UNIVERSITY OF NAIROBI

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Centralized Opportunistic Scheduling Technique based on LEACH for TV White Space spectrum

BY

BUGINGO Jean de Dieu

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DECLARATION

This thesis is my original work, except where due acknowledgement is made in the text, and to the best of my knowledge has not been previously submitted to the University of Nairobi or any other institution for the award of a degree or diploma.

BUGINGO Jean de Dieu

Signature ______________________ Date ______2nd July,2021___

This thesis has been submitted for examination with our approval as university supervisors:

Dr. G. N. Kamucha

Signature ____________________ Date 06/07/2021

Dr. A.M. Nyete

Signature ____________________ Date 6/7/2021

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Abstract

This research thesis aims at improving the efficient use of the unlicensed spectrum freed by Analogue to Digital TV transmission transition referred to as Television White Space (TVWS). TVWS networks have a wide scope of applications. One of the recent growing applications is in the domain of Internet of Things (IoT), which permits inter-communication of different things or gadgets through the Internet. Wireless networks in TVWS face challenges such as short network lifetime, untimely energy exhaustion and interference with primary users and hence the need to optimize their operations. In this research work, a centralized opportunistic scheduling technique (COST) based on Low Energy Clustering Hierarchy (LEACH), with cognitive nodes capable of sensing primary users is used to provide a solution to these challenges. A MatLab r2014b based simulation package has been designed to simulate the technique for the TVWS spectrum in a Wireless Sensor Network (WSN). A low consumption energy protocol for WSNs based on remaining energy of cognitive nodes and primary user's energy detection by cognitive nodes is adapted for TVWS networks. Energy detection allows the cognitive nodes/secondary users to co-exist with primary users with minimum interference. Transmission paths are determined according to the position of cognitive nodes and their cluster heads. By comparing the actual distance of the cognitive node to White Space Base Station (WBS) and the pre-set threshold distance, a decision is made whether to use direct communication from cognitive node network cluster head to White Space Base station or through white space Modem here after referred as Modem (MD). The comparison of the proposed protocol with LEACH and LEACH-C is done in MatLab. Performance analysis of the metrics namely throughput, network lifetime and energy consumption show that the COST-LEACH protocol outperforms both.

Contents

List of Abbreviations and Acronyms:

AFH: Adaptive Frequency Hopping

BCSP: base station centralized simple clustering protocol

BS: Base Station

CH: Cluster Head

CNR: Carrier-Noise-Ratio

CPE: Consumer Premises Equipment

CEPT: European Conference of Postal and Tele-communications Administrations

DCA: Dynamic Channel Allocation

DD: Digital Dividend

DSO: Digital Switch Over

ETSI: European Telecommunication Standards Institute

FCA: Fixed Channel Allocation

FCC: Federal Communication Commission

FDMA: Frequency Division Multiple Access

FH: Frequency Hopping

GLDB: Geo-Location Database

LEACH: Low Energy Adaptive Clustering Hierarchy

LTE: Long Term Evolution

Modem: Modulation and Demodulation

MCS: Modulation Coding Scheme

MD: Modem

MIC: Ministry of Internal Affairs and Communications (Japan)

MS: Mobile Station

ODEUR: Opportunistic relative Distance-Enabled Unicast Routing

OfCom: Office of Communication (UK)

OFDMA: Orthogonal Frequency Division Multiple Access

PF: Proportion Fairness

PU: Primary User

QoS: Quality of Service

RN: Relay Node

RRM: Radio Resources Management

SE: Spectral Efficiency

SFS: Schedule Flow Sub-channel

SINR: Signal to Interference and Noise Ratio

SNR: Sensor Node Radio

TCP: Transmission Control Protocol

TDMA: Time Division multiple Access

TVWS: Television White Space

UE: User Equipment

WBS: White Space Base Station

WSD: White Space Device

WSN: Wireless Sensor Network

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1. CHAPTER ONE: INTRODUCTION

1.1. Background

Due to the rise of commercial mobile networks in numerous parts of the world, radio frequency is getting increasingly scarce. People, organizations and governments depend on this asset for communication. Studies have uncovered that TV broadcasting is not utilizing the spectrum efficiently i.e., TV channels are not being utilized in some areas at their full potential. The unused TV channels are the result of the transition from analogue to digital TV transmission which has freed unlicensed spectrum which spans from 54MHz to 806 MHz described as TV White Space (TVWS). Note that every given region has its own spectrum range within this limit, this depends on the country and its regulations.

TVWS is very similar to other wireless networks such that when using a wireless medium, a signal can be subjected to different vulnerabilities which can result in the discarding of the transmission process among the end users. These vulnerabilities can be categorized into two different types. The first relates to common challenges in both conventional wireless and the TVWS devices, and the second category is specific to TVWS users as discussed in section 2.1.3 of this thesis. The vulnerability specific to TVWS can be overcome by TVWS frequency spectrum scheduling [1].

In 2010, the United States Federal Communication Commission (FCC) made the TVWS spectrum accessible for unlicensed public use because the TVWS spectrum is superior to other means of wireless communication available [2]. For example, the TVWS covers a larger area than Wi-Fi since the Wi-Fi router has a relatively restricted range. Opportunities in the TVWS resources over Wi-Fi are later discussed in this thesis. The freed channels are reallocated by regulators to other services through auctions.

Many researchers have conducted multichannel scheduling for wireless networks using Low Energy Adaptive Clustering Hierarchy (LEACH) derivatives protocols [3] and distributed Opportunistic Scheduling for wireless Ad hoc networks [4]. The wireless computer standard that allows wireless local area network communication in TVWS is IEEE 802.11af, also known as WhiteFi or Super-WiFi, while IEEE 802.19.1 is a Wireless Coexistence standard in the TV Bands [5] [6].

Cognitive radio is currently an intensive research field and is seen as the authorizing technology for license-exempt access to TVWS. Cognitive radio is an innovative, versatile, smart radio technology used in wireless network systems that can automatically scare up available white space channels in a given area to avert interference and congestion in the network. To utilise the TVWS, the White Space Devices (WSDs) can communicate with a Geo-location database to obtain the list of currently available White Spaces. Also WSDs can access the available TVWS spectrum by sensing means same as in other wireless sensor networks.

In this research, a spectrum allocation technique based on Low Energy Adaptive Clustering Hierarchy (LEACH) technique is used. LEACH is one of the widely used dynamic clustering protocols. It has been applied in wireless networks to monitor and collect data from WSNs in different geographical locations. For instance, LEACH protocols are used in setting up communication among different entities hence the application in security, industries, offices, and homes smart monitoring [7].

The availability of TVWS greatly depends on time and location. It is therefore necessary to optimise the allocation and scheduling of services according to the available White Space in a given region. Multiple allocated secondary networks are deemed to use the TVWS, each with different spectrum channels. Thus, all networks must comply with their specific channels to avoid interference. In an opportunistic technique, the Scheduling algorithm goes for the users in the best channel condition to use the available resources [8].

1.2. Problem Statement

The interest for wireless broadband has increased uncontrollably due to technology innovation such as 3G, 4G, and 5G mobile services. Thus, the high demand of wireless services has led to spectrum scarcity. TVWS has provided a way to overcome the spectrum scarcity but still, there is a problem since the channels are unlicensed and everyone can access them without any license.

The White Space Devices (WSDs) must be allocated on a specific spectrum so that they can guarantee non-interference transmission among themselves and with the primary networks. There is therefore need to come up with an efficient scheduling technique for the available TVWS in a multichannel network that can overcome spectrum resource misuse and other limitations such as inefficient use of energy and short network lifetime of the existing scheduling techniques.

1.3. Objectives

The general objective of this research was to develop a scheduling technique based on the LEACH Protocol for Wireless Sensor Network (WSN) working over the TVWS spectrum.

- **Specific Objectives**

The specific objectives were:

a. To investigate and determine how much TVWS available in a given area, namely in Kenya, where TVWS trials have been conducted in Nanyuki and Kalema.
b. To develop a centralized opportunistic scheduling technique based on LEACH (COST-LEACH) of the available TVWS spectrum that will optimise the wireless sensor network's lifetime and the throughput.
c. Evaluate the metrics of COST-LEACH protocol compared to other protocols techniques in wireless sensor network namely conventional LEACH and LEACH-C protocols.

1.4. Justification for the Study

As wireless technology is growing rapidly, interference mitigation is inevitable because wireless systems are prone to interference. In general, TVWS access worldwide is still low compared to the future projection of utilization in this area. As TVWS has free unlicensed channels that can be accessed by any secondary user, optimum scheduling of its spectrum will come in handy in handling the disorderly use of the TVWS spectrum. To achieve optimum scheduling of TVWS devices, requests are made by the device to an authorized white space manager. The white space manager automatically lay out accessible channel data per a set of regulationss such as those set by the Federal Communication Commission (FCC) [9].

In this thesis, the emphasis is on how TVWS free frequencies can be shared and scheduled for use by specific wireless cognitive nodes. The centralised opportunistic scheduling protocol based on LEACH is used to overcome the spectrum scarcity by mitigating the interference with PUs and allowing the multichannel network transmission thus improving the network life time. This will improve spectrum access and ease the free movement of potential spectrum users

The existing opportunistic scheduling's main shortcomings are latency when the channel variations are too slow, and the fact that its scheduling algorithm is only concerned with maximizing long term average throughput [8]. This results in high throughput but at the sacrifice of other users' transmission. The improved LEACH protocol which has been designed has overcome these shortcomings by incorporating primary users' energy detection in the algorithm.

1.5. Contribution of the research

In general, the major contribution of this research is to give an insight of TVWS resources opportunities and provide a schedule to use them fairly.

- **Specific contributions**
  a) Provide a brief review on where trials on TVWS have been conducted namely Nanyuki and Kalema in Kenya
  b) Provide an account on LEACH protocol and its derivatives as well as other scheduling techniques in wireless sensor networks.
  c) Development of centralized opportunistic scheduling technique, cognitive nodes and base station based. Improvement of conventional LEACH and centralized LEACH protocol to reach very high network life span and throughput for wireless network working over TVWS spectrum.

1.6. Scope of work

The work involves assessing the existing Scheduling techniques in a wireless sensor network and the development of an Optimal Scheduling technique for wireless sensor network which can be adapted in networks working in TV White Space spectrum. This study reveals how much TVWS free frequencies are available and how much data it can support in Nanyuki and Kalema, region in Kenya where trials have been conducted. The COST-LEACH is derived from LEACH protocols. The proposed protocol can assign an appropriate task to each cognitive node, determining on which path every transmission has to be done. Each cognitive node activity will start and end by providing optimum, long wireless network life, interference mitigation, the ability to work in multichannel and higher throughput.

1.7. Organisation of the Thesis

The rest of the thesis is organized as follows:

- Chapter two contains the literature review. Prevailing rules and regulations while working in TVWS as well as a review of other authors' works in wireless network scheduling are described in this chapter.
- Chapter three is composed of the methods and tools used to achieve the intended results. It contains steps and measures taken to optimise the conventional LEACH for higher throughput and life time. It describes the proposed protocol in details; network model of the cognitive network, steps taken into account to build the proposed network and energy detection process by cognitive nodes. The network model is built in MatLab environment to attain the output desired.
- Chapter four gives results of the conventional LEACH and centralized LEACH as regards network life time, throughput and energy consumption compared with those of the designed COST-LEACH protocol. Results are analysed and plotted using Matlab.
- Chapter five gives a brief conclusion and suggestions for further works in LEACH as well as in TVWS resources scheduling.

2. CHAPTER TWO: LITERATURE REVIEW

2.1. Brief background on TVWS

Investigations have uncovered that TV broadcasting is not utilizing the spectrum efficiently i.e., the TV channels are not being exploited in some geographical areas. These unused TV channels are the result of the transition from analogue to digital TV transmission. The freed unlicensed spectrum spans from 54MHz to 806 MHz and the same unexploited channels between the active ones in VHF and UHF spectrum due to the analogue to digital transition are named as TV White Space (TVWS).

2.1.1. TVWS rules and regulations existing in different countries

Federation Communication Commission of the US allowed opportunistic access to TV bands in 2004. After research and substantial tests, the FCC acquired in November 2008 a report, and put in place a set of rules to permit the operation of cognitive radio devices in TVWS on an unlicensed basis [10] [11]. The United States Federal communication commission (FCC) in 2011 allowed in United States unlicensed devices to utilize TVWS. It also allowed the coexistence of licensed and unlicensed users in TVWS at some geographical areas.

