events monitoring to maintain the balance between energy supply and consumer demand. Thus, it significantly reduces the cost and increases the reliability, efficiency and transparency of power generation, distribution and supply between the utilities and the electricity users (Klemenjak *et al.*, 2020).

In greater detail, the cornerstone of a smart grid is the ability for multiple entities such as intelligent devices, dedicated software, processes, and control centre to interact via an efficient and reliable communication infrastructure. Therefore, the smart grids success heavily relies upon communication technologies. The main aim of Communication Technologies (CTs) is to connect different types of Cyber-Physical

Systems (CPSs) via the Internet of Services (IoS) for sharing information, thereby enabling close cooperation between the utilities and customers (Manavalan and Jayakrishna, 2019). It enables the real-time data collection and sharing of smart grid systems on the cyber layers to carry out monitoring and control logic intelligently from any remote location, worldwide. Currently, there are two types of CTs, namely wired and wireless. The main aim of both CTs at the communication layer is to provide highly stable networking for the automated exchange of information of different types of power grid systems. However, the design and implementation of these CTs in a two-way manner is extremely challenging due to the diverse QoS requirements of smart grid applications. Presently, many devices located in different remote places are connected through wired networks working over industrial protocols to streamline management operations in the traditional power grids (Krishnan *et al.*, 2020; Ding *et al.*, 2018). However, the sheer number of communications links in many smart grid applications makes the use of wired solutions economically and/or physically prohibitive. Therefore, compared to a wired network, the wireless networking solution plays a complementary role to empower control, management competencies of the system and subsystem elements in the smart grid (Tightiz and Yang, 2020).

In this respect, WSNs significantly improve the electricity quality by making installation easier, increasing flexibility, speeding up power generation, and streamlining operations at a reduced cost in the smart grid. In the smart grid, WSNs through advanced CTs connect various industrial components of the power grid to the information world, which results in high-quality power generation and distribution and innovative services (Alcaraz *et al.*, 2020; Afianti and Suryani, 2019; Dhunna and Al-Anbagi, 2019). This makes them to be a part of the strategic decision-makers and flexible problem-solvers in the technical complexity that even creates entirely new power generation concepts. Therefore, the WSNs are widely recognized as a promising technology for enhancing various aspects of the electric power grid and realizing the vision of the next-generation electric power system in a cost-effective and efficient manner (Das *et al.*, 2020). The current and envisioned applications of WSNs in the smart grid span a wide range, including substation automation, overhead transmission line monitoring, energy management, advanced metering infrastructure, outage management, distribution automation, demand response, dynamic pricing, and load control (Das *et al.,* 2020; Tightiz and Yang, 2020; Kalalas *et al.,* 2016). Importantly, all these applications lead to new products, processes and services for improving industrial efficiency while providing a competitive edge for the fourth-generation global marketplace**.** At the same time, it ensures the reliability of the electric power infrastructure, helping to improve the daily lives of ordinary citizens. However, the realization of all these currently designed and envisioned smart grid applications directly depends on the reliable and efficient communication capabilities of the deployed network (Hemalatha *et al.,* 2019).

## 1.2 Problem Background and Motivation

The traditional electricity infrastructure is a complex and aging system characterized by centralized power generation and distribution. Lack of user–utility interaction due to one-way power flow in the existing power grid leads to poor peak load management, power quality issues, energy loss, overload conditions, fraud detection, distribution automation, system failures, faulty diagnostics, lack of renewable energy usage, and time wastage manual operational processes (Ferrag *et al.,* 2020). On the other hand, the traditional electricity infrastructure fails to integrate the widely diffused renewable energy resources incorporating thousands of generators around the world, which produce a few kilowatts in the case of residential photovoltaic systems, up to some megawatts in the case of large photovoltaic and wind generators, characterized by different technologies, voltage, current, and power levels as well as topologies (Hu *et al.,* 2020). It causes problem for the utilities and customers, being unreliable, with low power quality, hence too high and increasing cost and low customer satisfaction. Thus, the aging power grids fail to meet the 21$^{st}$ century energy demands in a sophisticated, dynamic and cost-effective manner. The need for reliability, scalability, manageability, environmentally friendly energy generation, interoperability, and cost-effectiveness, bring forward the necessity for a modernized and intelligent grid for tomorrow; a new, reliable, efficient, flexible, and secure energy infrastructure, known as the smart grid (León *et al.,* 2020).

In recent years, the key idea of the smart grid is introduced to address the concerns of the aging power grids in a sophisticated manner by employing bi-directional communications, pervasive computing and sensing technology. In smart grid, the wireless sensor networks due to their identifying, sensing, networking, and processing capabilities, are an invaluable technology for realizing the vision of low-cost remote monitoring and control applications (Sarobin, 2020). Such type of networks consists of several tiny, low-power, and low-cost on-chip sensors. The main attributes of WSNs-based networks are to increase economic benefits with least breakdowns and maintenance costs in a bounded time interval by optimizing operations of the interconnected elements of the legacy electricity network. Generally, a sensor node consists of four main components, namely, sensing unit, microcontroller, communication unit, and small battery (Ma *et al.*, 2019; Alsaba *et al.*, 2018; Modieginyane *et al.*, 2018). The key purposes of these components are data acquisition, local data processing, allow transmission/reception of information between connected devices, and supply power for the operations, respectively. Typically, the sensor nodes have short communication ranges with restricted bandwidth, which leads to multi-hop communications with low data rates. These tiny sensor nodes in the smart grid sense the surrounding environments and send observed information via multiple-hops or directly to a central device called the sink and then to the electric utilities. The real-time information gathered from these sensors is analyzed to diagnose problems early and serves as a basis for taking necessary actions in an active or passive manner to achieve high system efficiency. Thus, every node plays the role of the data source and/or router node to deliver packets to both utilities and customers for sustainable operations (Mahmud *et al.*, 2020).

However, the field tests and measurements show that WSNs-based communications in the smart grid have considerable unique challenges such as multipath fading, extremely high attenuation and excessive interference due to nonlinear electric power equipment (Das *et al.*, 2020; Yigit *et al.*, 2016). In the smart grid, it is observed that the average noise level varies between −89 dBm and −93 dBm in outdoor 500 kV substation environment (Fadel *et al.*, 2017). Obviously, the average noise level is higher in a 550 kV and varies between −83 dBm and −91 dBm outdoor substation environment. It brings time and location-dependent link quality variations, which result in a poor quality of data gathering with high latency and energy consumption for the single channel-based WSNs in SG. After deployment, the sensor nodes, due to the absence of energy efficient packets forwarding techniques, drain their batteries within a couple of days for various time-critical smart grid applications. Also, due to the presence of high electromagnetic interference, it is extremely challenging or impossible to recharge or replace their batteries in the SG (Gungor *et al.,* 2012). Therefore, one of the fundamental design objectives is the entire network must operate for a longer time in the sensing regions and make individual decisions for high-quality data transmission without excessive human intervention. However, the existing studies in smart grid are found to be limited due to late recognition of smart grids (Yigit *et al.,* 2016). Though some advanced communication frameworks for smart grid exist in the literature, their scope is limited to certain applications such as smart metering, asset management, and transmission line monitoring (Hariri *et al.,* 2019; Bukhari *et al.,* 2018; Rehmani *et al.,* 2016).

