

CRSN Energy-Efficient Mechanism Based on Dynamic Spectrum Access and Asynchronous Sleep-Wake Scheduling

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Declaration

I Koketso Keoagile Ntshabele declare that this project “**CRSN Energy-Efficient Mechanism Based on Dynamic Spectrum Access and Asynchronous Sleep-Wake Scheduling**” is my work carried out at the North-West University, Mafikeng Campus and has not been submitted in any form for the award of a degree to any other university or institution of tertiary education or published earlier. All the material used as source of information has been duly acknowledged in the text and in the references.

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Dedication

I dedicate this research to my beloved Ntshabele family, my siblings, my mother Mrs. K.T. Ntshabele and my late father Mr. N.R. Ntshabele, for the support and sacrifices they have invested in my studies.

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Abstract

Cognitive Radio Sensor Network (CRSN) is considered as a viable wireless networking paradigm solution to address the issues of spectrum underutilization and uncontrollable interferences in Wireless Sensor Network (WSN) due to wireless sensor devices proliferation. However, CRSN itself is the technology is faced with several challenges such as interference in the wireless channels, operational complexities, poor Quality of Service (QoS), and high energy consumption. These challenges are mainly inherited from both the Cognitive Radio (CR) and the WSN. In particular, the high energy consumption is due to wireless nodes performing channel sensing and switching, data transmission and re-transmission due to packet loss. Therefore, an energy-efficient mechanism is required to ensure that sensor nodes are not crippled by fast energy depletion.

This is addressed in this research by employing two strategies: Sensor-Medium Access Control (S-MAC) protocol and the K-Means clustering algorithm. These strategies are designed and implemented in the CRSN to improve the existing energy-aware mechanism and to minimize high energy consumption. K-Means clustering reduces the overall network complexities by partitioning the network into sub-networks while the S-MAC protocol proffers periodic and asynchronous data transmission and sleep-wake cycles to control the flow of data and reduce interferences in the network.

To evaluate the performance and effectiveness of the solution, simulations were conducted on six S-MAC's duty cycles of 3%, 5%, 10%, 15%, 25%, and 50% and assessed using metrics such as throughput, average consumed energy, residual energy and delay. The simulation results show the higher attainable efficiency for 10% S-MAC's duty in all six metrics than the other simulated duty cycles considered. Based on the simulations conducted, the 10% duty has the highest attainable efficiency due to the minimized duty cycle, and this lead to selecting it for the best possible implementation of an energy-efficient mechanism in a real world CRSN.

Keywords: *WSN, CR, CRSN, Energy, Efficiency, Interference, Periodic, Spectrum, Channel, Primary user, Secondary user, Base station, Asynchronous, K-Means, S-MAC, Duty cycles, Clustering.*

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List of Acronyms

ACK	Acknowledgement
AWK	Aho, Weinberger, and Kernighan
CH	Cluster Head
CM	Cluster Member
CR	Cognitive Radio
CRSN	Cognitive Radio Sensor Network
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTS	Clear To Send
CRWSN	Cognitive Radio Wireless Sensor Network
CWPCN	Cognitive Wireless Powered Communication Network
WPCN	Wireless Powered Communication Network
CogLEACH-C	Cognitive C Centralized Low Energy Adaptive Clustering Hierarchy
CSAC	Centralized Spectrum Aware Clustering
C_{sn}	Cognitive Sensor Nodes
CSNA	Cognitive Sensor Node Awareness
DSAC	Distributed Spectrum Aware Clustering
D_{FRAG}	Data Fragment
D_T	Data transmission Time
DSRA	Data Sensor Resource Allocation
D2D	Device-to-Device
DSA	Dynamic Spectrum Access
DCA	Distributed Control Algorithm
DEEC	Distributed Energy-Efficient Clustering
ECR	Energy and Cognitive Radio
EH	Energy Harvesting
IEEE	Industrial, Engineering
E_o	Overall Energy
E_c	Clustering Energy
E_s	Sleeping Energy
E_L	Listening Energy

E_R	Receiving Energy
E_T	Transmitting Energy
E_{mode}	Mode Energy
E_{RES}	Residual Energy
E_{SYNC}	Synchronization Energy
E_{RTS}	Request-to-Send Packet Energy
E_{CTS}	Clear-to-Send Packet Energy
E_{SHARE}	Channel Sharing Energy
E_{CHAN}	Channeling Energy
EHCRSNs	Energy Harvesting Cognitive Radio Sensor Networks
HCRSN	Harvesting Cognitive Radio Sensor Network
F_{SEQ}	Fragment Sequence
HEED	Hybrid Energy-Efficient Distributed Clustering
ISM	Industrial, Scientific and Medical
IoT	Internet of Things
I_{sleep}	Sleeping Current
I_{wake}	Waking Current
I	Current
LEACH	Low Energy Adaptive Clustering Hierarchy
LEACH-C	Centralized Low Energy Adaptive Clustering Hierarchy
MAC	Medium Access Control
NS-2	Network Simulator Version 2
PSNR	Peak Signal to Noise Ratio
P	Power
PU	Primary User
PSA	Prioritized Spectrum Access
PEGASIS	Power-Efficient Gathering in Sensor Information System Protocol
QoS	Quality of Service
RF	Radio Frequency
SACRB-MAC	Spectrum Aggregation Cognitive Receiver-Based Medium Access Control
SSS	Spectrum Sensor Scheduling
RSA	Random Spectrum Access

RTS	Request To Send
SCEEM	Spectrum Aware Cluster based Energy Efficient Multimedia
S-MAC	Sensor-Medium Access Control
SU	Secondary User
SEP	Stable Election Protocol
TDMA	Time Division Multiple Access
T_{wake}	Wake Time
T_{sleep}	Sleep Time
T_c	Clustering Time
P_{RTS}	Request-to-Send Packet
P_{CTS}	Clear-to-Send Packet
P_{SWITCH}	Switching Power
V	Voltage
WIT	Wireless Information Transmission
WET	Wireless Energy Transfer
WSN	Wireless Sensor Networks

Definition of Concepts

WSN: Wireless Sensor Network (WSN) is a wireless networking paradigm composed of a plethora of battery powered wireless sensor nodes distributed in a geographical location to relay communicated data between the sender and receiver using the wireless channel. The wireless sensors suffer from fast energy depletion as they are battery powered [1-12].

CR: Cognitive Radio (CR) is a networking paradigm proposed to act intelligently by allowing the wireless sensors nodes to select the channel of choice for their transmission [6-12].

CRSN: Cognitive Radio Sensor Network (CRSN) is a wireless networking paradigm produced by the amalgamation of WSN and CR to circumvent the spectrum underutilization and uncontrollable interferences caused by WSN due to the proliferation of wireless devices in the wireless channel. CRSN proffers other benefits such as alleviated high energy consumptions, improved QoS and throughput to name a few [1, 6-12].

Asynchronous: Asynchronous refers to operations not occurring at the same due to the scheduled time slots [12-16].

Duty-Cycle: Duty-cycle in networking refers to devices having different transmission and no-transmission time slots to reduce unnecessary collisions and packet re-transmissions [17-19].

K-Means: The K-Means is an ad-hoc unsupervised clustering algorithm that groups the nodes in the networking depending on their similar characteristics. It groups the nodes using a Euclidean distance by choosing the K-centroid(s) and calculating the distance between the nodes and centroid and nodes will be grouped to the nearest centroid [20-23].

S-MAC: The Sensor-Medium Access Control (S-MAC) is a MAC protocol that follows periodic sleep-wake duty cycles where nodes synchronize with their neighbors to share their scheduling tables [17-19].

DSA: Dynamic Spectrum Access (DSA) is a wireless channeling mechanism proposed to circumvent unwanted interferences by allowing cognitive nodes to utilize the licensed channel for transmission in the absence of licensed (primary) users and vacate the channel when licensed users re-appear in the channel [7, 9-12].

Secondary Users: SUs (Secondary users (SUs) are also referred to as cognitive users. These users only utilize the unlicensed channel for their channel but can switch to the licensed channel in the absence of the licensed users and vacate the channel when the licensed users re-appear. This is made possible by DSA mechanism [1, 6-12].

Primary Users: Primary users (PUs) are also referred to as licensed users. These users are equipped with the privileges of transmitting in the licensed channel anytime they wish to [1, 6-12].

Clustering: Clustering refers to grouping the nodes together in smaller groups by partitioning the network to reduce complexities [3, 24, 25].

Spectrum: The spectrum refers to the channels used by devices for transmissions. The spectrum differs in range in terms of the wavelength and the application or the type of the data transmitted [8-12].

Chapter 1

Introduction

1.1 Background

A WSN is an event-driven and ad-hoc wireless communication paradigm operating in the unlicensed Industrial, Scientific and Medical (ISM) radio bands, which is a shared resource [10, 26] with other communication technologies. The technology is made up of plethora of sensor nodes relaying data via the gateway or directly via the Internet [26-28]. However, these wireless sensors are battery-powered and equipped with monitoring capabilities [29], hence energy preservation to sustain a battery life is a challenge. Moreover, the ISM coexistence can downgrade the WSN's performance due to uncontrollable interference that leads to large amounts of power being consumed, wide deployments and large IEEE 802.11 devices network coverage range when overlapping occurs in frequency bands [26].

CR is considered the next promising generation of wireless communication paradigm and an *ad hoc* network to overcome the WSN's challenges of spectrum underutilization [10, 26]. CR is a technique that has the capabilities of understanding its environment and acting upon it through different phases, namely: perceiving, planning, reasoning, acting, continuously and autonomously learning through upgrading and updating the studied history [26]. The amalgamation of WSNs and CR has manifested in a new wireless networking paradigm called CRSN. The amalgamation was to address the challenges inherent in WSN; however, CRSN itself is not exempted from those challenges. CRSN is also faced with the challenge of energy inefficiency rendered by WSN performing CR capabilities [10]. That is, a considerable amount of energy is consumed, which affects the smooth operations of the technology, hence studies should be conducted for channel accessing to improve energy efficiency in CRSNs [7].

Therefore, to address this challenge and minimize the rate of energy consumption of existing energy-aware mechanism while maintaining the adhoc nature and dynamism of CRSN, this research seeks to implement the traditional K-Means clustering to reduce network complexities which might lead to high energy consumptions. It also implements S-MAC protocol with different duty cycles to allow comparing with the traditional Medium Access

Control (MAC) protocol implemented in existing energy-aware mechanisms. The S-MAC protocol reduces energy consumption through wireless sensor nodes periodic sleep-wake duty cycle. This avoid repetitive wake ups, and implement node auto-synchronization where sensor nodes perform Dynamic Spectrum Access (DSA) only in the scheduling and listening phase[30]. The S-MAC is also reducing contention latency for WSN applications by the process of store and forward before data transmission in a network.

With the benefits to be offered by the proposed scheme in this research, the anticipated results are to show the decrease in the total energy consumed by the wireless sensor nodes.

1.2 Problem Statement

WSN utilizes the unlicensed ISM radio bands as a shared resource [8, 10, 26, 31, 32] for communication. However, the proliferation of wireless sensor nodes affects the overall WSNs performance due to congested network leading to uncontrollable interference and high energy consumption [28]. CR emerged as a viable and effective solution to address the challenges in WSN to sustain its lifespan and improve QoS [7, 12, 33, 34]. The challenges are inherited from both WSNs and CRs [35] due to the nature of wireless sensor nodes being battery-powered and implemented with CR capabilities that occur simultaneously. Ashraf *et al.* [36], also stated that retransmission of packets in the specified spectrum due to packet loss is also another energy inefficiency factor that affects network performance [26].

To address this challenge, DSA [7, 10, 12, 37] has been proposed as a channelling mechanism that permits cognitive wireless sensor nodes to dynamically access the idling licensed spectrum bands and utilize the bands without causing any interference that leads to poor QoS [7, 12]. Other energy-aware approaches to improve DSA efficiency included clustered CRSN [7, 12, 35, 38, 39], involving both intra-cluster and inter-cluster data transmissions [7, 12], and the sleep-wake approach [12, 40], which equips cognitive radios with capabilities to control data transmission flow between the wireless sensor nodes and base stations to avoid fast energy depletion of battery-powered sensor nodes. However, these proposed schemes provide limited energy efficiency and performing channel sensing still remains a repetitive process for wireless sensor nodes, which consumes a considerable amount of energy if all the wireless sensor nodes are equipped with channel sensing capabilities [7, 12, 33].

Given the critical context, this research addresses the aforementioned energy inefficiency challenge and extends the work by Akhila *et al.* [12]. To this end, two protocols are implemented. The first is the implementation of a contention-based carrier sense multiple access/collision avoidance (CSMA/CA) S-MAC protocol, which is an energy-aware protocol supporting asynchronous sleep-wake scheduling. It proffers DSA through neighbour node awareness and the use of Request To Send (RTS), Clear To Send (CTS) and acknowledgement (ACK) packets between the sender and the receiver to reduce interference when wake nodes are in scheduling and listening phase to avoid uncontrollable interference [30]. The second is the use of a traditional K-Means clustering algorithm. This algorithm groups the sensor nodes based on nearby distances to the chosen cluster head in order to avoid unnecessary long transmissions to distant nodes, as this could deplete the node energy quickly due to the fact that the distant node might not be wishing to communicate at that point in time, or more data retransmission might occur due to packet loss.

1.3 Research Questions

The research attempts to answer the following questions:

RQ1: What are the factors that contribute to energy-inefficiency in CRSNs and their impacts in CRSN?

To answer RQ1, the following sub-questions will be addressed:

RQ1.1 How do the clusters improve energy efficiency in CRSNs?

RQ1.2: How does DSA manage the uncontrollable interference in CRSNs?

RQ1.3: How does Sleep-Wake scheduling mechanism reduce energy consumption in clustered CRSN?

To answer the above RQ1, comprehensive research was conducted as an ongoing task to have an insight into the outlined aspects. A comprehensive literature review is presented in Chapter 2.

RQ2: How can we design and develop an improved energy-efficient mechanism in clustered CRSNs?

To design and develop the proposed energy-efficient CRSN mechanism, relevant tools are critical. These tools are the simulation tools that support CR capabilities, clustering, DSA algorithm, and S-MAC protocol that will support asynchronous sleep-wake scheduling. The design and development is reported in Chapter 4.

RQ3: How can the proposed energy-efficient CRSN mechanism performance be assessed?

Upon completion of the design and development stage in Chapter 4 according to the desired objective(s), then follows the simulations to collect the data used for performance and effectiveness assessment phase in Chapter 5. Six different S-MAC duty cycles (3%, 5%, 10%, 15%, 25% and 50%) were simulated and the most energy efficient duty cycle was chosen to complete and conclude the proposed energy-efficient CRSN mechanism.

To satisfy all the outlined objectives that were used as an attempt in answering the research questions the research methodology outlined in chapter 3 was followed.

1.4 Research Goal

The aim of this research was to design and develop an energy-efficient CRSN mechanism to reduce network complexities and high energy consumption.

1.5 Research Objectives

To achieve the main aim of this research, the following objectives were carried out:

RO1: Gain insights into clusters in CRSNs, studying in-depth the DSA implementation in CRSNs and the sleep-wake scheduling mechanism.

RO2: Improving the existing energy-efficient mechanism(s) by developing and designing an energy efficient mechanism with a cluster algorithm that supports the dynamism of CRSNs and the asynchronous sleep-wake scheduling mechanism to control data flow in the network and avoid unnecessary interference using DSA. It involves also designing both mathematical and system models.

RO3: Conducting simulations for data collection to assess the proposed energy-efficient mechanism effectiveness and performance.

1.6 Research Justification

CRSN, which emerged as a promising paradigm to circumvent the WSN issues, still suffers from energy inefficiency and spectrum interferences caused by the amalgamation of WSN and CR. However, this research proposes a new protocol, which is less complex and satisfies the outlined objectives. An energy-efficient CRSN mechanism is proposed to improve existing energy-aware CRSNs. The proposed energy-efficient CRSN mechanism reduces the networks complexities by deploying a traditional K-Means clustering algorithm, and to

regulate data transmission and channel accessing periods, an S-MAC protocol is deployed with a minimized duty cycle to avoid lengthy sleeping periods of cognitive nodes. Neighbor node awareness is also integrated in S-MAC to reduce interferences within wake transmitting Secondary Users (SUs). Interferences are also reduced between the Primary Users (PUs) and the SUs by deploying a fixed channeling scheme for PUs, where this scheme allocates a specific channel to PUs and restricts the SUs use of it.

1.7 Research Contribution

In the existing literature, the majority of research uses the traditional 802.11 MAC protocol, which provides less support of ad hoc operations such as sleep-wake scheduling and the dynamism of CRSN. However, designing such ad hoc mechanism with traditional 802.11 MAC protocol requires more operational implementations, which can result in complexities to manage the network.

As a contribution to knowledge in this research, a contention collision avoidance based energy-efficient mechanism with periodic/asynchronous sleep-wake scheduling in a clustered CRSN is proposed and designed. This proposed mechanism will yield a new protocol which will be tested to determine its support CRSN dynamism with minimized complexities while performing according to the outlined objectives. The proposed mechanism is based on combining S-MAC and K-Means, since this has not been before, to the best of our knowledge. The K-Means algorithm will partition the network into sub-networks to reduce network complexities and high energy consumptions, while the S-MAC protocol will control data flow and reduce interferences. These protocols are ad-hoc and energy-aware protocols that support CRSN dynamism, with less complexity, and simple implementation while yet minimizing high energy consumptions when used together. Moreover, in the existing works by other researchers, these protocols were implemented individually, especially in the perspective of WSN, as the implementation in CRSN needs additional components to function to its peak.

1.8 Methods of Investigation

A constructive research methodology is used in this research, aiming to produce new knowledge by providing a novel solution to a practically identified existing problem. The research method(s) are very critical in any research to answer the research questions. In this case, research methods are to be chosen and research design followed which is consistent

with the chosen research methods. A research design in this research will be used as a blueprint outlining how the identified problem shall be addressed by achieving the desired objectives. The research methods suitable for this research are: comprehensive literature review, formal methods, model design and simulations.

Detailed research methodology and design is discussed in Chapter 3.

1.9 Research Scope and Limitations

This research is strictly based on developing and designing the proposed energy-efficient CRSN mechanism implementing K-Means clustering and S-MAC protocol. The K-Means clustering is implemented with static cluster-head selection to partition the network into sub-networks, to reduce overall network complexities and implementation. The S-MAC supports asynchronous sleep-wake scheduling and DSA using neighbor node awareness. Fixed channel allocation and access of PUs is also deployed. However, this research does not consider designing new or improving cluster head selection algorithms, and dynamic duty cycle, as these can be proposed as a future work.

1.10 Research Organization

The remaining chapters of this research are:

Chapter 2: Literature Review: This chapter discusses in detail WSNs, CRs, CRSNs, their technologies and architectures, and some of the commonly used WSN energy-efficient clustering protocol and their architectures. Furthermore, the related works is also part of the discussion.

Chapter 3: Research Methodology and Design: Detailed discussion of the proposed constructive research methodology with mixed methods and research design approaches that will be followed to carry out this research.

Chapter 4: CRSN Energy-Efficient Framework: This chapter covers the full detailed development and design of the proposed energy-efficient CRSN. The design is also based on mathematical and system modelling.

Chapter 5: Results Analysis and Discussion: Following Chapter 4, simulations are conducted to collect the data to be used for assessing the performance and effectiveness of the proposed mechanism. Moreover, the extent to which the energy efficiency has been improved in existing mechanisms is discussed.

Chapter 6: Summary, Conclusion, Recommendations and Future Work: The work conducted in this research is summarized and concluded in Chapter 6 provided all the outlined objectives are met. Further recommendations and future work outline the aspects that can be improved in the proposed energy-efficient clustered CRSN mechanism.

1.11 Research Outputs

1. First review paper is published based on energy-inefficiencies affecting CRSN detailed as K. Ntshabele, B. Isong, N. Dladlu, and A. M. Abu-Mahfouz, "Analysis of Energy Inefficiency Challenges in Cognitive Radio Sensor Networks," in *IECON 2018-44th Annual Conference of the IEEE Industrial Electronics Society*, 2018, pp. 4699-4705.
2. Second review paper is published based on surveying energy consumption challenges in clustered CRSN detailed as K. Ntshabele, B. Isong, N. Dladlu, and A. M. Abu-Mahfouz, "Energy Consumption Challenges in Clustered Cognitive Radio Sensor Networks: A Review," in *2019 IEEE 28th International Symposium on Industrial Electronics (ISIE)*, 2019, pp. 1294-1299.
3. Journal paper titled "Energy-efficient for CRSNs mechanism based on Dynamic Spectrum Access" is being reviewed, pending submission.

1.12 Chapter Summary

In this Chapter, we have introduced the concept of CRSN and identified the existing practical problem that we are trying to solve in this research. The research goal is also discussed. Furthermore, the justification for conducting this research is discussed. The research limitations to narrow the scope are also discussed. Moreover, the research methodology to solve the outlined problem is discussed, but directed to Chapter 3, section 3.3 for full discussion. Furthermore, the research outline and the research outputs are given.

Chapter 2

Literature Review

2.1 Chapter Outline

This Chapter discusses the concept of wireless sensor networks, cognitive radio and the deployment of cognitive radio sensor networks with their general topology architectures. The discussion continues to clustering in cognitive radio sensor networks with its topology. Moreover, the sleep wake scheduling is also discussed. Furthermore, different energy-efficient clustering algorithms in WSN are discussed. The related works are also discussed in this chapter. The last section is the chapter summary.

2.2 Wireless Sensor Networks

WSN emerged as a paradigm in wireless communication as a research interest for both academics and industry [28, 29]. Communication occurs as event driven in WSN [26], and the existing plethora of sensor nodes are limited to a few meters and are responsible for perceiving their environment and relaying data for communication in a real-world application [26, 28]. WSN in another context is referred to as an intelligent distributed measurement paradigm requisite for a variety of control and monitoring events [41]. These wireless sensors are battery-powered [41] equipped with the ability to monitor parameters such as temperature, pressure, humidity, wind speed and direction, etc. [29, 41], where communications are carried out in a fixed and unlicensed spectrum band. This technology possesses an ad hoc network implementation where there is less human intervention or central management [29]. Moreover, the use of WSN is beneficial in various aspects, to name a few; in the military, industries, Internet of Things (IoT) utilized in smart trends [28, 29]. Moreover, due to the nature of WSN, several challenges are inevitable, such as uncontrollable interference due to the proliferation of newly developed wireless devices which enlarges the network in size, and this might affect the Quality of Service (QoS) of the network, high energy and bandwidth consumption, data processing and compressing methods, QoS and a host of other challenges [1,5].

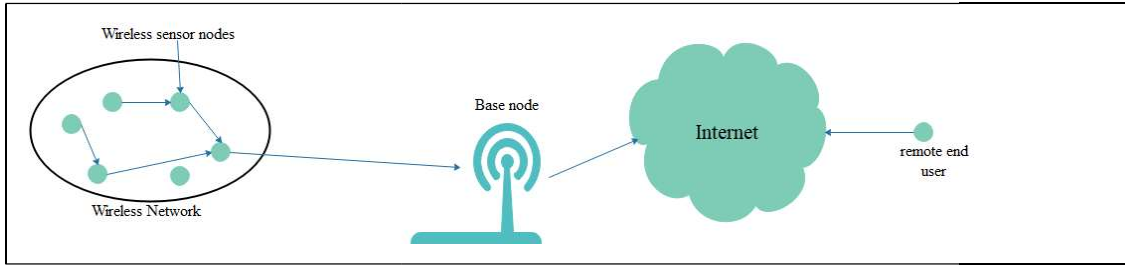


Figure 2.1: A Typical WSN Model

As depicted by figure 2.1 above, the WSN key components are the internet acting as the medium to share the data across the networks, the sensor nodes and the sink nodes are both equipped with transceivers and microprocessors [41]. With these nodes being battery powered, the WSN faces challenges of rapid energy consumption due to the restrictions of battery recharge or replacements caused by the environmental nature where nodes are deployed [41]. With WSN facing rapid energy consumptions, this challenge affects networks, which have high Quality of Service (QoS) and long network lifespan [41]. Different energy aware scavenging approaches such as piezoelectric, solar panel and acoustic transducers are used to recharge the sensor batteries; but this does not change the fact that energy is a scarce and limited resource that requires strategic mechanisms at the wireless nodes to extend the network lifespan [41].

2.3 Cognitive Radio

CR emerged as a next generation wireless communication paradigm and an *ad hoc* network to overcome the challenges of spectrum underutilization and spectrum congestion in licensed and free spectrum bands. CR make use of free spectrum opportunistically to provide efficient operations [42], having the ability to understand its environment and act upon it through different phases such as perceiving, planning, reasoning, acting, continuously and autonomously learning through upgrading and updating the studied history [26]. CR network is composed of two participants, the PU operating in the licensed spectrum band and the SU operating in the unlicensed spectrum band but with CR capabilities equipped in it, SU can switch to the licensed band in the absence of PU and vacate when PU reappears [8, 26, 28, 43, 44]. The CR provides the following capabilities;

- *Spectrum Sensing*: The ability SUs have to sense the spectrum for idling licensed bands, then switch to those bands for transmission in the absence of PUs [8, 44].

- *Spectrum Decision*: The SUs are capable of switching to the idling licensed bands of choice, based on adjusting operational parameters to allow data transmission [8].
- *Spectrum Sharing*: The CR capability equipped in SUs to allow them to autonomously occupy the licensed spectrum band without causing unwanted interference to the PUs [8].
- *Spectrum Mobility*: The CR capability that allows the SUs to vacate from the utilized licensed spectrum in the event of PU reappearance [8].

2.4 Cognitive Radio Sensor Network

CR is a new paradigm specifically proposed to overcome spectrum underutilization in WSN, but it can still be used for reducing spectrum bands congestion [7]. CRSNs, the specialized *ad-hoc* networks, are the recent wireless networking technology formed by incorporating CR into WSN [26] where CRSNs operate on distributed sensor nodes with CR functionalities [26, 45, 46] and other functionalities such as prediction, fairness, packet routing, reconfiguration, trust and security, power control and so on. Thus, the merging is aimed at overcoming the spectrum underutilization in WSN [47]. CRSNs constitute distributed networks made of wireless with CR functionalities [26, 45, 46] and others such as prediction, fairness, packet routing, reconfiguration, trust and security, power control and so on, and autonomously communicating the sensory readings dynamically over shared spectrum bands using multi-hops to route the data to the desired destination, until all application specific requirements are met [43].