The UK regulator, OfCom (Office of Communication) is responsible for authorising the TV and Radio spectrum use. In the digital dividend review released by the OfCom in 2007, they proposed to allow the use of unlicensed spectrum left by the analogue to digital shift in the Cognitive radio devices [10].At any specific location, there are a wide range of unused channels that could be utilized on secondary basis for different applications which exhibit relatively lower TV radiation. The regulation parameters which were proposed by the OfCom are in some way similar with those proposed by FCC.

The European Conference of Postal and Tele-communications Administrations (CEPT) have also begun setting TVWS regulations [9] [11]. The regulation tasks are handled by the CEPT Group SE43, incorporated in June 2009. SE43 is at present considering TVWS utilization characterizing technical and operational of WSD requirements in the 470 MHz to 790 MHz spectrum band.

In Japan the Ministry of Internal Affairs and Communications (MIC) opted to consider TVWS exploitation. With the set of an Evaluation Committee (EvC) 2009, it assessed the utilization models and technical challenges toward TVWS exploitation. Information about the latter can be found in [11]. And Singapore in 2010, the government chief information officer introduced its television white space technology information package and trial plan, and allowed organizations to show their commitments to be part of white-space trials [12].

The regulators, in South Africa, adapted the use of TVWS by selecting the 470-694 MHz band as "interleaved" or shared spectrum. Before the completion of digital switch over efforts, vacant spectrum between 694-790 MHz was accessible for shared use [9]. This proposition permitted devices to use accessible channels in this band as long as they will not interfere with licensed users. Especially, Independent Communications Authority of South Africa (ICASA) recognized the technical parameters for TVWS operation and established procedure for TVWS devices to use available spectrum.

The US and UK completed the digital switch over (DSO) in 2009 and 2012 respectively. The same was met by all (almost) the countries in Europe. Among the few Africa countries that fulfilled the DSO time limit are Tanzania, Kenya and Mauritius countries which are part of International Telecommunication Union region 1 alongside Europe, Middle East and parts of Asia. The 790-862 MHz frequency band is referred to as digital dividend 1 (DD1) while the 694-790 MHz frequency band is referred to as digital dividend 2 (DD2). Significant applications of TVWS will be met if DD1 and DD2 are allowed by all countries involved. African countries were in concurrence that DD1 be assigned to mobile services after the digital switchover (DSO) time limit of June 17, 2015 [13].

The TVWS promise to become one of the major pillars in wireless telecommunication. One of the merits of TVWS Spectrum is the Long-Term Evolution (LTE) femtocell also known as the Home eNode Base (HeNB). This can improve the indoor coverage and cell capacity [14].

2.1.2. Opportunities provided by TVWS

The conventional wireless means are either very expensive or not practical in some areas where population is scarce. As we grow more dependent on the internet for communication, information, medical services, and businesses, it has become easy to perceive that connectivity should be taken as a basic human need. Regrettably the usual means cannot satisfy enough area and that is where TVWS resources come in handy. Beside TVWS connecting people, it is also capable of bringing together smart cities with for example connected home devices, stadiums, shopping malls, municipal area and more [8].

TVWS can make internet of things technology a reality by giving a broadband signal the capability to handle multiple devices sending and receiving large amounts of data across long distances. TVWS spectrum has more capability over other means of Wi-Fi available [2]. TVWS technology can cover up to about 100 times the distance (10000 meters) compared to the Wi-Fi. TVWS offers an effective substitute to microwave by using UHF signals that can pass through obstacles and cover challenging geographical region without necessarily adding on antennas [15]. This is illustrated in figure 2.1

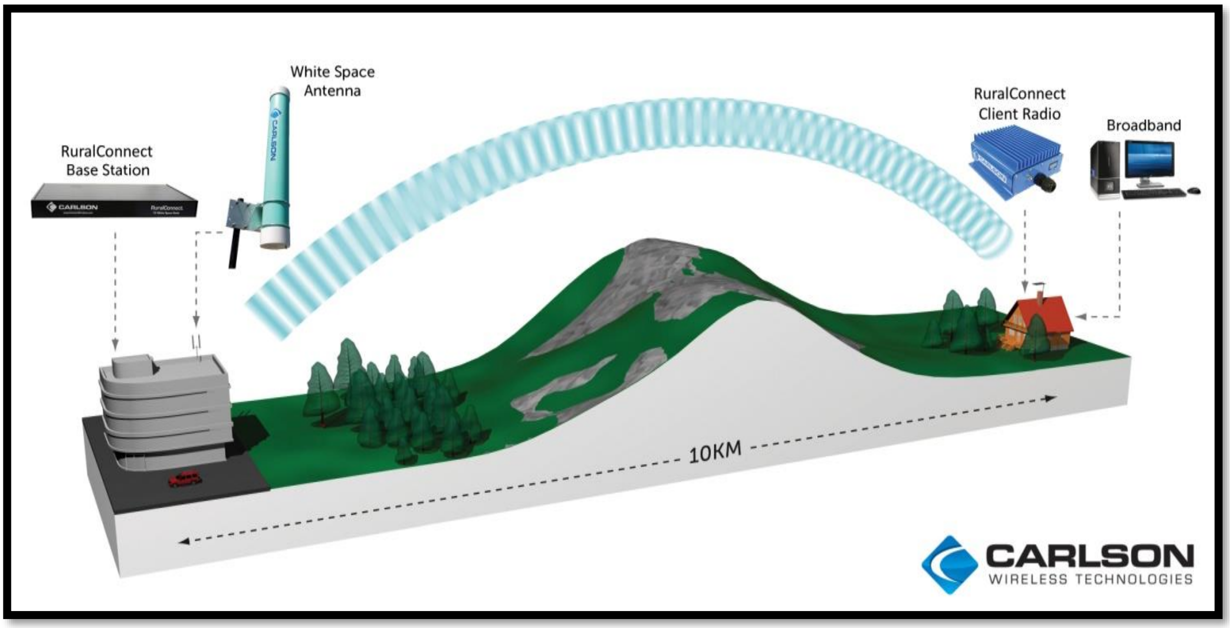

Figure 2.1: Carlson base station to Client Radio ruralConnect **[15]**.

Some of the main opportunities and advantages of TVWS are:

a. Low risk regulations; TVWS technology involve secondary utilization of spectrum. It does not require new assignment to be regulated [13].
b. Availability of unused spectrum makes TVWS a great rural technology
c. TVWS provides entrepreneurship opportunities and lower cost band accessibility.
d. These opportunities will make it possible for users to apply TVWS in many fields such as telemedicine, teleconference, and education [13].

2.1.3. Challenges in wireless access to TVWS

As for any other breakthrough technology, TVWS is not challenges exempt technology. TVWS spectrum can be utilized by all secondary wireless network entities. This results in the congestion and interference among wireless networks which can happen without proper co-existence procedures. It is necessary to ensure the co-existence of primary user devices and White Space Devices (WSD)/secondary user devices without interference due to the following reasons [8]:

1. There is increase of the interference in TVWS due to its high demand.
2. Since the number of channels depends on the region, scarcity of TVWS in urban areas may occur. Interference and congestion cannot be avoided because of the imbalance between the supply and the demand in TVWS.
3. Short life span and low throughput in the wireless sensing network.

To overcome these challenges WSD must be allocated on specific spectrum. To ensure they can guarantee long network life, a non-interference transmission environment between primary users and secondary users need to be maintained. Alternatively, as the technology is advancing, primary users can incorporate built in filters to eliminate interference.

Other challenges in TVWS are from the accessibility point of view and the optimisation of the available TVWS resources. Below is a list of challenges associated with accessing TVWS via the geo-location database, beacon, spectrum sensing or Hybrid (geo-location database access and spectrum sensing). The TVWS accessing methods are discussed later in this thesis, in the section 2.5.

1. According to FCC rules [2], WSD are required to identify with accuracy the vacant channels, which is a challenging practice. The Global positioning system (GPS) receivers will not necessarily mean the geo-location detection for white space channels for WSDs will be error free.
2. There are some factors which can lead to data base access congestion; those factors are high density and mobility of WSDs.
3. The main challenge in spectrum sensing techniques is that WSDs are not able to differentiate primary users and secondary users. This will result in loss of spectrum resources opportunities.
4. The spectrum sensing performance is also influenced by two major factors which are the multipath fading and shadowing. The effect of mobility on spectrum sensing is analysed considering the two factors.

However, in this thesis we have addressed challenges related to spectrum sensing. The solution for these challenges is to efficiently schedule the usage of wireless cognitive nodes working over TVWS spectrum band. The use of the scheduling techniques such as centralized Scheduling technique is proposed. In centralized scheduling techniques all the transmission decisions of base station and users are made by base station or the modem. In the centralized scheduling model, the Base Station (BS) receives periodic channel quality indication from the User Equipment (UE) and cognitive nodes. This technique plays a major role in overcoming primary users and secondary users’ challenges such as: congestion, loss of spectrum opportunities, short wireless sensor network life time and low throughput. The proposed technique is discussed in section 2.7.

2.2. Concept of Television White Space Scheduling

To exploit the unused TVWS spectrum efficiently, regulatory agencies have started putting in place regulations to allow the utilization of TVWS by unlicensed wireless devices as long as the interference is mitigated with licensed devices. To avoid interference amongst channels (licensed and unlicensed), the network utilizes Google’s spectrum database or geo-location database to identify the available white space or the spectrum sensing capability of sensing nodes or WSD. The FCC is to make the TVWS spectrum available for unlicensed use and has launched new broadband market and White Space Devices [2].

In the future, many heterogeneous and independently operated wireless networks may utilize the TVWS. Coexistence between these networks is essential in order to provide a high level of QoS to end users. Consequently, the IEEE 802 LAN/MAN standards committee has approved the P802.19.1 standardization project to specify radio-technology-independent methods for coexistence among dissimilar or independently operated wireless devices and networks [16]. In table 2.1 different white space devices characteristics and mode of their operation are given and compared. Their main difference is their way of identifying available accessible channels and how often they monitor their database access. The FCC has defined three mechanisms to protect licensed incumbent TV broadcasters from interference from unlicensed WSDs [17]:

- WSD geo-location with access to a TV bands database
- WSD transmit power limitations (transmit spectral mask)
- Operating channel radio sensing of protected licensed users

Table 2.1: Classification of WSDs [2] [15].

TV band devices	Determination of channel availability	Maximum transmit power (EIRP)	Detection threshold	In service monitoring
Fixed device	Geo-location/database access	1 W/6 MHz	-114 dBm	At least once a day (Database access)
Portable device (Mode 1)	From a fixed device or Mode 2 portable device	100 mW/6 MHz	-114 dBm	At least once every 60 s
Portable device (Mode 2)	Geo-location/database access	100 mW/6 MHz	-114 dBm	At least once a day (Database access) and at least once every 100 s
Portable device (Sensing only)	Spectrum sensing	50 mW/6 MHz	-114 dBm	At least once every 60 s

The available of TVWS is resolved by PUs position recorded in the Geo-location database. To determine the availability of the channel, the FCC requires that WSDs must accurately detect vacant channels to be used in TVWS network [18].

2.3. Overview of Wireless Sensor Networks

Television White Space has found use in several areas such as in connection, monitoring and management of regional facilities remotely It is being used to provide wireless broadband in designated regions such as campuses. In the USA at West Virginia University, TVWS technology has been used in e-hailing for mass transportation [19]. Here in Kenya, connectivity has been provided in some remote areas using TVWS. A typical example is in Nanyuki, where TVWS network has been set by Mawingu Networks [20].

Wireless sensor network (WSN) communications have enabled the development of low-cost, low-energy consumption, multipurpose sensor nodes that are relatively small in size and communicate un-tethered in short distances. These sensor nodes process data and then forward them to the control station/base station (BS). Sensor nodes are positioned according to the following two approaches [21]:

- Sensors can be deployed far from their actual base station. In this case, highly complex sensors are used to be able to differentiate between transmission signals and noise.
- Sensors are deployed randomly in the same network area with the BS.

In both cases, sensor nodes send their sensed data packets to the base station to be aggregated, analyzed and computed. Sensor networks may include of many different types of sensors such as seismic, low sampling rate magnetic, thermal, visual, infrared, and acoustic and radar, which can monitor a wide variety of environmental ambient conditions that consist of the following:

- The presence or absence of different types of objects,
- Mechanical stress levels on attached objects, and
- The characteristics such as speed, direction, and size of an object.

Sensor nodes can be used for continuous sensing, event detection, event identification, location sensing, and local control of actuators. The idea of micro-sensing and wireless network of these nodes guarantees a variety of applications. WSN has mainly three challenges:

- ✓ **Deployment challenges:**

The WSN nodes are impromptu in nature and when deployed, the nodes self-arrange. The nodes are deployed in an environment and overseen remotely. The deployment is either fixed or random. In fixed deployment, the location of node placement is preordained whereas in a random deployment, the deployment is done randomly in the network and the position of the nodes is not preordained.