The majority of these existing solutions are designed to meet application-specific design objectives and requirements in a particular scenario. Ain *et al.* (2018) focus on minimizing latency issues for efficient data collection in the smart grid. Baroudi *et al.* (2019), Lin *et al.* (2017), Ye *et al.* (2016), and Kim and Jin (2015) improve the packet delivery ratio with low packet error rates in the smart grid. Other studies such as Hemalatha *et al.* (2020), Anees *et al.* (2019), de Souza *et al.* (2018), and Bilgin *et al.* (2016) address the issue of load balancing and energy consumption for efficient data gathering in the smart grid. Although the existing studies focus on routing issues that provide valuable insights and guide design decisions for WSN-based smart grid applications, these studies generally ignore the impact of fading, external interference, and noise on transmission reliability in the smart grid. The existing studies do not incorporate dynamic channel adaptation for higher data rate in WSNs-based smart grid applications. Therefore, the existing schemes fail to mitigate the interference at a certain channel and thus face high packet error rate, latency and poor network throughput for WSN-based smart grid applications. In addition, these studies are not fully able to optimize routing performance for reliable data transmission since these schemes always route packets over shortest hops, which leads to high internal interference, data path loops, and average longer path length between the source and the destination in the network. It results in high latency, congestion, invalid data packets, and energy consumption with poor load balancing for WSN-based smart grid applications. Thus, the current single channel allocation-based schemes fail to accommodate the requirements of higher data rates for long-lasting network operations in the smart grid.

In this respect, the concept of Multichannel Wireless Sensor Networks is recently proposed for energy efficient and reliable data transmission at a higher rate for WSN-based smart grid applications (Fadel *et al.*, 2017). MWSNs supports the high data transfer rates with low corrupted data packets by resolving the bandwidth scarcity issues in which a sensor node transmits its data in unused vacant channels without causing harmful interference to neighbor nodes. In Figure 1.1, the white regions show the vacant channels, while the colored boxes indicate the channels occupied by secondary users. In MWSNs, primary users are referred to as those users who have higher priority or legacy rights for the usage of a part of the channels. In MWSNs, if a secondary user encounters the high noise and/or primary user, it changes its channel or stays in the same band without creating interference with the licensed-user by adapting its radio parameters (Mishra *et al.*, 2019). Consequently, in unlicensed vacant channel bands, all secondary users have the same right to access the channels by avoiding noisy channels. Hence, multichannel communication is used to improve the channel utilization efficiency, parallel transmissions, network capacity, and robustness against internal or external perturbations for WSNs-based smart grid applications.

However, the reliable channel detection, the channel assignment and the data packets forwarding between the source and destination is challenging due to the time-varying nature of the SG environments. Although a few MWSNs-based routing schemes to mitigate some of the issues faced by single-channel based WSNs are proposed by Yang *et al.* (2018), Fadel *et al.* (2017), Yigit *et al.* (2016), and Shah *et al.* (2013), these studies are facing the issue of poor channel detection that increases the probability of false alarm and missed-detection, which leads to harmful interference to the primary users in SG. In addition, most of the time these existing studies fail to find an empty channel quickly with desired data capacity in the network. Moreover, the existing schemes due to lack of considering the channel idle probability, effect of external interference and noise on transmission reliability face the issues of high latency, corrupted data packets and packet retransmission energy consumption in the SG (Kurt *et al.*, 2016). Furthermore, during packet forwarding process, the aforesaid studies do not consider the impact of data path loops and co-channel interference, which further contributes to high latency and corrupted data packets in the network.

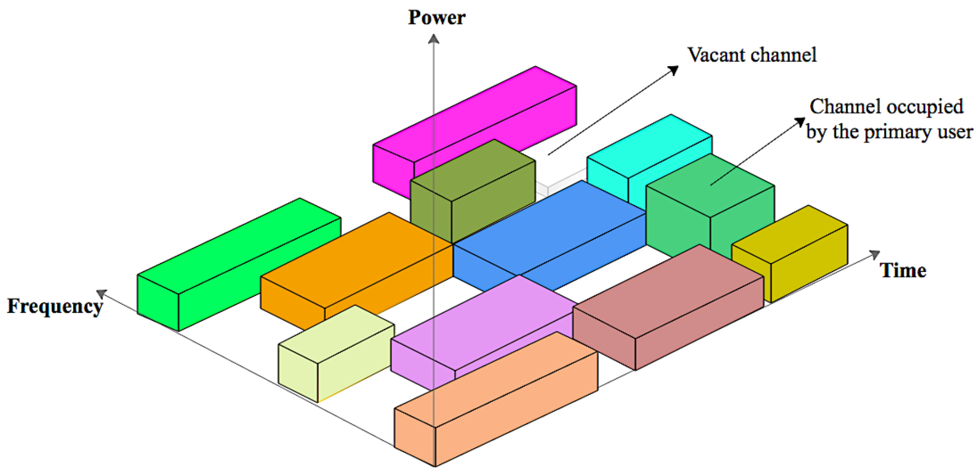


Figure 1.1 Vacant Channels in MWSNs (adopted from Zhang *et al.*, (2016))

Hence, the existing network solutions due to the fixed or inefficient channel allocation strategies are not resilient or efficient enough to provide the desired reliable data delivery with low energy consumption in the SG (Arjoune and Kaabouch, 2019). In this respect, the development of a reliable and energy efficient communication mechanism is necessary for the connection between the huge number of distributed elements such as generators, substations, energy storage systems, and users, enabling a real-time exchange of data and information necessary for the management of the system for ensuring improvements in terms of efficiency, reliability, flexibility, and investment return for all those involved in a smart grid: producers, operators and customers (Yigit *et al.*, 2014a; Gungor *et al.*, 2012). The limitations of the existing studies and the above-mentioned advantages of multichannel communication motivate to propose an energy efficient multichannel packet forwarding mechanism for WSNs-based smart grid applications.