CRSNs exploit the capabilities of both WSN and CR to provide much more efficient wireless networks. They are not only designed to overcome the spectrum underutilization in WSN, but also to address CRSNs challenges such as processing and communication demands, and multi-hop accessing schemes over unlicensed and licensed spectrum bands [10]. Other potential benefits are improved spectrum efficiency, enhanced transmission and ease of communication amongst heterogeneous WSNs [10]. The deployment of CRSNs provides lots of benefits such as better operating or power/energy efficiency to sustain the wireless sensor nodes battery life time [7, 12]. With the energy constraint faced by WSN to perform CR capabilities [10], it is vital that the lifespan of wireless sensor nodes be sustained, since the network operates autonomously without human intervention or any central management.

2.4.1 CRSN Topology Architecture

CRSN architecture is made up of the following components: the base station, sink, PU and the SU [3, 13, 14, 15]. In both PU and SU, data transmission occurs over an available spectrum in an opportunistic manner using hops and eventually to the sink node [43]. By utilizing CR capabilities, users and sink can exchange extra information such as spectrum allocations, spectrum hand-off aware route with relevance to specific topology and also control data used for group formations [43].

- *A base station:* A base station is a node which receives aggregated transmitted data from the sink node and further transmits the data to the users via the internet [26, 43].
- *A sink:* A sink is a wireless node which receives the transmitted sensor data from the sensor nodes and further transmits it to the base station via the internet [2, 26, 48]
- *PU:* The PU is a wireless device that has the capabilities of operating in a licensed ISM band when they want [26, 43].
- *SU:* The SU is a wireless device that only operates in an unlicensed ISM band but can switch to licensed bands provided it has the CR capabilities [26, 28].
- Both PU and SU are wireless nodes, their data transmission occurs over an available spectrum in an opportunistic manner using hops and eventually to the sink node [43]. Using CR capabilities, users and sink can exchange extra information such as spectrum allocations, spectrum hand-off aware route with relevance to specific topology and control data used for group formations [43].

The CRSN topology architecture is illustrated in figure 2.2 below.

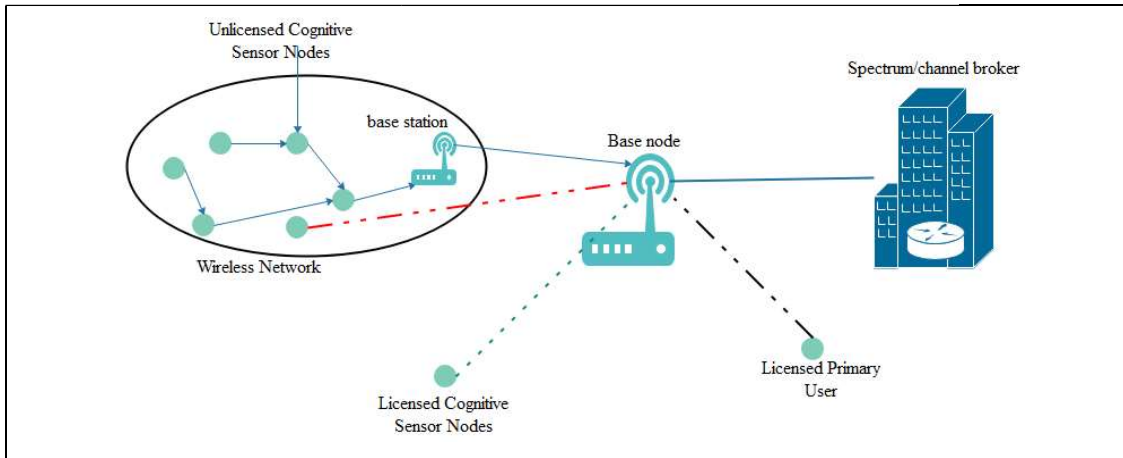


Figure 2.2: CRSN Topology Architecture

2.5 Clustering

The conventional clustering algorithms or protocols in the traditional WSNs are insufficient with regards to energy saving and reduction of operational complexities. However, clustering protocol is composed of layered protocols that partition the network into sub-networks. For a cluster topology, large networks can be partitioned into small networks called clusters where each cluster is made up of ordinary nodes called cluster members (CMs) and the leader is called the cluster head(CH) [39]. The operations of a cluster network are split into large number of data periods[12, 49]. The CMs are responsible for sensing the data on the geographical area they are situated on, and then the cluster heads are responsible for collecting the sensory data transmitted by the cluster members, and they then aggregate and relay the data further to the base station.

The selection of a specific CH is pre-selected by the cluster designer or the cluster sensors based on the specific cluster routing protocols, and the selection of the CH can be random or based on a sensor node with more resources [49]. The cluster head is also responsible for gathering cluster members information, then ensuring that resources such as idling and occupied channel, channel parameters etc. are acquired and broadcasted to the cluster members [7, 8, 12, 27]. The clustering topology data transmission is divided into two transmissions; inter-cluster data transmission which is used by the CH to relay aggregated data to the base station, and the intra-data transmission which is the transmission used by CMs to transmit data amongst other CMs and to the CH as well [12, 39, 43].

2.6 Clustering Topology Architecture in CRSN

The general clusters topology architecture of CRSN consists of a set of cognitive wireless sensor nodes that are distributed over a geographical area. These wireless sensor nodes are deployed in the specific geographical area to monitor the environment. The wireless sensor nodes form sub-networks called clusters, and each cluster is made up of cluster members and the cluster head [7, 12]. The clusters topology architecture is illustrated in figure 2.3.

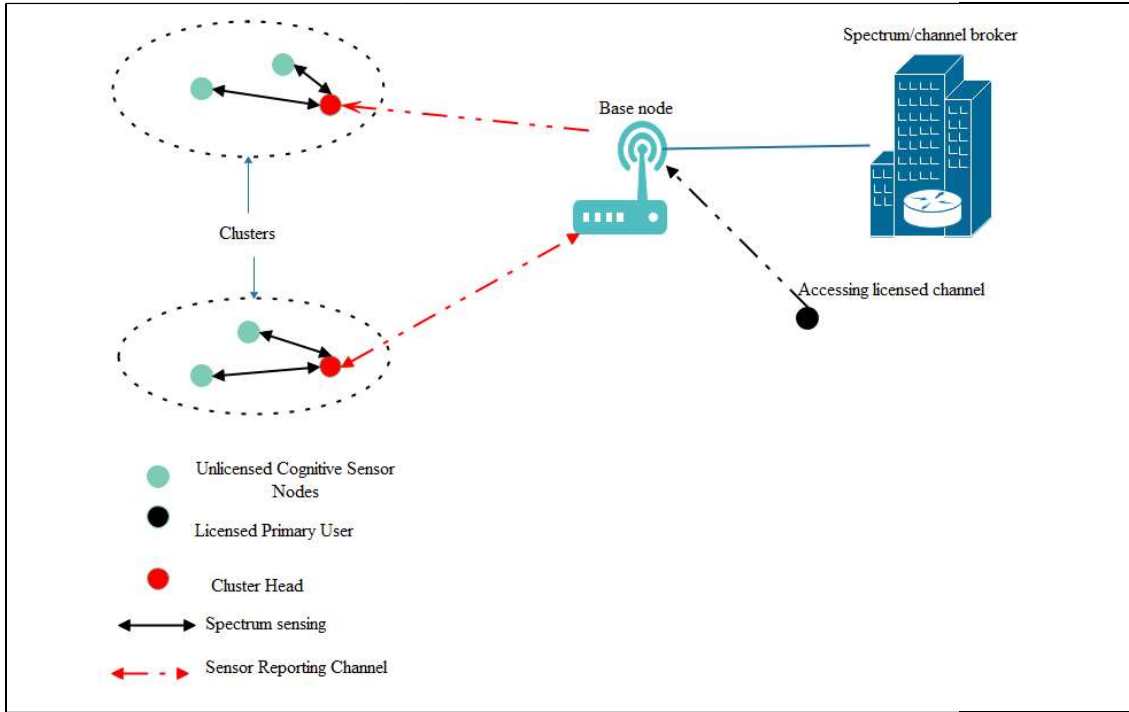


Figure 2.3: Clustering Topology Architecture in CRSN

2.7 Sleep Wake Scheduling Mechanism

A sleep wake scheduling mechanism can be regarded as an energy-aware mechanism that allows every cognitive radio sensor to intelligently switch between sleep and wake states with a probability m (the sleeping rate). This mechanism allows only nodes in wake mode to perform sensing and transmissions [12, 40, 49].

2.8 Energy Efficient Clustering Algorithms in WSNs

The traditional WSN clustering protocols are designed to obtain information with less energy consumption. However, these clustering protocols are not compatible with CRSNs, specifically the spectrum sensing scenario. The following are some of the most common clustering protocols implemented in CRSNs.

2.8.1 Low energy Adaptive Clustering Hierarchy (LEACH) [49-54]

The LEACH protocol was the first ever WSN clustering protocol to be designed, and it uses a single hop data transmission between the nodes and the base stations. The selection of cluster heads is based on the predetermined probability and energy drain, the CM will then join the nearby CH. LEACH protocol is composed of two phases; the set-up phase for cluster

formation, and the steady set-up phase which concerns the transmission of data between the nodes and the base station(s). The following formula is used for CH selection;

$$T(n) = \begin{cases} \frac{p}{1-(r \bmod \frac{1}{p})}, & \text{if } n \in G \\ 0, & \text{otherwise} \end{cases} \dots\dots\dots(2.1),$$

where r is the round for CH selection, p is the CH percentage, G is the group of the wireless sensor nodes not regarded as CHs in final rounds of $\frac{1}{p}$ and $T(n)$ is the threshold. The sensor nodes randomly choose numbers between 0 and 1, should the chosen number be less than $T(n)$ then the node will be elected as the CH. In the next round of CH selection, nodes that are CMs in the previous round qualify to be the next CHs as there are no specific chosen CHs. Time Division Multiple Access (TDMA) is used by CH to transmit data to its CMs to avoid collisions.

2.8.2 Centralized Low energy Adaptive Clustering Hierarchy (LEACH-C) [50, 55, 56]

The LEACH-C protocol is the extension of the traditional LEACH protocol but a centralized control procedure introduced by Heinzelman and other students. The LEACH-C protocol nearly performs the same way as the LEACH protocol; however, the major difference is that in the LEACH-C the CH selection is performed by the base station whereas in LEACH the CH selection is randomly performed by sensor nodes. In the state phase of LEACH-C, the base stations gain information of the sensor nodes locations and residual energies, then the base station uses that information to select the appropriate CH, then afterwards associates the sensor nodes with the relevant chosen CH. The implementation of LEACH-C shows no superiority against the LEACH; this is based on the fact that LEACH-C protocol has more complexities due to the centrality control at the base stations which carries out all the operations.

2.8.3 Hybrid Energy-Efficient Distributed Clustering (HEED) [49, 50, 53]

The HEED protocol is based on cluster head selection by selecting a sensor node with more neighbouring nodes and residual energy. This protocol is designed to balance overall energy consumption and main efficient cluster formation and CH selection. During cluster formation, a sensor node generates a “hello” message and sends it across a network to discover information about its neighbours, then upon choosing a CH, the sensor node(s)/CM will join the suitable CH depending on different transmission ranges [50]. The CH is chosen based on the following:

$$CH_{prob} = C_{prob} \frac{E_r}{E_{max}} \dots\dots\dots (2.2),$$

where E_r is the node residual energy, E_{max} is the node maximum energy, C_{prob} is the CHs percentage amongst all wireless sensor nodes[50]. The value of CH_{prob} should always be above the given threshold.

2.8.4 Power-Efficient Gathering in Sensor Information System Protocol (PEGASIS) [50, 53, 54, 57, 58]

The PEGASIS protocol is another type of a clustering that improves the traditional LEACH protocol. However, PEGASIS uses chains and the sensor nodes connect with their neighbouring nodes only, and the sensor nodes in the chains where the data is transmitted to the base stations for every round, to alleviate energy consumptions. The use of chain formation by PEGASIS allows routing to occur in multi-hops rather than using multiple sensor nodes as in LEACH protocol. With sensor nodes only connecting to neighbouring nodes, the key component is the signal strength of neighbours to calculate the distance to allow allocating the closest sensor node. The CH are only selected after chain formation, where this CH steps in as the gateway between its respective chain and the base station.

2.8.5 Distributed Energy-Efficient Clustering (DEEC) [49, 50]

The DEEC protocol was designed to support heterogeneous networks. The DEEC protocol performs the CH selection using the wireless sensor nodes with more initial energy and residual energy. To select a CH, the energy information of each sensor node needs to be known across the entire network.

2.8.6 Stable Election Protocol (SEP) [49, 53]

The SEP protocol was designed to support heterogeneous networks and to extend the time interval before the complete energy depletion of the first sensor node. The selection of the CH is based on distinguishing the normal sensor nodes and advanced sensor nodes.

2.8.7 K-Means Clustering [20-23]

The K-Means clustering protocol is designed to partition the network into sub-networks or *K-clusters* given a set of sensor nodes ($S_1, \dots, S_n$) where the sensor nodes will belong to the nearest cluster with the nearest mean to the node. K-Means is partitioned into two phases;

- a) *Calculation of k-centroid*: To partition the network into K-clusters, the value of K will be chosen or calculated to represent the number of K clusters; this value of K can be referred to as the centroid(s). In this state, based on the value of K, sensor nodes chosen as a k-node will be chosen to be the cluster heads. E.g. =2, then two sensor

nodes will be chosen as cluster heads, hence there will be only two clusters formed. To calculate the value of K , the sum of the squares for different K -value is calculated and plotted in a graph of number of clusters vs the sum of the squares for different K -value. However, the K -value will be chosen in a graph as a point where the number of clusters starts to decrease slowly.

- b) *Clustering*: The deployed cognitive wireless sensor nodes from their respective initial points will be grouped with respect to the nearest K -centroid to them. The distance between the nodes and the k -centroid is calculated using the Euclidean distance

$$d = \| S_n (x,y,z) - C_n \| \dots\dots\dots(2.3).$$

However, to satisfy the operations of K-Means clustering, the centroid value will be recalculated using the following formula

$$C_n = \sum_{x \in C_k} \sum_{y \in C_k} \sum_{z \in C_k} \dots\dots\dots(2.4).$$

provided the error value is satisfied.

- c) S is the sensor node,
d) (x,y,z) represents the coordinates each sensor node has, and
e) C_n represent the centroid in which the distance is measured to it from the sensor node.

However, the aforementioned clustering protocols are only for WSNs, which they support only the fixed or static spectrum allocations, hence they are incompatible with the dynamic nature of the CRSNs, expect for K-Means clustering which can be implemented in both WSN and CRSNs. Therefore, it necessitates designing the clustering protocols which will support the CRSNs dynamicity. Such clustering protocols are discussed in the section below.

2.9 Related works

Peer-reviewed sources have been used for constructing the relevant literature. Several works are surveyed on energy inefficiency, proposed solutions, the approaches and tools used.

2.9.1 QoS (Quality of Service)

The deployment of WSN for a wireless communication can result in energy inefficiencies that affect the network performance and the communication QoS [2, 8]. This can be due to WSN using ISM unlicensed bands as a shared resource, hence resulting in congested spectrum bands as new wireless devices are developed for ISM bands [10]. To proffer a solution to improve WSNs network performance and the communication QoS, CRSNs are studied to overcome such challenge.

Shah et al. [59] proposed the cross-layer framework that deploys CR communications to overcome the challenges of power consumption and also provides support for smart grid applications QoS. The importance was based on the popularity gained by smart grid devices for the next generation of powered systems that have the capabilities of perceiving and managing electronic devices autonomously as well as managing the power operations equipment that is being utilized in distribution and power generation efficiently.

- 1) *Proposed Network*: CRSN
- 2) *Challenge(s)*: Multi-paths effects, equipment noise, electromagnetic interference and harsh obstructions in smart grid environments.
- 3) *Proposed solution*: They proposed a framework for achieving end-to-end application specific goals within the sensory network. It is also for preserving QoS-Aware communication for smart grid applications based on providing vision. Moreover, it incorporates learning and reasoning between the communication upper layers as well as efficient and opportunistic spectrum accessing at the communication physical layer. The proposed framework uses Lyapunov Drift Optimization for maximizing the utility, Cross Layer distributed control algorithm (DCA) to optimize the MAC and physical layer functions as well as the routing functions.
- 4) *Results and improvements*: The proposed scheme is efficient in preserving smart grid applications QoS communication based on increased number of flows for lower priority classes which poses less threat in the performance of higher priority classes for given attributes. It also shows that increasing the number of channels does not increase the performance, having same ratio and is limited to high variance within the common control channel.
- 5) *Tools Used*: NS-2
- 6) *Future Work*: N/A

Ashraf et al. [36]

This study proposes an energy harvesting mechanism using radio frequency (RF) from transmission within primary spectrum for Cognitive Radio Wireless Sensor Networks (CRWSNs). The advantages of the proposed work based on energy harvesting is to reduce the carbon emission in the perceived environment, to improve the life span of utilized networks and the availability of power to the utilized devices that cannot be recharged with fixed power outlets.

- 1) *Proposed Network:* CRWSNs
- 2) *Challenges:* Simultaneous use of the frequency band leads to interferences and suffering from battery power exhaustion at the receiving nodes.
- 3) *Proposed solution:* The research proposes Energy harvesting transmission mechanism based on the primary spectrum user for CRSNs to avoid battery replacement on sensor nodes. The energy harvesting is based on Radio Frequency (RF) energy rather than renewable energy since RF energy is controllable. Also, an optimization algorithm is utilized for optimizing WSN performance due to its transmission power from primary transmitters, sensors and primary transmitters' density.
- 4) *Results and improvements:* The results show improved efficiency as the overall success probability and total throughput outperforms the existing schemes. This is because sensors transmission power, primary transmitters' transmission power and primary transmitters' spatial density were optimized.
- 5) *Tools Used:* MATLAB
- 6) *Future Work:* N/A

2.9.2 Clustering and DSA

Proliferation of wireless devices in the fixed unlicensed ISM radio bands leads to uncontrollable interference. This can be due to licensed spectrum bands being underutilized, hence congestion and underutilization can cause energy inefficiencies [60].

Studies have proposed the use DSA to proffer solutions to overcome spectrum underutilization and uncontrollable interference in spectrum bands. Some proposed schemes in clustered CRSNs and some are not. Clusters in CRSNs are found to have better energy consumption; this is due to reducing the complexity of a deployed network by partitioning the network into sub-networks that are responsible for perceiving the environment based on the desired specifications. This however, allows the deployed sensor nodes to sense different forms of data and relay the sensory data within the same network.

Ren et al. [7]

The authors discovered that without proper channelling accessing mechanisms, spectrum bands face congestion problems that lead to uncontrollable interferences. However, they

proposed dynamic channel access to circumvent energy inefficiency within the clustered CRSNs. Performance analysis concludes that in intra cluster data transmission there is less packet rate per energy consumption, in inter cluster data transmission less energy is consumed when time increases for channel accessing and also total consumed energy is less for different amounts of data traffic.

- 1) *Proposed Network:* Clustered CRSNs
- 2) *Challenges:* Issue of having sensor nodes consuming high amounts of energy to perform sensing and switching operations.
- 3) *Proposed solution:* DSA with two accessing and sensing schemes, the joint power allocation and channel accessing scheme, which are used for intra and inter clusters of CRSNs for data transmission and obtaining optimal energy efficiency. This is to determine the conditions in which a sensor node can sense and switch to licensed bands.
- 4) *Results and improvements:* Simulations have been performed to demonstrate the efficiency of the proposed schemes to improve energy consumption in CRSNs. Results showed that the proposed scheme significantly reduces energy consumption during transmissions as compared to other researchers' proposed schemes. For improvements, a mechanism such as sleep and wake and energy harvesting mechanisms can be used to allow only sensor nodes to transmit data set to active while others are inactive to enhance energy consumption rate.
- 5) *Tools Used:* OMNET++
- 6) *Future Work:* Investigation on rechargeable CRSNs by leveraging stochastic harvested energy to support CR techniques.

Akhila et al. [12]

The authors made comments that having the capabilities of using cognitive radios to reduce the challenges encountered by WSN which are utilizing the idling free spectrum bands, there still exist challenges of high energy consumption from sensors when performing sensing and switching of free underutilized bands in the absence of PUs. However, they proposed a scheme of using dynamic channel access with asynchronous sleep-wake scheduling to improve energy efficiency in CRSNs. Performance evaluation shows that the use of both DSA and asynchronous sleep-wake scheduling mechanism outperforms mechanism without

asynchronous sleep-wake scheduling mechanism in terms of energy consumption in both inter and intra clusters.

- 1) *Proposed Network*: CRSN
- 2) *Challenges*: Uncontrollable interference in the network while utilizing the free licensed spectrum bands due to a plethora of connecting devices.
- 3) *Proposed solution*: Joint power allocation and channel accessing schemes are two dynamic channel accessing schemes proposed to overcome intra and inter-clustering data transmission for reducing energy consumption for intra and inter cluster data transmissions. Also, asynchronous sleep-wake scheduling mechanism is used to reduce energy consumption.
- 4) *Results and improvements*: Clusters in CRSNs reduce energy consumption, thus preserving the sensor nodes lifespan. However, the proposed schemes using sleep-wake scheduling based on clusters is much more efficient in terms of less packet rate per energy consumption than the cluster approach without sleep-wake scheduling. For improvements, a central manager can be used to reduce sensor nodes operation complexities and reduce their energy consumption rate, while managing the channel sensing and channel accessing. The sensor nodes only access the channels from the cluster head without having to perform channel sensing and accessing.
- 5) *Tools Used*: NS2
- 6) *Future Work*: N/A

2.9.3 DSA

With the implementation of DSA to avoid unnecessary interference, several works have been proposed by other researchers to improve DSA with efficient PU and SU user-detection and switching mechanisms.

Sarma et al. [61]

This paper proposed a novel chain routing protocol that reduces energy consumption in the network.

- 1) *Proposed Network*: CRSN based on chain formation
- 2) *Challenges*: Routing challenges in CRSNs namely; the design of efficient energy routing protocols for preserving network lifetime and joint node-channel assignment for enabling DSA.

- 3) *Proposed solution:* Energy balanced routing protocol which organizes the wireless sensor nodes within the field in a form of a chain where only the sensory data is relayed to the sink(s) using different chains following a balanced energy manner. This solution is to leverage network and improve energy usage of sensor nodes. The proposed scheme makes use of the following approaches in five different phases: localization, synchronization, chain formation, energy balanced data forwarding and chain reformation.
- 4) *Results and improvements:* Simulation results show that the energy efficiency for the proposed scheme outperforms the existing Energy and Cognitive Radio aware routing protocol (ECR). The proposed scheme transmits more data per energy consumed and less energy is consumed when the network size increases, and more nodes remain alive with increase in time. For future work to improve the proposed scheme, an analytical modelling of the proposed energy balancing routing protocol can be used together with protocol rigorous analysis.
- 5) *Tools Used:* MATLAB
- 6) *Future Work:* Analytical modelling of the proposed energy balancing routing protocol can be used together with protocol rigorous analysis.

Mahmood et al. [60]

WSN can be used as a promising solution to monitor real life events such as environmental natural disasters. An event-driven WSN is one of the promising technologies that can be implemented in a clustered networking environment. This paper proposed an approach to assessing a structural health using cellular networks as a primary network. This kind of event-driven mechanism is used to detect seism activities within buildings.

- 1) *Proposed Network:* WSN
- 2) *Challenges:* Seism Activities
- 3) *Proposed solution:* An event driven WSN using CR capabilities for gathering data and reporting information due to seism activity in buildings. It utilizes white spaces using a cellular network under CRSN based on average energy consumption and packet delays. This is geared towards providing a network with efficient uses of resources for buildings and offices using cellular networks as a primary network.
- 4) *Results and improvements:* Simulations were conducted to analyse the performance of the average cluster formation and average consumed energy for WSN both in steady

states and cluster formations. Results show efficiency in using cellular networks as primary network. It is more suitable for data transmission to the secondary network without hindering the primary network performance. Moreover, WSN is also capable of sending relevant seism activities information for experts' analysis. For improvements, analysis should be conducted on interference due to seism activities in both primary and secondary networks to determine which network suffers most from interference, as well as improving the network to increase accuracy of data transmitted.

5) *Tools Used*: N/A

6) *Future Work*: WLAN implementation as primary system.

Zhang et al. [32]

This study focuses on a new paradigm of Energy Harvesting Cognitive Radio Sensor Networks (EHCRSNs) that improves the capabilities of energy harvesting within heterogeneous cognitive sensor networks. The networks make use of spectrum sensor nodes for cooperatively and efficiently sensing underutilized licensed channels and the data sensor nodes that are responsible for resource allocations such as time, power and channels.

1) *Proposed Network*: Energy Harvesting CRSN

2) *Challenges*: By using Harvesting Cognitive Radio Sensor Networks (HCRSN), the traditional CR models and energy harvesting dynamics face challenges of scheduling the utilized spectrum sensor and data sensors resource allocations.

3) *Proposed solution*: Proposed resource allocation scheme based on HCRSN to have the sensor and spectrum sensors energy sustained. It uses two algorithms operating one after the other; a Spectrum Sensor Scheduling (SSS) Algorithm for allocating spectrum sensors the channels. This is important to ensure that detected average available time for channels can be maximized considering EH dynamics while protecting PU transmissions and a Data Sensor Resource Allocation (DSRA) Algorithm.

4) *Results and improvements*: Results shows that harvested energy is much more efficient than battery-powered energy, hence improving the life-span of the sensor nodes. That is, it also shows efficiency of using primary network channels occurring in real time using harvested energy and optimized scarce resource allocations to the battery powered sensor data nodes. For improvements, future work can be based on analysis of routing protocol designs and channel allocation in energy harvesting multihop HCRNS based on different time rates of energy harvesting as well as how the sensors threshold can be detected adaptively.

5) *Tools Used*: MATLAB

- 6) *Future Work:* Routing and spectrum allocation for energy harvesting aided multihop considering the adaptive detection and time varying energy harvesting threshold of wireless sensors.