- ✓ **Communication challenges:**

The WSN links have limited bandwidth and because of its wireless channels, they are unreliable and liable to attacks. The links due to the dense deployment of nodes will have more collisions and more delays.

- ✓ **Device challenges:**

The device has fixed memory storage; limited power as they are battery operated and limited processing capability. These challenges are addressed to make WSN working in TVWS be more practical. Other issues may arise in WSN and this thesis research aims to address them to efficiently work in TVWS. Those issues are:

- ✓ **Heterogeneity:**

There are two categories of wireless sensor networks, homogeneous and heterogeneous [22].In homogeneous WSN, all sensors have the same capability and the network is very simple. All the nodes drain their energy uniformly and also the cost of hardware is low. In heterogeneous WSN, nodes with different capability concerning battery, storage, mobility, and processing are used. The advantage of such heterogeneity is that the life of the network can be drastically increased. The control and coordination roles of the network can be handled by nodes with high energy and nodes with low energy can be used for sensing the environment, hence making the network more efficient in terms of energy.

- ✓ **Mobility:**

The sensor nodes in a wireless sensor network move from one area to another [23]. The movement of sensor nodes plays a role in avoiding the network disruption due to node failures resulting in the network being fault tolerant. The mobility of sensor nodes helps accomplish scalability and energy efficiency. Mobility can be associated with Base Station and sensor nodes. Movement of the sink in the wireless network, makes the data gathering from sensor nodes simple and maximizes the efficiency of the wireless network [24].

The dead nodes caused by battery exhaustion can be replaced by mobile sensor nodes. The mobility in a wireless sensor network is conscious, resulting in the movement of nodes to be controlled and coordinated. The mobility is an issue that is not discussed at the full extent in wireless sensor network. Many of the existing protocols utilizes static WSN; after deployment all nodes are in a fixed position. The mobility approach comes with a setback in localizing sensors nodes. In a Clustered WSN environment, the movement of the nodes causes the nodes to leave and enter into a new cluster.

For a longer WSN life time, low energy adaptive clustering hierarchy-based protocol is used in this research thesis. Note that, wireless sensor network life time is the maximum period in which the network is operational and able to fulfill its dedicated task. It can also be defined as the time at least one sensor node has quantifiable energy to perform its task in WSN.

2.4. Channel Allocation schemes

In radio spectrum management for wireless and cellular networks, channel allocation schemes are required to allocate bandwidth and communication channels to base station access point and terminal equipment; the idea is to do the same by the optimum scheduling of the TVWS frequency spectrum. The objective is to achieve optimum use of White Space Devices bit/hertz/site through TVWS frequency scheduling and assure a certain grade of service to avoid channels interference among nearby devices that share the bandwidth. Below are some approaches used on radio spectrum management and allocation and they can be of use in the optimum scheduling of TVWS spectrum**.**

2.4.1. Fixed Channel Allocation (FCA)

Each device should be assigned a predetermined set of frequency channels. FCA requires manual frequency planning which is a tough task since many Time Division Multiple Access (TDMA) and Frequency Division Multiple Access (FDMA) devices are highly sensitive to interference [25].

2.4.2. Dynamic Channel Allocation (DCA)

This could be used in TVWS networks as it is used in wireless networks with several adjacent non-centrally controlled access points. The access points automatically select channels with low interference levels [25].

2.5. Cognitive methods to access TVWS

Cognitive radio systems are ongoing advances in wireless communication, where they mean to improve the radio spectrum range that exists as of now. We realize that cognitive radio is the exceptional class of limit wherein they expect to improve the absolute access of wireless systems. Many techniques have been proposed to help WSDs access empty available channels. In this thesis, a brief discussion is carried out on the following access methods:

- Geo-location database
- Spectrum sensing
- Beacon
- Hybrid of geo-location and spectrum sensing

2.5.1. Geo-location database access method

Essentially unique to the detection of available spectrum is technique whereby spectrum range accessibility data is put in a central database to which all the participants have safe access without dread of making destructive impedance to each other. In the advancement of TVWS innovation, this thought was realized in a type of geo-location database (GLDB) administration that is called White Space Database (WSDB). The task guideline is very straightforward:

- PUs devices register with WSDB giving their transmitter characteristics.
- SU devices send an inquiry over the Internet containing area and transmitter attributes to the database.
- WSDB computes the safe zone of the PUs by applying a propagation model to PUs enlistment data and sends a reaction to SU containing a list of channels that are locally accessible for communication. The list likewise contains the most extreme permitted transmission control for each open channel.

The undeniable quality of this arrangement is the simplicity of administration since it allows central management of the devices, and regulators all over the world, for example, FCC or Ofcom, adopted this approach for TVWS. From a specialized point of view, WSDB is usually implemented as a cloud administration [26] [8].

2.5.2. Spectrum sensing

In the spectrum sensing approach, a cognitive node begins by utilizing an inbuilt sensing algorithm to determine whether PUs are present in a specified channel. If the presence of the PU signal is sensed, then a cognitive node, as a secondary user, will not transmit through it. The cognitive radio system of the white space device scans the spectrum continuously to establish the channel which is available for secondary use This is essentially a Listen Before Talk (LBT) approach, which means that the gadget tunes in to a particular channel for quite a while before it can use it for transmission. The main problem of this technique is that, at times, the cognitive node fails to detect transmissions from nearby PUs. This is referred to as hidden node problem [3] [8] [26]. Geo-location database technique does not suffer from this problem.

2.5.3. Beacon approach

Another method for accessing the spectrum is by using a system of radio beacons which send data of spectrum availability. In the beacon technique, a devoted channel is utilized to offer information to White Space Devices (WSDs) with respect to which channels are accessible for secondary users' transmissions. The WSD will only operate in a particular channel in the event that it gets a signal from the beacon giving it consent to transmit in that channel. It will be able to use the channel until it receives a signal from the beacon to halt transmission [26].

Such a framework would have some advantages as contrasted with WSDBs. For one, there is the absence of optional correspondence channel prerequisite, known as a bootstrapping problem. Secondly, the gadgets would not need geo-location capacity. However, the technique has one main disadvantage in that it requires beacon infrastructure, which is usually in the form of base stations, to be established. The expenses of rolling out of such an infrastructure covering a whole nation, coupled with maintenance costs, make this technique prohibitive. The technique also has another disadvantage in that the beacons require some spectrum allocation [3].

2.5.4. Hybrid of geo-location database and spectrum sensing approach

Combining spectrum sensing and GLDB results in an approach which benefits from the advantages of the two techniques while eliminating their individual limitations. A GLDB will, for example, contain data on TV transmitters but will lack information on existing dynamic incumbent systems namely wireless microphones and talkback devices, since their information has not been entered in the central database. Spectrum sensing will on the other hand be able to detect devices which are not registered, but it suffers from hidden node problem.

2.6. Scheduling Techniques for various wireless networks

The deployment of different wireless devices for mobile, home, and enterprise networks, all operating in the unlicensed band, is met with growing concerns about signal interference and performance degradation. The important factor affecting the spectrum scheduling in cognitive radio networks is the ON/OFF activities of the primary users (PU) [27]. Whenever a PU is detected, the cognitive radio/sensor node devices have to vacate the licensed band occupied by the PU as transmission link failure could occur.

To address these challenges, several industries led activities have focused on the coexistence of these devices in the same environment. There are many techniques used to schedule frequency spectrum depending on the devices used and the range of the frequency to be scheduled. Due to the variability of the environment, the quality of available channels can vary significantly and randomly over time across channels and different links, so the proposed technique must work accordingly. In this thesis, the focus is on improving conventional LEACH so that it can be adapted for wireless network working in TVWS. Some of the existing scheduling techniques are discussed in the next subsections.

2.6.1. Coordinated scheduling

Coordinated scheduling's main objective is to increase the number of users as much as possible that can be scheduled, and ensuring their QoS requirements with the minimum transmit power [28]. Coordinated scheduling is expected to play a major role in overcoming interference in a wireless network. The algorithm of coordinated scheduling is based on centralized scheduling architecture. It assumes the knowledge of the channel condition of base stations to user links within the cluster at the scheduler. This scheduling technique is mainly used to control the interference that the user experiences from the base station within a cluster.

Coordinated scheduling is mainly implemented to improve the performance of densely deployed interference limited networks namely wireless networks. The idea of coordinated scheduling for wireless networks is done by using Soft Frequency Reuse (SFR) [29]. The coordinated scheduling encounters a coordinated problem known as Power Zone Assignment (PZA), which means that every client can't be served by more than one base-station, yet can be served by at least one power-zone inside each base-station outline. [29].

2.6.2. Interference Aware scheduling technique

Interference is the main limiting factor of all wireless network communications. To satisfy the end users, techniques have to be put in place to overcome the interference and overlapping of frequencies. Interference aware scheduling is one of the techniques used to overcome interference in WiMAX networks and this technique can be adapted by TVWS networks to overcome frequency interference and scarcity. The technique evaluates the interference of the communication to obtain a realistic model that can be exploited in scheduling [30].

In [30], the authors propose an efficient admission control and flow scheduling algorithm that schedules available spectrum in such a manner that the bandwidth and delay of the transmitted signal flow requirement will be met. The Interference Aware Scheduling technique schedules non interfering links concurrently leading to efficient spatial reuse.

- **Heuristic Algorithm for Interference Aware Scheduling.**

Heuristic algorithms are used to determine the proper or the best possible transmission line to avoid the interference of the signals during the transmission. These algorithms usually are the best solution to avoid interference and they are faster and easy to use. For TVWS spectrum scheduling, the Interference Aware Scheduling can be used, as the scheduling is done according to the service class priority. For TVWS frequency, first before running the algorithm, the Television White Space available will have to be determined using geo-location database and then proceed to the following two stages:

The first stage consists of identifying and scheduling the free timeslots and sub channels to the flow and finding out the maximum frequency bandwidth to be allocated to them. If any task has been allocated large frequency bandwidth than the required frequency bandwidth we tag these extra frequencies bandwidth as timeslot-sub channels, and these can be used for other flow tasks if required. If the frequency bandwidth assigned to a specific flow link is lesser than the minimum frequency bandwidth required then proceed to the second stage.

The second stage consists of finding out the bandwidth frequencies tagged as extra frequencies bandwidth and allocate them with the flow tasks which are being carried out. All the flow tasks are scheduled in Interference Aware manner. Note that this scheduling technique can be either static or dynamic [30]. There are some other algorithms which can be used in Interference Aware scheduling such as Naïve algorithm [31] and SFS algorithm [30], among others.

Figure 2.2 illustrates the coverage of TVWS and how TVWS spectrum is dispatched to the TVWS Consumer Premises Equipment (CPE) from TVWS base station and the geo-location database.

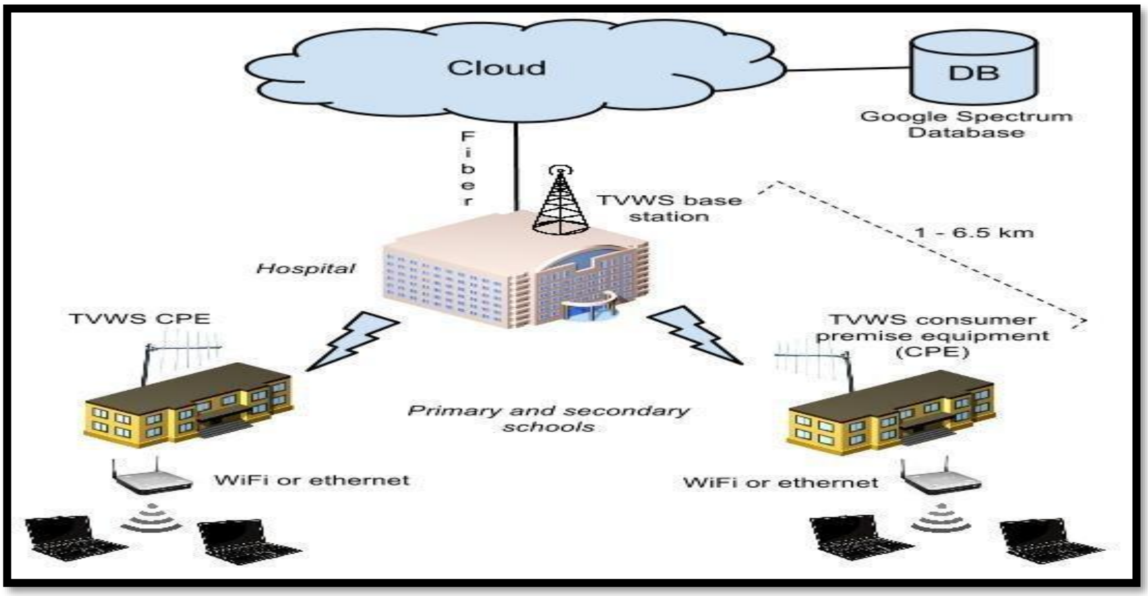

Figure 2.2: Geo-location Data base and coverage of TVWS **[32]**.