## 1.3 Problem Statement

The power grid infrastructure is very critical and contains a huge number of interconnected components such as generators, power transformers and distribution feeders that are geographically spread. Control, automation, optimization, reliable, and efficient monitoring of these systems is based on the real-time communications between sensors installed on these systems. However, the smart grid environment factors such as equipment noise, electromagnetic interference, fading, and multipath effects adversely affected the energy-efficient packet forwarding for MWSNs. Recently, different types of packet forwarding schemes have been proposed. However, due to the lack of an appropriate mechanism, these schemes fail to find the best next-hop relay node based on the highest weight from the source towards the sink. The existing schemes cannot provide the optimized routes between source and sink in MWSNs in SG. As a result, the existing schemes are facing the issues of high latency, energy consumption, buffer overflow, and data path loops in the MWSNs. Therefore, it is essential to develop an energy-efficient packet forwarding scheme, which improves the aforesaid factors for MWSNs in SG. On the other hand, the existing energy-based channel detection schemes, due to lack of considering an appropriate energy level threshold value, fail to detect the presence or absence of the primary user in the smart grid. Therefore, the existing channel detection schemes are facing the issues of high probability of channel false alarms and missed-detection in the MWSNs.

In addition, the existing schemes due to lack of considering a hybrid local channel detection and group-based channel detection technique fail to find the vacant channels robustly for SUs in the MWSNs. Therefore, it is desirable to develop an efficient channel detection scheme, which significantly improves the probability of channel detection and minimizes the probability of false alarms along with the probability of missed-detection in the MWSNs. Moreover, the capacity-aware channel assignment is another challenging task for MWSNs in the SG. Recently, different types of channel assignment schemes have been proposed for MWSNs in the SG. However, the existing schemes have failed to explore the high capacity channels with a longer idle probability at a low interference in MWSNs in SG due to frequent use of non-overlapping channels. Moreover, the existing schemes have failed to compute the numeric impact of interference, capacity, idle probability, and workload of an occupied channel in the MWSNs. Therefore, the existing schemes cannot mitigate the noisy and congested channels, and thus failed to improve the network capacity and throughput with low corrupted data packets in the MWSNs. Thus, it is desirable to develop a dynamic channel assignment scheme which mitigates the noisy and congested channels, yielding high data capacity channels with longer idle probability at low interference to improve the network capacity, and throughput with low corrupted data packets in the MWSNs.

## 1.4 Research Questions

Based on the discussion provided in Section 1.2, research questions are formulated as follows:

i. How to select the optimized routes between the source and the sink so that it will reduce the latency, congestion and energy consumption in MWSNs?
ii. How to identify the signal energy threshold value to find vacant channels for the secondary users so that it will improve the channel detection probability with low probability of missed-detection and false alarms in the MWSNs?
iii. How to allocate low interference-aware channels to secondary users with longer idle probability so that it will improve the network capacity with low corrupted data packets in the MWSNs?

## 1.5 Research Aim

The aim of this research study is to design an enhanced packet forwarding scheme, channel detection scheme and channel assignment scheme to improve the network capacity, packet delivery ratio, congestion management, throughput, and channel detection performance with the low probability of missed-detection, false alarms, packet error rate, latency, and energy consumption for MWSNs-based applications in the SG.

## 1.6 Research Objectives

The following research objectives are to be achieved during the research work. These objectives are in the perspective of the research questions mentioned in Section 1.4 as follows:

i. To enhance the packet forwarding scheme by selecting the optimized routes between the source and the sink to minimize the latency, congestion and energy consumption in the MWSNs.
ii. To enhance the channel detection scheme by finding the vacant channels for the secondary users with improved channel detection probability, low probability of missed-detection and false alarms in the MWSNs.
iii. To enhance the channel assignment scheme by providing the higher data rate channels to secondary users with longer idle probability at low interference, which improves the network capacity and data packet delivery with low corrupted data packets in the MWSNs.

## 1.7 Research Scope

The scope of this research study is given below:

i. This research study focuses on a 550kV outdoor power grid station.
ii. The sensor nodes deployed for smart grid events monitoring have limited resources.
iii. This research study does not consider security issues and hidden terminal problems.

iv. This research study does not consider the mobility issues of the sensors and sink.

v. This research study does not consider the interference of the cellular networks operated in the vicinity of the smart grid.

## 1.8 Research Significance

This research focuses on developing an energy efficient multichannel packet forwarding scheme for WSNs in smart grid applications. The proposed scheme is capable of connecting distributed power generation sources into the power transmission and distribution systems as integral components. In addition, it enables efficient monitoring and control of the power generation and distribution processes in the smart grid. It supports reliable and dynamic data capacity requirements of different types of an advanced cyber-physical systems equipped with sensors and devices to operate them in an optimal manner, either manual or automatic controls and provide information about their operations to the utilities. In case of faults, the designed scheme intelligently detects and identifies the faulty systems located in a remote position and notifies the user in real-time, so that appropriate actions are taken in order to supply steady electricity to the customers. This reduces the overall electricity generation and distribution expenses that will be of immediate benefit to the customers. Hence, it allows electric utilities to real-time monitor, analyse and control the existing electrical power systems for maximizing the throughput of the systems as efficiently and economically as possible. In addition, it plays an important role in the extension of the smart grid towards residential premises, enables various demand and energy management applications.

## 1.9 Thesis Organization

This thesis comprises six chapters. The rest of the chapters are organized as follows: Chapter 2 provides an extensive review of the literature of research area, problem background and highlights the shortcoming of most existing single and multichannel WSNs-based routing schemes designed for smart grid applications. Chapter 3 describes the research methodology and various simulation experiments used to develop the objectives of this research. It highlights the design, implementation and verification of the proposed Energy Efficient Packets Forwarding (ERM) scheme, Efficient Channel Detection (ECD) scheme and Dynamic Channel Assignment (DCA) scheme that are applied in this study. Chapter 4 presents the design and development of an Energy Efficient Packets Forwarding (ERM) scheme. The simulation experiments are performed in order to measure the relative performance of the proposed scheme against other relevant schemes by considering different performance evaluation metrics in the SG. Chapter 5 presents the design and development of an Efficient Channel Detection (ECD) scheme. The simulation experiments are performed in order to measure the relative performance of the proposed scheme against other relevant schemes by considering different performance evaluation metrics in the SG. Chapter 6 presents the design and development of a Dynamic Channel Assignment (DCA) scheme. The simulation experiments are performed in order to measure the relative performance of the proposed scheme against other relevant schemes by considering different performance evaluation metrics in the SG.  Chapter 7 concludes the contributions that are made in this study and suggests possible future directions.

# REFERENCES


Abdel Hakeem, S. A., Hady, A. A., and Kim, H. (2019). RPL Routing Protocol Performance in Smart Grid Applications Based Wireless Sensors: Experimental and Simulated Analysis. *Electronics, 8*(2), 1-23.

Abdrabou, A. (2014). A wireless communication architecture for smart grid distribution networks. *IEEE Systems journal,* 10(1), 251-261.

Afianti, F., and Suryani, T. (2019). Lightweight and DoS resistant multiuser authentication in wireless sensor networks for smart grid environments. *IEEE Access,* 7, 67107-67122.

Aijaz, A., Su, H., and Aghvami, A.-H. (2015). CORPL: A routing protocol for cognitive radio enabled AMI networks. *IEEE Transactions on Smart Grid,* 6(1), 477-485.