Lee and Zhang [62]

This study focuses on a new technology known as Cognitive Wireless Powered Communication Network (CWPCN) where secondary WPCN utilizes the same spectrum with its Wireless Information Transmission (WIT) and Wireless Energy Transfer (WET) using an existing communication system.

- 1) *Proposed Network: Cognitive Wireless Powered Communication Network (CWPCN)*
- 2) *Challenges:* Under-optimization of the total throughput for CWPCN within each sensory model under ITC/PRC due to less optimized time and power allocation in secondary WIT, WET and CWPCN.
- 3) *Proposed solution:* Proposed new CR with enabled secondary WPCN is proposed for spectrum sharing within a shared primary wireless communication system. It uses two coexisting spectrum sharing models (underlay and overlay)-based WPCNs. Both models are used for maximizing the total throughput of CWPCNs by allowing the transmission to be optimized under varied constraints used to protect PU transmissions.
- 4) *Results and improvements:* The experiments have been conducted to compare the total throughput of CWPCN against the rate that can be achieved for the PUs using two proposed coexisting models. The results show that the overall total throughput decreases when path loss exponent increases. That is, the throughput increases when the hybrid access point transmission power is maximized. For future work, a general CWPCN setup, full duplex systems and user fairness systems can be used. To create multileveled equations, it may be necessary to treat the equation as a graphic and insert it into the text after your paper is styled.
- 5) *Tools Used:* N/A
- 6) *Future Work:* User fairness, Full duplex systems, General CWPCN setups

Sakr and Hossain [63]

Despite the cognitive radio capabilities of efficient spectrum wireless communication, there is still a need to enhance energy efficiency so as to sustain the network performance and reliable communication channels. Thus, having a proposed model based on radio energy frequency energy harvesting from ambient interference; this enables a model for energy-efficient wireless communication.

- 1) *Proposed Network:* Cognitive and Energy Harvesting-Based D2D Communication
- 2) *Challenges:* Improving energy efficiency of CRs in cellular network communications.
- 3) *Proposed solution:* They proposed a Cognitive and Energy Harvesting-Based Device-to-Device (D2D) model based on cellular networks communications. The study focuses on two policies for spectrum accessing for cellular communications using downlink or uplink. They are Random Spectrum Access (RSA) being used for selecting available channels including channels utilized by D2D transmitters and a Prioritized Spectrum Access (PSA) that allows the D2D channels to be utilized when active channels are occupied.
- 4) *Results and improvements:* Cognitive D2D power consumed by using harvested energy has a better performance. It shows cognitive channel has better D2D users outage probability both in spectrum access policies under the same signal-to-interference-plus-ratio outage requirements. Also prioritized access policies have better D2D users' performance as compared to random access policies. Moreover, the uplink channel outperforms the downlink in terms of D2D users' congested networks. The performance analysis also shows that PSA and RSA provide the same outage probability for cellular users.
- 5) *Tools Used:* N/A
- 6) *Future Work:* N/A

However, dynamic channel allocations to avoid unnecessary interference while maintaining energy efficiency in clustered CRSNs can be challenging when there is no clustering algorithm that supports the dynamicity channel allocations of CRSNs and the CR capabilities.

Li et al. [64]

Failure to improve the energy efficiency of CRSNs can lead to challenges such as reduced network lifetime and more energy consumption. This paper suggests improving energy

efficiency to prolong network lifespan hence proposing the use of a cluster based multi-channel CRSN. The improvements to obtain the desired outputs are dependent upon two techniques, namely packet size adaptation exploitation technique and channel assignment technique.

- 1) *Proposed Network*: Cluster-based multichannel CRSNs.
- 2) *Challenge(s)*: Unbalanced residual energy for energy constrained wireless sensor nodes.
- 3) *Proposed Solution and Approach(es)*: DSA with two techniques; Packet size adaptation exploitation technique to allow differentiating packet size to adapt to the transmission within a specified state varying channel and the Channel assignment technique with residual energy of sensors awareness for allowing sensors to use their energy in a balanced way to extend network and battery lifespan.
- 4) *Results*: The packet size adaptation exploitation scheme obtains energy efficiency upon successful information delivery by keeping the Energy-per-bit at the lowest levels possible.
- 5) *Tools Used*: N/A
- 6) *Future Work*: Extending the work to including inter cluster performance as the proposed work focuses only on intra cluster channel assignment and performance analysis.

Ejaz et al. [34]

In a cognitive radio sensor network, throughput and energy efficiency are key aspects that need attention when designing low-powered devices. The study conducted examines the energy and throughput trade-offs using cooperative spectrum sensing; however, its objective is based on minimizing the consumed energy for spectrum sensing, reporting cooperative decisions to a cluster head and data transmission.

- 1) *Proposed Network*: CRSNs
- 2) *Challenge(s)*: Minimizing total consumed energy for spectrum sensing, reporting cooperative decisions to a cluster head and data transmission.
- 3) *Proposed Solution and Approach(es)*: A heuristic solution to determine conditions for sensing, reporting and data transmission duration to obtain the best possible trade-off between throughput and PUs. This heuristic solution is based on energy efficient spectrum access algorithm.

- 4) *Results*: The obtained results show that the maximum throughput decreases when signal-to-noise ratio of received signal decreases. The results also show that the increase in cooperative users firstly increases average throughput then decreases it afterwards. Moreover, energy efficiency and normalized throughput rapidly changes as the transmission time and number of cooperative SUs increases. Lastly, the desired maximum throughput is obtained when using the optimal reporting time.
- 5) *Tools Used*: Low-power chipcon CC2420 transceiver based on the IEEE 802.15.4/ZigBee.
- 6) *Future Work*: N/A

Zhang et al. [38]

Within a CRSN the cognitive radio capabilities of allowing secondary nodes to access the idling licensed bands might result in interference when the PU reappears. However, this paper proposes the Distributed Spectrum Aware Clustering (DSAC) scheme that is specifically-based at creating energy efficient clusters that autonomously self-organize while trying to reduce interference to the PU and also reduce communication energy using a group wise/pairing approach in clusters by minimizing intra cluster distance.

- 1) *Proposed Network*: Distributed spectrum-aware clustered CRSNs
- 2) *Challenge(s)*: Uncontrollable interference and high clusters communication power
- 3) *Proposed Solution and Approach(es)*: The authors proposed a distributed spectrum aware clustering scheme to create energy efficient schemes and a group wise or pairing approach of clusters to reduce/minimize intra cluster distance.
- 4) *Results*: Extensive simulations were conducted using Monte Carlo experiments to compute a target value based on scalability, stability and energy consumption. The results show that the proposed DSAC scheme proffers the preferred stability and scalability due to its quick convergence and low complexity under dynamic change of PUs activity.
- 5) *Tools Used*: Monte Carlo experiments
- 6) *Future Work*: N/A

Zhang et al. [65]

The emergence of CRSNs introduced a challenge of designing the topology maintenance techniques, which accommodate the change in PUs' activities. However, this paper proposed two spectrum aware clustering schemes; a DSAC scheme and a Centralized Spectrum Aware

Clustering (CSAC) scheme to determine a suitable scheme for reducing energy consumption while still determining an optimal number of clusters.

- 1) *Proposed Network*: Spectrum Aware Clustered CRSNs
- 2) *Challenge(s)*: Distributed clustering within a dynamic wireless network, the design challenges of maintenance techniques for activity changes in PUs change, and high energy consumption in clusters.
- 3) *Proposed Solution and Approach(es)*: DSAC scheme and a CSAC scheme to alleviate cluster network energy efficiency and still maintain stability and scalability. Approach used is the group-wise constrained clustering to determine the optimal number of clusters.
- 4) *Results*: Centralized clustering scheme was proposed to effectively cluster the CRSN by globally pairing two nodes with a common channel but it had the two disadvantages of high energy consumption due to high signal rate exchange between base station and cluster head, and difficulties in detecting a direct connection wireless channel between base station and cluster head. However, they proposed distributed clustering that will reduce energy consumption by locally pairing closest nodes with a common channel. The results show that the distributed spectrum aware clustering scheme forms more clusters with less iterations, the average node power is minimum when there are about five or six clusters, and the desired stability and scalability is obtained.
- 5) *Tools Used*: N/A
- 6) *Future Work*: Theoretical analysis for the proposed schemes to investigate adaptations of different Primary User (PU) spectrum occupation schemes to obtain a vigorous performance. This creates an option for experimented on test beds before any practical implementations for future use.

Shah et al. [66]

Multimedia applications are well known for transmitting data that is highly sensitive to delays and requires high bandwidth. Implementing CRSNs to support multimedia applications is subject to spectrum and energy constraints. However, the authors propose a Spectrum Aware Cluster based Energy Efficient Multimedia (SCEEM) scheme in CRSNs to circumvent spectrum and energy limitations of multimedia. The proposed scheme does not only overcome spectrum and energy limitations but with clustering it proffers better QoS and efficient routing.

- 1) *Proposed Network*: CRSN
- 2) *Challenge(s)*: Multimedia routing in CRSN.
- 3) *Proposed Solution and Approach(es)*: A SCEEM solution with approaches; Carrier Sense Multiple Access (CSMA) for inter cluster routing and TDMA for intra cluster data transmission.
- 4) *Results*: Clustering based solution is proposed to manage QoS routing and dynamic channel accessing for multimedia CRSNs. The performance results show that the proposed SCEEM scheme obtains more Peak Signal to Noise Ratio (PSNR) for cognitive users video transmissions through cluster based data transmissions and adaptive data sources.
- 5) *Tools Used*: NS-2 and IEEE 802.11 MAC protocol for cognitive support customization.
- 6) *Future Work*: N/A

Ozger et al. [39]

The wireless sensor networks adopted the use of dynamic spectrum access namely CRSNs to overcome spectrum underutilization, however, the energy efficiency aspect of CRSNs requires thorough attention as the sensor nodes are energy constrained. The authors proposed an energy efficient scheme for resource constrained CRNS nodes. An event driven clustering is proposed for CRSN as the traditional cluster protocols for WSNs are not applicable in CRSN.

- 1) *Proposed Network*: Event driven clustered CRSN.
- 2) *Challenge(s)*: Spectrum Underutilization/Scarcity and high energy consumption in delay tolerant systems
- 3) *Proposed Solution and Approach(es)*: An Event driven clustering protocol is used in CRSN to create temporal clusters for each event using a cluster head selection among eligible nodes based on their available channels, node degree and the distance between the nodes and the base station in their neighbourhood.
- 4) *Results*: The simulations were conducted to evaluate the proposed scheme performance to improve the energy efficiency of delay tolerant systems and also circumvent spectrum underutilization. The results show efficiency as the proposed scheme alleviates energy consumptions with delays caused by spontaneous formations of clusters.
- 5) *Tools Used*: MATLAB
- 6) *Future Work*: N/A

There is a necessity of evaluating the channelling protocols in CRSNs to reduce issues such as uncontrollable interference. As argued in this paper, few studies are carried out on channel assignment energy consumption, whereas most studies conducted on channel assignment are based on improving the efficiency of spectrum use and using optimization protocols to create models that manage PUs activities so as to reduce unwanted collision as well as improving QoS performance based on throughput and delays. However, this paper proposes an *R-coefficient* protocol to reduce CRSNs energy consumption to help extend battery lifespan of energy constrained nodes.

- 1) *Proposed Network*: Cluster-based multichannel CRSN
- 2) *Challenge(es)*: Channel assignment problem
- 3) *Proposed Solution and Approache(es)*: This paper proposes R-coefficient to estimate the amount of expected energy consumption and the residual energy based on the sensory information and the PU activities in the specified channel, Greedy Channel Search to maximize total expected residual energy for sensors in channel assignment, and the Optimization based Channel Assignment for extending network lifetime.
- 4) *Results*: Three channel assignment schemes R-coefficient, greedy channel search and optimization based channel assignment were simulated to compare their numerical performance based on residual energy and energy consumption. The results show efficiency for R-coefficient based on improving channel assignment by considering the residual energy and reduced energy consumption, while the Greedy channel search is efficient in terms of maximizing the total expected residual energy for each sensor when performing channel sensing; this improves network performance. Moreover, the optimization approach is efficient as it outperforms greedy channel search in terms of improving network lifetime.
- 5) *Tools Used*: N/A
- 6) *Future Work*: An Inter cluster performance analysis and throughput analysis based on mathematical models will be carried out as the analysis conducted was only for intra cluster channel assignment.

Latiwesh et al. [67]

The amalgamation of WSNs and CRs was done to produce a new paradigm to overcome scarcity dynamically. Clustering is proposed as one of the supporting algorithms for CRSNs. However, the traditional clustering algorithms are based on fixed spectrum utilization, hence they do not support CRSNs dynamicity, hence the authors proposed a centralized CRSNs protocol named Cognitive Centralized LEACH (CogLEACH-C).

- 1) *Proposed Network*: Clustered CRSN
- 2) *Challenge(es)*: Fixed spectrum bands utilization by traditional clustering algorithms
- 3) *Proposed Solution and Approach(es)*: CogLEACH-C which is cognitive LEACH protocol selecting cluster heads in a centralized fashion based on nodes with more residual energy and more idling channels, and using the Semi-Markov approach for modelling PUs behaviour was proposed.
- 4) *Results*: The results show adequacy in terms of having a better efficiency over the existing CogLEACH protocol which doesn't support centralization for cluster head selection. CogLEACH-C extends network lifetime by not allowing nodes to die quickly hence keeping more nodes alive for a considerate amount of time.
- 5) *Tools Used*: MATLAB
- 6) *Future Work*: N/A

Pei et al. [68]

Traditional WNs and CRs clustering are fixed spectrum band specific hence do not support the channel dynamicity of the CRSNs paradigm amalgamated by WSN and CRs. However, the author proposed LEAUCH which will both support channel dynamicity of CRSNs as well as balancing the energy of cluster heads.

- 1) *Proposed Network*: Clustered CRSN
- 2) *Challenge(es)*: Incompatible clustering nature of CRs and WSNs in CRSNs.
- 3) *Proposed Solution and Approach(es)*: LEACH protocol to alleviate high energy consumptions and the use of uneven clustering for balancing cluster heads energy consumption in multi-hops was proposed.
- 4) *Results*: The proposed LEAUCH protocol shows efficiency against its rivals, traditional WSNs and CRs clustering protocols in two factors; extension of network lifetime and efficiently balancing cluster heads energy consumption.
- 5) *Tools Used*: MATLAB

- 6) *Future Work*: The proposed work is mainly based on the evaluation of the overall network energy efficiency and lifetime; hence future work will be based on the evaluation of more application-based scenarios of complex topologies for evaluation of packet loss rate, throughput and delay.

Saini et al. [35]

The new paradigm of CRSNs faces issues of energy usage in a network and the dynamicity of spectrum band usage hence the need of an efficient protocol to manage both issues. However, designing this protocol is a challenge in terms of energy consumed for communication between the nodes, hence the authors proposed a distributed event-driven clustering protocol.

- 1) *Proposed Network*: Distributed event-driven clustered CRSN.
- 2) *Challenge(es)*: Incompatible clustering nature of CRs and WSNs in CRSNs.
- 3) *Proposed Solution and Approach(es)*: The authors proposed distributed event driven clustering to provide better cluster head selection and communication between nodes and sink as well as selection of route that are robust to PUs behaviours, but also alleviating high energy consumptions.
- 4) *Results*: The proposed scheme is efficient in terms of the selection of route between node and sink which remains stable throughout the communication and also the route is robust to PUs behaviour.
- 5) *Tools Used*: N/A
- 6) *Future Work*: N/A

2.9.4 MAC Protocols in CRSN

Though some of the above discussed solutions alleviate the high energy consumptions on CRSNs, the type MAC protocol used is a critical aspect when designing energy-aware mechanism. Some of the proposed MAC CRSN mechanisms are discussed below.

Abolarinwa et al. [69]

The authors proposed a model that can sufficiently maintain green communication and still alleviate high energy consumptions. The authors proposed a learning inspired CRSN model using dynamic channel sensing, decision and allocations that allows wireless nodes to autonomously and intelligently access vacant channel based on historical information concerning the energy consumption rate.

- 1) *Proposed Network:* CRSN
- 2) *Challenges:* Energy inefficiencies in green communication network
- 3) *Proposed solution:* The authors proposed learning inspired CRSN model based on historical information with dynamic channel sensing, decision and allocations that allows wireless nodes to autonomously and intelligently access vacant channel based on historical information concerning the energy consumption rate
- 4) *Results and improvements:* Simulations were used to generate the data for analysis to assess the effectiveness and performance of the proposed learning technique based on historical data. The results show efficiency in energy consumption where the sensor agents can access any available channel for transmission considering its energy consumption rate.
- 5) *Tools Used:* N/A
- 6) *Future Work:* N/A

Jamal et al. [70]

Dynamic Spectrum Access (DSA) is an approach used for CRs to allow SUs to access the idling bands that are underutilized by PUs. Synchronous multichannel schemes and single channel MAC schemes are proposed by other authors to access the underutilized bands. However, this scheme faces problems such as sensing period's challenges, broadcasting over wide network and the use of high priority mechanisms.

- 1) *Proposed Network:* Multichannel MAC Scheme
- 2) *Challenges:* The use of single channel MAC protocol is found to be inefficient in terms of communication the sensor nodes hence lowering the performance of the network and increasing energy consumption.
- 3) *Proposed solution:* A novel MAC scheme based on the efficiency of energy and spectrum aware multi-channel MAC protocol is proposed to overcome single channel, synchronous schemes and multi-channel schemes such as Y-MAC and MCMAC multichannel schemes. They all face sensing period's challenges, broadcasting over wide network and the use of high priority mechanisms. However, the proposed novel MAC scheme uses a spectrum aware asynchronous duty cycle responsible for data transmission and channel acquisition.
- 4) *Results and improvements:* Theoretical analyses and simulations were performed in which simulation results outperform the theoretical results. The normalized delays

increase at fewer rates per cycle length; more throughputs are obtained at less cycle lengths and less packet size. Moreover, the simulation results show that the proposed scheme is much more efficient as compared to MCMAC based on more energy spent on synchronization phase.

5) *Tools Used*: N/A

6) *Future Work*: N/A

Liu et al. [71]

Within the wireless networking paradigm, the machine to machine communications emerged to provide a diverse connection everywhere for wireless devices. This machine to machine network suffers from challenges such as massive connections and access, low power and unreliable communications and channel scarcity which lead to low throughput. However, the authors in this paper proposed a mechanism that will proffer better spectrum information and access to improve the overall network throughput.

1) *Proposed Network*: Cognitive machine to machine network.

2) *Challenges*: Low throughput and channel scarcity

3) *Proposed solution*: Spectrum database driven MAC protocol for machine to machine devices to allow optimized spectrum access and information from the spectrum database or the localized spectrum accessing mechanism and the Iterative adaptive dynamic algorithm technique to proffer the devices with the optimized spectrum accessing policies were proposed.

4) *Results and improvements*: The proposed solution shows efficiency in terms of elevating the reliability by ensuring that the overall network throughput is obtained yet alleviating unwanted interferences within the primary network.

5) *Tools Used*: N/A

6) *Future Work*: N/A

Hawu et al. [1]

1) *Proposed Network*: CRSN

2) *Challenges*: Low throughput and fast energy depletion

- 3) *Proposed solution*: The authors proposed novel, fully distributed Self learning MAC protocol for energy harvesting and Two state discrete Markov chain to model the activity of the user using a slotted licensed user environment.
- 4) *Results and improvements*: The proposed solution shows efficiency in terms of improving the overall network harvested energy and throughput yet maintaining robustness in case of changes. Moreover, the solution proffers reduced costs suffered by centralized mechanism.
- 5) *Tools Used*: N/A
- 6) *Future Work*: N/A

Yang et al. [72]

Due to the proliferation of wireless sensor nodes in the WSN, the smart grid network suffers from high capacity of reliability and throughput based on the fact that the spectrum is shared amongst the users. However, the authors proposed a spectrum aggregation technique to elevate throughput and increase the reliability as well.

- 1) *Proposed Network*: CRSN
- 2) *Challenges*: Low throughput and reliability
- 3) *Proposed solution*: Spectrum Aggregation Cognitive Receiver-Based (SACRB) protocol to improve the overall network throughput in smart grid by deploying a spectrum aggregation technique was proposed.
- 4) *Results and improvements*: The results show efficiency in terms of reliability and high capacity effectiveness and performance.
- 5) *Tools Used*: MATLAB
- 6) *Future Work*: Fairness and the coexistence of secondary networks using the same PU resources will be investigated.

Zikria et al. [73]

The IoT paradigm is composed of a proliferation of networked devices for communication purposes. This network suffers from spectrum underutilization and scarcity. However, the authors proposed an ad-hoc CRSN that is implemented with Opportunistic MAC protocol and a channel/spectrum selection scheme to reduce spectrum scarcity and underutilization.

- 1) *Proposed Network*: CRASN

- 2) *Challenges*: Spectrum scarcity and underutilization
- 3) *Proposed solution*: Opportunistic MAC protocol and a channel/spectrum selection scheme to reduce spectrum scarcity and underutilization were proposed.
- 4) *Results and improvements*: The results show efficiency in terms of improved system goodput and spectrum utilization and also the proposed solution outperforms random spectrum allocations and round robin considering spectrum utilization and system goodput.
- 5) *Tools Used*: N/A
- 6) *Future Work*: N/A

Yang et al. [74]

WSN have been deployed for years and considered as a solution to enhancing different aspects of electric smart grid devices. However, this network when implemented in smart grid suffers from energy inefficiencies hence the authors proposed the ECR-MAC to circumvent such challenge.

- 1) *Proposed Network*: CRSN
- 2) *Challenges*: Energy inefficiency
- 3) *Proposed solution*: Energy efficient receiver based MAC (ECR-MAC) which is receiver based MAC protocol that uses an energy efficient auction mechanism to allow the wireless nodes to compete for forwarding position and the node with more transmission energy is chosen as the forwarding node. The ECR-MAC deploys a preamble sampling to accommodate high reliability and energy efficiency CRSN requirements.
- 4) *Results and improvements*: The proposed solution in lossy wireless networks shows efficiency by generating fewer re-transmissions and enhanced energy efficiency. It also increases reliability by deploying more wireless sensor nodes using the receiver-based nature.
- 5) *Future Work*: N/A

In spite of the related works discussed above, performing channel sensing is still a repetitive process for wireless sensor nodes, where a considerable amount of energy will still be consumed and the proliferation of sensor nodes leads to uncontrollable interference if all the

wireless sensor nodes are equipped with channel sensing capabilities[7, 12, 33]; however, it necessitates the need for conducting a comprehensive research to discover ways in which the existing cluster based CRSNs with dynamic channel allocations support can be further improved with regards to the alleviation of high energy consumption.

With the highlighted challenges, several mechanisms have been proposed such as the DSA which is famously used to overcome uncontrollable interferences, the energy harvesting mechanisms such as using renewable energy to allow active nodes to operate autonomously and continuously without depleting battery energy. For instance, battery-power exhaustion is due to simultaneous communication between the sensor nodes and the base stations as well as uncontrollable interference where the channel is congested. Others include the failure to vacate the SUs from the licensed spectrum when PUs reappears, routing challenges due to hops and redirecting the data to the desired destination, scheduling the sensor nodes and data resources to be allocated fairly to the users, and under-optimized throughput.

All these tend to degrade the network performance and affect the QoS hence radio frequency energy is often used to avoid battery-power exhaustion. These mechanisms are mostly proposed for clusters and using approaches such as asynchronous sleep-wake scheduling mechanism for inter and intra clusters. This mechanism allows only active wireless nodes to transmit data when other wireless nodes are put to sleep mode. Furthermore, even though these mechanisms are providing a certain level of energy-efficiency, it still necessitates the design or implementation of an energy-aware MAC protocol. Several authors in related works proposed some of the energy-aware MAC protocols that will not only improve energy efficiency but also improve throughput and ensure reliability. However, these mechanisms can still be further improved for better energy efficiency, equipping each wireless node with the capabilities to perform its own operations but yet being aware of its neighbours scheduling to avoid interferences and collisions.

The importance of the proposed mechanisms in related works is to enhance cluster energy consumption by reducing the wireless sensor nodes operation complexity, improve network performance and resource allocations. Table 2.1 summarized the different energy challenges faced in CRSNs, the approaches, solutions and improvements. Energy inefficiency can degrade the performance of the whole network hence affecting the QoS communication between the sensor nodes and the base stations.