2.6.3. Opportunistic Spectrum Scheduling

With the rulings of the Federal Communication Commission which allowed the use of unlicensed TV spectrum in the US, other countries are stepping in to exploit also that new technology. Regardless of licensed or the unlicensed spectrum, frequencies have to be used efficiently. Therefore, frequency reuse is crucial; here fractional frequency reuse can be used. The main idea is to divide the entire frequency spectrum into several sub-bands and each sub-band is differently assigned to a specific sub-area.

By not considering the detection problem of primary users, the FCC allowed the use of the Geo-location database to help the secondary users find the best TV white space in the vicinity and avoid TV signals [33]. Opportunistic scheduling in wireless networks has been initially implemented in cellular networks, to enhance the capability of a wireless network. In opportunistic scheduling, BS assesses the channel quality from the channels of all registered users and selects one based on the efficiency and the previously offered services. However, opportunistic scheduling in cellular networks does not support the use of multi channels [34]. Figure 2.3 shows a star network of unlicensed users' base station and how they can coexist with licensed base station without interfering with each other.

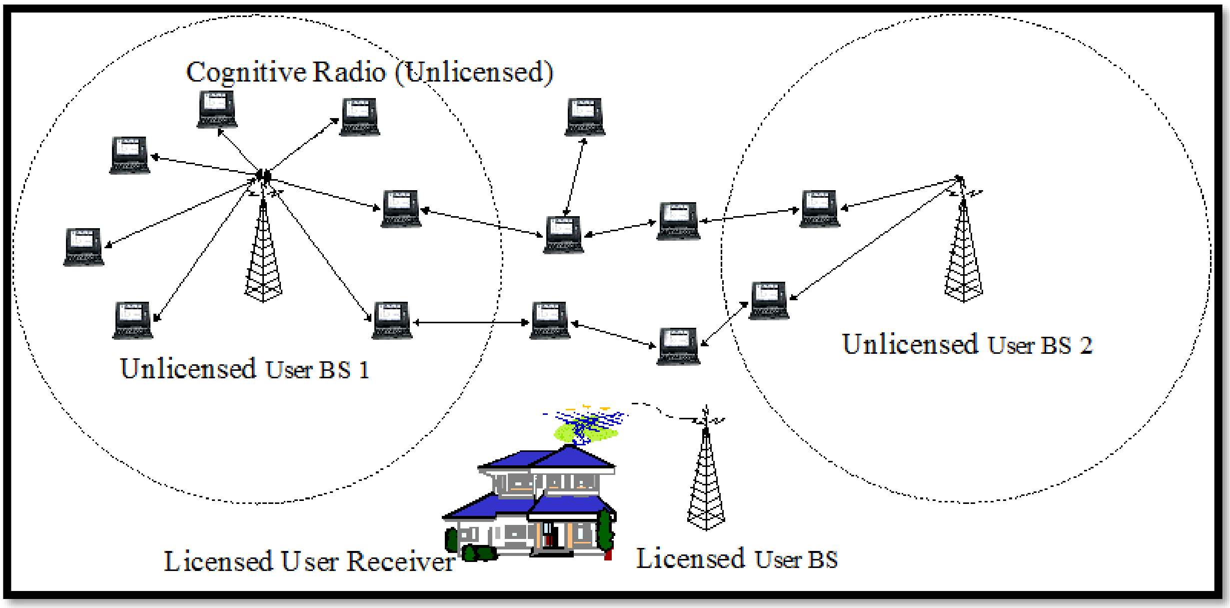

Figure 2.3: Multiple access channel control for unlicensed spectrum (TVWS) **[33]**.

To verify the service given to the user who is using an opportunistic scheduler, it is important to describe the offered traffic at the flow level. However, the scheduling performance is evaluated at the packet level, assuming there is an infinite backlog of packet in each transmission queue. Scheduling in wireless networks (Wi-Fi and TVWS) is mainly done to improve the throughput and QoS by selecting which channel the network users will have to use to transmit or receive the data. The scheduling decisions are made by the scheduler which is an algorithm frequently executed centrally at the base station of a network or simply by using secondary users as cognitive radios. Cognitive radios are devices in a wireless network that can intelligently detect vacant channels for smooth wireless communication. The multi-user diversity among the users can be a barrier in sharing the available channels; this can cause spectrum scarcity. To avoid that scarcity, it is imperative to consider both channel conditions and the QoS demands of the user into consideration to design the scheduling algorithm [35].

Opportunistic scheduling has many advantages over other techniques as it is designed to be able to take advantage of the variation of channel conditions to enhance channel efficiency, and it gives some degree of freedom to the system: time domain diversity. This improves spectrum efficiency, especially for delay tolerant data transmission. The other advantage of opportunistic Scheduling also includes the capability to operate in the presence of other resource management techniques [36]. The use of a cognitive node is broadly recommended for opportunistic scheduling [36].

A general problem that can be taken into account is how to select the best channel and rate considering the number of users in the network, to provide the best QoS and throughput. This is a very considerable drawback of the opportunistic scheduling [34]. However opportunistic scheduling encounters so many other challenges and limitations. For instance, estimation errors in opportunistic scheduling techniques arise as users have to know and estimate the channel conditions.

There are many sources of estimation error such as error of estimation of channels, an error of estimation of parameters implicated in scheduling techniques and error derived from various delays thus the decrease of wireless sensor network lifetime and throughput [36]. However, in this thesis, we tackled some of the challenges in wireless networks such as network lifetime, throughput and energy consumption of the network by using energy detection Cognitive nodes.

2.6.4. Low Energy Adaptive Clustering Hierarchy (LEACH) and its derivatives for wireless sensor networks

There are many derivatives of LEACH based on Energy consumption, the distance between nodes and their base station, how their CH are elected among others. However, in this research work, focus was made on those relevant to our study.

2.6.4.1. Conventional LEACH

The conventional LEACH is cluster-based routing that uses a random rotation of cluster heads to fairly distribute the available energy amongst sensor nodes in WSN. The routing technique is such that, all nodes arrange themselves to be part in distinctive cluster as a cluster head (CH) or a cluster member (CM). The cluster head of every cluster has the task of gathering the sensed data of each node that is associated to the cluster. When the cluster head has collected all the cluster information, it transmits the data to the base station [37].The conventional LEACH protocol operates with several rounds. It has mainly two-phases; setup phase as well as steady state phase. In the setup phase, clusters are built in an adaptive mode wherein the steady state phase, information is transmitted. The time for steady states is relatively longer than the time in setup phase to ensure the transmission of encrypted data [38].

CH election in conventional LEACH as well as in most derivatives of LEACH is based on mode zero and unity. If the number is lesser than the threshold $T(s)$ then the node becomes CH in the next cycle. $T(s)$ is given by:

$$\boldsymbol{T(S)} = \begin{cases} \dfrac{\boldsymbol{p}}{\boldsymbol{1-p\left(r mod\left(\frac{1}{p}\right)\right)}}, & \boldsymbol{if\ S = C} \\ \boldsymbol{0} & \boldsymbol{otherwise} \end{cases} \tag{2.1}$$

$T(s)$ = Predefined threshold

p = Number of Cluster heads

r = The current round,

C = Nodes not selected as CH in actual round.

S = Number of nodes

Even though the LEACH protocol is an energy adaptive protocol, it does have challenges. As sensor nodes have limited energy capacity, it is incapable of ensuring a fair distribution of the CHs in WSN since BS does not have an influence on the CHs election. This results in relatively high energy consumption thus reducing network life.

2.6.4.2. Derivatives of LEACH protocol

i. The modified LEACH protocols

In the modified LEACH (LEACH MOD) protocol, the network is divided using a simulated annealing technique so as to increase the performance of the network lifetime. Unlike conventional LEACH, CHs in LEACH Mod are elected by the base station based on their remaining energy. The LEACH-MOD protocol does not necessitate the transmission probability computation as it does not consider the role of the probability in increasing the performance of the wireless network.

It is of importance to note that the conventional LEACH and LEACH-MOD protocols can ensure that there are no nodes that can be chosen as Cluster Head (CH) for consecutive rounds. If the number of nodes waiting for transmission is higher in LEACH-MOD, it causes high collision inside a cluster build-up process, causing quick energy exhaustion in nodes of the network system [39].

In any design of wireless sensor networks which includes white space sensor networks, energy consumption and network lifetime are very crucial. Sensor nodes in the wireless sensor networks are highly energy-constrained. This is a key factor to restrict its performance. So far, many energy-efficient routing protocols have been proposed [38]. Efficient and definite routing is very important in Wireless Sensor Networks (WSN).

ii. Centralized LEACH protocols

Centralized leach protocols compared to the conventional LEACH and LEACH-MOD performs better. As in conventional LEACH protocol, all transmissions are controlled by the base station. However, the cluster heads election depends on the base station and the distance between sensor node and BS. There are some derivatives of LEACH-C such as base station centralized simple clustering protocol (BCSP) and improved LEACH-C protocol [38].

In base station centralized simple clustering protocol (BCSP) it demands no position information of the sensor nodes. In lieu, BCSP uses information on the energy of each sensor node and the number of cluster heads which is switching depending on the situation of the sensor network. This protocol is used in a bid to improve the conventional LEACH using a centralized approach. In BCSP, the BS elects CH by taking into consideration the remaining sensor nodes, and the base station itself communicates the newly elected CH to the sensors [38].

The cluster heads election depends on the base station and the distance between sensor node and BS. The base station sends a test packet so to ensure that all the nodes know its location, sensor nodes at their turn send their location and their remaining energy. In improved LEACH-C energy is relatively evenly distributed compared to BCSP thus iLEACH-C offers longer lifetime and throughput. Both BCSP and iLEACH-C present protocol overhead disadvantage, so techniques such as Opportunistic relative Distance Enabled Unicast Routing (ODEUR) for WSN were developed [7].

In ODEUR, the challenge of the resulting intermittent connectivity in WSN is resolved by using opportunistic routing protocols [3]. However, as the ODEUR protocol has unicast based transmission it consumes relatively high energy. Therefore, COST-LEACH algorithm is proposed for efficient use of energy. In most of the LEACH derivatives, normal nodes are used. However, in this thesis, energy detection cognitive nodes are used for opportunistic scheduling of available channels without interference between secondary wireless networks working in TVWS and primary wireless networks.

iii. Cognitive radio nodes in WSN over TVWS based on LEACH protocols

In WSNs architecture, cognitive radio nodes-based protocols are proposed to overcome interference among primary users and secondary users and enhance the overall performance of WSNs. Cognitive radio is hugely researched nowadays as it is one of many ways to avoid collision and interference between primary users and secondary users. Cognitive radios are capable to adapt to the conditions of available spectrum band and detect automatically and intelligently available channels and choose which channels they can operate on.

This enables more communication to be made at the same time in WSN. Researchers have shown that spectrum freed by analog to digital migration is significantly under-exploited in certain areas. The need for secondary users to operate over these freed spectrums is crucial without interfering with primary users and hence widespread use of Cognitive radios in TVWS [40].The ability of Cognitive radios to adapt according to their surrounding environment for optimum performance make it possible the primary networks and secondary networks to coexist [41].

Cognitive nodes detect signals to get necessary information about the available spectrum. This method uses the capability of cognitive nodes sensing the available channels to use without interfering with primary networks. Various cognitive radio protocols have been developed. However, in this section, discussion focuses on those relevant to this research, such as cognitive LEACH (CogLEACH), Adaptation of LEACH routing Protocol to cognitive radio sensor networks [42] and wireless Sensor Networking Over White space (SNOW) protocol [43].

The latter is cognitive radio-based protocol for wireless sensor network. CogLEACH is a probabilistic clustering protocol that uses the number of available channels as a weight in the probability of each node to become a cluster head. Cognitive LEACH is a decentralized protocol and a derivative of the LEACH protocol which is spectrum aware protocol. CH selection in CogLEACH is similar to LEACH cluster head election, as both depend on the threshold $T(s)$ [43]. However, the management of cognitive nodes in CogLEACH protocol in WSN comes at a cost as CN energy consumption is very high and delays may occur. This reduces the network lifetime significantly [43].