Ain, Q.-u., Iqbal, S., Khan, S., Malik, A., Ahmad, I., and Javaid, N. (2018). Iot operating system based fuzzy inference system for home energy management system in smart buildings. *Sensors,* 18(9), 1-30.

Akerele, M., Al-Anbagi, I., and Erol-Kantarci, M. (2019). A Fiber-Wireless Sensor Networks QoS Mechanism for Smart Grid Applications. *IEEE Access*, 7*(2),* 37601-37610.

Alcaraz, C., and Lopez, J. (2013). Wide-area situational awareness for critical infrastructure protection. *Computer,* 46(4), 30-37.

Alcaraz, C., Rubio, J. E., and Lopez, J. (2020). Blockchain-assisted access for federated Smart Grid domains: Coupling and features. *Journal of Parallel and Distributed Computing*, 10(1), 124 -135.

Alishahi, M., Moghaddam, M. H. Y., and Pourreza, H. R. (2018). Multi-class routing protocol using virtualization and SDN-enabled architecture for smart grid. *Peer-to-Peer Networking and Applications,* 11(3), 380-396.

Almasaeid, H. M., and Kamal, A. E. (2015). Receiver-based channel allocation in cognitive radio wireless mesh networks. *IEEE/ACM Transactions on Networking (TON),* 23(4), 1286-1299.

Alsaba, Y., Rahim, S. K. A., and Leow, C. Y. (2018). Beamforming in wireless energy harvesting communications systems: A survey. *IEEE Communications Surveys & Tutorials,* 20(2), 1329-1360.

Anees, J., Zhang, H.-C., Baig, S., and Lougou, B. G. (2019). Energy-Efficient Multi-Disjoint Path Opportunistic Node Connection Routing Protocol in Wireless Sensor Networks for Smart Grids. *Sensors,* 19(17), 3776-3789.

Arjoune, Y., and Kaabouch, N. (2019). A Comprehensive Survey on Spectrum Sensing in Cognitive Radio Networks: Recent Advances, New Challenges, and Future Research Directions. *Sensors,* 19(1), 1-32.

Artale, G., Cataliotti, A., Cosentino, V., Di Cara, D., Fiorelli, R., Guaiana, S., et al. (2018). A new PLC-based smart metering architecture for medium/low voltage grids: Feasibility and experimental characterization. *Measurement,* 12(4), 479-488.

Astudillo León, J., and de la Cruz Llopis, L. (2018). A joint multi-path and multi-channel protocol for traffic routing in smart grid neighborhood area networks. *Sensors,* 18(11), 1-23.

Baroudi, U., Bin-Yahya, M., Alshammari, M., and Yaqoub, U. (2019). Ticket-based QoS routing optimization using genetic algorithm for WSN applications in smart grid. *Journal of Ambient Intelligence and Humanized Computing,* 10(4), 1325-1338.

Basar, E., Wen, M., Mesleh, R., Di Renzo, M., Xiao, Y., and Haas, H. (2017). Index modulation techniques for next-generation wireless networks. *IEEE Access,* 5(1), 16693-16746.

Bilgin, B. E., Baktir, S., and Gungor, V. C. (2016). Collecting smart meter data via public transportation buses. *IET Intelligent Transport Systems, 10*(8), 515-523.

Bukhari, S. H. R., Rehmani, M. H., and Siraj, S. (2018). Remaining idle time aware intelligent channel bonding schemes for cognitive radio sensor networks. *Wireless Networks,* 8(2), 1-17.

Cao, H., Liu, S., Wu, L., Guan, Z., and Du, X. (2019). Achieving differential privacy against non-intrusive load monitoring in smart grid: A fog computing approach. *Concurrency and Computation: Practice and Experience,* 31(22), 1-14.

Chang, X. (1999). Network simulations with OPNET. *Proceedings of the 31st Conference on Winter simulation: Simulation-a Bridge to the Future,* 1, 307-314.

Charan, C., and Pandey, R. (2019). Cooperative Spectrum Sensing Using Eigenvalue-Based Double-Threshold Detection Scheme for Cognitive Radio Networks. In *Applications of Artificial Intelligence Techniques in Engineering*, *Springer,* 18(1), 189-199.

Cheng, J., Ye, Q., Jiang, H., Wang, D., and Wang, C. (2012). STCDG: An efficient data gathering algorithm based on matrix completion for wireless sensor networks. *IEEE Transactions on Wireless Communications,* 12(2), 850-861.

Dannana, S., Chapa, B. P., and Rao, G. S. (2018). Spectrum Sensing Using Matched Filter Detection. In *Intelligent Engineering Informatics, Springer,* 12(3), 497-503.

Das, L., Munikoti, S., Natarajan, B., and Srinivasan, B. (2020). Measuring smart grid resilience: Methods, challenges and opportunities. *Renewable and Sustainable Energy Reviews*, 13(2), 109918.

de Souza, R. W. R., Moreira, L. R., Rodrigues, J. J., Moreira, R. R., and de Albuquerque, V. H. C. (2018). Deploying wireless sensor networks–based smart grid for smart meters monitoring and control. *International Journal of Communication Systems*, 31(10), 23-38.

Dehay, D., Leskow, J., and Napolitano, A. (2013). Central limit theorem in the functional approach. *IEEE Transactions on Signal Processing,* 61(16), 4025-4037.

Deng, X., He, L., Li, X., Liu, Q., Cai, L., and Chen, Z. (2016). A reliable QoS-aware routing scheme for neighbor area network in smart grid. *Peer-to-Peer Networking and Applications,* 9(4), 616-627.

Dhunna, G. S., and Al-Anbagi, I. (2019). A low power WSNs attack detection and isolation mechanism for critical smart grid applications. *IEEE Sensors Journal,* 19(13), 5315-5324.

Ding, Jishiyu, Huile Xu, Jianming Hu, and Yi Zhang (2017). Centralized cooperative intersection control under automated vehicle environment. *IEEE Intelligent Vehicles Symposium*, 5, 972-977.

Ding, Y., Li, X., Tian, Y.-C., Ledwich, G., Mishra, Y., and Zhou, C. (2018). Generating scale-free topology for wireless neighborhood area networks in smart grid. *IEEE Transactions on Smart Grid*, 10(4), 4245-4252.

Dong, C., Qu, Y., Dai, H., Guo, S., and Wu, Q. (2018). Multicast in multi-channel cognitive radio ad hoc networks: challenges and research aspects. *Computer Communications*, 132, 10-16.

Dong, M., Ota, K., and Liu, A. (2016). RMER: Reliable and Energy-Efficient Data Collection for Large-Scale Wireless Sensor Networks. *IEEE Internet of Things Journal*, 3(4), 511-519.

Eze, J., Zhang, S., Liu, E., and Eze, E. (2018). Cognitive radio-enabled Internet of Vehicles: a cooperative spectrum sensing and allocation for vehicular communication. *IET Networks*, 6(2), 211-219.