Table 2.1: Existing CRSN Energy-inefficiency Challenges and Proposed Solutions

Ref	Network	Challenges(s)	Proposed Solution	Approach(es)	Tool(s) Used	Implementat ion	Future Work
[59]	CRSN	QoS WSN based grid application devices: Multi-Paths effects, Equipment noise, Electromagnetic interference, Harsh obstructions.	QoS-Aware communication for grid applications	Lyapunov Drift Optimization for utility maximization Cross Layer Distributed Algorithm (DCA) for MAC and PHY layer optimization and routing functions	NS-2	Smart grid applications	N/A
[36]	CRWSN	Battery-power exhaustion due to simultaneous communication	Energy Harvesting transmission mechanism	Optimization Algorithm to maximize the WSN overall probability.	MATLAB	N/A	N/A
[61]	CRSN based on chain formation	Routing challenges in CRSNs namely; the design of efficient energy routing protocols for preserving network lifetime and joint node-channel assignment for enabling DSA.	Energy balancing routing protocol	Localization, synchronization, chain formation, energy balanced data forwarding and chain reformation	MATLAB	Simple sensor hardware even without GPS support	Analytical modelling of the proposed energy balancing routing protocol can be used together with protocol rigorous analysis
[60]	WSN	Seism Activities	An event driven WSN with CR capabilities	Cellular network for white space utilization in CRSN	N/A	Conventional cellular systems	WLAN implementation as primary system
[32]	Energy Harvesting CRSNs	Scheduling the utilized spectrum sensor and data sensors resource allocations		Two algorithms: Spectrum Sensor Scheduling (SSS) for spectrum allocation and Data Sensor Resource Allocation (DSRA)	MATLAB	N/A	Routing and spectrum allocation for energy harvesting aided multihop considering the adaptive detection and time varying energy harvesting threshold of wireless sensors.
[62]	CWPCN	Under-optimization of total throughput	CR enabled with secondary WPCN	Two coexisting sharing models: Underlay and Overlay based WPCNs	N/A	General CWPCN setup for full duplex systems and user fairness systems	User fairness, Full duplex systems, General CWPCN setups
[63]	Cognitive and Energy Harvesting -Based D2D Communic	Energy inefficiency of CRs in cellular network communications	Cognitive and Energy Harvesting-Based D2D Communication	Two spectrum policies: Random Spectrum Access (RSA) for D2D transmitters	N/A	N/A	N/A

	ation			channel selection and Prioritized Spectrum Access (PSA) for D2d channel utilization when active channels are occupied			
[7]	Clustered CRSNs	Resource allocation problems to allow efficient use of licensed spectrum for inter and intra cluster data transmission	Dynamic Channel Access	Joint power allocation and channel accessing scheme for inter and intra clusters	OMNET++	N/A	Using rechargeable batteries for CRSNs using stochastic energy harvesting approach.
[12]	Clustered CRSNs	Uncontrollable interference and difficulties to determine the wireless sensor nodes conditions for channel sensing and switching	Dynamic Channel Access	Asynchronous Sleep-wake scheduling mechanism	NS-2	N/A	N/A
[64]	Cluster-based multichannel CRSNs	Unbalanced residual energy for energy constrained wireless sensor nodes	Dynamic Channel Access	Packet size adaptation exploitation technique and Channel assignment technique with residual energy of sensors awareness	N/A	N/A	Inter cluster channel assignment and performance analysis
[34]	Clustered CRSNs	Minimizing total consumed energy for spectrum sensing, reporting cooperative decisions to a cluster head and data transmission.	A Heuristic solution	Energy efficient spectrum access algorithm	Low-power chipcon CC2420 transceiver based on the IEEE 802.15.4/Zig Bee	N/A	N/A
[38]	Distributed spectrum aware clustered CRSN	Uncontrollable interference and high cluster communication power	Distributed Spectrum Aware Clustering	GroupWise constrained agglomerative clustering	Monte Carlo experiments	N/A	N/A
[65]	Spectrum Aware Clustered CRSNs	Distributed clustering within a dynamic wireless network, model design challenges of PU activity detection and high network energy consumption	Distributed Spectrum Aware Clustering (DSAC) scheme and a Centralized Spectrum Aware Clustering (CSAC)	GroupWise Constrained Clustering	N/A	N/A	Theoretical analysis on the proposed schemes
[66]	Clustered CRSN	Multimedia routing in CRSNs	A Spectrum Aware Cluster based Energy Efficient Multimedia	CSMA for inter cluster routing and TDMA for intra cluster data transmission.	NS-2 and IEEE 802.11 MAC protocol for cognitive support	N/A	N/A

					customization		
[39]	Clustered CRSN	Spectrum Underutilization/Scarcity and high energy consumption in delay tolerant	An Event driven clustering protocol	Cluster Head Selection	MATLAB	N/A	N/A
[44]	Cluster-based multichannel CRSN	Channel assignment problem	R -coefficient, Greedy Channel search and Optimization based channel assignment	Residual energy prediction	N/A	N/A	Inter cluster performance analysis and throughput analysis based on mathematical models
[67]	Clustered CRSN	Fixed spectrum bands utilization by traditional clustering algorithms	CogLEACH-C	Semi-Markov	MATLAB	N/A	N/A
[68]	Clustered CRSN	Incompatible clustering nature of CRs and WSNs in CRSNs.	LEAUCH	Uneven Clustering	MATLAB	N/A	Evaluation of more application based scenarios of complex topologies for evaluation of packet loss rate, throughput and delay
[35]	Distributed event-driven clustered CRSN.	Design challenges of efficient communication protocol in CRSNs	Distributed event driven clustering	Self-organized cluster head selection	N/A	N/A	N/A
[69]	CRSN	Energy inefficiencies in green communications	Learning inspired CRSN model based on historical information	Dynamic spectrum access and decision technique	MATLAB	N/A	N/A
[70]	Multichannel MAC CRSN	Inefficiency of single MAC protocol	Multichannel MAC protocol	Spectrum aware asynchronous duty cycle	N/A	N/A	N/A
[71]	Cognitive machine to machine	Low throughput and channel scarcity	Spectrum database driven MAC protocol	Iterative adaptive dynamic algorithm	N/A	N/A	N/A
[1]	CRSN	Low throughput and fast energy depletion	Self learning MAC protocol for energy harvesting	Two state discrete Markov chain	N/A	N/A	N/A
[72]	CRSN	Throughput and reliability	SACB-MAC protocol	Spectrum aggregation	MATLAB	Smart grid AMI networks	Fairness and the coexistence of secondary networks using the same PU resources
[73]	CRASN	Spectrum scarcity and underutilization	Opportunistic MAC protocol and a	Channel/Spectrum selection scheme	NS-2	N/A	N/A

[74]	CRSN	Energy inefficiency	ECR MAC	Preamble sampling	MATLAB	Smart grid	N/A
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2.10 Chapter Summary

In this Chapter, the discussion was based on the background of WSN, CR, CRSNs and the topology of CRSNs. Furthermore, the discussion was based on clustering, the clustering topology in CRSNs, and the most commonly used WSNs energy efficient clustering algorithms. Moreover, the sleep-wake scheduling was also discussed. Lastly related works were discussed.

Chapter 3

Research Methodology and Design

3.1 Chapter Outline

This Chapter discusses the methodology used in this research and its design. It begins with an introduction, followed by detailed constructive methodology, research methods, and design on how to reach the desired research aim. Moreover, it also presents data collection, analysis and evaluation methods used as well as administrative and ethical procedures that outline proper protocols for conducting the proposed research. Lastly, we present the overall steps followed in this research and the chapter summary.

3.2 Introduction

Research is a process or a task of searching the data for facts that can be proven to contribute to the level of knowledge within the specific research field [75-79]. The investigated data can be modified or extended to produce a new solution. In a scientific way, research can be referred to as the systematic way of providing solutions to an identified existing problem. Research provides a platform for the researchers to thoroughly describe a procedure in which they will conduct their studies in terms of identifying, discussing, predicting, evaluating and analyzing some researched phenomena [75-77, 79]. The aim of having a relevant research methodology within a research field is to have a logical sequence of the following aspects [75, 77, 78];

- Comprehensive literature study to deduce a practical existing problem and gain a thorough insight on the selected topic of research.
- Formulation of a hypothesis to derive facts to be tested and proven. This allows us to direct the focus of the research on what can be expected at the end of the research, and should it not produce the desired results, deduce what caused it.
- Design of the proposed research
- Execution of the proposed research
- Data collection: This stage of the research is based on the type of research conducted (qualitative or quantitative research) where the data will be collected either via simulations or collecting samples externally.

- Data analysis: This stage of research involves the analysis of the collected raw data from the data collection stage to deduce meaningful, logical and analytical thinking and reasoning and interpretations. It involves data tabulations and data statistical deductions.
- Hypothesis testing, if a hypothesis is proposed
- Data evaluation for data generalization, summarization and interpretation.
- Recommendations and conclusions.

However, to conduct research using a specific research methodology, relevant research methods are to be selected [75, 77, 78, 80-82]. Methods are concerned with the techniques of data collection, techniques for identifying relationships in the collected data, research connections, and contributions in the specific field, and the evaluation of the collected data for accuracy, precision, and consistency [75, 77, 80-82]. In the field of Computer Science, relevant research questions can be answered using several methods such as simulation method, theoretical method, case studies and experimental method [83, 84]. Moreover, a proper research design is critical to achieving the desired results expected of the research [78-82].

In the context of this research, the aim is to design and develop a strategy to address the challenge of energy inefficiency in CRSN caused by the combined effect of both WSN and CR. To achieve this, appropriate research methodology has to be chosen and followed throughout the course of this research in order to achieve a novel solution to theoretically and practically existing problems. In this case, this research framework is captured in Figure 3.1 and the detailed constructive research is discussed in-depth in Section 3.3. Moreover, the research is designed and appropriate research methods identified and selected in order to meet the aim and objectives defined in Chapter 1, sub-section 1.5. Additionally, effective data collection and analysis methods are outlined and the evaluation and administrative procedures are discussed.

3.3 Research Methodology

This section presents the methodology applied in this research.

3.3.1 The Constructive Research

Constructive research is a critical research methodology in Computer Science and is aimed at producing new knowledge and provides novel solutions to theoretically and practically

existing problems. The constructive research methodology followed to achieve the aim defined in this research is discussed as follows:

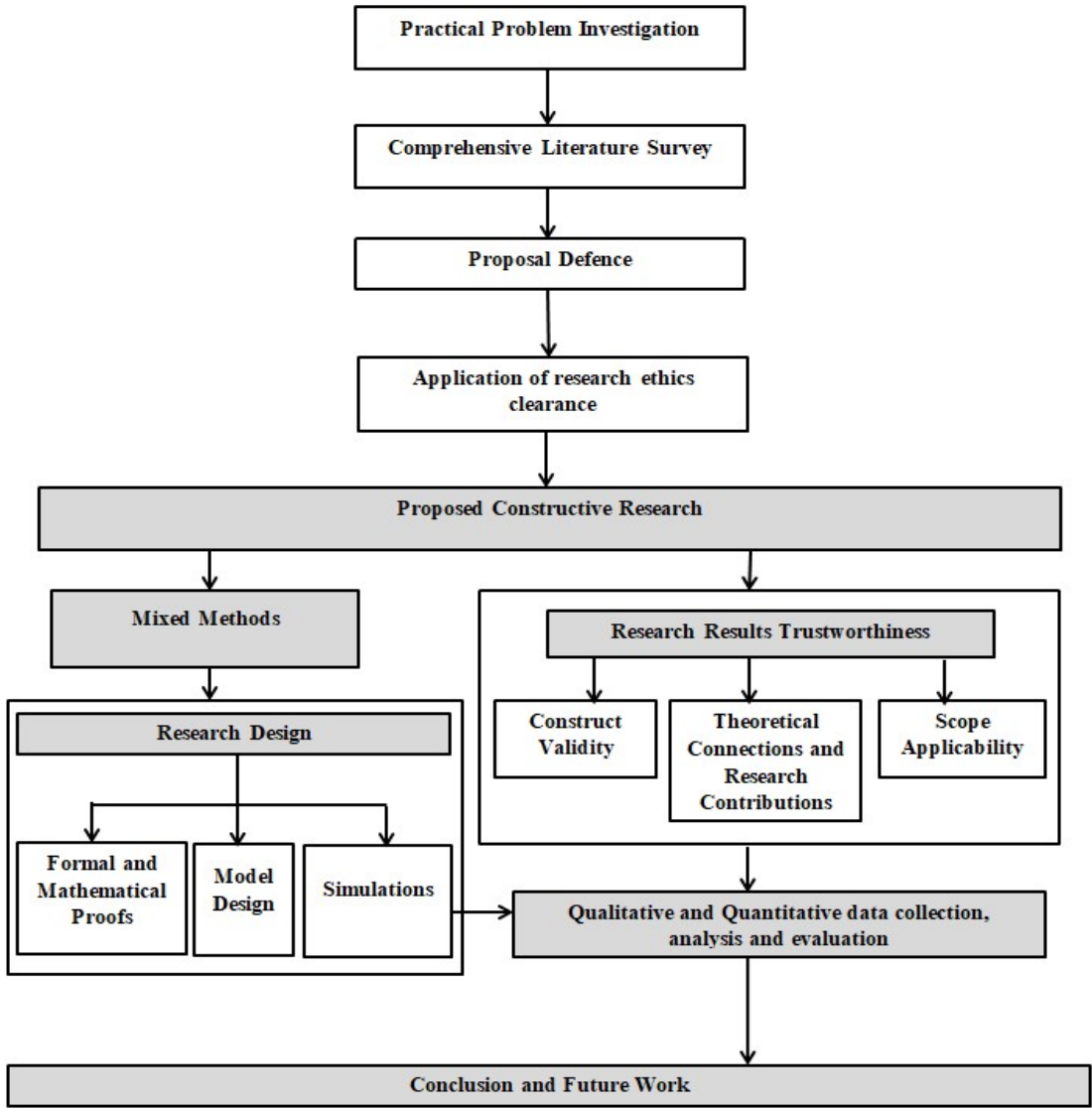


Figure 3.1: Research Work Flow

- a) **Practical Problem Investigation:** This is the first step and task performed in this research. It involves getting an insight survey on the energy inefficiency challenges of CRSNs and the basis of identifying an existing practical problem as well as the nature of the energy-inefficiency problem in order to devise strategies that will proffer a solution to overcome the identified problem.

- b) Comprehensive Literature Review:** A clear understanding of our identified research problem and the topic will be driven by conducting an insight survey and analysis of the existing energy inefficiency challenges of WSN and CRs and their impacts on CRSNs paradigm, use of clusters, DSA, sleep-wake scheduling mechanism in CRSNs and the MAC protocols. This was achieved by performing a comprehensive literature survey in Chapter 2.
- c) Construct Innovation/design:** By adopting the constructive research methodology, the scope of promoting the design of the proposed construct/mechanism will be possible based on improving the existing energy efficient mechanisms. That is, the insights from the literature review conducted on the existing energy inefficiency challenges will be employed. The design will be driven by the collection of information based on the use and implementation of the chosen clustering algorithm, S-MAC protocol, DSA and sleep-wake scheduling mechanism in CRSNs.
- d) Construct Validity:** To show that the existing identified problem can be solved with the proposed construct; a construct prototype will be designed and implemented. Although, other researchers have already proposed energy efficiency mechanisms using DSA and sleep-wake scheduling mechanism, the approach in the context of this research is based on introducing a traditional energy efficient clustering approach, but implemented with minimized duty cycle S-MAC protocol which supports asynchronous sleep-wake and neighbor-node synchronization. To validate the proposed mechanism, simulations will be used to test the performance and the effectiveness and validate the trustworthiness of the collected simulation data. Moreover, the complete research will be published in peer-reviewed conference proceedings and journals.
- e) Theoretical Connections and Research Contribution:** Upon completion of this research, this research has identified what we have accomplished and to what extent our proposed solution offers improvement and energy efficiency in clustered CRSNs. In essence, the solution offered in this research will be evaluated against what others have done in the literature.

- f) Scope applicability:** Based on the results obtained in the simulations, the proposed energy efficient mechanism for CRSN can be recommended for deployment in real world scenarios to demonstrate its effectiveness in resource management of CRSN.

3.4 Research Design and Approach

This section presents the design and the approach utilized in this research to meet the defined aim and objectives.

3.4.1 Research Design

Research design is the blueprint outlining how the identified existing problem is addressed and how the proposed solution achieved the desired research goal [80-82]. The research design strategies are conducted based on the chosen research methods that are used to answer the outlined research questions in sub-section 1.3 of Chapter 1. To this end the research methodology and methods are the key factors of selecting relevant research design strategies. In the context of this research, the research design strategies have been sequentially arranged and executed. This is shown in Figure 3.2.

3.4.2 Research Methods

Research methods are a critical part of any research; hence it necessitates the researcher to be clear and thorough on which appropriate method(s) will be used to conduct the research study on the identified research area. It is a more generalized guideline framework followed to conduct a research in which different research questions will be tackled to proffer a solution to the identified research problem [80-82]. Moreover, the research methods are used differently with a specific goal based on the identified research area. The identified research methods used for this research are as follows:

- a) Comprehensive literature review:** This method was employed to identify the existing problem and other related works on the research area. The goal was to gain insights and knowledge of what has been done to deduce appropriate solutions and techniques. This was performed in Chapter 2.
- b) Formal and mathematical proofs:** The design of the proposed solution was based on the cognition process which needs mathematics and logic to use relevant rules to proffer correct results through calculations before simulations. Through this method, only specific properties are identified and used to design the proposed solution. In this case, four aspects of the proposed energy efficient mechanism are considered for developing

and designing the proposed mechanism; these aspects are; sleep-wake scheduling, nodes awareness, cognitive sensor nodes clustering, and DSA; all these aspects required a thorough selection of relevant algorithms and rules/equations before simulating the designed energy-efficient CRSN mechanism. This allowed us to make proper calculations to avoid ambiguous operations of the proposed mechanism.

- c) *Model design*: Based on the knowledge gained from the literature review and the formal and mathematical proofs and computation, the framework or model of the proposed solution was designed. Moreover, the model was supported with Software Engineering analysis and design models such as use case diagram and sequence diagrams to model the overall flow of data in the network, the sequence of the sleep wake scheduling between the clustered sensor nodes and lastly the sequential order of dynamic spectrum.
- d) *Simulations*: Simulations are used to avoid costs that could be incurred in real world operation. Based on the design of the proposed construct, the appropriate tool was used to conduct simulations to collect the data, analyze, and evaluate the performance, effectiveness, and trustworthiness of the proposed solution. A suitable tool for simulations was chosen that supports the CR properties namely:
 - a. dynamic spectrum access to avoid unnecessary interference for channel selection, and
 - b. the sleep wake scheduling to control the network data flow and clustering to partition the network into sub-networks.

Six S-MAC with several duty cycles have been simulated on the proposed designed CRSN mechanism. The essence is to allow analyzing and validating the results and choose the most energy-efficient SMAC best performing duty cycle that will be used for real world implementation of energy-efficient CRSN.

In reality, both the research methods and research design correlate and are used jointly to allow further extensions and changes of the research should it be necessary to do so. This is, if the research design is altered then, possibly, the research methods might change or lead to the selection of a relevant research method that correlates to the new research design and vice versa. The proposed solution design and approach in this research is shown in Figure 3.2.

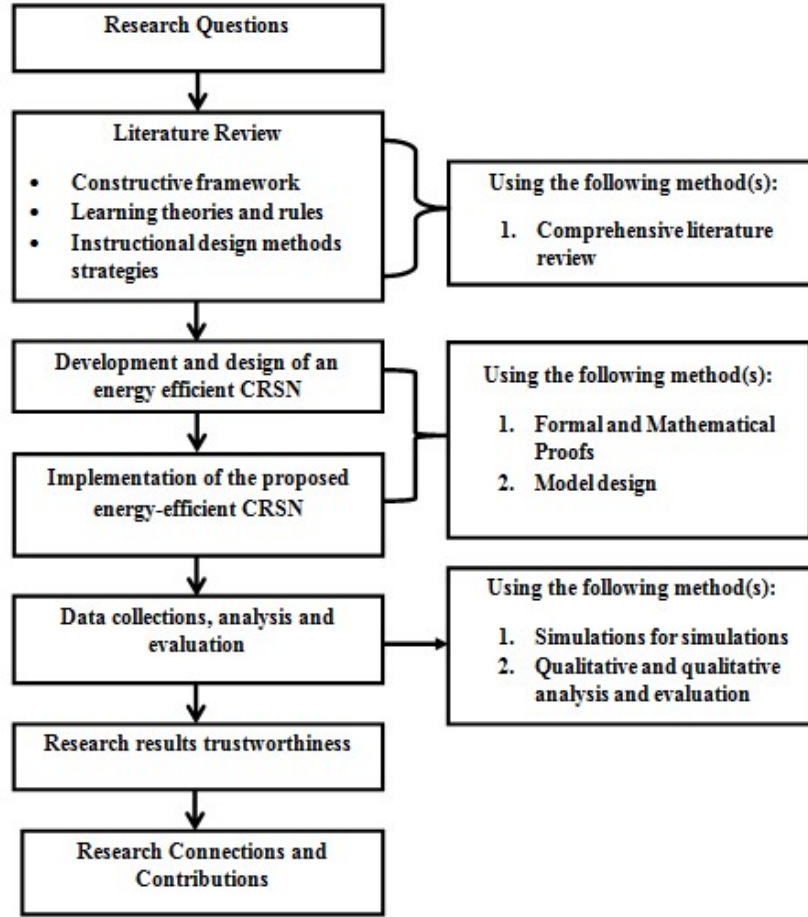


Figure 3.2: Research design and approach

3.5 Data Collection and Analysis

In the context of this research, data was not collected externally, but rather generated from simulations of the proposed energy efficient CRSN mechanism. Data analysis can be regarded as one of the crucial stages of any research where it requires interpretation of collected data which can be based on logical and analytical reasoning to uncover patterns, trends and relationships for easy understanding. However, data was collected and analysis performed on simulated six different S-MACs duty cycles of 3%, 5%, 10%, 15%, 25%, and 50%.

Moreover, due to the aim of this research and the research methods chosen, both data collection and analysis were done qualitatively and quantitatively. This is important to provide a firm guideline for conducting the research in order to achieve the desired objectives and proffer solutions to the outlined research questions [80, 82].

Qualitative analysis is based on the exploratory approach of the proposed work to gain insights into the identified motives and opinions. The aim is to uncover trends and have a clear insight of the identified problem and proposed relevant hypothesis and ideas [81, 82, 85-89]. It involves research connections and contributions to uncover trends and future research directions. In this research context, this provided a guideline for us to conduct a survey on the existing energy inefficiency challenges in CRSNs and to identify the existing practical problem and propose an appropriate solution to overcome the challenge.

This is achieved via:

- Literature review – in-depth understanding of the simulated S-MAC duty cycles and metrics used for measuring effectiveness and performance was performed.
- Challenging the assumptions made towards the proposed research (if any).

Quantitative analysis is numerical and the analysis follow mathematical and statistical methods [81, 82, 85-87]. In the context of this research, it aids us in comprehending the performance, effectiveness, and trustworthiness of the solution offered through the simulation results. That is, it is based on analysing the data generated by simulations and determining the extent to which existing solutions have been improved by the solution in this research. This was achieved through:

- Conducting simulations several times for accuracy and consistency
- Collecting data for analysis and presenting them in visualized graphs
- Considering significant changes (if any) in data.

3.6 Research Evaluation

Data collection and data analysis set the stage for research evaluation, where the proposed research and results are evaluated in terms of trustworthiness. The evaluation was done qualitatively and quantitatively. The S-MAC protocol and K-Means clustering protocol was considered to be critical for evaluation and effectiveness, however; this protocol lead to evaluating the proposed solution using the following metrics:

- *Throughput* which measures the amount of successfully transmitted packets in a channel.
- *Average consumed energy* which measures the overall amount of energy consumed in the network.

- *Residual energy* which measures the total amount of energy remaining in the network.
- *End-to-end delay* which measures the difference in packet transmission time from the source to the destination.

Performing these evaluations helps to:

- 1) Provide contextual data collected to address issue(s) identified in identifying the existing practical problem and also answer the questions (why did it happen, how did it happen and what caused it) raised by the quantitative data.
- 2) Measure the breadth and depth of the collected data generated before and after the simulations of the proposed solution. This involves
 - a. Data generalization/collection - data collected through samples or simulations,
 - b. The data analysis -summarization and interpretation of the collected data, and
 - c. The precision and consistency evaluation – accuracy of simulations.

Another important way of evaluating and ascertaining the trustworthiness of this research solution is by submitting scientific academic articles to peer reviewed and accredited conferences and journals.

3.7 Administrative and Ethical Procedures

This is the administrative procedure required by the faculty and the department of Computer Science at the North-West University Mafikeng Campus to authorize the administration of this research and its approval. To conduct the proposed study, three major activities are required; proposal writing, defending the research proposal, conducting corrections outlined by the department during proposal presentations, and the submission of research ethics clearance application. The research proposal was successfully defended on the 30th of August 2018, followed by correcting the final proposal based on recommendations from the team of reviewers which was submitted on the 3rd of October 2018. Accordingly, the proposal corrections in table format was submitted to the head of research on the 5th of October 2018, and lastly was the application of the research ethics which was submitted to the department on the 3rd of September 2018.

The research ethics clearance serves as an obligation between the department, supervisor and the supervisee so as to have a mutual understanding of the principles to conduct the proposed study. To this end, an ethics clearance form was filled and submitted to the relevant

school/faculty representative of the Human Ethics Committee for onward processing and approval by the Chair of the research ethics committee. Once submitted and approved, the ethics clearance certificate was issued signaling the go ahead of the research.

3.8 The Stages of the Research Study

This section presents the overall framework of this research aimed at meeting the aim and objectives defined in this research study. Figure 3.3 shows the framework which depicts how the research was conducted in several research stages from literature review to the final phase which is evaluating the trustworthiness of the collected research results. That is, it demonstrates the specific steps to be followed to proffer a solution to the identified practical problem by achieving the desired objectives which supports the outlined research questions.

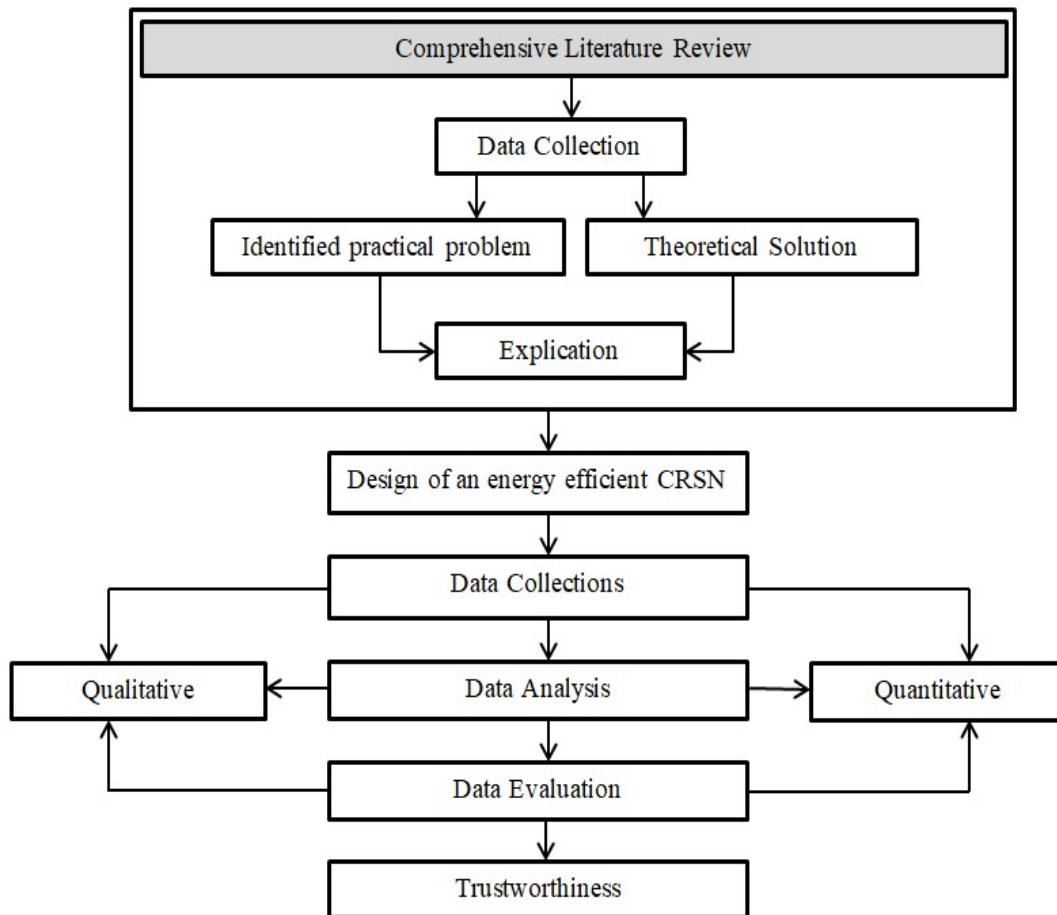


Figure 3.3: Overall research framework

As shown on Figure 3.3, a comprehensive literature review was carried out as shown in Chapter 1 and Chapter 2. The literature study was based on qualitative data collection which

involved in-depth understanding of the research area and identifying the practical problem that affects the proposed research area. Based on the knowledge gained, a practical solution was proposed to solve the identified practical problem. However, both the identified practical problem and the proposed solution are to be explained. That is, the identified practical problem was thoroughly analyzed to reveal its root causes within the researched area, what solution strategy will be employed that will address the identified practical problem, and to what extent the proposed solution will improve the identified problem.