Adaptive Cluster-based routing protocols have received much recognition due to their wide range of applications in systems working over WSN. Adaptation of LEACH routing protocol to cognitive radio sensor network is developed to overcome challenges faced in other cognitive protocols in LEACH, such as relatively high energy consumption. In an adaptation for LEACH routing protocol to cognitive radio sensor network, multiple access channel protocol is used during the CH election to reduce collision among transmissions. But in other previously discussed protocols, energy in adaption for LEACH routing protocol to cognitive radio network is not efficiently used since cognitive nodes are at different distances.

Wireless sensor networks over TVWS have interested many researchers; some WSN systems were proposed such as SNOW to leverage opportunities of sensor networks working over TVWS. SNOW can achieve deployment sensors over large geographic areas. TVWS band spectrum enables large-scale wireless network systems that depend on real-time communication over wireless sensor-actuator networks. This method can be applied to cognitive radios working over the white space spectrum when CRs have to be deployed in large geographic areas. However, SNOW has constraints such as inefficient use of energy as sensor nodes are deployed over large areas. Efficient WSN protocols to handle mobility are developed, so to be adapted in WSN over TVWS [43].

In this thesis, an improved LEACH protocol based on a Centralized opportunistic scheduling protocol for a high network lifetime and throughput for a network working in the TVWS band spectrum has been proposed. The system architecture is based on randomly deployed cognitive nodes, a modem in a given area and base station out of that area. The idea is to reduce the distance between nodes which are relatively far to communicate with a base station; they can communicate with BS via modem which is centrally deployed in the area of cognitive nodes.

Many techniques have been used to work over the TVWS spectrum using Cognitive radio sensing. These methods have been subdivided into three major categories based on the way of sensing. These types are namely Primary user transmission detection, Noise detection, and energy detection to identify the presence of primary users [44] [45]. In this thesis, we focused on energy detection for CN to be able to operate without interfering with primary users. The energy detection technique is used for its easy implementation and relatively low computational complexities. This approach reduces the energy consumption of WSN considerably hence increasing the network lifetime.

2.7. COST-LEACH protocol for TVWS

The FCC's opening up on TV White Space for unlicensed use has led to innovation in cognitive radio, spectrum sensing, as well as proposals on how that spectrum can be accessed dynamically [46]. The main idea behind the cognitive network is to allow the secondary users (SUs)/cognitive nodes/sensor nodes to utilise the temporally not used spectrum by the primary users (PUs) opportunistically. For efficient use of TVWS opportunities in a wireless sensor network, two major requirements are taken into account.

The need to protect primary users is crucial so WSD can access channels not being used by primary users is the first requirement. Secondly is to harness as much as possible TVWS resources taking into account the first requirement. To harness the available TVWS resources, two approaches are used. The first approach to access is to use geo-location database to identify the available white space spectrum and the second approach is to use cognitive radios to sense the available TVWS resources. In this thesis, we opted to use the spectrum sensing of the available spectrum as the focus in this thesis is to efficiently use the energy to improve network lifetime and throughput.

System architecture is proposed using TVWS in a network composed of: (a) A base station to handle all the transmission tasks (b) Cognitive radio to sense the available spectrum and communicate to the base station (c) a modem centrally deployed in the network to facilitate transmission and reception of nodes far from the base station. Many researchers have conducted multichannel scheduling using a distributed Opportunistic Scheduling for wireless Ad hoc network [4].

However, in this research, centralised scheduling for an improved LEACH with the presence of cognitive radios as sensor nodes is used. A Centralised Opportunistic scheduling based on LEACH is proposed to schedule multi-channel networks, to optimise the spectrum interference mitigation and to overcome other shortcomings of the existing LEACH protocols and opportunistic scheduling technique such as short network life and low throughput. The proposed centralised opportunistic scheduling is easy to control as it takes into consideration a master-slave approach. The algorithm attempts to identify the packet data to be transmitted over a network spectrum that should receive the most attention and then dedicate the most attention to these packets of data.

The algorithm accomplishes an interference aware schedule for a centralised opportunistic spectrum scheduling by creating and removing tasks dynamically or by varying the data transmission work of individual tasks. The advantages of a centralised architecture for wireless sensor networks are many, some of which are outlined in [47]. The major merit of this proposed centralized scheduling technique is that it will perform many tasks at the same time such as:

(a) To work in a multichannel environment and this will increase the data rate allocation thus improving the white space network life and throughput

(b) Interference aware schedule in the proposed opportunistic scheduling technique will exploit the time- varying channel conditions in the TVWS spectrum network to increase the performance of the whole system as secondary users are intelligently choosing channels.

(c) it can be easily debugged as it is centralised and follows a master-slave model.

(d)Cognitive radios are energy detection operated as the primary user signal presence is detected by comparing the received energy with a predetermined energy threshold.

There is some information that must be conveyed to the Base station to perform the centralized scheduling:

- First, the scheduler has to identify the packet data to be transmitted.
- Whether that packet has to pass through the modem/central node or it has to be transmitted directly to the base station.
- To identify the exact modem/central node the transmitted packet data from WSD will pass through if it is not sent directly to the base station. However, in this thesis, we do consider a single modem at the centre of the wireless sensor system.

3. CHAPTER THREE: MATERIALS AND METHODOLOGY

3.1. Introduction

An improved LEACH protocol is proposed, which is based on the hierarchical clustering structure model. LEACH involves two main phases; the construction phase and the steady-state phase. These are built upon each other to create simulation models of wireless sensor networks. By introducing the centralized opportunistic scheduling technique, the lifetime and throughput of wireless working in the TVWS spectrum network is improved. The behaviour of the scheduled TVWS spectrum is taken into consideration using the COST-LEACH protocol implemented in Matlab r2014b, installed in a computing device namely a laptop with as specifications: i5-5300U CPU, 2.30GHz processor, RAM 4GB, 64-bit operating system and compared with other LEACH protocols.

3.2. Methodology

Nowadays a lot of emphasis is on how to design and produce suitable scheduling protocols for wireless networks working in the TV white space spectrum. The main aim is to obtain free-flowing of data and have the maximum possible network lifetime, throughput and QoS over the TVWS spectrum. Two main methods are usually used to access the spectrum. In the first method, a geo-location database is consulted to determine if there are any TVWS free channels which can be used without interfering with the primary users in that given region. The second method utilizes spectrum sensing. In this research, spectrum sensing of the already designated white space channels is used. Energy detection based Cognitive nodes are used to mitigate interference with PUs.

The Federal Communication Commission allows the use of Geo-location database to help primary users avoid interference and there are some countries that use the database to protect their White Space Devices, for example, wireless microphones. By assuming the knowledge of available TVWS channels, the scheduling protocol is developed to increase the network lifetime, fairness amongst cognitive nodes and the throughput. In this work, the developed centralised Scheduling protocol for base station and modem initially assess the channels availability, their quality; the data rate it can transmit and all channels to be used by primary users and choose one based on energy efficiency, the spectral efficiency, and the fairness.

This research emphasized on the improvement of an existing technique namely the conventional LEACH, as it is applicable on single channels and is non-interference aware; proposing an improved Centralised Opportunistic LEACH scheduling protocol. By dividing the available channels into non-overlapping channels, the opportunistic Scheduling technique is applicable to multi-channel systems. The performance of the proposed scheduling protocol is tracked using the r2014b MatLab tool. The metrics of the Centralised Opportunistic Scheduling protocol is analysed and compared with the traditional LEACH protocol.

3.3. Network set up of COST-LEACH protocol for TVWS Spectrum

The system architecture is based on a stationary base station and modem as a central node among the secondary users/cognitive nodes; in a network serving multiple primary users and secondary users/sensor nodes. The network is centralized since most of the network task is managed by either the base station or modem (central node). For the centralized scheduling of the network when all the White space devices (Cognitive nodes) are arranged into clusters, each Cluster Head (CH) creates time division multiple access (TDMA) based time slots for its member nodes. And for CH near the WBS, they communicate directly to the WBS and for CH near the modem, they communicate through the modem to the WBS.

The scheduler is in both base station and the modem, and these two will decide and choose how many packets and at which frequency and time slot they will receive data from the WSD/cognitive nodes. Figures 3.1, 3.2 and 3.3 illustrate LEACH, LEACH-C and proposed techniques respectively, in which the wireless network cognitive nodes are positioned randomly in the area to monitor the environment.

In LEACH [49]:

- The base Station is deployed in the sensing network area.
- Sensor nodes as well as the BS are not dynamic after deployment.
- Sensor nodes can communicate amongst themselves by taking into consideration their transmission power in the sensor network field, hence clusters keep changing in position and are considered virtual clusters.
- Election of CHs is based on probability.

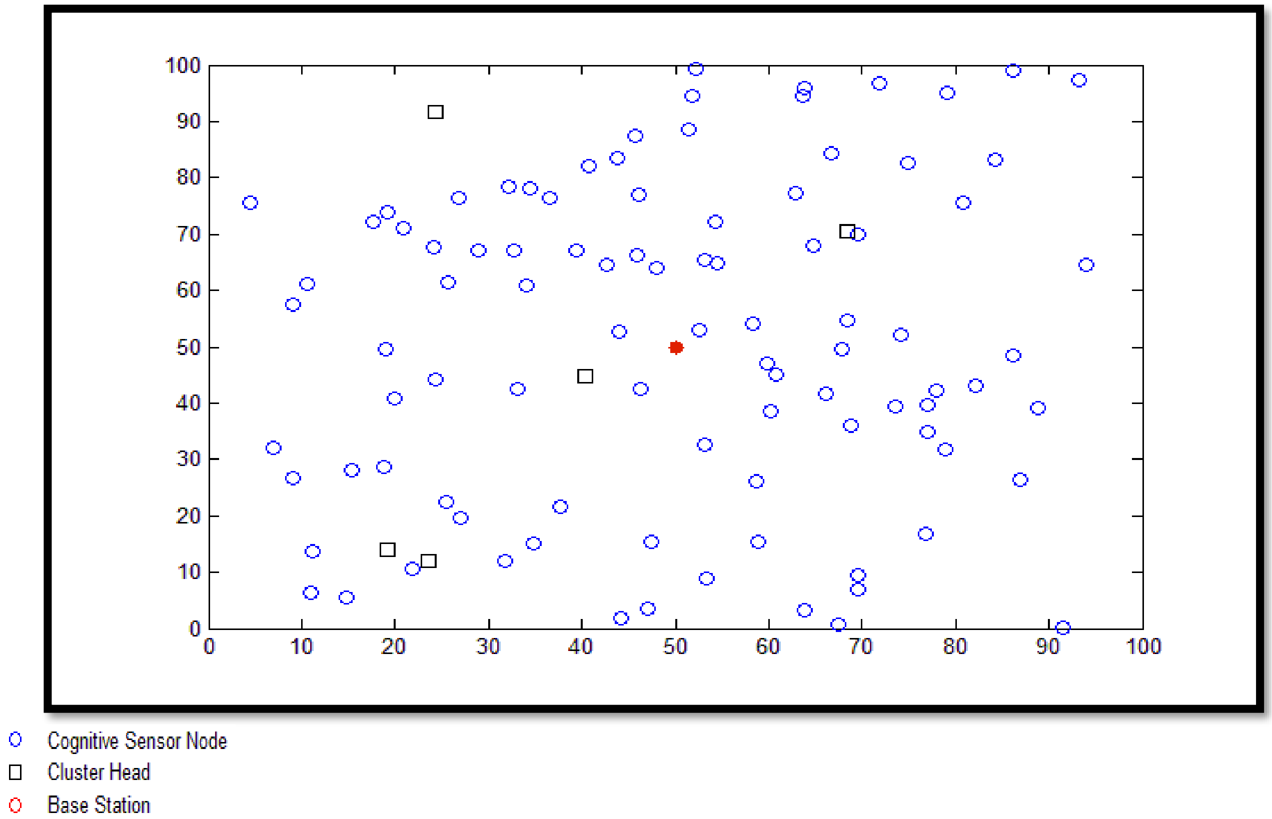

Figure 3.1: CH position in LEACH network model

In LEACH-C [50].

LEACH-C has same characteristics as the conventional LEACH protocol except:

- ➢ Base station in centralized LEACH controls all transmissions.
- ➢ Cluster heads are relatively centralized amongst sensor nodes.
- ➢ Sensor nodes are member of clusters with nearer CH. Hence LEACH-C has low energy consumption compared to conventional LEACH.