Fadel, E., Faheem, M., Gungor, V. C., Nassef, L., Akkari, N., Malik, M. G. A., et al. (2017). Spectrum-aware bio-inspired routing in cognitive radio sensor networks for smart grid applications. *Computer Communications*, 101, 106-120.

Fahimi, M., and Ghasemi, A. (2016). Joint spectrum load balancing and handoff management in cognitive radio networks: a non-cooperative game approach. *Wireless Networks*, 22(4), 1161-1180.

Farhangi, H. (2009). The path of the smart grid. *IEEE Power and Energy Magazine*, 8(1), 18-28.

Farooq, H., and Tang Jung, L. (2013). Energy, traffic load, and link quality aware Ad Hoc routing protocol for wireless sensor network based smart metering infrastructure. *International Journal of Distributed Sensor Networks*, 9(8), 1-13.

Ferrag, M. A., Babaghayou, M., and Yazici, M. A. (2020). Cyber security for fog-based smart grid SCADA systems: Solutions and challenges. *Journal of Information Security and Applications*, 52, 102500-102514.

Gao, J., Zhang, J.-j., and Guang, X.-l. (2019). An improved routing algorithm for advanced metering infrastructure in smart grid. *Cluster Computing*, 1-10.

Garau, M., Ghiani, E., Celli, G., Pilo, F., and Corti, S. (2018). Co-simulation of smart distribution network fault management and reconfiguration with lte communication. *Energies*, 11(6), 1332-1339.

Goel, D., Krishna, V. S., and Bhatnagar, M. (2016). Selection relaying in decode-and-forward multi-hop cognitive radio systems using energy detection. *IET Communications,* 10(7), 753-760.

Gungor, V. C., and Hancke, G. P. (2009). Industrial wireless sensor networks: Challenges, design principles, and technical approaches. *IEEE Transactions on Industrial Electronics,* 56(10), 4258-4265.

Gungor, V. C., Lu, B., and Hancke, G. P. (2010). Opportunities and challenges of wireless sensor networks in smart grid. *IEEE Transactions on Industrial Electronics,* 57(10), 3557-3564.

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., et al. (2011). Smart grid technologies: Communication technologies and standards. *IEEE Transactions on Industrial Informatics,* 7(4), 529-539.

Gungor, V. C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C., et al. (2012). A survey on smart grid potential applications and communication requirements. *IEEE Transactions on Industrial Informatics,* 9(1), 28-42.

Hariri, A.-M., Hejazi, M. A., and Hashemi-Dezaki, H. (2019). Reliability optimization of smart grid based on optimal allocation of protective devices, distributed energy resources, and electric vehicle/plug-in hybrid electric vehicle charging stations. *Journal of Power Sources,* 436, 1-15.

Hemalatha, R., Prakash, R., and Sivapragash, C. (2019). Analysis on energy consumption in smart grid WSN using path operator calculus centrality based HSA-PSO algorithm. *Soft Computing*, 1-13.

Hosseini, H., Anpalagan, A., Raahemifar, K., Erkucuk, S., and Habib, S. (2016). Joint wavelet-based spectrum sensing and FBMC modulation for cognitive millimeter wave small cell networks. *IET Communications,* 10(14), 1803-1809.

Hou, R., Wang, C., Zhu, Q., and Li, J. (2014). Interference-aware QoS multicast routing for smart grid. *Ad Hoc Networks*, 22(6), 13-26.

Hu, S., Chen, X., Ni, W., Wang, X., and Hossain, E. (2020). Modeling and Analysis of Energy Harvesting and Smart Grid-Powered Wireless Communication Networks: A Contemporary Survey. *IEEE Transactions on Green Communications and Networking,* 4(2), 461-496.

Iniyan, S., Jebaraj, S., Suganthi, L., and Samuel, A. A. (2020). Energy models for renewable energy utilization and to replace fossil fuels. *Methodology,* 67(2), 28-37.

Islam, M. M., Zhong, X., Sun, Z., Xiong, H., and Hu, W. (2019). Real-time frequency regulation using aggregated electric vehicles in smart grid. *Computers & Industrial Engineering,* 134(1), 11-26.

Kubinidze, N., Ganchev, I., & O'Droma, M. (2006). Network simulator ns2: shortcomings, potential development and enhancement strategies. In *Modeling and Simulation Tools for Emerging Telecommunication Networks*, 13(7), 263-277.

Jorge, N. (2004). A Comprehensible GloMoSim Tutorial. *March,* 4, 2004.

Juneja, D., Sharma, A., and Kumar, A. A Query Driven Routing Protocol for Wireless Sensor Nodes in Subsurface. *International Journal of Engineering Science and Technology*, 2(6), 1836-1843.

Kabalci, Y. (2016). A survey on smart metering and smart grid communication. *Renewable and Sustainable Energy Reviews, 57*, 302-318.

Kalalas, C., Thrybom, L., and Alonso-Zarate, J. (2016). Cellular communications for smart grid neighborhood area networks: A survey. *IEEE Access,* 8(3), 1469-1493.

Kenosi, K., Ravi, S., Rohini, R., and Annapoorani, K. I. (2019). Development of an Outage Management System for Power Distribution Networks. *International Journal of Simulation Systems, Science & Technology,* 20(2), 1-8.

Khaled, O., Marín, A., Almenares, F., Arias, P., and Díaz, D. (2016). Analysis of secure TCP/IP profile in 61850 based substation automation system for smart grids. *International Journal of Distributed Sensor Networks,* 12(4), 1-11.

Khan, Z. A., Zafar, A., Javaid, S., Aslam, S., Rahim, M. H., and Javaid, N. (2019). Hybrid meta-heuristic optimization based home energy management system in smart grid. *Journal of Ambient Intelligence and Humanized Computing,* 10(12), 4837-4853.

Khorov, E., Kiryanov, A., Lyakhov, A., and Bianchi, G. (2018). A Tutorial on IEEE 802.11 ax High Efficiency WLANs. *IEEE Communications Surveys & Tutorials,* 21(1), 197-216.

Khuntia, S. R., Rueda, J. L., and van der Meijden, M. A. (2019). Smart asset management for electric utilities: Big data and future. *In Asset Intelligence*

*Through Integration and Interoperability and Contemporary Vibration Engineering Technologies*, 9(1), 311-322.

Kim, K., and Jin, S.-i. (2015). Branch-Based Centralized Data Collection for Smart Grids Using Wireless Sensor Networks. *Sensors, 15*(5), 11854-11872.

Kim, K., Kim, H., Jung, J., and Kim, H. (2015). AFAR: A robust and delay-constrained communication framework for smart grid applications. *Computer Networks,* 91, 1-25.

Klemenjak, C., Kovatsch, C., Herold, M., and Elmenreich, W. (2020). A synthetic energy dataset for non-intrusive load monitoring in households. *Scientific Data*, 7(1), 1-17.