To achieve the aim, the proposed solution was carried out by designing an energy-efficient CRSN mechanism to address the problem of energy inefficiency in CRSN. Detailed qualitative and quantitative data collection and analysis as well as data evaluation are discussed in sections 3.6 to section 3.8. In chapter 4, the actual energy efficient CRSN mechanism to solve the energy inefficiency is proposed, designed, and implemented. In this case, simulations are conducted to collect the data to be used for analysis and evaluations. The simulations are carried out several times for data accuracy and consistency. The essence is to determine whether the outlined objectives are met and the research questions are tackled thoroughly. Table 3.1 summarizes the relationship between the collection, analysis, and evaluation of data in this research study.

Table 3.1: Data collection, Analysis and Evaluation Relationship

Procedure	Qualitative	Quantitative
Data Collection	• Literature • Challenging assumptions made beforehand (if any)	• Simulations
Data Analysis	• Research connections and contributions	• Extent of improving existing mechanism • Data changes observation
Data Evaluation	• Tackling the why, how and what questions raised by quantitative data	• Data generalization • Data summarization • Data precision and consistency

3.9 Chapter Summary

This chapter presented the comprehensive research methodology employed in the course of this research. It discussed the constructive research methodology to meet the desired aim of the proposed research study, the research methods, and the research design which are crucial stages of the research. It also discussed the administrative and ethical procedures, outlining

the relevant protocol of conducting the proposed research study. Moreover, the overall steps followed in this research study were shown and discussed.

Chapter 4

CRSN Energy-Efficient Framework

4.1 Chapter Outline

This chapter discusses the proposed energy-efficient mechanism for CRSN. It starts with a system overview and progresses to discussion on its mechanisms. The energy-efficient mechanism is based on the system analysis involving the system requirements, system modelling, its architectural design, and operations. Lastly, we provide a summary of the chapter.

4.2 Introduction

In this chapter, an energy-efficient mechanism for CRSN based on clustering and asynchronous sleep-wake scheduling is proposed and designed with two unsupervised and ad-hoc energy-aware approaches: S-MAC protocol and the K-Means clustering. The S-MAC protocol is a contention-based CSMA/CA MAC layer protocol used to improve the energy consumption using low duty cycle where the designed energy-aware CRSN mechanism is based on the following operations:

- 1) Periodic/asynchronous sleep-wake and DSA when nodes are in scheduling and listening phase before data transmission, neighbor node synchronization to reduce overheads when nodes are scheduled for data transmission, and
- 2) K-Means clustering algorithm which reduces the overall energy consumption of the network by partitioning the network into small networks (i.e., clusters) to reduce the network complexities as it has been argued by some researchers that clustering minimizes high energy consumption when implemented in WSNs[49, 90-95].

The choice of these two approaches is based on the comprehensive literature conducted in chapter 2; where several researchers implemented these protocols separately, mostly in the context of WSNs. The existing implementations either used S-MAC alone or proposed own clustering algorithms or improved existing clustering protocols, or implement K-Means and then proposed their own sleep-wake mechanisms. Moreover, K-Means is an unsupervised protocol which also supports energy-efficiency and less network complexities while S-MAC is an energy-efficient protocol which can support an unsupervised approach through its duty-cycling [17-23]. However, in the context of this research, we are proposing a different

energy-aware mechanism which merges both K-Means and S-MAC and implemented with CR capabilities and dynamicity. The incorporation of both to produce a hybrid model in CRSN will yield an energy-efficient, ad-hoc with less complexities and easy to use model.

Furthermore, the cognitive sensor nodes in CRSN communicate through a shared medium (spectrum). However, without a relevant MAC protocol in the network to enforce discipline about the channel access, the shared information can get lost or intercepted due to collisions, overhearing or interferences of other devices. Although MAC implementation can maximize several factors such as latency, throughput, and spectrum utilization, the energy efficiency is of great importance due to inherent energy constraint nodes in WSN. Thus, the need of MAC protocol that can support energy efficiency [96] is highly indispensable. Accordingly, due to the nature of sensor nodes being battery powered in particular, the network can suffer from four major factors which are sources of high energy consumptions: 1). overhearing of transmitted packets over a shared wireless channel, 2). packet collisions which need packet retransmission to deliver the packet successfully, 3). control packet overhead where the sender and the receiver exchange packets, and 4). repetitive sensor nodes idle listening where the sensor nodes can consume huge amount of energy by repetitively listening to an idling channel to receive the relayed data [97],[98]. To address the challenge of incessant energy consumption in this research, an ad-hoc contention based CSMA/CA energy-efficient CRSN mechanism with periodic sleep-wake scheduling and less complexities is proposed, designed, and implemented. Our proposed CRSN energy-efficient mechanism is composed of two phases:

- 1) **Phase 1:** Cluster formation process using K-Means clustering algorithm where the cognitive wireless sensor nodes are grouped into small networks according to their similar characteristics, and
- 2) **Phase2:** S-MAC implementation to support periodic/asynchronous sleep-wake scheduling where the DSA occurs when the cognitive sensor nodes are in both scheduling and listening phase.

However, the proposed mechanism does not focus on two things:

- 1) PU detection is not considered as this research proposed a fixed channel allocation to the PU where only the PU can transmit the data, and
- 2) This research does not consider improving or designing a new cluster head selection algorithm as the implemented K-Means clustering algorithm allows choosing cluster

head nodes initially as centroids, where the nearby nodes will be grouped to the nearest centroid after the completion of K-Means. The clustered nodes transmit their data directly to the base station in a single-hop manner. For this fact, cluster head node operational complexities will be minimized. Thus, less energy will be consumed as its responsibility is only to partition the network into clusters.

Accordingly, with the implementation of the S-MAC protocol, the neighboring nodes should be in listening mode to transmit data in between. However, this might lead to latency, packet re-transmission which causes high energy consumptions, and if the receiving node in communication phase is sleeping then the active node (sender) will be forced to idle until the receiving node is active again.

4.2.1 System Architecture

The proposed system architecture shows different components that support the system to operate to its full desired potential. The system architecture is illustrated in Figure 4.1.

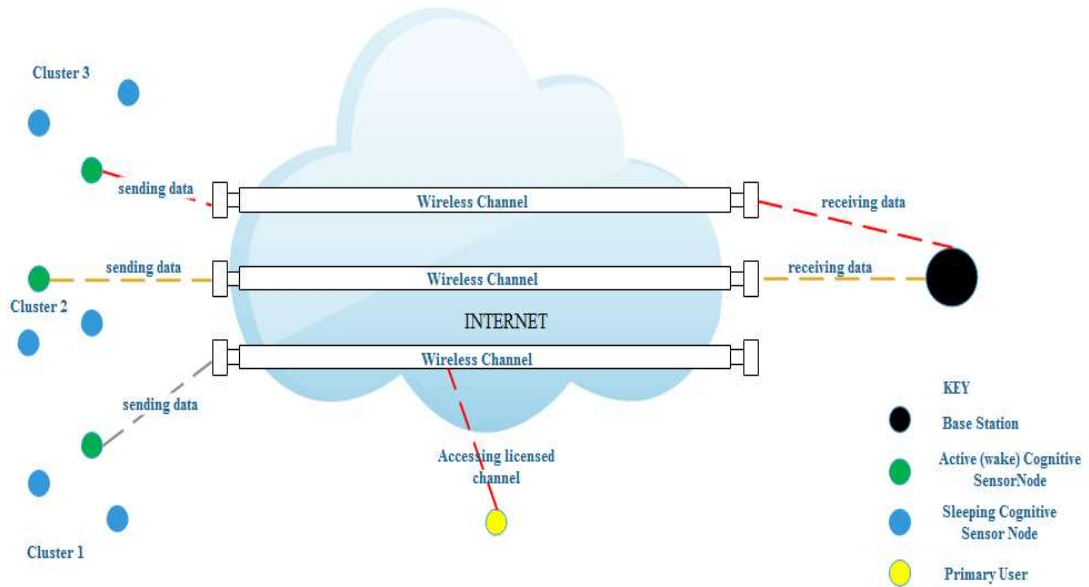


Figure 4.1: Proposed system architecture

- a) *Cluster*: This is created using the K-Means clustering protocol to group the cognitive sensor nodes with similar characteristics.

- b) *Wireless channels*: These are used as data carriers between the sensor nodes and the base stations. They also function as the channel completion platform for the sensor nodes wishing to communicate with the base station.
- c) *Internet*: This is the intermediary platform which allows wireless transmission between the sender and the receiver through a wireless channel.
- d) *Base station*: This communicates directly with the sensor nodes which won the wireless channel using Request-to-Send/Clear-to-Send (RTS/CTS) packets.
- e) *PU*s: These are the licensed users who can access the licensed channel in their own preference.

4.2.2 Assumptions

In this research, the proposed network is implemented with a base station that is always active, where the wake cognitive sensor will only be transmitting the data to the base station to avoid high latencies that might be caused by sleeping receiving cognitive sensor nodes within each cluster.

- a) The systems constraints should be executed based on the desired systematic, sequential operations and functions of the proposed system; this is based on deploying the wireless sensor nodes equipped with cognitive capabilities to perceive and act upon their environment in an ad-hoc manner while maintaining less energy consumptions.
- b) The ad-hoc operations of the proposed energy-efficient mechanism should be executed for any desired phase in the system, clustering, and periodic sleep-wake scheduling using S-MAC, contention phase and the data transmission phase where DSA will be effective to avoid any undesired and uncontrollable interference.
- c) The proposed energy-efficient mechanism shall not consume more than 30% of the node energy within the stipulated time.
- d) The S-MAC protocol can only be executed efficiently provided that the K-Means has finished its execution successfully.

4.3 The Proposed Energy-efficient CRSN and Mechanism

This section provides detailed analysis and design of the proposed energy-efficient mechanism to proffer a solution to the outlined objectives and to address the identified

practical problem of energy inefficiency discussed in Chapter 1, sub-section 1.2. They are discussed as follows:

4.3.1 Energy-efficient Model

In this Section, a mathematical model is designed to minimize the energy consumption of the proposed energy-efficient mechanism. The mathematical model is based on the overall energy of the whole network which is formulated as:

$$E_o = E_c + E_s + E_L + E_{mode} \dots\dots\dots (4.1)$$

where:

E_o - the overall energy

E_c - the clustering energy

E_s - the sleeping energy

E_L - the listening energy

E_{mode} - the mode energy for switching between wake and listening mode

E_{RES} - the residual energy remaining after every operation that consumes energy

E_T - the transmission energy consumed during data transmission

E_R - the receiving energy consumed by cognitive nodes to receiver transmitted data

In the models below, energy (E) is computed as $E_i = P * T$ where power (P) is calculated as $P = I * V$ and T is the time taken to consume the energy either in wake or sleep mode, I is the current flowing in the radio, V is the voltage flowing in the radio, and i is the index of the calculated energy; where P , I and V are constant throughout.

Other relevant acronyms are:

E_{SYNC} - the synchronization energy consumed when cognitive nodes synchronize with their one-hop neighbor nodes

T_{sleep} - the sleep energy consumed by cognitive nodes when their radios are turned-off

T_{wake} - the idling/wake energy consumed by cognitive nodes when in listening mode to synchronize and transmit data

E_{SHARE} - the sharing energy consumed by cognitive nodes when they are sharing their scheduling tables with their one-hop synchronized neighbours

E_{CHAN} - the channel energy consumed by cognitive nodes when switching channels for data transmission

A. Clustering Energy (E_C)

In this perspective, the energy consumed on clustering for a clustering time(T_C) is directly proportional to the value of K (K_C) in K-Means and the clustering power (P),

$$E_C = (P * T_C) * K_C \dots\dots\dots (4.2)$$

$$P = I * V \dots\dots\dots (4.3)$$

Substituting (3) in (2) we obtain clustering energy as

$$E_C = (((I * V) * T_C) * K_C) \dots\dots\dots (4.4)$$

B. S-MAC Energy (E_S and E_L)

In this context, after the deployed SUs are clustered using K-Means clustering algorithm where E_C is consumed as shown in equation (4.4), the S-MAC phase is computed next to schedule cognitive sensor nodes sleep-wake scheduling. The total S-MAC energy consumed to schedule the sleep-wake phases are of two forms:

$$\text{Sleep energy, formulated as } E_S = (E_C - (P * T_{sleep})) \dots\dots\dots (4.5)$$

$$\text{Listen energy, } E_L = E_S - (E_{SYNC} + E_{SHARE} + E_{CHAN} + E_T + E_R) \dots\dots\dots (4.6)$$

T_{wake} is the wake time, and T_{sleep} is the sleep time.

C. Synchronization Energy (E_{SYNC})

In the transmission phase, SUs are to be aware of their neighbours by synchronizing with their 1-hop neighbours so that their schedule tables may be shared

$$E_{SYNC} = (P * T_{wake}) \dots\dots\dots (4.7)$$

Substituting equation (4.3) in (4.7) the consumed energy for synchronization is:

$$E_{SYNC} = ((I * V) * T_{wake}) \dots\dots\dots (4.8)$$

D. Schedule table sharing energy (E_{SHARE})

The SUs schedule tables are to be shared between 1-hop synchronized clustered SUs for the stipulated wake time. Thus, the consumed energy for sharing tables is given by:

$$E_{SHARE} = P * T_{wake} \dots\dots\dots (4.9)$$

Accordingly, substituting equation (4.3) in (4.9) the consumed energy for sharing schedule table becomes:

$$E_{SHARE} = (E_{SYNC} - ((I * V) * T_{wake})) \dots\dots\dots (4.10)$$

E. Channel competition energy(E_{CHAN})

When two or more SUs in listening mode wishing to transmit data to the base station in the same channel at the same time, channel competition occurs, and this phase uses RTS packets $P_{(RTS)}$ and CTS packets (P_{CTS}) to overcome the interference. In this case, energy is calculated for both the transmission and the reception of RTS and CTS packets.

i) *RTS Packet (P_{RTS}) energy*

$$E_{RTS} = (E_{SHARE} - (P * T_{wake}) * P_{RTS}) \dots\dots\dots (4.11)$$

Substituting equation (4.3) in (4.11) the consumed energy for transmitting RTS packets is

$$E_{RTS} = (E_{SHARE} - (((I * V) * T_{wake}) * P_{RTS})) \dots\dots\dots (4.12)$$

ii) *CTS Packet (P_{CTS}) energy*

$$E_{CTS} = (E_{RTS} - ((P * T_{wake}) * P_{CTS})) \dots\dots\dots (4.13)$$

Substituting equation (3) in (13) the consumed energy for transmitting CTS packets is

$$E_{CTS} = (E_{RTS} - (((I * V) * T_{wake}) * P_{CTS})) \dots\dots\dots (4.14)$$

Therefore, the final channel competition energy is $E_{CHAN} = (4.12) + (4.14)$

$$E_{CHAN} = E_{RTS} + E_{CTS}$$

$$E_{CHAN} = (E_{SHARE} - (((I * V) * T_{wake}) * P_{RTS})) + (E_{RTS} - (((I * V) * T_{wake}) * P_{CTS})) \dots\dots\dots (4.15)$$

F. Transmission Energy(E_T)

The energy consumed for data transmission is directly proportional to the P and the data transmission time (D_T). However, the data is transmitted in fragments one-by-one as:

$$D_{FRAG} = \frac{1}{data} \dots\dots\dots (4.16)$$

and the energy is given as:

$$E_T = (E_{CHAN} - ((P * T_{wake}) * D_{FRAG})) \dots\dots\dots (4.17)$$

By substituting equation (4.3) and (4.16) in (4.17), the consumed energy for transmitting data fragments now becomes:

$$E_T = (E_{CHAN} - (((I * V) * T_{wake}) * \frac{1}{data})) \dots\dots\dots (4.18)$$

G. Reception Energy (E_R)

For every packet received, an ACK packet is sent to the sending wake SU during time T_{wake} , where the reception energy consumed is directly proportional to the P and each fragment sequence number (F_{SEQ}) transmitted and acknowledged. The transmission energy is given by:

$$E_R = (E_T - ((P * T_{wake}) * F_{SEQ})) \dots\dots\dots (4.19)$$

By substituting (4.3) in (4.19), the reception energy is then:

$$E_R = (E_T - (((I * V) * T_{wake}) * F_{SEQ})) \dots\dots\dots (4.20)$$

Moreover, synchronization, sharing, channel, transmission, and reception energies compute the listening energy as follows:

$$E_L = E_S - (E_{SYNC} + E_{SHARE} + E_{CHAN} + E_T + E_R) \dots\dots\dots (4.21)$$

Then, substituting all these energies we obtained the final listening energy as follows:

$$E_L = [E_S - ((I * V) * T_{wake}) + (E_{SYNC} - ((I * V) * T_{wake})) + (E_{SHARE} - (((I * V) * T_{wake}) * P_{RTS})) + (E_{RTS} - (((I * V) * T_{wake}) * P_{CTS})) + (E_{CHAN} - (((I * V) * T_{wake}) * \frac{1}{data})) + (E_T - (((I * V) * T_{wake}) * F_{SEQ}))] \dots\dots\dots (4.22)$$

H. Mode Energy (E_{mode})

E_{mode} is the energy consumed when SUs switch off their radio from listening to wake modes, and it is given by:

$$E_{mode} = (E_L - (\frac{P_{SWITCH}}{2} * T_{sleep})) \dots\dots\dots (4.23)$$

Accordingly, its consumed P is given by:

$$P = (I_{sleep} - I_{wake}) * V \dots\dots\dots (4.24)$$

By substituting (4.24) in (4.23), the switching energy is then obtained as follows:

$$E_{mode} = (E_L - ((\frac{I_{sleep} - I_{wake}}{2}) * V) * T_{sleep}) \dots\dots\dots (4.25)$$

I. Overall Energy (E_o)

Based on the above computed energies consumed, the overall energy, therefore, is the sum of all the energy computed as shown in equation (4.1). By substituting all the formulated equations (4.2)-(4.25), a minimized overall energy is obtained as follows:

$$E_o = (((I * V) * T_c) * K_c) + (E_c - (P * T_{sleep})) + [E_s - ((I * V) * T_{wake}) + (E_{sync} - ((I * V) * T_{wake})) + (E_{share} - (((I * V) * T_{wake}) * P_{rts})) + (E_{rts} - (((I * V) * T_{wake}) * P_{cts}))]] + (E_{chan} - (((I * V) * T_{wake}) * \frac{1}{data})) + (E_t - (((I * V) * T_{wake}) * F_{seq})) + (E_L - ((\frac{I_{sleep} - I_{wake}}{2}) * V) * T_{sleep}) \dots\dots\dots (4.26)$$

4.3.2 Phase 1: K-Means Clustering Algorithm

The traditional K-Means clustering is discussed in depth in Chapter 2, sub-section 2.8.7. In this Section, we discuss in detail how the algorithm is implemented for cluster formation in the context of this research. The steps applied are as follows:

The steps:

- i. In this research context, K is initialized to 3; $K = 3$ (where 3 is the number of the desired clusters $C_l = \{C_1, C_2, C_3, \dots, C_k\}$, which implies 3 cognitive sensor will be initialized as cluster heads).
- ii. For each given set of cognitive wireless sensor nodes ($C_{s1} \dots C_{sn}$), their Euclidean distance d will be calculated between them and all the three chosen centroids. We used the following Euclidean distance formula to calculate the distance:

$$d = \|C_{sn}(x, y, z) - C_k\| \dots\dots\dots (4.27)$$

where:

- C_{sn} is the cognitive sensor node.
- (x, y, z) represents the coordinates each cognitive wireless sensor node has, and

- C_k represents the centroid in which the distance is measured to it from the cognitive wireless sensor node (C_{sn}).
- iii. The cognitive wireless sensor nodes will then be grouped to the cluster with the nearest centroid to them.
- iv. After the Euclidean distance d is computed for all the cognitive wireless sensors and they are clustered to the nearest centroid based on d , the re-calculation of a new cluster centroid position will be conducted using the following formula:

$$C_k = \frac{\sum_{x \in C_k} \sum_{y \in C_k} \sum_{z \in C_k} \dots}{N} \quad (4.28)$$

- v. Repeat step iv until the tolerance value or error value is satisfied.

Figure 4.2 captures the deployed cognitive sensor nodes of the proposed energy-efficient mechanism clustering after completing steps i to v , provided step v is satisfied. Table 4.1 presents the pseudocode for K-Means.

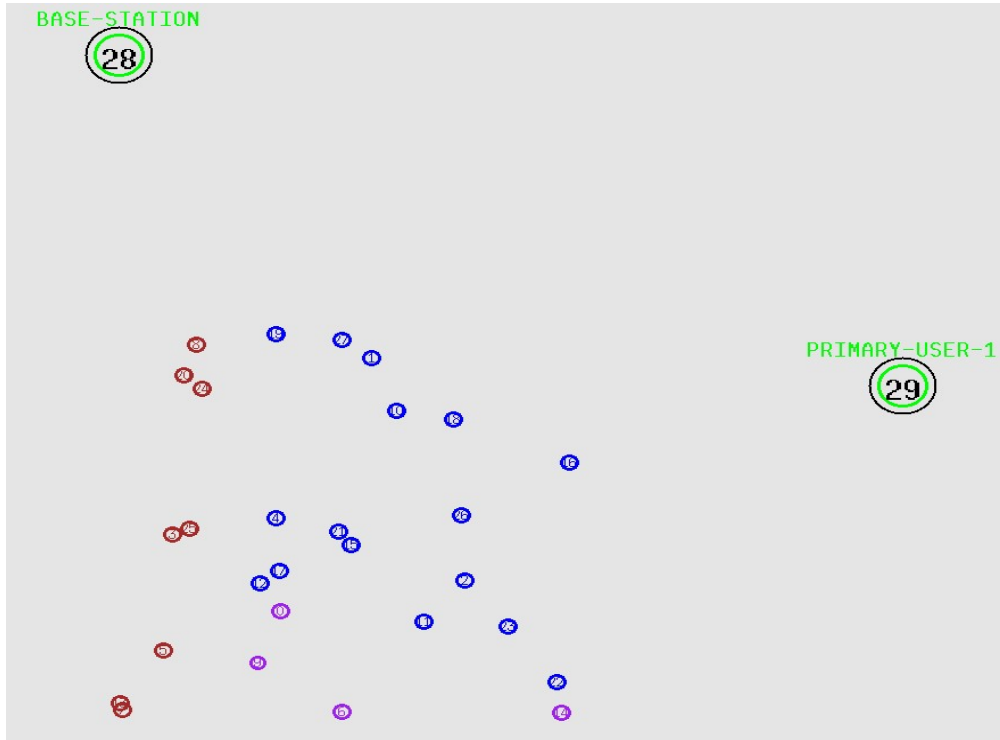


Figure 4.2: Clustered cognitive wireless sensor nodes

Table 4.1: K-Means Pseudocode

K-Means Pseudocode
Input: Unclustered SUs

Output: Clustered SUs

Steps:

- Set $K = 3$ (3 cluster heads chosen)
 - Calculate Euclidean distance " d " from cluster heads to SUs
 - Group SUs to the nearest cluster head
 - Re-calculate " d " until error-value is satisfied
 - Repeat 1-4 until clustering is complete
-

4.3.3 Phase 2: S-MAC Protocol

Following the successful K-Means clustering to partition the network into sub-networks, the S-MAC protocol will take effect to schedule data transmission where nodes will switch between sleep and wake mode periodically, depending on their desired activity using the S-MAC duty cycle. The protocol is designed to avoid collisions and interference so that two or more nodes are not transmitting at the same time in the same channel. Low duty cycles are used as a tradeoff for less energy consumption. It is implemented as the second technique for minimizing high energy consumptions following K-Means clustering. Though S-MAC is used for improving energy in WSN, in the context of this research it is incorporated with CR capabilities to produce CRSN S-MAC based protocol. It uses a fixed duty cycle to alternate the nodes periodically between the sleep and wake cycles. The cognitive sensor nodes in listening phase shall send and receive the data and the cognitive sensor nodes in sleeping phase are equipped with capabilities to switch off their radio to preserve energy. The nodes are put into sleep mode periodically using duty cycle to avoid cognitive sensor listening repetitively when it is not transmitting.

Accordingly, for S-MAC to function to its peak potential within the specified time frame, it is designed into three phases:

- 1) the periodic sleep-wake scheduling phase
- 2) the contention-phase with CSMA/CA for SUs free spectrum access and
- 3) Data transmission phase.

These phases are discussed in detail in terms of their implementation and functionalities in this research following the successful K-Means clustering technique. These phases are illustrated Figure 4.3.