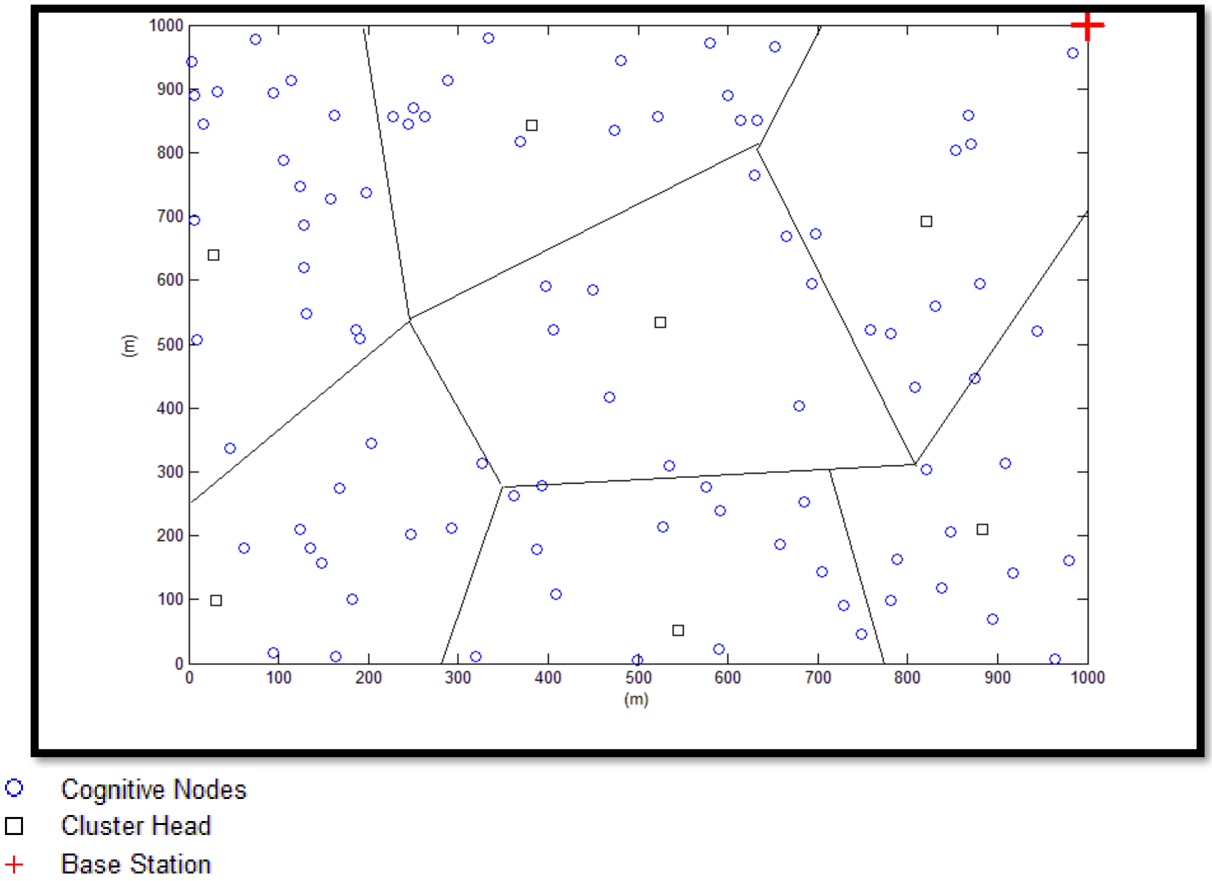

Figure 3.2: CH position in LEACH-C network model

In COST-LEACH protocol:

- ➢ The WBS is positioned in the sensing network area the same as the Modem.
- ➢ White space base station is at a fixed position after deployment.
- ➢ Cognitive nodes of the same characteristics with same computational and sensing abilities are used.
- ➢ Every cognitive sensor node is assigned with a distinctive marker or identifier.

- The Modem is equipped by a rechargeable battery and has enough memory and computing capability for energy-intensive tasks.
- The communication with cognitive sensor nodes is done through a white space base station or Modem. The energy detection approach is used to determine the presence of Pus and to avoid interference amongst Pus and CNs
- Multi-hop network approach to allow multiple transmission paths to the base station.
- The sensor network is divided into logical areas.
- CH heads are centralized in every area of the network.
- Election of the CH is based on probability and the remaining energy in the wireless network.

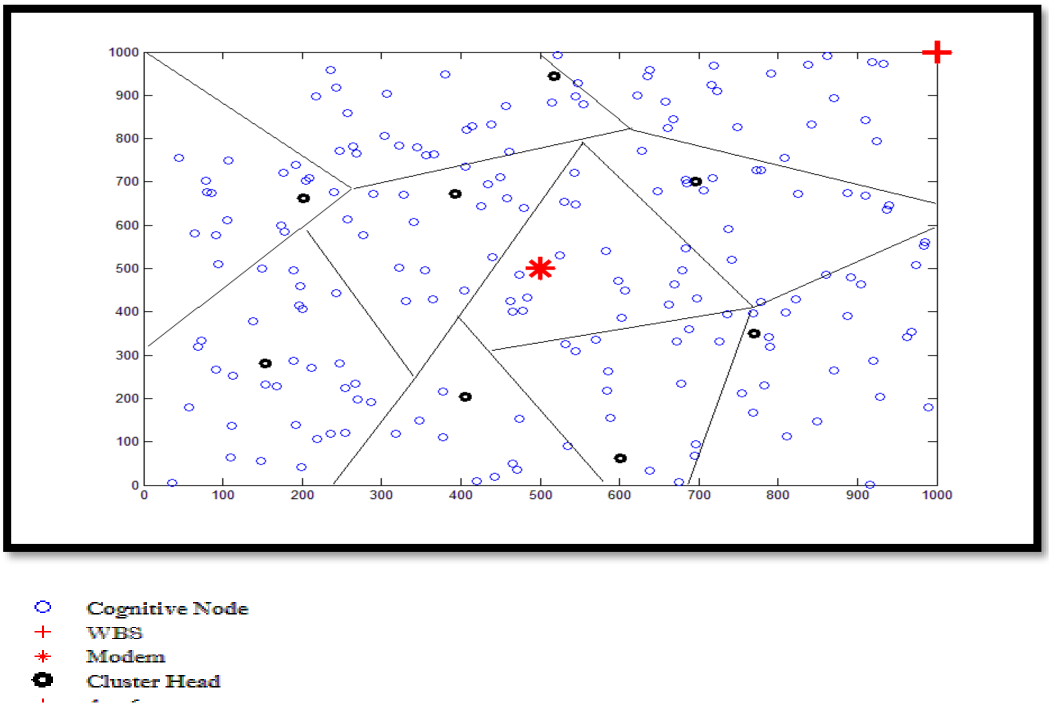

Figure 3.3: Network model of the proposed protocol

For the proposed protocol adapted for TVWS resources, the first order radio model is used for transmission and reception of data. Some of the proposed network components' characteristics are discussed in section 3.3.1 and 3.3.2.

3.3.1. White space base station function

The white space base station is a fixed module in the network with a major role of sending data to Cognitive radio networks, according to the requested and available channels. The WBS is responsible for storing all data collected from cognitive nodes. WBS also performs post-processing of the data received from each cognitive node. For the white space BS to be used in physical implementation, it has to bear some key characteristics such as:

- Minimum energy consumption.
- Rechargeable battery incorporated.
- Minimum delay for real-time applications in wireless sensor networks.
- High-speed data packet transmission and aggregation.
- It has to fall into the IEEE 802.11af protocol for WSN working over white space.

3.3.2. Cognitive sensor node role in network

A cognitive sensor node is an intelligent radio which can be dynamically programmed and configured [43]. It is a transceiver designed to sense the best and available spectrum channels in the area in which it is located without interfering with primary user nodes. Apart from searching the best spectrum channel available, the cognitive sensor node has other major functions such as to coordinate the use of the vacant channels in the area and by doing that ensuring the smooth spectrum channel sharing among the users.

In this research cognitive radio uses first-order radio model that is shown in figure 3.4 that it uses to communicate with the base station or to the base station through the center modem in the wireless network. A CR can be deployed in any field position considering it has a radio communication model to the white base station or modem. CRs merge automatically to create a multi-hop network resulting in multiple paths to the WBS.

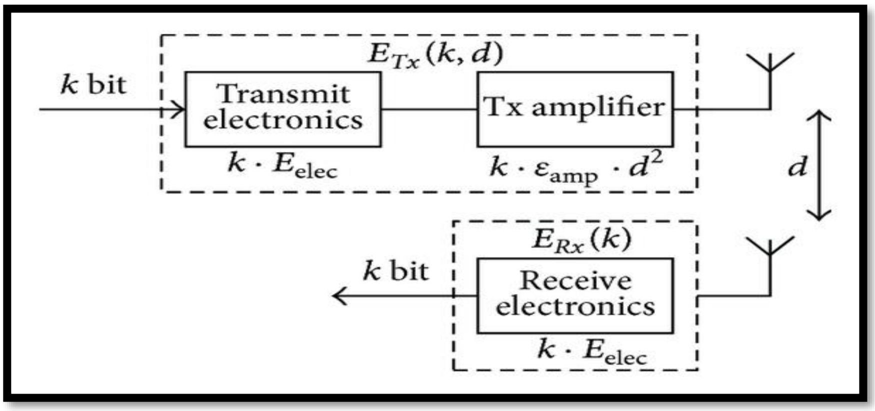

Figure 3.4: First order radio model **[39]**.

The energy E_{TX} required to move a data packet of k bits to a distance d and to retrieve a data packet of k bits and E_{RX} , energy used to receive the packet are given by the following expressions [51]:

$$\mathbf{E_{TX}(k, d) = E_{TX-elec}(k) + E_{TX-amp}(k, d)}$$
$$\mathbf{E_{TX}(k) = E_{elec} \times k + E_{amp} \times k \times d^2} \quad (3.1)$$

$$\mathbf{E_{RX}(k, d) = E_{RX-elec}(k) E_{RX}(k) = E_{elec} \times k}$$
$$E_{RX}(\mathbf{k}) = \mathbf{E_{elec} \times k} \quad (3.2)$$

The remaining energy for node S(i) using direct transmission to BS in LEACH and LEACH-C be E_{BS}, is given by:

$$\mathbf{S(i).E_{BS} = E_{TX}(k, d) - E_{RX}(k, d)} \quad (3.3)$$

The threshold for separation between short and comparatively long distances is given by:

$$\mathbf{d} \le \sqrt{\frac{\mathbf{E_{fs}}}{\mathbf{E_{amp}}}} \quad (3.4)$$

Where, E_{fs} is the energy radio for free space and E_{amp} is the amplifier energy. The COST-LEACH protocol is adapted for TVWS resources using the first order radio model to represent the energy usage of sensor nodes for sending, receiving and collection of packets data. Cognitive nodes are assumed to possess the required energy to communicate with their cluster heads.

3.4. Scheduling analysis

Allowing unlicensed devices to mix their transmissions with those of licensed primary users presents challenges in ensuring that such unlicensed transmissions do not interfere with the licensed ones. Methods being used by the FCC and Ofcom do differ but all emphasize on the use of a regulator-approved database which WSD will need to check before accessing the spectrum. Therein comes the need to schedule the available resources to avoid interference.

In scheduling analysis of wireless network-based resources, two aspects; Spectral efficiency (SE) and fairness Indices, are considered. SE and Fairness will help to properly schedule and improve the network lifetime and the throughput of the proposed scheduling technique in systems working in the TVWS spectrum. As the channel conditions can change very often, the latency may occur before a user is scheduled; this can result in some users' starvation. To avoid such starvation, the proposed scheduling protocol has to take into account not only the channel condition but also the network lifetime and the QoS demands.

3.4.1. Spectral Efficiency

Spectral efficiency (SE) or bandwidth frequency is the information rate that can be transmitted over a given bandwidth in a communication system. The SE is a major aspect to be considered in all scheduling techniques protocols. SE for a system is calculated using. maximum theoretical achievable throughput per bandwidth averaged over the users in the entire network. In most cases, the throughput of a WSN increases with the frequency spectrum available. The SE of the digital communication system is measured in [bit/s/Hz]. From this, the expression for the Maximum Average System Spectral Efficiency (MASSE) is derived [17] for constant power, optimal rate adaptation when Additive White Gaussian noise is considered. It is given by:

$$\sum_{\mathbf{i-1}}^{\mathbf{N}} \mathbf{p_i} \int_{\mathbf{0}}^{\infty} \mathbf{log(1+\Upsilon)\, pr_i^*\, (\Upsilon) d\Upsilon}, \qquad (3.5)$$

Where,

$N =$ The number of users in the system,

p_i =The probability of the user i being selected in any time-slot (access probability),

$pr_i^*(\Upsilon)$= The Probability Density Function of the CNR for the scheduling policy under study when the user i is selected, where Υ is signal-to-interference-plus-noise ratio.