Krishnan, S., Umasankar, P., and Mohana, P. (2020). A smart fpga based design and implementation of grid connected direct matrix converter with IoT communication. *Microprocessors and Microsystems*, 76(3), 1-11.

Kshetri, N. (2016). The evolution of the internet of things industry and market in China: An interplay of institutions, demands and supply. *Telecommunications Policy*, 41(1), 49-67.

Kumar, B. A., and Rao, P. T. (2017). MDI-SS: matched filter detection with inverse covariance matrix-based spectrum sensing in cognitive radio. *International Journal of Internet Technology and Secured Transactions,* 7(4), 353-363.

Kurt, S., Yildiz, H. U., Yigit, M., Tavli, B., and Gungor, V. C. (2016). Packet size optimization in wireless sensor networks for smart grid applications. *IEEE Transactions on Industrial Electronics*, 64(3), 2392-2401.

Lai, J., Zhou, H., Hu, W., Zhou, D., and Zhong, L. (2015). Smart demand response based on smart homes. *Mathematical Problems in Engineering*, 60(1), 1-8.

Langer, L., Skopik, F., Smith, P., and Kammerstetter, M. (2016). From old to new: Assessing cybersecurity risks for an evolving smart grid. *Computers & Security*, 62, 165-176.

León, J. P. A., Begin, T., and Busson, A. (2020). A Fair and Distributed Congestion Control Mechanism for Smart Grid Neighborhood Area Networks. *Ad Hoc Networks*, 102169.

Li, Y., Cheng, X., Cao, Y., Wang, D., and Yang, L. (2017). Smart choice for the smart grid: Narrowband Internet of Things (NB-IoT). *IEEE Internet of Things Journal, 5*(3), 1505-1515.

Lin, J., Zhu, B., Zeng, P., Liang, W., Yu, H., and Xiao, Y. (2015). Monitoring power transmission lines using a wireless sensor network. *Wireless Communications and Mobile Computing*, 15(14), 1799-1821.

Lin, S., Li, F., Tian, E., Fu, Y., and Li, D. (2017). Clustering load profiles for demand response applications. *IEEE Transactions on Smart Grid,* 10(2), 1599-1607.

Liu, B. J., Yu, P., Xue-song, Q., and Shi, L. (2020). Survivability-aware routing restoration mechanism for smart grid communication network in large-scale failures. *EURASIP Journal on Wireless Communications and Networking,* 20(1), 1-21.

Liu, X., Wei, Q., Wang, Q., Zhao, Z., and Yin, Z. (2018). CAFA: A Checksum-Aware Fuzzing Assistant Tool for Coverage Improvement. *Security and Communication Networks,* 18(1), 1-13.

Liu, Y., Zhong, Z., Wang, G., and Hu, D. (2015). Cyclostationary detection based spectrum sensing for cognitive radio networks. *Journal of Communications,* 10(1), 74-79.

Logambigai, R., Ganapathy, S., and Kannan, A. (2018). Energy–efficient grid–based routing algorithm using intelligent fuzzy rules for wireless sensor networks. *Computers & Electrical Engineering,* 68, 62-75.

Luitel, S., and Moh, S. (2018). Energy-efficient medium access control protocols for cognitive radio sensor networks: A comparative survey. *Sensors*, 18(11), 3781-3797.

Ma, D., Lan, G., Hassan, M., Hu, W., and Das, S. K. (2019). Sensing, Computing, and Communications for Energy Harvesting IoTs: A Survey. *IEEE Communications Surveys & Tutorials*, 22(2), 1222-1250.

Machalek, D., and Powell, K. (2019). Automated electrical demand peak leveling in a manufacturing facility with short term energy storage for smart grid participation. *Journal of Manufacturing Systems*, 52, 100-109.

Mahmud, K., Khan, B., Ravishankar, J., Ahmadi, A., and Siano, P. (2020). An internet of energy framework with distributed energy resources, prosumers and small-scale virtual power plants: An overview. *Renewable and Sustainable Energy Reviews*, 127(1), 1-19.

Mahoor, M., Majzoobi, A., and Khodaei, A. (2018). Distribution asset management through coordinated microgrid scheduling. *IET Smart Grid,* 1(4), 159-168.

Mak, S. T. (2015). Advanced metering infrastructure (AMI) and general operational and communication issues. In *New Technologies for Smart Grid Operation*: IOP Publishing, 65, 1-11.

Manavalan, E., and Jayakrishna, K. (2019). A review of Internet of Things (IoT) embedded sustainable supply chain for industry 4.0 requirements. *Computers & Industrial Engineering*, 127, 925-953.

Margoosian, A., Abouei, J., and Plataniotis, K. N. (2015). An accurate kernelized energy detection in Gaussian and non-Gaussian/impulsive noises. *IEEE Transactions on Signal Processing,* 63(21), 5621-5636.

Markkula, J., and Haapola, J. (2018). Ad hoc LTE method for resilient smart grid communications. *Wireless Personal Communications, 98*(4), 3355-3375.

Men, S., Chargé, P., Wang, Y., and Li, J. (2019). Wideband signal detection for cognitive radio applications with limited resources. *EURASIP Journal on Advances in Signal Processing,* 20(1), 1-10.

Mishra, D., De, S., Jana, S., Basagni, S., Chowdhury, K., and Heinzelman, W. (2015). Smart RF energy harvesting communications: Challenges and opportunities. *IEEE Communications Magazine,* 53(4), 70-78.

Mishra, S., Singh, S., and Mishra, B. S. P. (2019). A Comparative Analysis of Centralized and Distributed Spectrum Sharing Techniques in Cognitive Radio. In *Computational Intelligence in Sensor Networks*, 46, 455-472.

Modieginyane, K. M., Letswamotse, B. B., Malekian, R., and Abu-Mahfouz, A. M. (2018). Software defined wireless sensor networks application opportunities for efficient network management: A survey. *Computers & Electrical Engineering,* 66, 274-287.

Mu, J. (2014). A minimum physical distance delivery protocol based on ZigBee in smart grid. *EURASIP Journal on Wireless Communications and Networking,* 20(1), 108-118.

Muchandi, N., and Khanai, R. (2016). Cognitive radio spectrum sensing: A survey. *International Conference on Electrical, Electronics and Optimization Techniques*, 23(8), 3233-3237.

Munoz, O., Pascual-Iserte, A., and Vidal, J. (2014). Optimization of radio and computational resources for energy efficiency in latency-constrained application offloading. *IEEE Transactions on Vehicular Technology,* 64(10), 4738-4755.

Na, W., Yoon, J., Cho, S., Griffith, D., and Golmie, N. (2017). Centralized cooperative directional spectrum sensing for cognitive radio networks. *IEEE Transactions on Mobile Computing*, 17(6), 1260-1274.