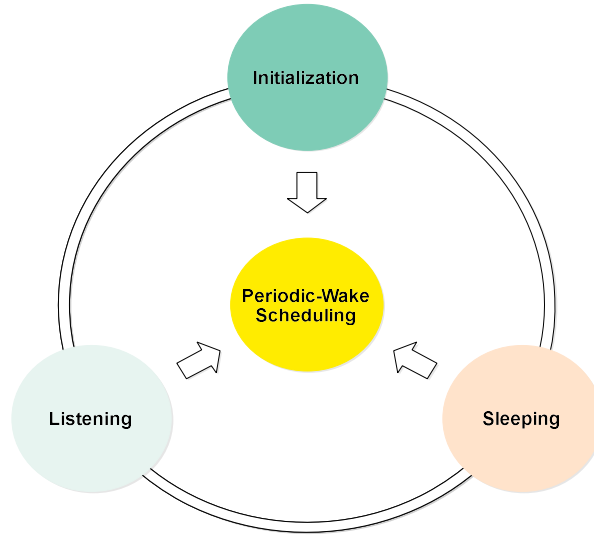


Figure 4.3: Period sleep-wake scheduling cycle

A. *Periodic sleep-wake scheduling phase*

To allow the cognitive wireless sensor nodes to periodically switch between sleep-wake modes, the S-MAC protocol is implemented for cognitive sensor nodes periodic sleep and wake mode. Each deployed cognitive sensor node will be implemented with three different fixed phases as shown in Figure 4.3. The algorithm of the operation is captured in Table 4.2. Moreover, the phases involved are discussed as follows:

Table 4.2: Periodic-Wake Scheduling Algorithm

Periodic-Wake Scheduling Algorithm
Input: Clustered SUs
Output: scheduled sleep-wake periodic time slots for cognitive wireless sensor nodes
Steps:
Sleep-wake schedule initiated for SUs
All SUs sleep for (T_{sleep})
At elapsed (T_{sleep}), SUs wake for (T_{wake})
For each cluster (C_i) {
Each SU sync with 1-hop neighbor
Each SU create their own scheduling tables
Sync'd SUs share schedule tables
Spectrum sharing occurs
Channel Competition for wake SUs wishing to transmit to base station
}

- a) *Initialization phase*: Cognitive sensor nodes are being deployed in a specific geo-location and clustered using K-Means clustering, each node will be allowed to initiate its own schedule for sleep and wake modes. After scheduling, all the deployed nodes excluding the base station and the PU will schedule their own sleep time for their chosen specified periodic sleeping time (T_{sleep}). After all the nodes schedule their sleeping time, they will be put into sleeping mode, and at the elapse of the periodic sleeping time, all the cognitive sensor nodes will be switched to wake mode to check if any node is transmitting. Sleep-wake scheduling will be repeated periodically until the battery life of the sensor nodes is depleted.
- b) *Sleeping phase*: For the cognitive sensor nodes to be put into a sleeping mode, they are equipped with a node radio and it will be switched off by a node based on the cognitive sensor node scheduled sleeping time.
- c) *Listening phase*: As shown in Figure 4.4, the node listening time is partitioned into two:
 - i. sync packet which shares the node ID and the sleeping time, and
 - ii. data packet which carries node information to be transmitted.

In this case, all the cognitive sensor nodes are equipped with the CR capabilities of scheduling their own sleep and wake time periods, but this can lead to overheads. In order to minimize the overheads, the following operations will occur within each cluster:

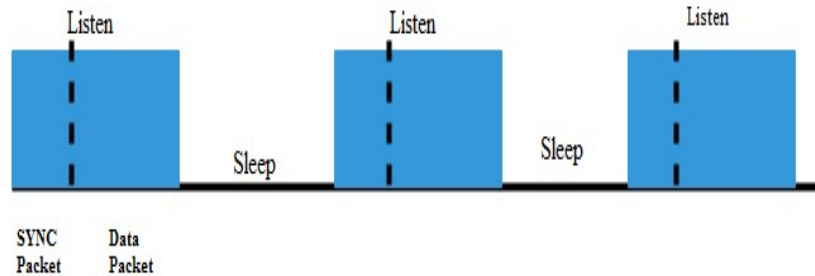


Figure 4.4: Listening time packet

- Each cognitive wireless sensor node is put in wake mode where it synchronizes with its 1-hop neighbor using a SYNC packet which can contain information such as the cognitive sending node id, wake, and sleep time, and the neighbor node ID.

- Synchronization will fail if communicating cognitive sensor nodes transmit data in a multi-hop manner. Figure 4.5 illustrates neighbor nodes synchronization in a single hop manner.

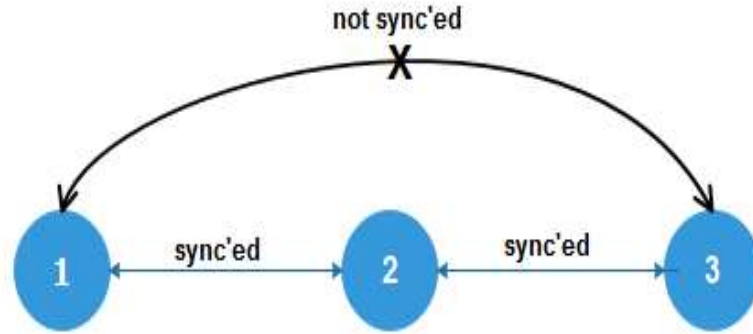


Figure 4.5: Neighbour node synchronization

Following neighbor node synchronization, the listening phase contains the following activities:

- 1) *Cognitive sensor nodes awareness (CSNA)*: In this state, all the cognitive sensor nodes will share their schedule tables with their neighbors. Node schedule is illustrated in Table 4.3, where Node ID is the sender's node, neighbor is the receiver, sleeping time (T_{sleep}) and waking time (T_{wake}) are for the sender. Figure 4.6 below illustrates nodes sharing their schedules with their neighbors.

Table 4.3: Node schedule table

Node ID	Neighbor	T_{sleep}	T_{wake}

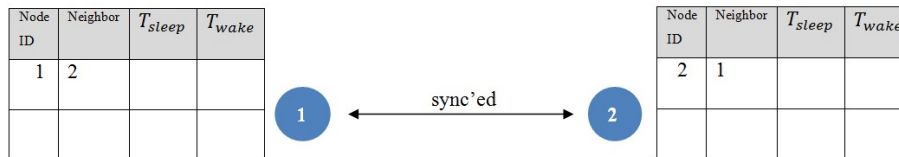


Figure 4.6: Neighbour nodes scheduling table

Cognitive sensor nodes awareness allows the nodes to update their scheduling tables after sourcing the information about their neighbors for easy data transmission and reducing overheads.

- 2) *Spectrum Sharing*: The network operates with multiple channels and multiple node radios to reduce congestion and overheads in a single channel when data is transmitted to the base station. However, should multiple nodes in wake mode wish to occupy the free channel, this will lead to channel competition state.
- 3) *Channel competition state*: In this state, cognitive sensor nodes are put into adaptive listening mode only if they are involved in communication in which they wake up on the occurrence of hearing their neighbors' transmission(s). The cognitive sensor nodes in listening phase will compete for the channel using RTS/CTS packets. The transmitting nodes will transmit RTS packets to the receiver (base station), and if the transmitting node RTS packet reaches the base station first as compared to other nodes, that node will win the channel and the base station will send back the CTS packet to the sender node to authorize the node to transmit. If a cognitive sensor node overhears an RTS/CTS packet in the channel, it turns off its radio and wakes up after the end of data transmission at its elapsed sleeping time. However, justified in Chapter 1 under research scope and limitation and Chapter 4 overview paragraph four, the PU does not compete for the channel, as within the created multi-channels it has been allocated a fixed channel to utilize anytime it wishes to transmit; this will reduce delays and interference in the channel.

B. Contention phase

The contention phase deals with DSA to avoid unwanted collisions, overhearing, and interferences amongst the clustered cognitive sensor nodes that are synchronized with their neighbors and the base station.

Each cognitive sensor node within each cluster synchronizes with its neighbor to share their scheduling tables. These cognitive sensor nodes are configured to use the same number of channels and radios. The cognitive sensor nodes transmit the data directly to the base station to avoid depleting the cluster head energy quickly by relaying the data to and from the base station as well as storing each node schedule to select the channel for data transmission.

As shown in Figure 4.7, say in cluster with blue colored nodes, if “cognitive sensor node 1 (C_{n1})” is a single hop neighbor node of “cognitive sensor node 2 (C_{n2})”, then they will exchange their scheduling tables. This is illustrated with the following pseudocode:

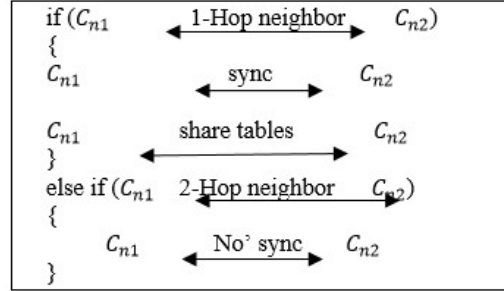


Figure 4.7: One-hop neighbour node synchronization process

If C_{n1} is transmitting to the base station, then C_{n2} goes to sleep for its chosen periodic sleep time T_{sleep} ; this is because C_{n2} has the scheduling table of C_{n1} and vice-versa, so both are aware of their neighbors schedules.

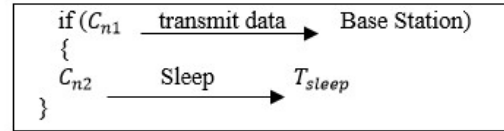


Figure 4.8: One-hop neighbour node awareness

If cognitive sensor nodes from the same cluster or even different clusters wish to transmit data at the same time to the base station, then channel competition occurs.

a) Channel competition phase

In sub-section A above, sleep-wake scheduling, the channel competition is discussed, however, in this sub-section channel selection will be presented using the pseudocode shown in Figure 4.9.

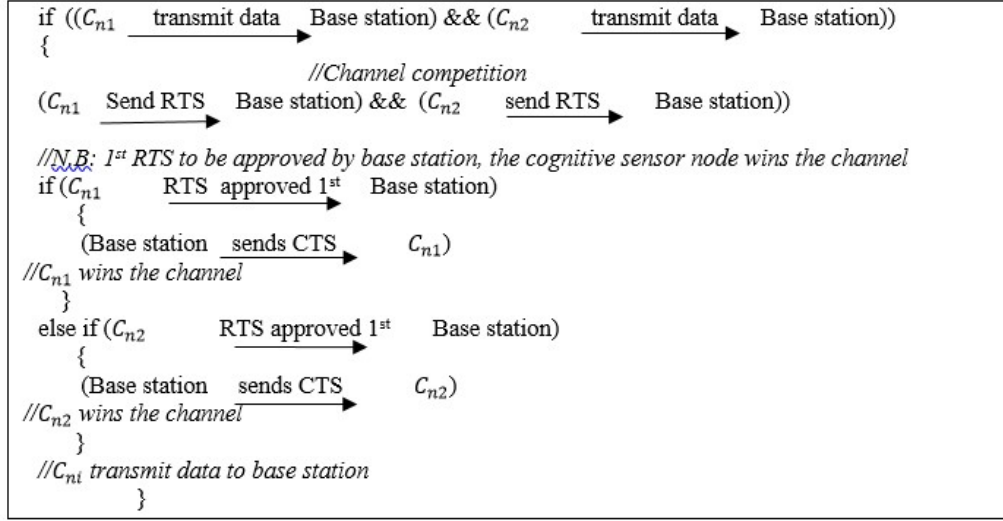


Figure 4.9: Channel Competition pseudocode

C. Data transmission phase

Data transmission phase can also be referred to as the message passing phase where data is being transmitted between the sender and the receiver. The RTS/CTS mechanism is used by the cognitive sensor nodes to transmit the data between the sending and receiving cognitive sensor nodes. Thus, only the data will be transmitted to the receiver provided the sender has received the ACK packet from the receiver. The following steps summarise the message passing phase:

- The sending cognitive sensor node sends an RTS packet to the receiving cognitive sender node.
- The receiving cognitive sensor node (base station) approves sender's RTS packet and sends a CTS packet to the sending cognitive wireless node.
- Upon the receiving of the CTS packet at the sender, the sender prepares the data to be transmitted to the receiving cognitive sensor node.
- The data will be partitioned into data fragments, and the wake cognitive sensor node will transmit the fragments one-by-one to the receiving cognitive node.
- For each fragment received by the receiving cognitive sensor, an ACK packet will be sent to the sender that the next fragment can be transmitted.
- Should the ACK packet not arrive at the sender within the given transmission time, the sender will re-transmit the fragment to be acknowledged by the receiver.

Table 4.4: Data Transmission Algorithm

Data Transmission Algorithm
Input: RTS/CTS packets
Output: Relayed data between SU (sender) and BS (receiver)
Steps:
Wake SU sends RTS to BS
If (BS approves RTS) {
BS sends CTS to SU
Channel selected for data transmission
Then SU transmit data in fragments
Every fragment received by BS is approved with ACK packet
ACK packet send to SU for allow further transmission }
If (RTS not approved) {
No transmission
SU keeps sending RTS until elapsed (T_{wake})
At elapsed (T_{wake})SU sleeps }}
At elapsed (T_{sleep}) SU wakes to check for if it can transmit

Table 4.4 presents the data transmission algorithm that illustrates the data transmission between the base station and the wake cognitive sensor nodes. For data transmission to occur, the RTS/CTS packets are used. The wake cognitive sensor nodes send the RTS packet to the base station to ask for permission to transmit the data as well as to select the channel for transmission, and if the RTS is approved by the base station, then the base station will transmit the CTS packet to the wake cognitive sensor node(s). Furthermore, every packet transmitted by the wake cognitive sensor node is divided into fragments, where each fragment transmitted by the base station will be approved with an ACK packet. This ACK packet will be sent to the transmitting cognitive sensor node to acknowledge that the fragment has been received and more fragments can be transmitted. However, if the RTS is not approved, then no data transmission will take place, however, the wake cognitive sensor node will keep on sending RTS packets until its wake time elapses.

4.4 System Analysis

This section presents the system services and the imposed constraints on their execution. These specific sets of system services and constraints are critical to satisfying all the desired objectives in order to provide answers to the outlined RQs. We categorized them into two

sections: the functional requirements (FR) and the non-functional requirements (NFR) given the SUs, PUs and the base station.

4.4.1 System Requirements

The system requirements are considered as a detailed sensible collection of functional and non-functional requirements which provide the essence of how the proposed energy-efficient CRSN mechanism should operate to solve the stated problem in research as outlined in chapter 1. System requirements are of great significance when designing a system to ensure that the system is not compromised throughout its design. Furthermore, for the proposed system to operate to its full potential, the system requirements provide a clearer understanding of each entity's functionalities and provide the constraints for the systems' error-free execution.

a) Functional Requirements

The FRs in the context of this research are a statement of expertise of what the proposed system shall do, its services, and the constraints imposed on them. The requirements are outlined to satisfy the SUs, base station and the PUs in Table 4.5.

Table 4.5: System's functional requirements

Req. ID	Description
SU	FR1.1: Each wireless sensor nodes should be equipped with the CR capabilities to be compatible with the CRSN network FR1.2: The K-Means clustering protocol should be executed efficiently within the sensor nodes to partition the network successfully without any hindrances FR1.3: Following the successful K-Means clustering, the S-MAC protocol should execute successfully to schedule nodes periodic sleep-wake scheduling using duty cycle. FR1.4: The clustered cognitive sensor nodes shall be able to have information about their neighbors by synchronizing with one-hop their neighbors to share their scheduling table. FR1.5: The cognitive sensor nodes shall be able to update their scheduling tables after receiving neighbors scheduling table. FR1.6: Wake neighboring cognitive sensor nodes shall be able to compete for the channel before data transmission with an RTS packet that is sent to the base station for channel competition and data transmission requisition. FR1.7: The data shall be transmitted to the base station (receiver) provided a CTS and

ACK packets are sent back to the cognitive sensor node (sender) that won the channel.

FR1.8: The cognitive sensor shall be equipped with multiple interfaces and multiple channel(s) and should be able to transmit the data in the vacant licensed channel of choice.

PU

FR2.1: The PU shall only occupy the allocated fixed channel.

**Base
Station**

FR3.1: The base station shall send the CTS and ACK packets to the cognitive sensor node that won the channel to allow data transmission

FR3.2: The base station shall receive the data only from the cognitive sensor node that won the channel

b) Non-functional Requirements

The system's NFRs detail the behavioral aspects of the system and act as the specific constraints imposed on the systems' behavior. They can be considered as the verdict point that outlines the specific criteria of the proposed systems operations. This is shown in Table 4.6.

Table 4.6: System's non-functional requirements

Req. ID	Description
	NFR 1: The proposed energy-efficient mechanism shall execute successfully when both the K-Means clustering algorithm and S-MAC protocol are correctly implemented.
	NFR 2: Data will only be transmitted by cognitive sensor nodes that won the channel.
	NFR 3: Data can only be transmitted when there is a link formed between the base station and the cognitive sensor nodes provided RTS,CTS and ACK packets are created, transmitted and approved between the base station and the sending cognitive sensor nodes.
	NFR4: Uncontrollable interference shall be maintained through the implementation of S-MAC protocol which proffers DSA in the proposed energy-efficient network.
	NFR 5: The cognitive sensor nodes shall select channels using multi-channel multi-interfaces.
	NFR 6: The PU data shall be transmitted in the allocated fixed licensed channel without using the RTS/CTS to and from the base station.

4.4.2 System Modeling

This subsection presents the abstract model to depict the detailed structures of the proposed system based on the requirements. We employed systems modeling to provide in detail, how the cognitive wireless sensor nodes will be clustered in a specified geographical location, and use the S-MAC protocol to schedule periodic sleep-wake operations based on the activity of

the cognitive wireless sensor nodes. Moreover, it also shows how the DSA will be used to avoid any undesired interference between the SUs and PUs. In the context of this research, the S-MAC protocol will proffer DSA to control interference that might lead the system to failure and alleviate the increase in energy consumption. Accordingly, the K-Means clustering algorithm will not only partition the network to reduce complexities but it also reduces energy consumption.

1) System actors

Figure 4.10 below shows three involved participants in the proposed energy-efficient model so as to be able to interact and transmit the data across the channel.

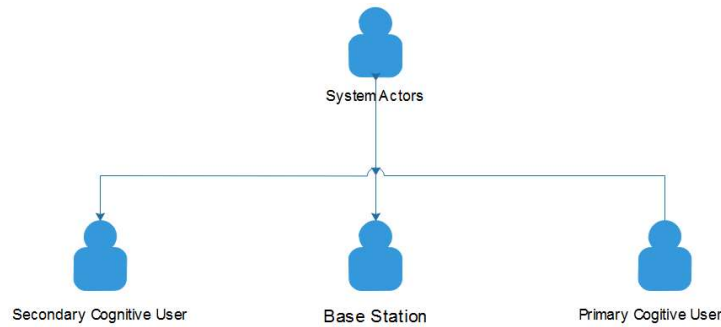


Figure 4.10: System actors

2) Actors roles

Cognitive user: The cognitive users, also referred to as the secondary users, are the clustered cognitive nodes (senders) that communicate directly with the base station using RTS/CTS/ACK packets.

Base station: The base station is a receiver of the relayed data from the clustered cognitive users (sender) using RTS/CTS/ACK packets for communication.

Primary user: The PUs the licensed users are allocated a fixed channel for transmission any time they desire.

3) System use case

The system use case illustrates the list of steps or operations that define in depth the interactions that the proposed system actors and the proposed system engage on to satisfy the outlined objectives of the proposed system objectives stated in Chapter 1. The system use case is shown in Figure 4.11, showing the functionalities and system interactions in the proposed energy-efficient mechanism.

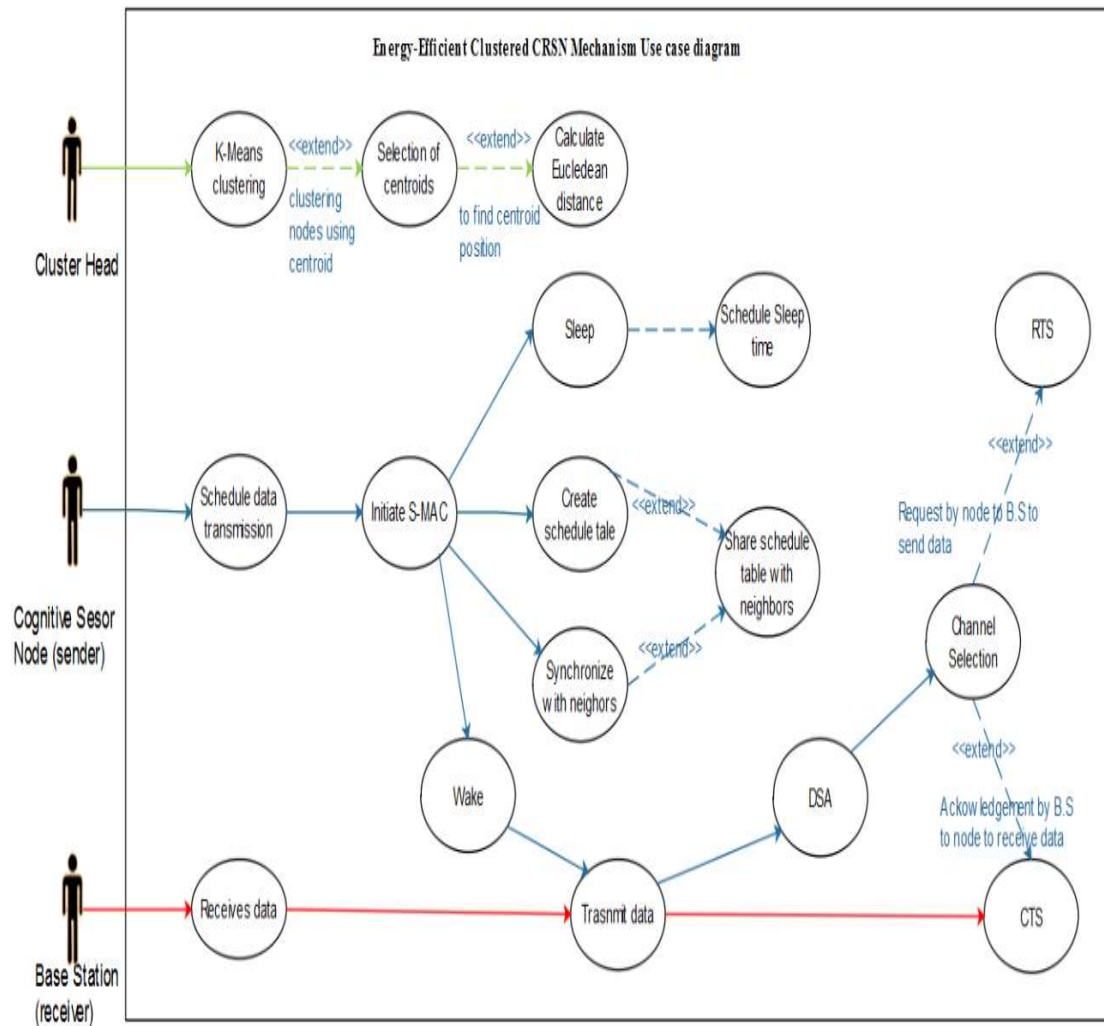


Figure 4.11: System use case diagram

4) System sequence diagram

The system sequence diagram is used as a graphical illustration of operations from the start to the end of the system. We employed it to show the interactions and relationships between the proposed system actors of the proposed system. The detailed system sequence diagram is captured in Figure 4.12.

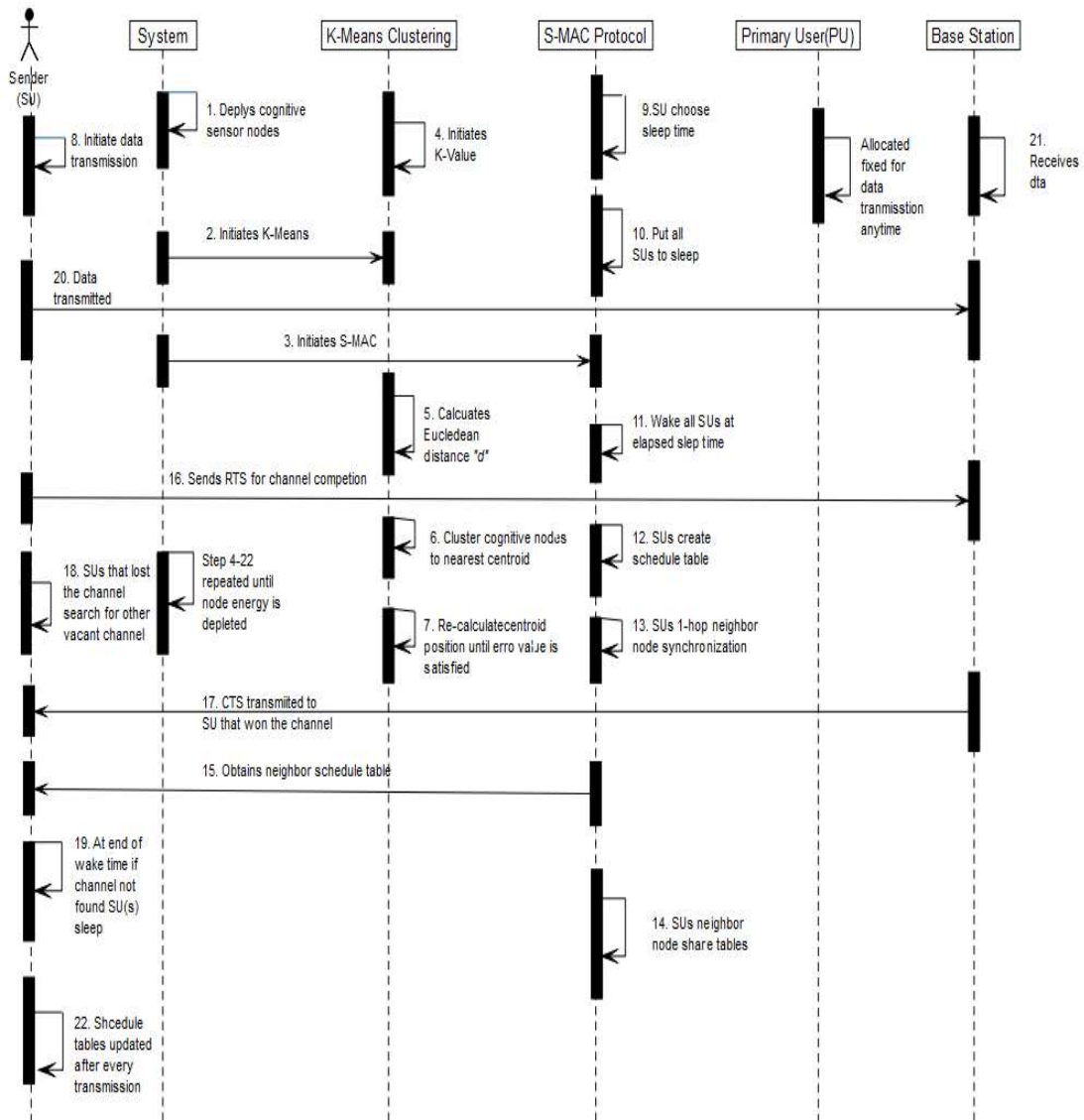


Figure 4.12: System sequence of operation

As shown in Figure 4.12 above, the SU data can only transmit to the base station provided the sending SU won the channel using the RTS/CTS packets to and from the base station. However, the data of the sending SU is divided into fragments, but the data fragments can all be transmitted provided that each fragment is acknowledged by the base station using an ACK packet that will be transmitted to the sending SU. The system initiates the K-Means clustering, and S-MAC protocol before data can be transmitted to the base station. SUs in a cluster will use a one-hop neighbor node synchronization to avoid interference in data transmission. Furthermore, the PUs are allocated a fixed licensed channel to transmit anytime they wish to occupy the channel.