The expression of Maximum Average System Spectral Efficiency above expects that a single user is scheduled at a given time [35]. To obtain a fair spectral Efficiency in this research work, the improved LEACH protocol is utilized to maximize the throughput and wireless network lifetime.

3.4.2. Opportunistic Scheduling

In this work, the WBS serves a relatively large number of cognitive sensor nodes. The channel used by each user is analysed separately and this can result in the latency of the transmission or the transmission to be discarded. To overcome this problem, we exploit the broadcast nature of the transmission and make sure the information/packet transmitted is received by all the users without interfering with primary users. In this thesis, transmission energy detection of primary users' approach is used by secondary users/CR to avoid interference. The approach of energy detection by cognitive nodes to avoid interference is commonly used as it is easier for simulation and computation purposes. This approach does not require prior conditions of the primary user signal. The primary users' energy signal is solely detected to assess if there is a presence or not of primary user signal [39]. The detected signal at the secondary user is given by:

$$\boldsymbol{Y\ (n)\ = x(n)\ + w(n)} \qquad (3.6)$$

Where

$x(n)$ represents the primary user signal to be detected,

$w(n)$ represents additive white Gaussian noise (AWGN) and n is the sampling index. The primary user signal detection is considered to be a true or false, depending on the presence (True) and absence (false) [49]. It is represented as:

$$\boldsymbol{y(n)} = \begin{cases} \boldsymbol{w(n)}, & \boldsymbol{A_o} \\ \boldsymbol{x(n)} + \boldsymbol{w(n)}, & \boldsymbol{A_1} \end{cases} \qquad (3.7)$$

A_o and A_1 are assumptions of the primary absence or presence in the channel of interest respectively [50]. The form energy detector is given by:

$$\boldsymbol{Y} = \sum_{\boldsymbol{n=0}}^{\boldsymbol{K}} |\boldsymbol{y(n)}|^2 \qquad (3.8)$$

K is the observation vector. The channel condition is further obtained by comparing the energy detected Y with the pre-set threshold energy y_o. The energy detection in cognitive radio node is implemented in both frequency and time domain using Fast Fourier Transform algorithm, to convert a received signal y(n) from its original domain energy signal to represent it in a recognizable signal entity as the resulting signal u by cognitive node. The $y(n)$ signal is passed via a filter namely ideal bandpass filter (BPF) with center frequency f_o and the bandwidth W as shown in figure 3.5. After the original signal is passed through BPF, it is then squared and integrated in an interval of time T to produce the signal u. The resulting signal u is compared with pre-set energy threshold y_o.

Figure 3.5: The ideal bandpass filter

The transfer function $H(f)$ is given by [51]:

$$\boldsymbol{H(f)} = \begin{cases} \dfrac{\mathbf{2}}{\sqrt{\boldsymbol{N_o}}}, |\boldsymbol{f} - \boldsymbol{f_o}| \leq \boldsymbol{W} \\ \mathbf{0}, \ |\boldsymbol{f} - \boldsymbol{f_o}| \quad > \boldsymbol{W} \end{cases} \tag{3.9}$$

Where,

N_o represents the noise power spectral density

W represents the bandwidth

f_o is the center frequency of the BPF

A pre-set threshold helps to determine whether primary user is present or absent. The same threshold is used to define other parameters such as probability of detection p_d and probability of false alarm p_f.

For the CR to operate using the energy detection approach to avoid interference with PUs, the separation of genuine energy signal to be detected and noise is crucial. Hence the need for probability of detection p_d and probability of false alarm p_f. The probability of detection is the probability of a cognitive radio/secondary user to detect a genuine signal from primary user and Probability of false alarm is the false signal picked which can mislead the CR to consider the presence of PU. The p_d and p_f are mathematically represented as [52]:

$$\boldsymbol{p_d} = \boldsymbol{Pr}\{\boldsymbol{decision} = \boldsymbol{A_1}|\boldsymbol{A_1}\} = \boldsymbol{Pr}\{\boldsymbol{Y} > \boldsymbol{y_o}|\boldsymbol{A_1}\} \tag{3.10}$$

$$\boldsymbol{p_f} = \mathbf{Pr}\{\boldsymbol{decision} = \boldsymbol{A_1}|\boldsymbol{A_0}\} = \mathbf{Pr}\ \{\boldsymbol{Y} > \boldsymbol{y_o}|\boldsymbol{A_0}\} \tag{3.11}$$

The probability of detection has to be higher compared to the false alarm probability in order to accurately detect primary users available in the vicinity. However, there are some missed opportunities by CR/ Secondary Users due to the false alarm probability. The probability of missed p_m opportunities is given by $p_m = 1 - p_d$. In addition, the signal to noise ratio (SNR) is taken into account as it is present in the primary user received signal.

3.4.3. Fairness for the white space network system

As any other wireless sensor network system, fairness in TVWS networks is crucial. It is used to fairly schedule and share the available network resources amongst applications or users. There are many mathematical and conceptual definitions of fairness, such as Transmission Control Protocol (TCP) fairness, Jain Fairness, max-min fairness; fairly shared spectrum efficiency, Control Protocol fairness and Quantity of Experience fairness among others [53] [54]. In this thesis Jain's fairness is briefly discussed in the next subsection.

3.4.3.1. Jain's fairness Index

Fairness indices are tools used to measure the fairness level and provide guidelines for a fairly distribution of resources. Fairness can be measured in the process of resource allocation or utility. Among fairness indices, Jain's is the earliest proposed and the most studied. Jain's fairness index provides feedback to the allocation mechanisms to make fair decision and measure the fairness in the network. Fairness in wireless network is the measure of how evenly radio resources are distributed among users. The Jain's fairness index is given by [17]::

$$\boldsymbol{F}(\boldsymbol{K}) = \frac{(\boldsymbol{E_K}[\boldsymbol{x}])^{\mathbf{2}}}{\mathbf{E_K}[\mathbf{X^2}]} = \frac{(\boldsymbol{E_K}[\boldsymbol{X}])^{\mathbf{2}}}{(\boldsymbol{E_K}[\boldsymbol{X}])^{\mathbf{2}} + \boldsymbol{var}(\boldsymbol{X})}, \qquad 3.12$$

Where,

$X =$ A random variable describing the amount of resource allocated to the user,

$K =$ Time slots,

$E_K[.] =$ Expectation calculated over the distribution of the resource allocation within a time window of K (time slots),

$Var(X)$ = Corresponding variance.

Note that this fairness index is bounded between zero and unity [55]. However, in this thesis an improved low energy adaptive clustering hierarchy is utilized for the sake of users' satisfaction and the system available resources. The constrained accessibility of the frequency spectrum makes it hard for unlicensed clients to situate in the spectrum. The fair spectrum sharing of the available spectrum channels should be possible through cognitive radio. In this investigation, the energy-based detection process is used for the identification of vacant frequency band in the spectrum. With this technique, spectrum sensing is done effectively and the fair spectrum is ensured.

3.5. Algorithm of the COST-LEACH protocol

The initial schedule will rely on heuristic information, initial sensing of available channels by cognitive radio nodes and, if many channels are applicable. The sensing procedure by cognitive radio nodes/secondary users utilise the designated vacant channels determined by comparing the threshold energy of PUs to the detected energy by CR.

Phase 1: Spectrum sensing and Construction phase

In the spectrum sensing of the unoccupied channels, each cognitive node senses the vacant channels and vacate channels occupied by the primary users. If the CR detects energy above the preset threshold energy in the channel, it considers the channel as occupied by primary user. The energy Detection is achieved by comparing the output of the radiometer (energy detection component) output with the threshold set.

To determine vacant channels the CR estimates the probability of detection and probability of false alarm. The assumption that all PUs dissipates the same energy is made.
The construction phase of the network follows the same approach as in LEACH WSNs; Cognitive sensor nodes S of the same characteristics were used. Nodes S are positioned randomly in the network. The white space base station sends a test packet to get the location of all cognitive nodes. Cognitive Sensor nodes send their position to WBS.

The white space base station gets the position of every CR and records all information of the cognitive Radios nodes. The white space base station divides the network into various areas. Depending on the energy detected by the Cognitive nodes the decision is made whether PUs are present in the channel. Cognitive nodes in one area send their data packets using the white space base station using the distance d_{WBS} of these nodes from the white space base station. In similar way nodes within distance d_{MD} closer to the modem create another area and their data are sent using the modem MD. The modem collects data packets received and sends them to the WBS. Equations were derived to estimate the position of WBS and Modem. Transmission lines$d_{WBS}$and d_{MD} of the proposed network model are illustrated in figure 3.6.

d_{WBS} and d_{MD}, are given respectively by the equations:

$$\boldsymbol{d_{WBS}} = \sqrt{(\boldsymbol{S(i)_x} - \boldsymbol{WBS_x})^2 + \left(\boldsymbol{S(i)_y} - \boldsymbol{WBS_y}\right)^2} \qquad (3.13)$$

$$\boldsymbol{d_{MD}} = \sqrt{(\boldsymbol{S(i)_x} - \boldsymbol{MD_x})^2 + \left(\boldsymbol{S(i)_y} - \boldsymbol{MD_y}\right)^2} \qquad (3.14)$$

Where,

$S(i)_x$,$S(i)_y$ = the position of the cognitive node i at X-axis and Y-axis respectively

WBS_x, WBS_y =Position of White space base station at X-axis and Y-axis respectively

MD_x, MD_y = position of the modem at X-axis and Y-axis respectively

The remaining energy of cognitive nodes is time-varying and position-dependent due to the random deployment of secondary users. COST-LEACH protocol opportunistically chooses nodes allowed to transmit and transmission path based on detected energy level by a cognitive node in the sensing field. When Cognitive nodes detect high energy level around them, they vacate the channel and allow PUs deployed at distance d_{WBS} to the white space base station to be given priority to transmit through their respective priority channels. Some nodes relatively far from the WBS consider the secondary base station as a relay and use transmission through modem of distance d_{WBSMD}. However, the proposed protocol can opt for a longer path for distances marginally greater than the threshold distance, this may cause transmission delay. The distance d_{WBSMD} covered by transmission made through the MD is given by:

$$\mathbf{d_{WBSMD}} = \mathbf{d_{WBS}} + \mathbf{d_{MD}} \qquad (3.15)$$

By using the equations of the first order radio model, replacing distances d_{WBS} and d_{MD} accordingly, the estimation of energy consumed by transmissions made directly to WBS or through the modem to the WBS is calculated.

Note that:

$$\mathbf{d_{WBS}}, \mathbf{d_{MD}} \leq \sqrt{\frac{\mathbf{E_{fs}}}{\mathbf{E_{amp}}}} \qquad (3.16)$$

The remaining energy E of node $S(i)$ for transmissions done through modem is given by the total energy at the start of transmission removing the energy exhausted at the receiver. The modem is assumed to behave like any other node as it possesses energy.

$$\boldsymbol{S(i).E_{\mathrm{MD}} = E_{TX-elec}(k) + E_{TX-amp}(k, d_{MD}) - E_{RXMD-elec}(k) + E_{MD}} \quad (3.17)$$

Where,

E_{MD}= Initial energy of the modem

$E_{RX_{MD}}$= Used energy to receive from a cognitive node to modem

$S(i).E_{\mathrm{MD}}$= Remaining energy in a cognitive node before forwarding data to the WBS

The total energy remaining for transmissions through modem we calculated its value as follows:

$$\boldsymbol{S(i).E = S(i).E_{\mathrm{MD}} - E_{RXWBS-elec}(k)} \quad (3.18)$$

Where,

$E_{RX_{WBS}}$= Energy used to receive from cognitive node to the white space base station.

For a system having n nodes, the total energy E_{tot} of the proposed network model is given by:

$$\boldsymbol{E_{tot} = n.E_o + E_{MD}} \quad (3.19)$$

Where

$\boldsymbol{E_o}$ = Initial energy at every node

Note that nodes away from the modem and white base station are arranged also into areas that give COST-LEACH protocol an advantage over other LEACH. They are termed as clustered areas. Cognitive radios in every clustered area arrange amongst themselves into sets called clusters. Figure 3.6 shows the illustrated transmission lines of the proposed network model.