Nan, S., Zhou, M., and Li, G. (2018). Optimal residential community demand response scheduling in smart grid. *Applied Energy, 210*, 1280-1289.

Naparstek, O., and Cohen, K. (2019). Deep multi-user reinforcement learning for distributed dynamic spectrum access. *IEEE Transactions on Wireless Communications*, 18(1), 310-323.

Nassar, J., Gouvy, N., and Mitton, N. (2017). *Towards multi-instances QoS efficient RPL for smart grids.* ACM Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks, 51(3), 85-92.

Nassef, L., Elhebshi, R., and Jose, L. (2018). Evaluating performance of wireless sensor network in realistic smart grid environment. *International Journal of Wireless & Mobile Networks (IJWMN),* 10(3), 1-10.

Ogbodo, E. U., Dorrell, D., and Abu-Mahfouz, A. M. (2017). Cognitive radio based sensor network in smart grid: Architectures, applications and communication technologies. *IEEE Access,* 5(4), 19084-19098.

Oyewobi, S. S., and Hancke, G. P. (2017). A survey of cognitive radio handoff schemes, challenges and issues for industrial wireless sensor networks (CR-IWSN). *Journal of Network and Computer Applications,* 97, 140-156.

Pandey, S., and Varma, S. (2016). A Range Based Localization System in Multihop Wireless Sensor Networks: A Distributed Cooperative Approach. *Wireless Personal Communications*, 86(2), 615-634.

Penna, F., and Garello, R. (2012). Decentralized neyman-pearson test with belief propagation for peer-to-peer collaborative spectrum sensing. *IEEE Transactions on Wireless Communications*, 11(5), 1881-1891.

Prasad, R. G., and Venkatesan, P. (2018). Group Based Multi-Channel Synchronized Spectrum Sensing in Cognitive Radio Network with 5G. *Mobile Networks and Applications*, 4(2),1-13.

Rahman, P., Karmaker, A., Alam, M. S., Hoque, M. A., and Lambert, W. L. (2019). CUMAC-CAM: a channel allocation aware MAC protocol for addressing triple hidden terminal problems in multi-channel wsns. *Applied Sciences,* 1(7), 1-20.

Ranjeeth, M., Nallagonda, S., and Anuradha, S. (2017). Optimization Analysis of Improved Energy Detection based Cooperative Spectrum Sensing Network in Nakagami-m and Weibull Fading Channels. *Journal of Engineering Science & Technology Review,* 10(2), 1-8.

Rehan, W., Fischer, S., Chughtai, O., Rehan, M., and Saleem, S. (2020). A Novel Dynamic Confidence Interval based Secure Channel Prediction Approach for Stream-based Multichannel Wireless Sensor Networks. *Ad Hoc Networks*, 108, 1-19.

Rehan, W., Fischer, S., Rehan, M., and Rehmani, M. H. (2017). A comprehensive survey on multichannel routing in wireless sensor networks. *Journal of Network and Computer Applications,* 95, 1-25.

Rehmani, M. H., Rachedi, A., Erol-Kantarci, M., Radenkovic, M., and Reisslein, M. (2016). Cognitive radio based smart grid: The future of the traditional electrical grid. *Ad Hoc Networks,* 41, 1- 4.

Rehmani, M. H., Viana, A. C., Khalife, H., and Fdida, S. (2013). Surf: A distributed channel selection strategy for data dissemination in multi-hop cognitive radio networks. *Computer Communications,* 36(10), 1172-1185.

Rekik, M., Chtourou, Z., Mitton, N., and Atieh, A. (2016). Geographic routing protocol for the deployment of virtual power plant within the smart grid. *Sustainable Cities and Society,* 25, 39-48.

Sabino, S., and Grilo, A. (2018). Routing for Efficient Alarm Aggregation in Smart Grids: A Genetic Algorithm Approach. *Procedia Computer Science,* 130, 164-171.

Sahin, D., Gungor, V. C., Kocak, T., and Tuna, G. (2014). Quality-of-service differentiation in single-path and multi-path routing for wireless sensor network-based smart grid applications. *Ad Hoc Networks,* 22, 43-60.

Sahoo, P. K., Mohapatra, S., and Sheu, J.-P. (2017). Dynamic spectrum allocation algorithms for industrial cognitive radio networks. *IEEE Transactions on Industrial Informatics,* 14(7), 3031-3043.

Sarobin, M. V. R. (2020). Optimized Node Deployment in Wireless Sensor Network for Smart Grid Application. *Wireless Personal Communications,* 111(3), 1431-1451.

Sarode, S., and Bakal, J. (2017). PFPS: Priority-first packet scheduler for IEEE 802.15. 4 heterogeneous wireless sensor networks. *International Journal of Communication Networks and Information Security,* 9(2), 253-262.

Shah, G. A., Gungor, V. C., and Akan, O. B. (2013). A cross-layer QoS-aware communication framework in cognitive radio sensor networks for smart grid applications. *IEEE Transactions on Industrial Informatics,* 9(3), 1477-1485.

Shan, K., Wang, S., Yan, C., and Xiao, F. (2016). Building demand response and control methods for smart grids: A review. *Science and Technology for the Built Environment,* 22(6), 692-704.

Shi, Y., and Fang, H. (2010). Kalman filter-based identification for systems with randomly missing measurements in a network environment. *International Journal of Control, 83*(3), 538-551.

Singh, S., Roy, A., and Selvan, M. (2019). Smart load node for nonsmart load under smart grid paradigm: A new home energy management system. *IEEE Consumer Electronics Magazine,* 8(2), 22-27.

So, J., and Sung, W. (2016). Group-Based Multibit Cooperative Spectrum Sensing for Cognitive Radio Networks. *IEEE Transaction on Vehicular Technology,* 65(12), 10193-10198.

Sun, W., and Wang, J. (2014). Cross-layer QoS optimization of wireless sensor network for smart grid. *International Journal of Distributed Sensor Networks,* 10(12), 327067-327085.

Sutherland, C., Fuller, A. K., and Royle, J. A. (2015). Modelling non-Euclidean movement and landscape connectivity in highly structured ecological networks. *Methods in Ecology and Evolution,* 6(2), 169-177.

Tang, J., Huang, H., Guo, S., and Yang, Y. (2015). Dellat: Delivery latency minimization in wireless sensor networks with mobile sink. *Journal of Parallel and Distributed Computing,* 83, 133-142.

Tariq, M., Zhou, Z., Wu, J., Macuha, M., and Sato, T. (2012). Smart grid standards for home and building automation. *Power System Technology (POWERCON), 2012 IEEE International Conference on,* 6, 1-6.

Tightiz, L., and Yang, H. (2020). A Comprehensive Review on IoT Protocols' Features in Smart Grid Communication. *Energies,* 13(11), 2762.

Ullah, R., Faheem, Y., and Kim, B.-S. (2017). Energy and congestion-aware routing metric for smart grid AMI networks in smart city. *IEEE Access,* 5, 13799-13810.