4.5 System Operations

This section provides a high-level understanding of the proposed system operations as captured in Figure 4.13. A high-level activity diagram or flow chart is used to summarize the operations while maintaining the high-level understanding of the full functionalities of the system. It offers a guideline on how the proposed system should operate to achieve the outlined research objectives.

As shown in Figure 4.13, given the deployed wireless sensor nodes, the system initiates K-Means clustering protocol to allow all the nodes to be equipped with the CR capabilities, and also initiates the S-MAC protocol to allow the cognitive sensor nodes to schedule their sleep-wake cycle and use DSA to avoid unwanted interference upon data transmission to and from the base station.

- 1) If a node is in sleeping phase, the node will choose its time sleeping, then at elapsed sleeping time the nodes will be woken up for listening in the channel.
- 2) If the nodes are in wake/listening phase, they will schedule for neighbor synchronization in a one-hop manner to share their scheduling table.
- 3) If nodes are not synchronized, no data transmission and channel competition will take place, and
- 4) if the neighboring nodes are synchronized, they will share their scheduling table with their neighbors.

Furthermore, after successful cognitive sensor nodes synchronization and sharing scheduling table, the next phase is for data transmission:

- 1) if the nodes are not transmitting they will be put back to sleeping phase and
- 2) if they wish to transmit data to the base station, they will have to compete for the channel.
- 3) The listening nodes will transmit RTS packet to the base station, and
 - a. if the base station approves it, an ACK and CTS packet will be sent to the node(s) that won the channel to allow transmission.
 - b. PU is allocated a fixed channel to transmit the data directly to the base station any time.

These operations will be carried out until the cognitive sensor nodes battery life is depleted.

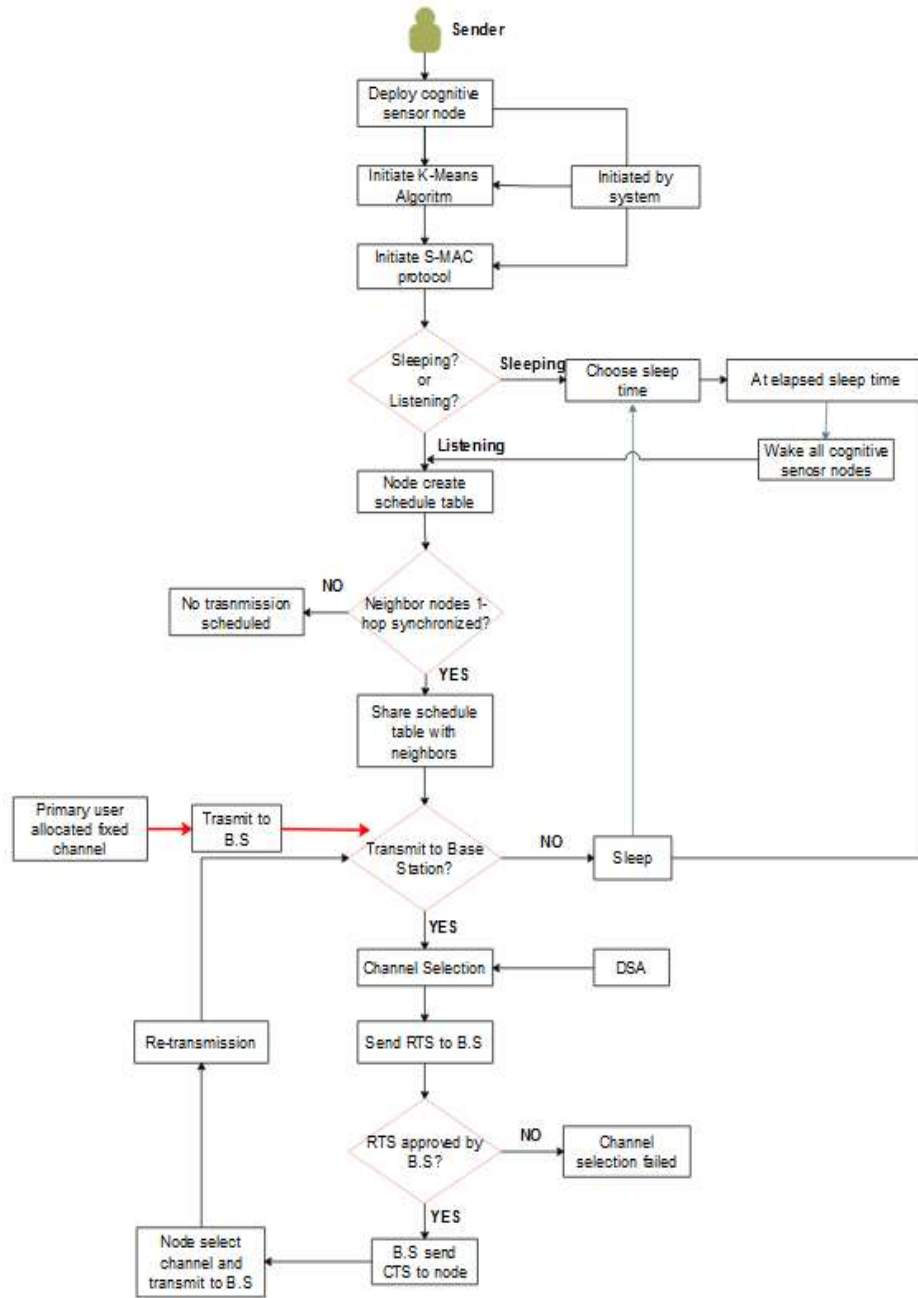


Figure 4.13: High-level system operations

4.6 Chapter Summary

This chapter discussed the proposed energy-efficient CRSN mechanism detailing in-depth the implementation of the proposed approaches to design our energy-efficient mechanism. Furthermore, the discussion was based on the in-depth understanding of the overall proposed mechanism operations and functionalities, and this was made possible through system

analysis which is structured into system requirements, system modelling, system architecture, system operations and system implementations. The results analysis and discussion of the proposed system are carried out in the Chapter 5.

Chapter 5

Results and Analysis

5.1 Chapter Outline

This chapter presents the implementation and results of the energy-efficient framework discussed in Chapter 4. It starts with an introduction, followed by simulation setup and progresses to the results and analysis of the simulated data. The overall discussion is based on the evaluation of the generated data, and lastly we present the chapter summary.

5.2 Introduction

Considering the main aim of this research, an energy-efficient mechanism for CRSN is proposed and designed in Chapter 4. The goal is to improve or minimize high energy consumption in the CRSNs as caused by both CR and WSNs. In any computing system, energy efficiency is a critical component and wireless network is not an exception. In wireless networks, energy efficiency is crucial and critical since the network is made up of battery-powered wireless devices which are naturally tagged resource constrained. In this case, if effective energy efficient models are not well implemented, this will lead to fast depletion of wireless sensor battery energy. Thus, to ensure proper design and implementation that addresses such challenge and in alignment with the research objectives stated in Chapter 1, this chapter implements the proposed energy-efficient mechanism designed in Chapter 4. Simulation is performed using Network Simulator2 (NS2) with CRCN patch to support the dynamicity of CRSN.

After the simulations have been carried out, the data generated are collected, analysed and evaluated both qualitatively and quantitatively. Accordingly, assessment will be based on four different S-MAC duty cycles to determine the most suitable energy-efficient duty cycle for usage.

5.3 Simulation Set-up

This Section presents and discusses the parameters used in performing the simulation of the proposed energy-efficient CRSN mechanism.

5.3.1 System properties

This sub-section presents the properties of the system used in performing the simulations. This is shown in Table 5.1.

Table 5.1: System properties

Parameter	Value
Software	Linux-Ubuntu 18.08 LTS, 64 bit operating system
	NS2 version 2.31
	CRCN patch
	Gnuplot
Hardware	Hard Disk 490.7 GB
	RAM 3.8GB
	Processor: Intel® Core™ i5-4570S CPU @ 2.90G

5.3.2 Evaluation parameters and process

A. Duty cycles

In this research, six different S-MAC duty cycles: 3%, 5%, 10%, 15%, 25% and 50% are used to assess the proposed mechanism implemented with S-MAC protocol based to determine the most energy-efficient duty cycle appropriate for the proposed energy-efficient CRSN mechanism.

B. Parameters

In order to assess the proposed energy-efficient CRSN mechanism based on the data generated through simulation, the efficiency in terms of effectiveness and performance is measured based on the following metrics: *average energy*, *residual energy*, *throughput* and *delay* when data is transmitted between the sender and the receiver. (See Table 5.2). The assessment using these metrics is based on the chosen S-MAC duty cycles. This is to assist in choosing the most appropriate (energy-efficient) duty cycle to implement the proposed energy-efficient mechanism in CRSN.

Moreover, NS2 is used, an open source and allows modifications and implementation of new protocols if it necessitates the researcher to implement a new protocol. The scripts/models are written using NS2 which is based on C++ and using Object-oriented Tool Command Language (OTCL) which is an objected oriented program platform of TCL (Tool Command Language) scripting language. The OTCL is used for simulation purposes to generate the data for analysis and assessing and also OTCL is used for C++ objects manipulation. The TCL language is compatible with LINUX environment, of which the TCL language supports

graphical user interfaces and is easy to integrate with other programming languages. The TCL in this research is used to write script for K-Means clustering algorithm, the S-MAC protocol, and the energy model. Table 5.3 presents the parameters used in the simulations.

Table 5.2: Evaluation metrics

Metric	Description
Throughput	The total amount of data transmitted per unit time
Average Energy	The average overall consumed energy in the network after the completion of the simulation
Residual energy	The total amount of energy remaining in the network after the completion of the simulation
Delay	The variance in sending and receiving periods in data transmission

Table 5.3: Simulation parameters

Parameter	Value
Algorithm	K-Means clustering
Protocol	S-MAC
Simulator	NS2 version 2.31
Patch	CRCN
Simulation Area	300*300 meters
Simulation Time	10-300 seconds
Node movement model	Disabled random motion
Transmission range	300m
Data transmission interval	0.1 seconds
File size	128 bytes
Routing protocol	AODV
Trajectory	Random
Transport Protocol Used	UDP
Application traffic instance	CBR
Initial energy per node	100 J
Number of Sus	26
Number of base station(s)	1
Number of PU(s)	1

Accordingly, the data collected through simulations used in analysis and assessment are generated by running NS2 TCL scripts which generate the trace files with extension .tr. Within this generated trace files, the detailed information is provided such as event (enqueueer “+”, dequeuer “-”, sending “s”, or receive “r”, and dropped “d”), time for data transmission, node id for sending node, packet type (cbr/tcp), packet size, packet id, layer type, and energy (residual energy, idle energy, sleep energy, and transmitting energy), source and destination address, and sequence number. Figure 5.1 shows the trace file format generated from the proposed mechanism implemented with S-MAC protocol.

```

1 s 0.000000000 _0_ RTR --- 0 ADDV 44 [0.00 0 0] [energy 100.000000 ei 0.000 es 0.000 et 0.000 er 0.000] ..... [0:255 -1:255 1 0] [0x1 1 [0 2] 4.000000] (HELLO)
2 s 0.000000000 _0_ RTR --- 0 ADDV 44 [0.00 0 0] [energy 100.000000 ei 0.000 es 0.000 et 0.000 er 0.000] ..... [0:255 -1:255 1 0] [0x1 1 [0 2] 4.000000] (HELLO)

```

Figure 5.1: Proposed mechanism trace file

Moreover, the TCL script also generates other files such as Chanfile which shows channel utilization for the proposed mechanism, the .namfile which is used to generate graphics of the proposed mechanism. In order to process the collected data for assessing the performance and effectiveness of the proposed system, the Aho, Weinberger and Kernighan (awk) scripts are used to process the data written to the trace file generated by NS2 TCL script. The awk scripts are executed in the LINUX terminal using the following commands; awk -f filename.awk filename.tr, where the filename.awk refers to the file name of the metric used for data analysis e.g. energy.awk, and filename.tr refers to the generated trace file from the TCL script. For data visualization, GNUPLOT is used to simplify the analysis and assessment of the generated data. GNUPLOT is a portable, easy-to-use command line driven for visualizing, and it is compatible with Microsoft windows, OS/2, virtual machines and LINUX operating systems.

Also, the mechanism written in NS2 TCL script is implemented with 30 nodes (28 SUs, one base station and one PUs). These SUs are implemented with multi-channel and multi-radio capabilities. The PU (node 2) is given the privileges of accessing a fixed channel 2 which is one of the channels created through CR multi-channel multi-interface configuration; this implies that the SUs can transmit in any other vacant channel of their choice but not channel 2. Fixed channel 2 is assigned to the PU. This is because this research has a limited scope of not implementing PU detection and channelling schemes but rather reducing high energy consumption in a network as well as minimizing the interference in the network when data is transmitted between the sender and the receiver. However, to accommodate the CRSN dynamism, modifications have been implemented in the NS2 background codes.

5.4 Results and Analysis

This section presents the results of the simulation and their analysis. This is based on the data generated and collected on different simulated S-MAC duty cycles (3%, 5%, 10%, 15%, 25% and 50%). The S-MACs duty cycle is used to schedule the sleeping period of the cognitive sensor nodes.

The simulation results are based on the following restrictions or hypothesis:

- a) If the duty cycle is set very high, then it will lead to high latencies as the nodes will be sleeping for lengthy periods whereas they should be transmitting and
- b) If the duty cycle is set very low then the cognitive sensor nodes will be repetitively waking up even when no data is transmitted to the base station, and this can result in high interferences in the network.

However, to reduce such interferences and latencies, the duty cycle should be minimized in a moderate manner (i.e., not too high nor too low) in order to produce high throughputs and low delays to result in minimized average network energy consumptions as well as high network residual energy. In this research context, throughput will measure the amount of data transmitted per stipulated time between the base station and the wake cognitive sensor nodes. Average consumed energy will measure the total network consumed energy of the overall network initial energy for the stipulated simulation time, and the residual energy measures the overall network remaining energy after the simulation. Furthermore, the K-Means clustering algorithm is employed to minimize the interference and overlapping signals from different clusters. The essence is to avoid packet retransmission due to packet losses.

Moreover, we collected data for analysis from the simulated S-MAC duty cycles for 0-300 seconds after clustering the cognitive sensor nodes. This is essential to determine which duty cycle is more energy-aware for real-world network implementation. The results of the simulations are presented using visual graphs for assessment.

5.4.1 Throughput

The throughput for different S-MAC duty cycles over time is captured in Figure 5.2 which visualizes the performance for different S-MAC duty cycles. The graph in Figure 5.2 shows an inversely proportional trend for 3% duty cycle. The indication is that, at lowest times it produced high throughput but as the time increases, the throughput decreases. This is due to cognitive sensor nodes shorter sleeping periods and wake ups even if they are not transmitting. Accordingly, the 5% duty cycle shows a slight increase in throughput as compared to 3% duty, but also the 5% duty cycle decreases with the increase in time for the same reasons as the 3% duty cycle.

Moreover, for 10% and 15% duty cycles, there is a significant increase in the generated throughput as compared to 3% and 5% duty cycles. However, for 15% duty cycle, at 200 seconds the throughput decreases because the duty cycle is increased, hence leading to cognitive sensor nodes sleeping for lengthy periods, which results in less data being

transmitted in the network. Similarly, 10% duty cycle shows a significant constant throughput rate between 0 seconds and 250 seconds, but as time increases after 250 seconds the throughput increases. This implies that the duty cycle is neither set high nor low but rather minimized, so the cognitive nodes does not sleep for lengthy periods and with the increase in time, more throughput will be generated. Moreover, the 25% duty cycle has better throughput as compared to 3%, 5%, 10% and 15%, but its throughput shows an inconstant trend throughout, thus we can conclude that some of the wake cognitive sensor nodes might not be transmitting. Furthermore, 50% duty cycle has more throughput as compared to 3%, 5%, 10%, 15% and 25% based on the increased throughput. This implies that cognitive sensor nodes are sleeping for lengthy periods, hence only a small portion of data is transmitted successfully without retransmission due to packet drops and this is presented by the delay graph in Figure 5.5.

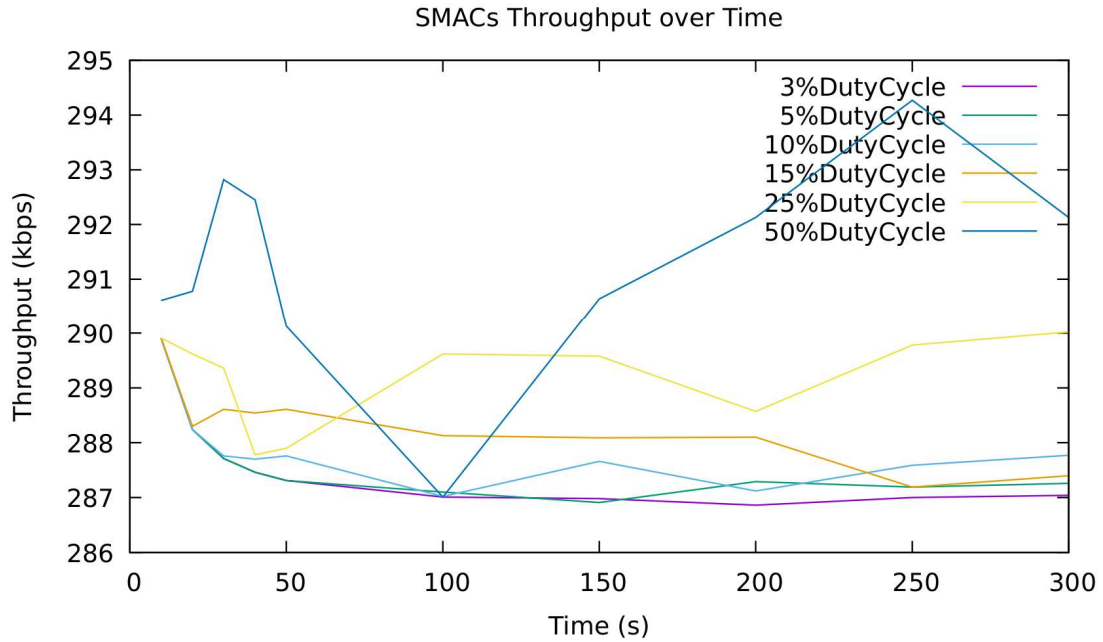


Figure 5.2: S-MAC duty cycles throughput over time

5.4.2 Network average consumed energy

The network average consumed energy for different S-MAC duty cycles over time is shown in Figure 5.3. The results show that, for 3%, 5% and 10% duty cycles, there is less average energy consumed in the network due to the low duty cycles as compared to 15% duty cycle. In this case, if the duty cycles are set low, then there will be less energy consumed in the network because the nodes are not sleeping for lengthy periods nor idling for lengthy periods

without data transmission. Thus, the nodes will only sleep for a short period, then wake up if it is their turn to transmit data, and when done transmitting the data, thus go back to sleep. However, the 10% duty cycle has a better average consumed energy over time than 3%, 5%, 15%, 25% and 50% because duty cycle is minimized. Moreover, for the 15% duty cycle, there is high average energy consumed in the network because of lengthy sleeping periods, so if the cognitive sensor nodes are sleeping for lengthy periods, then at the end of the simulation time more energy will be consumed in sleeping modes and transmission for nodes in wake mode. For this fact, this applies to 25% and 50% duty cycles. Accordingly, for 50% duty cycle, the average consumed energy is too low between 0 and 250 seconds, but immediately after 250 seconds the consumed energy increases because the overall energy consumed in the network for sleeping periods will affect the overall energy.

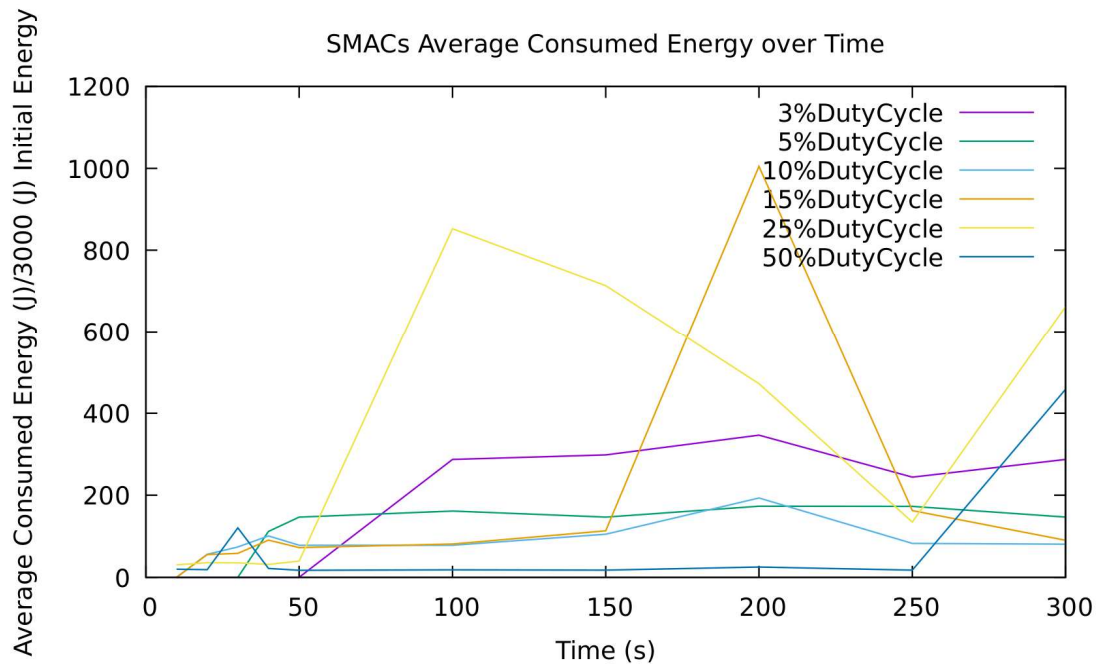


Figure 5.3: S-MAC duty cycles average consumed energy over time

5.4.3 Network residual energy

The result of the network residual energy for different S-MAC duty cycles over time is presented in this subsection. Figure 5.4 presents the graph of the network residual energy over time for different S-MAC duty cycles. The graph shows an exact inverse trend of the graph presented in Figure 5.3. That is, if the average consumed energy in Figure 5.3 is high then the residual energy will be low as shown in Figure 5.4 for all the S-MAC duty cycles. As

shown in Figure 5.4, 10% duty cycle has the lowest residual energy followed by 50% duty cycle while 15% and 25% duty cycles have the highest residual energy.

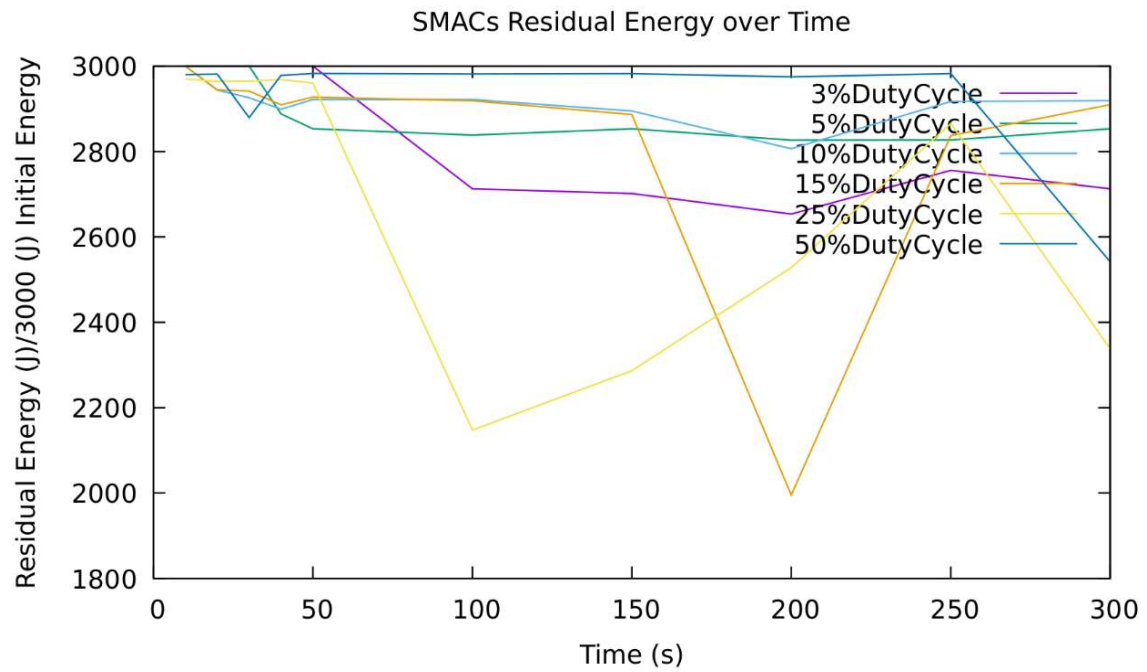


Figure 5.4: SMAC duty cycles network residual energy over time

5.4.4 Network delay

The results of the network delay are shown in Figure 5.5, which presents the network delay for different S-MAC duty cycles over time. For all the six simulated S-MAC duty cycles, the overall network delay is zero. This is due to no packet retransmission and packet loss. In this case, if there is no packet loss and packet retransmission occurring or minimized delays, then there will be minimized or no interference occurring within the clusters and during data transmission between the sender and the receiver.

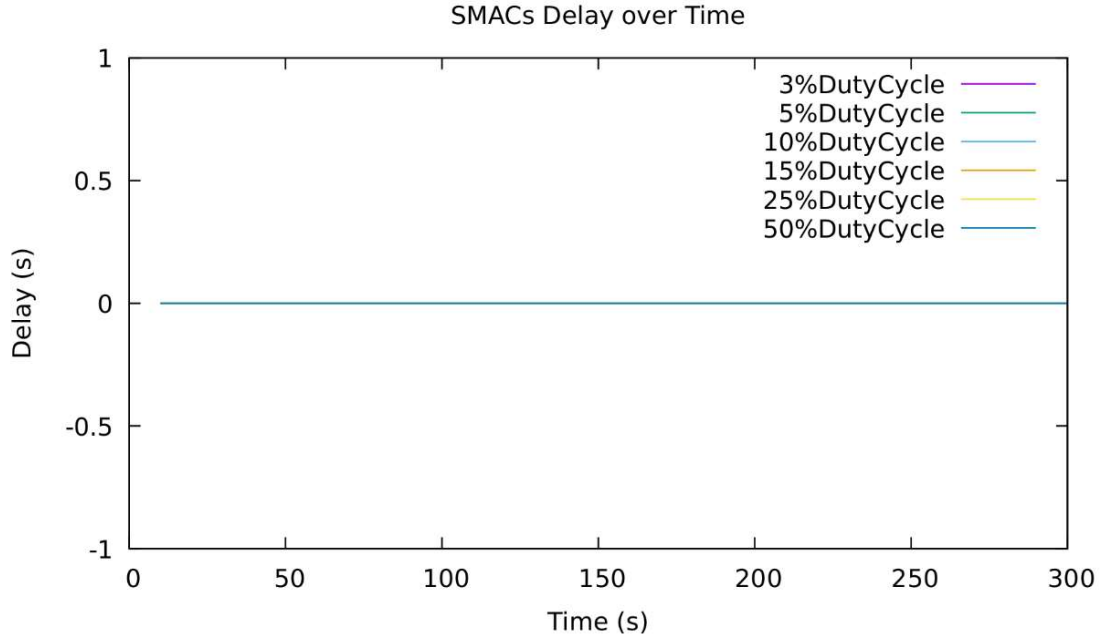


Figure 5.5: SMAC duty cycles delay over time

5.5 Discussion

This section presents the discussion on evaluation of the above presented simulated results. The objective is to choose the most suitable energy-aware S-MAC duty cycle that will be used to implement energy-efficient CRSN mechanism. Based on the results obtained, we chose 10% S-MAC duty cycle as the most energy-efficient of all the duty cycles. The rationale for this choice is as follows:

Duty cycle of 15% has a higher throughput than that of 10% duty cycle for about 200 seconds of the simulation time. However, there was a significant drop of the throughput for 15% duty cycle whereas the 10% duty throughput increases slightly. The indication is that for a large amount of time, the 10% throughput will increase rapidly while 15% throughput will be dropping. For 3% and 5% duty cycles, their throughput shows a slight increase but continues to remain low throughout the simulation. Hence it can be concluded that there will not be a significant change should the time increase. The 25% and 50% duty cycles have more throughputs but they are irregular and at 250 seconds there is a significant drop in the throughput. There is no guarantee that as times continue there will still be more throughput produced.

For the average consumed energy, the 10% duty has the lowest average consumed energy when compared to the other five S-MAC duty cycles. From 250 seconds the 10% duty cycle

has the lowest average consumed energy. However, the average consumed energy is inversely proportional to the residual energy. If the duty cycle average energy consumed is low, then its residual energy will be high.

As for the overall network delay, all six duty cycles have zero delays, which implies that the S-MACs are packet retransmission and packet loss free, which leads to minimized or no interference in the network during data transmission between the sender and the receiver.

Therefore, to implement the proposed energy-efficient mechanism in the CRSN, the mechanism should be composed of the traditional K-Means clustering algorithm and the S-MAC protocol with 10% duty cycle.

5.6 Comparison with Others

The results generated through the simulations can be compared to similar work done by other researchers, as outlined in Chapter 2 literature. Most researchers in the literature implemented the traditional 802.11 MAC protocol but implemented their own sleep-wake scheduling mechanism and clustering protocols. However, the results in this research can be compared in terms of the delay, average consumed energy, residual energy, and throughput to assess the performance and effectiveness of our designed energy-efficient CRSN. Furthermore, the results can be compared in terms of the MAC protocol efficiency for data transmission in the network to obtain a better throughput, and the clustering protocol to reduce the operational complexities in the network. The comparison is illustrated in table 5.4.

Table 5.4: Comparison of similar energy-efficient CRSN mechanisms

		Algorithms		Results			
Ref	Network	Protocol	Clustering	Throughput	Delay	Average consumed energy	Residual energy
Proposed	CRSN	S-MAC 10% duty cycle	K-Means Clustering	High	Zero	Low	High
[69]	CRSN	Learning inspired MAC	Clustering	–	–	Low	High
[70]	Multichannel CRSN	Multichannel asynchronous MAC protocol	–	Low	Minimum	Minimum	Minimum
[71]	Cognitive machine to machine	Spectrum database driven MAC protocol	–	High	–	Low	High
[1]	CRSN	Self learning MAC protocol for energy	–	High	Minimum	Low	High

		harvesting					
[72]	CRSN	SACB-MAC protocol	–	–	Low	–	–
[73]	CRASN	Opportunistic MAC protocol and a	–	High	–	Low	High
[74]	CRSN	ECR MAC	–	–	–	Low for high node density	High
[7]	CRSN	DSA and Joint power allocation and channel accessing scheme for inter and intra clusters	Inter and intra clustering	–	–	Low	High
[12]	CRSN	Asynchronous Sleep-wake scheduling mechanism	Inter and intra clustering	–	–	Low	High
[64]	CRSN	DSA and Packet size adaptation exploitation technique and Channel assignment technique	Multi-channel cluster based	Low	–	Low	High

5.7 Chapter Summary

This chapter discussed the simulation setup and results and analysis of the data generated based on the chosen S-MAC duty cycles simulated. We also performed evaluations on the results by comparing the effectiveness and performance of the duty cycles in order to choose a suitable duty cycle for implementation. The next chapter concludes this research.

Chapter 6

Conclusion

6.1 Conclusions

CRSN is a wireless networking paradigm to circumvent the wireless channel interferences due to the proliferation of wireless sensor devices. Other issues faced by CRSN are high energy consumptions, packet losses, packet retransmission, lengthy and repetitive idling, and poor channel switching mechanisms. These issues are caused by the issues inherent in WSN and CR. Thus, this research was conducted to improve existing energy-aware CRSN models by minimizing high energy consumptions and interferences in the CRSN. We proposed an energy-efficient mechanism which was composed of a traditional K-Means clustering to reduce network complexities by partitioning the network into sub-networks, and also the 10% duty cycle S-MAC to control flow and scheduling slots, yet maintaining low energy consumption, minimized or no interferences, maximum throughput and zero delays.

In particular, **Chapter 1** introduced the area of this research where the practical existing energy inefficiency problem was identified, as well as the research questions to be answered using the outlined research objectives to achieve the desired research aim. **Chapter 2** discussed the research literature in CRSN. To this end several clustering techniques in a traditional WSN were discussed in the related works section of existing works by other researchers to identify different tools used, identified problems, proposed solutions and approaches. **Chapter 3** discussed the proposed constructive research methodology and the research design appropriate to carry out this research. **Chapter 4** discussed in depth the proposed energy-efficient CRSN mechanism in terms of its analysis and design while **Chapter 5** presents the generated results for performance and effectiveness assessment. However, to reach our desired research aim, research questions have been answered in the following chapters as follows:

RQ1: What are the factors that contribute to energy-efficiency in CRSNs and the impacts?

To proffer answers to RQ1, an in-depth analysis was conducted in Chapter 2. To answer RQ1, the following sub-questions were addressed:

RQ1.1 How do the clusters improve energy efficiency in CRSNs?: This research sub-question was comprehensively answered in Chapter 2 sub-sections 2.5-2.6, 2.8 and some of

the related works. In the related works, different clustering algorithms were proposed, some modified to minimized energy inefficiency challenges encountered by CRSN. Different clustering algorithms in WSNs were also discussed, however, these algorithms did not support the CRSN dynamicity, and hence there was a discussion on related works for existing clustering algorithms which support CRSN dynamicity. The discussion emphasized that clustering reduces overall network energy consumptions, based on the reduced complexities of having smaller networks that can perform their operations by not overlapping to other sub-networks.

RQ1.2: How does DSA manage the uncontrollable interference in CRSNs?: The DSA was discussed in Chapter 2 sub-section 2.9.2 of related works. However, the discussion also included proposing clustering using DSA to further improve energy efficiency in CRSN while maintaining low interference between the cognitive users and the PUs. DSA is implemented with different algorithms to support the objectives of the researchers. Due to the proliferation of wireless sensor networks in the wireless channel, DSA allows the SUs to switch to the licensed vacant channel and vacate the channel when the licensed users PU re-appear in the channel. DSA does not only reduce interferences between the users during channel switching, but can also be used to minimize the interface during data transmission.

RQ1.3: How does Sleep-Wake scheduling mechanism reduce energy consumption in clustered CRSN?: The sleep-wake scheduling mechanism is also discussed in Chapter 2 section 2.7 and also in some of the related works where different sleep-wake scheduling schemes are proposed by different authors to support their objectives. A sleep-wake scheduling scheme has been proposed as an energy-efficient scheme that equips the cognitive sensor nodes with the capabilities to intelligently schedule their own transmitting and receiving slots using the wake and sleep modes.

RQ2: How can we design and develop an improved energy-efficient mechanism in clustered CRSNs?

Based on the in-depth analysis and discussions conducted in Chapter 2, the detailed discussion of development and the design of the proposed energy-efficient CRSN were carried out in Chapter 4. However, to be able to design and develop the proposed energy-efficient CRSN, the proposed constructive research methodology was used and thoroughly discussed in Chapter 3. This research methodology is conducted based on the type of research

to be conducted following the identified practical problem to be circumvented. However, to support the design and development of the proposed energy-efficient CRSN mechanism, diagrams such as use case diagram, activity diagram and sequence diagram are used to support the design and development stage to proffer a less complex mechanism while fulfilling the desired objectives.

RQ3: How can the proposed energy-efficient CRSN mechanism performance be assessed?

The proposed energy-efficient mechanism performance evaluation and assessment was conducted in Chapter 5. The metrics used for evaluation and assessment are throughput, network average consumed energy, network residual energy and network delay. However, six different S-MAC duty cycles: 3%, 5%, 10%, 15%, 25% and 50% were simulated to choose and conclude which S-MAC is energy-aware and can be used together with K-Means clustering algorithm to implement the proposed energy-efficient CRSN mechanism. To this end, 10% duty cycle was chosen to be more efficient based on the evaluation and assessment of the defined metrics. In this research an energy-efficient mechanism is proposed for CRSN which is composed of K-Means clustering algorithm and an S-MAC 10% duty cycle chosen as the most efficient as compared to other five other duty cycles of 3%, 5%, 15%, 25% and 50%. However, the 10% is chosen to implement our proposed energy-efficient CRSN mechanism based on the fact that it outperformed other duty cycles in terms of throughput, average consumed energy and overall network residual energy. This mechanism was proposed to produce an energy-efficient mechanism that has less complexities but yet satisfying the outlined objectives of this research.

Based on the performance and effectiveness of the 10% duty cycle throughput, for the first few seconds of the simulation, the throughput is inconstant but instantly increases as the time increases. For average consumed energy, the 10% duty cycle has the lowest consumed energy as compared to other duty cycles. Furthermore, the 50% duty cycle has the highest throughput, but was not chosen to be the more efficient due to its significant increase in average consumed energy at 250 seconds. However, if the consumed energy is low, then the residual energy will be high; therefore, the S-MAC 10% duty cycle has the best residual energy.

6.2 Recommendations and Future Works

This section presents the possible recommendations and future works based on this research. For recommendations in the proposed energy-efficient CRSN mechanism, the dynamic channelling mechanism can be used to avoid static channelling scheming for PUs for data transmission. To further improve the proposed energy-efficient mechanism, the following future works can be conducted; implementation of a dynamic cluster head selection algorithm in K-Means clustering to avoid having only one cognitive node as a cluster head, channelling mechanisms to allow dynamic switching of channels when PUs re-appear in the licensed occupied channel, and the dynamic duty cycle.

Appendix

Main activity code for the proposed energy-efficient CRSN mechanism

```
#Simulation are co-ordinates
set opt(x)      300                      ;# X dimension of topography
set opt(y)      300                      ;# Y dimension of topography

#Global variables/settings
set opt(chan)    Channel/WirelessChannel ;# Channel Type
set opt(prop)    Propagation/TwoRayGround ;# Radio propagation model
set opt(netif)   Phy/WirelessPhy         ;# Network interface type
set opt(mac)     Mac/SMAC                 ;# MAC type
set opt(ifq)     Queue/DropTail/PriQueue ;# interface queue type
set opt(ll)      LL                       ;# link layer type
set opt(ant)     Antenna/OmniAntenna      ;# Antenna model
set opt(ifqlen)  50                       ;# max packet in ifq
set opt(rp)      AODV                     ;# Routing Protocol script
set opt(seed)    0.0                      ;
set opt(nn)      28                       ;# number of mobilenodes
set opt(ni)      2                         ;# number of interfaces
set opt(channum) 2                         ;# number of channels per radio
set opt(connections) 50                   ;
set K            3                        ;# Number of clusters
set SensorNodeSize 10                     ;# size of a node
set opt(energymodel) EnergyModel          ;# Energy Model Set Up
#set opt(energymodel) RadioModel          ;# radio model
set opt(radiomodel) RadioModel            ;# energy model
set opt(logenergy) "on"                   ;# Log energy every 150 seconds
set opt(initialenergy) 100.0              ;# initial energy in joules
set opt(stop)     300                     ;# simulation stop time

# =====
# SMAC Sleep-Wake Settings
# =====
Mac/SMAC set syncFlag_ 1
Mac/SMAC set dutyCycle_ 10

# =====
# Main Program
# =====
# Initialize Global Variables
#Creating a ns simulation:
```

```

set ns_ [new Simulator]
set topo [new Topography]

#Creating nam and trace file:
set tracefd [open SUtest.tr w]
set namtrace [open SUtest.nam w]
set prop [new $opt(prop)]
#=====
# set up topography object
# =====
$topo load_flatgrid $opt(x) $opt(y)
ns-random 1.0
$ns_ trace-all $tracefd
$ns_ namtrace-all-wireless $namtrace $opt(x) $opt(y)

proc stop {} {
    global ns_ tracefd namtrace
    $ns_ flush-trace
    close $tracefd
    close $namtrace
    exec namSUtest.nam&
    exit 0
}

#=====
# Create God
# =====
create-god $opt(nn)

#=====
# configure node
# =====
$ns_ node-config -adhocRouting $opt(rp) \
    -llType $opt(ll) \
    -macType $opt(mac) \
    -ifqType $opt(ifq) \
    -ifqLen $opt(ifqlen) \
    -antType $opt(ant) \
    -propType $opt(prop) \
    -phyType $opt(netif) \
    -topoInstance $topo \
    -agentTrace ON \
    -routerTrace ON \
    -macTrace ON \
    -movementTrace ON \
    -energyModel $opt(energymodel) \
    -initialEnergy $opt(initialenergy) \

```

```

-rxPower 1.5 \
-rxTime 0.5 \
    -txPower 1.5 \
    -txTime 0.5 \
    -idlePower 0.1 \
    -idleTime 0.5 \
    -sensePower 0.1 \
    -senseTime 0.5 \
    -sleepPower 0.1 \
    -sleepTime 0.5 \
    -transitionPower 1.5 \
    -transitionTime 0.5

# =====
# Wireless channels creation
# =====
for {set i 0} {$i<[expr $opt(ni)*$opt(channum)]} {incr i} {
    set chan_($i) [new $opt(chan)] ;#new channel objects
}

# =====
# configure for interface and channel
# =====
$ns_ node-config -ifNum $opt(ni) -channel $chan_(0)
$ns_ node-config -ChannelNum $opt(channum)
for {set i 0} {$i<[expr $opt(ni)*$opt(channum)]} {incr i} {
    $ns_ add-channel $i $chan_($i)
}

# =====
# Wireless Nodes Creation
# =====
for {set i 0} {$i<$opt(nn)} {incr i} {
    set node_($i) [$ns_ node]
    $node_($i) set recordIfall 1 ;# interference information collection enabled
    $node_($i) random-motion 0 ;# disable random motion
    puts "...Cognitive Sensor Node $i is Created..."
}

# =====
# Provide initial location of mobilenodes (SUs)..
# =====
for {set i 0} {$i<$opt(nn)} {incr i} {
    set xx [expr {int(rand()*$opt(x))}]
    set yy [expr {int(rand()*$opt(y))}]

    $node_($i) set X_ $xx

```

```

$node_($i) set Y_ $yy

set nodeXpos($i) $xx
set nodeYpos($i) $yy
set nodeZpos($i) 0.0
$node_($i) color "black"
$ns_ initial_node_pos $node_($i) $SensorNodeSize
}

#=====
# Locations of BASE STATION (node 28) and PU (node 29)
#=====

set node_(28) [$ns_ node]
$node_(28) set X_ 1
$node_(28) set Y_ 500
$node_(28) set Z_ 0.0
$ns_ at 0.0 "$node_(28) label BASE-STATION"
$ns_ at [$ns_ now] "$node_(28) add-mark N2 black circle"
$ns_ initial_node_pos $node_(28) [expr $SensorNodeSize * 3 ]

set node_(29) [$ns_ node]
$node_(29) set isprimaryuser 1
$node_(29) set chanis 1
$node_(29) set X_ 500
$node_(29) set Y_ 250
$node_(29) set Z_ 0.0
$ns_ at 0.0 "$node_(29) label PRIMARY-USER-1"
$ns_ at [$ns_ now] "$node_(29) add-mark N2 black circle"
$ns_ initial_node_pos $node_(29) [expr $SensorNodeSize * 3 ]

puts "...RADIOS CREATED..." $opt(ni)"
puts "...WIRELESS CHANNELS CREATED per RADIO... $opt(channum)"
puts "...INTERFACE AND CHANNEL CONFIGURATION COMPLETE..."
puts " "
#=====
# Procedure for do..while
#=====
proc do {body keyword expression} {
    if {$keyword eq "while"} {
        set expression "!(($expression))"
    } elseif {$keyword ne "until"} {
        return -code error "unknown keyword \"$keyword\": must be until or while"
    }
    set condition [list expr $expression]
    while 1 {
        uplevel 1 $body
        if {[uplevel 1 $condition]} {
            break
        }
    }
}

```

```

    }
  }
return}

=====
# K-MEANS ALGORITHM
=====

puts " "
puts "...K-MEANS CLUSTERING OCCURING..."
set randnum 0
#set count 0
# Integer Random number generation
proc RandomInteger2 {max} {
  return [expr {int(rand()*$max)}]
}
for {set iter 0} {$iter< $K } { incr iter } {
  set generatedrand($iter) -1
}
# do while call
for {set iter 0} {$iter< $K } { incr iter } {
do {
  set firsttime 1
  # set randnum [expr $r % $NETWORK_NODE]
  set randnum [RandomInteger2 10]
  for {set i0 } {$i< [expr {$i&& $firsttime}]} {incr i} {
    if{$generatedrand($i) == $randnum} {
      set firsttime 0
    }
  }
  for {set j 0} {$j < 4000} {incr j} {
    ;
  }
} while {!$firsttime}

set generatedrand($iter) $randnum
set clusheadXpos($iter) $nodeXpos($randnum)
set clusheadYpos($iter) $nodeYpos($randnum)
set clusheadZpos($iter) $nodeZpos($randnum)
puts "clusheadXpos($iter) = $clusheadXpos($iter)"
puts "clusheadYpos($iter) = $clusheadYpos($iter)"
puts "clusheadZpos($iter) = $clusheadZpos($iter)"
}
for {set iter 0} {$iter<=27} {incr iter} {

  set X_pos1 [expr $clusheadXpos(0) - $nodeXpos($iter)]
  set Y_pos1 [expr $clusheadYpos(0) - $nodeYpos($iter)]
  set distmean1($iter) [expr {abs($X_pos1)} + {abs($Y_pos1)}]

```

```

set X_pos2 [expr $clusheadXpos(1) - $nodeXpos($iter)]
set Y_pos2 [expr $clusheadYpos(1) - $nodeYpos($iter)]
set distmean2($iter) [expr {abs($X_pos2)} + {abs($Y_pos2)}]

set X_pos3 [expr $clusheadXpos(2) - $nodeXpos($iter)]
set Y_pos3 [expr $clusheadYpos(2) - $nodeYpos($iter)]
set distmean3($iter) [expr {abs($X_pos3)} + {abs($Y_pos3)}]

puts "distmean1($iter) = $distmean1($iter)"
puts "distmean2($iter) = $distmean2($iter)"
puts "distmean3($iter) = $distmean3($iter)"
}
set listsize1 0
set listsize2 0
set listsize3 0

for {set iter 0} {$iter<=27} {incr iter} {
if [expr {$distmean1($iter) < $distmean2($iter)} && {$distmean1($iter) <
$distmean3($iter)}] {
set cluslist1Xpos($listsize1) $nodeXpos($iter)
set cluslist1Ypos($listsize1) $nodeYpos($iter)
set clusnodes1($listsize1) $iter
set listsize1 [incr listsize1]
$node_($iter) color green
$ns_ at 0.5 "$node_($iter) color purple"
puts "listsize1 = $listsize1\n"

} elseif [expr {$distmean2($iter) < $distmean1($iter)} && {$distmean2($iter) <
$distmean3($iter)}] {
set cluslist2Xpos($listsize2) $nodeXpos($iter)
set cluslist2Ypos($listsize2) $nodeYpos($iter)
set clusnodes2($listsize2) $iter
set listsize2 [incr listsize2]
$node_($iter) color yellow
$ns_ at 0.5 "$node_($iter) color brown"
puts "listsize2 = $listsize2\n"

} else {
set cluslist3Xpos($listsize3) $nodeXpos($iter)
set cluslist3Ypos($listsize3) $nodeYpos($iter)
set clusnodes3($listsize3) $iter
set listsize3 [incr listsize3]
$node_($iter) color blue
$ns_ at 0.5 "$node_($iter) color blue"
puts "listsize3 = $listsize3\n"
}
}

```

```

}
set centroidXpos1 0
set centroidYpos1 0

for {set iter 0} {$iter< $listsize1} {incr iter} {
    set centroidXpos1 [expr $centroidXpos1 + $cluslist1Xpos($iter)]
    set centroidYpos1 [expr $centroidYpos1 + $cluslist1Ypos($iter)]
}
set centroidXpos1 [expr $centroidXpos1 / $listsize1]
set centroidYpos1 [expr $centroidYpos1 / $listsize1]

set centroidXpos2 0
set centroidYpos2 0
for {set iter 0} {$iter< $listsize2} {incr iter} {
    set centroidXpos2 [expr $centroidXpos1 + $cluslist2Xpos($iter)]
    set centroidYpos2 [expr $centroidYpos1 + $cluslist2Ypos($iter)]
}
set centroidXpos2 [expr $centroidXpos2 / $listsize1]
set centroidYpos2 [expr $centroidYpos2 / $listsize1]

set centroidXpos3 0
set centroidYpos3 0

for {set iter 0} {$iter< $listsize3} {incr iter} {
    set centroidXpos3 [expr $centroidXpos3 + $cluslist3Xpos($iter)]
    set centroidYpos3 [expr $centroidYpos3 + $cluslist3Ypos($iter)]
}
set centroidXpos3 [expr $centroidXpos3 / $listsize1]
set centroidYpos3 [expr $centroidYpos3 / $listsize1]

#=====
#UDP Connection between senders (SUs "node 0-27) to receiver (Baste Station "node 28)
#=====
for {set i 0} {$i<28 } {incr i} {
    # defining transport agent for sending
    set udp [new Agent/UDP]
    # attaching transport agent to sender
    $ns_ attach-agent $node_($i) $udp
# defining transport agent for receiver
    set null [new Agent/Null]
    # attaching transport agent to reciever
    $ns_ attach-agent $node_(28) $null
# connect sender and reciever transport agents
    $ns_ connect $udp $null
# application instance defined
    set cbr [new Application/Traffic/CBR]

```

```

# attaching transport agent to application instance
    $cbr attach-agent $udp
# packet size in byte
    $cbr set packetSize_ 128
# interval in seconds
    $cbr set interval_ 0.1

    # starting time for generating packets
    $ns_ at 1.0 "$cbr start"
    # ending time for generating packets
    $ns_ at $opt(stop) "$cbr stop"
}

#=====
# Tell all the nodes when the simulation ends
#=====

set b [$node_(0) set mac_(0)]
#set c [$b set freq_]
set d [Mac/SMAC set syncFlag_]
#set e [$node_(0) set netif_(0)]
#set c [$e set L_]
set c [Mac/SMAC set dutyCycle_]
#puts $tracefd "M 0.0 nn $opt(nn) x $opt(x) y $opt(y) rp $opt(rp)"
#puts $tracefd "M 0.0 sc $opt(sc) cp $opt(cp) seed $opt(seed)"
#puts $tracefd "M 0.0 prop $opt(prop) ant $opt(ant)"
#puts $tracefd "V $b : $c : $d :"

puts "Starting Simulation..."
# stopping scheduler
$ns_ at $opt(stop) "puts \"end simulation\" ; $ns_ halt"
#$ns_ at $opt(stop) "ns halt"
$ns_ run

```

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