Urkowitz, H. (1967). Energy detection of unknown deterministic signals. *Proceedings of the IEEE,* 55(4), 523-531.

Varga, A. (2010). OMNeT++. In *Modeling and tools for network simulation, Springer,* 18(2), 35-59).

Wan, J., Tang, S., Shu, Z., Li, D., Wang, S., Imran, M., et al. (2016). Software-defined industrial internet of things in the context of industry 4.0. *IEEE Sensors Journal,* 16(20), 7373-7380.

Wang, S.-Y., Chou, C.-L., and Yang, C.-M. (2013). EstiNet openflow network simulator and emulator. *IEEE Communications Magazine,* 51(9), 110-117.

Wood, D. A. (2020). Predicting stability of a decentralized power grid linking electricity price formulation to grid frequency applying an optimized data-matching learning network to simulated data. *Technology and Economics of Smart Grids and Sustainable Energy,* 5(1), 1-21.

Wu, Y., Liu, K. S., Stankovic, J. A., He, T., and Lin, S. (2016). Efficient multichannel communications in wireless sensor networks. *ACM Transactions on Sensor Networks (TOSN),* 12(1), 1-23.

Xiang, Y., Hu, S., Liu, Y., Zhang, X., and Liu, J. (2019). Electric vehicles in smart grid: a survey on charging load modelling. *IET Smart Grid,* 2(1), 25-33.

Xin, Y., Zhang, B., Zhai, M., Li, Q., and Zhou, H. (2018). A smarter grid operation: new energy management systems in China. *IEEE Power and Energy Magazine,* 16(2), 36-45.

Xing, L., Mishra, Y., Tian, Y.-C., Ledwich, G., Zhou, C., Du, W., et al. (2019). Distributed state-of-charge balance control with event-triggered signal transmissions for multiple energy storage systems in smart grid. *IEEE Transactions on Systems, Man, and Cybernetics: Systems,* 49(8), 1601-1611.

Xue, X., Sun, W., Wang, J., Li, Q., Luo, G., and Yu, K. (2020). RVFL-LQP: RVFL-Based Link Quality Prediction of Wireless Sensor Networks in Smart Grid. *IEEE Access,* 8, 7829-7841.

Yadav, K., Bhowmick, A., Roy, S. D., and Kundu, S. (2019). Spectrum Sensing in Cognitive Radio Networks Under Security Threats and Hybrid Spectrum

Access. In *Cognitive Radio, Mobile Communications and Wireless Networks,* 8(1), 187-207).

Yang, M., Li, Y., Liu, X., and Tang, W. (2015). Cyclostationary feature detection based spectrum sensing algorithm under complicated electromagnetic environment in cognitive radio networks. *China Communications,* 12(9), 35-44.

Yang, Z., Han, R., Chen, Y., and Wang, X. (2018). Green-RPL: an energy-efficient protocol for cognitive radio enabled AMI network in smart grid. *IEEE Access,* 6, 18335-18344.

Ye, F., Liang, Y., Zhang, H., Zhang, X., and Qian, Y. (2016). Design and analysis of a wireless monitoring network for transmission lines in smart grid. *Wireless Communications and Mobile Computing,* 16(10), 1209-1220.

Yigit, M., Boluk, P. S., and Gungor, V. C. (2019). A new efficient error control algorithm for wireless sensor networks in smart grid. *Computer Standards & Interfaces,* 63, 27-42.

Yigit, M., Gungor, V. C., Fadel, E., Nassef, L., Akkari, N., and Akyildiz, I. F. (2016). Channel-aware routing and priority-aware multi-channel scheduling for WSN-based smart grid applications. *Journal of Network and Computer Applications,* 71, 50-58.

Yigit, M., Gungor, V. C., Tuna, G., Rangoussi, M., and Fadel, E. (2014a). Power line communication technologies for smart grid applications: A review of advances and challenges. *Computer Networks,* 70, 366-383.

Yigit, M., Incel, O. D., and Gungor, V. C. (2014b). On the interdependency between multi-channel scheduling and tree-based routing for WSNs in smart grid environments. *Computer Networks,* 65, 1-20.

Yu, J., and Zhang, X. (2015). A cross-layer wireless sensor network energy-efficient communication protocol for real-time monitoring of the long-distance electric transmission lines. *Journal of Sensors,* 115(1), 1-13.

Zhang, D., Chen, Z., Ren, J., Zhang, N., Awad, M. K., Zhou, H., et al. (2016). Energy-harvesting-aided spectrum sensing and data transmission in heterogeneous cognitive radio sensor network. *IEEE Transactions on Vehicular Technology,* 66(1), 831-843.

Zhang, F., Luo, F., Dong, Z., Liu, Y., and Ranzi, G. (2020). Hierarchical energy management scheme for residential communities under grid outage event. *IET Smart Grid*, 3(2), 174-181.

Zhang, L., Chen, H., Martin, K., Faris, A., Vutsinas, M., Bradberry, T., et al. (2017). Successful deployment and operational experience of using linear state estimator in wide-area monitoring and situational awareness projects. *IET Generation, Transmission & Distribution*, 11(18), 4476-4483.

Zhou, G.-P., Luo, H.-H., Ge, W.-C., Ma, Y.-L., Qiu, S., and Fu, L.-N. (2019). Design and application of condition monitoring for power transmission and transformation equipment based on smart grid dispatching control system. *Journal of Engineering*, 20(16), 2817-2821.

# LIST OF PUBLICATIONS

## Indexed Journal with Impact Factors

1. **Faheem, Muhammad,** Md A. Ngadi, Syed Bilal Hussain Shah, Rizwan Aslam Butt, Basit Raza, Muhammad Anwar, Muhammad Waqar Ashraf, and Vehbi C. Gungor (2018). Smart grid communication and information technologies in the perspective of Industry 4.0: Opportunities and challenges. *Computer Science Review*, 30 (2), 1-30. **(Q1, IF: 7.707)**
2. **Faheem, Muhammad,** Md A. Ngadi, Rizwan Aslam Butt, Basit Raza, Muhammad Waqar Ashraf, and Vehbi Cagri Gungor (2019). A multi-channel distributed routing scheme for smart grid real-time critical event monitoring applications in the perspective of Industry 4.0. *International Journal of Ad Hoc and Ubiquitous Computing*, 32 (4), 236-256. **(Q4, IF: 0.722)**

## Indexed Conference Proceedings

1. **Faheem, Muhammad,** Md A. Ngadi, Muhammad Umar, Rizwan Aslam Butt, Basit Raza, and Vehbi Cagri Gungor (2019). Software Defined Communication Framework for Smart Grid to Meet Energy Demands in Smart Cities. *7th International Istanbul Smart Grids and Cities Congress and Fair (ICSG)*, 7, 51-55. **(Indexed by Web of Science)**