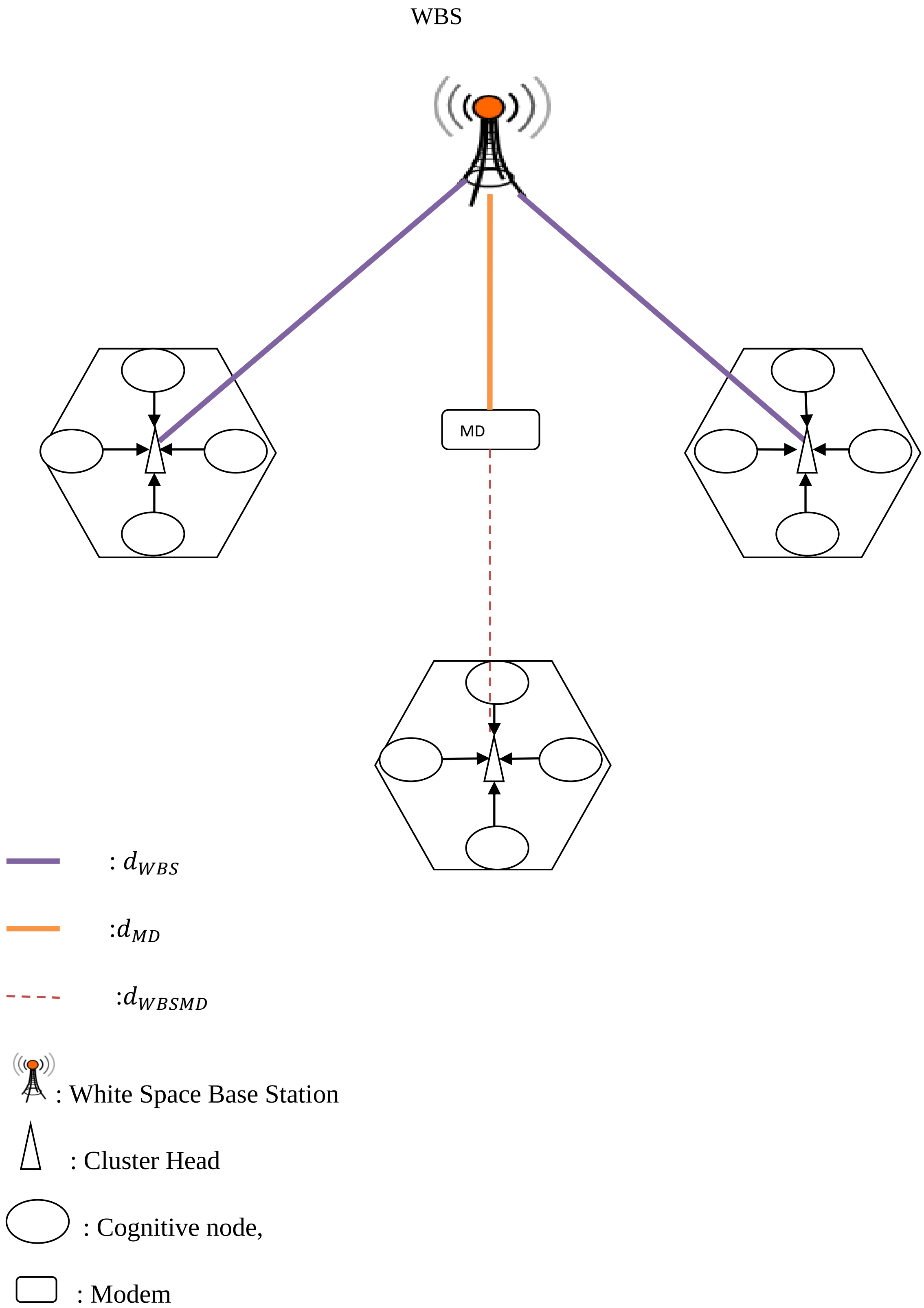

Figure 3.6: Transmission paths of proposed COST-LEACH

Phase 2: Cluster head election

Firstly, WBS arranges the network into areas. CHs are selected in every area independently. Let r_i represent the number of rounds to be a CH for the cognitive radio $S(i)$. Every CR node elects itself as clusters head once each given round $r_i = 1/p$ round. At the beginning of the rounds CR nodes have same energy and same chance to be chosen as CH. Cluster head in COST-LEACH protocol is elected based on the residual energy of sensor node and on probability p unlike in conventional LEACH and LEACH-C, where CH is elected based only on probability$p$. In each round, it is required to have $n \times p$ cluster heads, where n is the number of clusters. A cognitive node can be a cluster head only once in a specific span of time and cognitive nodes not elected as cluster heads in the actual round are members of C set. Chances of a cognitive node to be selected as cluster head increases in every round.

To make sure of a balanced number of CHs in the proposed protocol the residual energy $S(i).E$ in the threshold $T(s)$ formulae equation 3.20 was used; this plays a major role in electing cluster heads based on the remaining energy. In COST-LEACH, the PUs energy detection by cognitive nodes for different areas in the wireless network is taken into account to set the energy threshold for primary users to be sensed. Energy detected plays a major role in selecting channels to be used by secondary users/cognitive nodes. At the beginning of every round in transmission, a node $S(i)$ is a member of cluster head set C freely; uses energy E for transmission and chooses a random number from zero to unity.

If the set number for CR $S(i)$ is less than the pre-established threshold$T(s)$, then the node is chosen as CH in the actual round. Threshold value is given by:

$$\boldsymbol{T(S)} = \begin{cases} \dfrac{\boldsymbol{p}}{\boldsymbol{1-p\left(rmod\left(\frac{1}{p}\right)\right)*\left(S(i).\frac{E}{E_{tot}}\right)}}, & \boldsymbol{if\ S = C} \\ \boldsymbol{0} & \boldsymbol{otherwise} \end{cases} \tag{3.20}$$

$T(s)$ = Predefined threshold

p = Number of Cluster heads

r = The current round,

C = Set of nodes not elected as CH in the current round.

$S(i).E$ = Residual energy for each node

E_{tot} = Total energy of all the nodes

Phase 3: Steady-state and Schedule phase

In this thesis, Centralised Opportunistic scheduling is proposed to schedule multi-channel WSNs, in order to optimise the spectrum interference mitigation, maximizing the network lifetime, and energy to overcome other shortcomings of the existing opportunistic scheduling techniques such as high energy consumption and short network life. The proposed centralised opportunistic scheduling is easy to control as it takes into consideration a master-slave approach; only the WBS will be able to choose the transmission path opportunistically based on the remaining energy of cognitive nodes and the detected primary user energy.

When all the spectrum cognitive nodes are deployed in their respective clusters and area, each CH creates TDMA based time slots for its member nodes. The amalgamated nodes send their sensed data to CH in their own allocated time slot. By doing so the CR nodes make sure they are interference aware to avoid a collision in channels with primary users. Nodes failed to do so are termed inactive. The algorithm identifies the packet data to be transmitted over a network spectrum that should receive the most attention and then dedicate the most attention to these packets of data. COST-LEACH algorithm finds a vacant channel from nodes to a base station that can minimize interference between PUs and CR/SU by considering the probability of detection and probability of false alarm of primary users. If the energy being consumed by cognitive nodes is high the protocol assumes that the probability of detection is high and the presence of primary users is likely. The cognitive node has high interference, so it works accordingly.

By using the LEACH protocol, an improvement is done by introducing white space BS in the sensing network field, enhancing the threshold $T(s)$ of cognitive radio wireless sensor network and considering PUs energy detection. The modem role in the network is mainly to reduce the average transmission distance for nodes relatively far from the BS. This leads to a longer lifetime of the network, lower energy consumption, and high throughput. In this centralised scheduling, the energy information exchange along with location information exchange is crucial to detect energy above the preset energy threshold in the cognitive WSN to opportunistically schedule transmission of a packet by a cognitive node to WBS without interfering with primary users. The threshold is set to an optimal value to minimize the probability of false alarm in CR. A flow chart of the COST-LEACH protocol adapted for TVWS is shown in figure 3.7.

Flow chart of the COST-LEACH algorithm

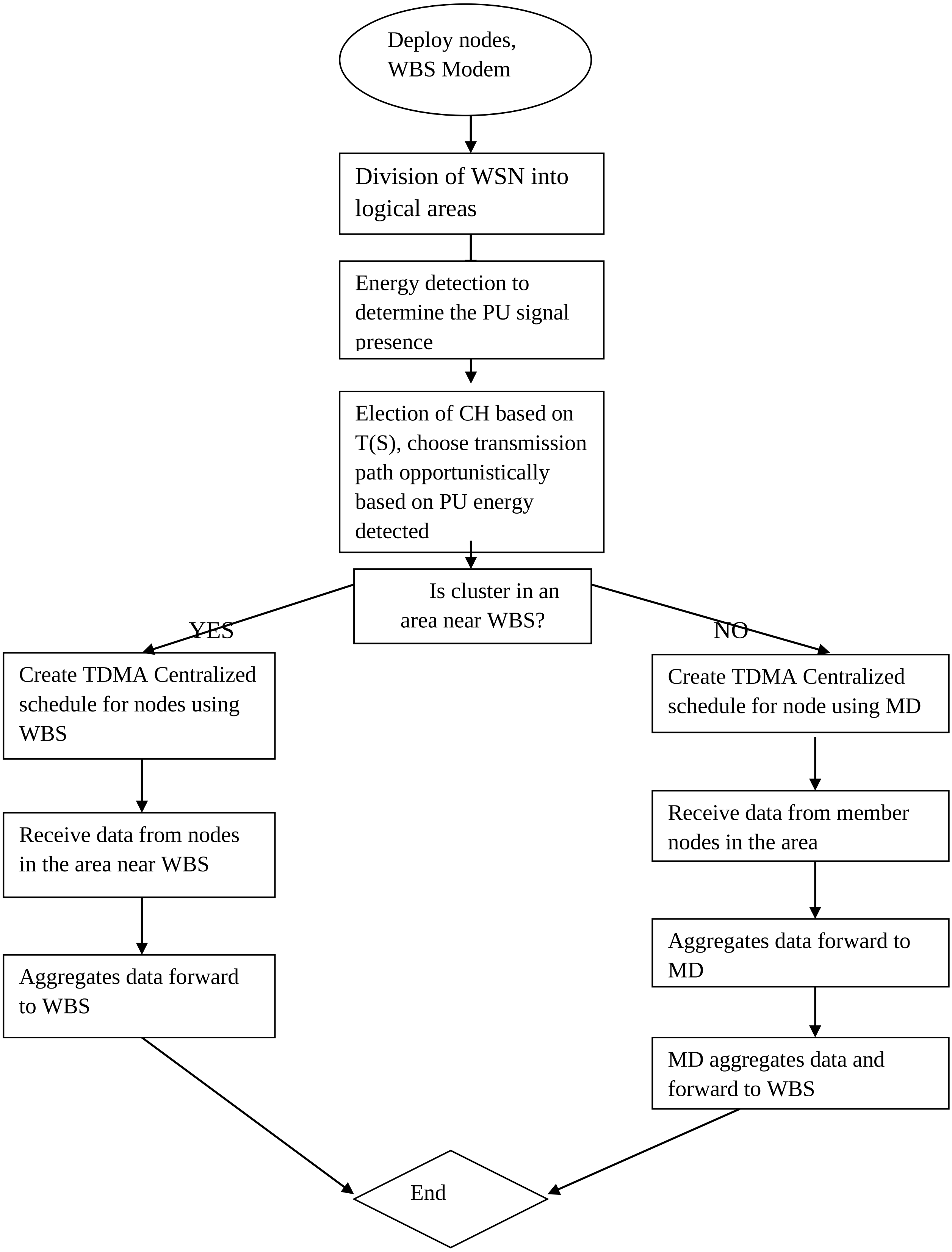

Figure 3.7: Flow chart of COST-LEACH protocol

3.6. TV white Space Test bed setup example

The analysis of the TVWS spectrum has gone beyond theoretical investigation in the controlled environment phase. Researchers have initiated experimental and pilot trials produced in a more realistic environment, resulting in various testbeds, example research a TV White Space Testbed with robust spectrum sensing algorithms M2M communication. In a realistic environment, a testbed can be set to determine the TV white space coverage as well as to test the centralized opportunistic scheduling technique in a realistic environment; however, in this research, the output study was done and simulated using Matlab r2014b software due to financial constraints.

The proposed test bed architecture consists of more than one cognitive node cluster set a modem and white space base station, for example, SLB802ODU White space base station. Cognitive nodes are dedicated to experimentation with spectrum sensing within a wireless cognitive network. Permission of the given regional regulator will allow the experimentation in TV white space as well as in frequency bands for unlicensed devices. For researchers working in a real environment, the use of short-range (0.5 GHz-1GHz) is recommended for experimental purpose. Set up architecture of COST-LEACH is shown in figure 3.8 in which the assumed Primary User's network has been included.

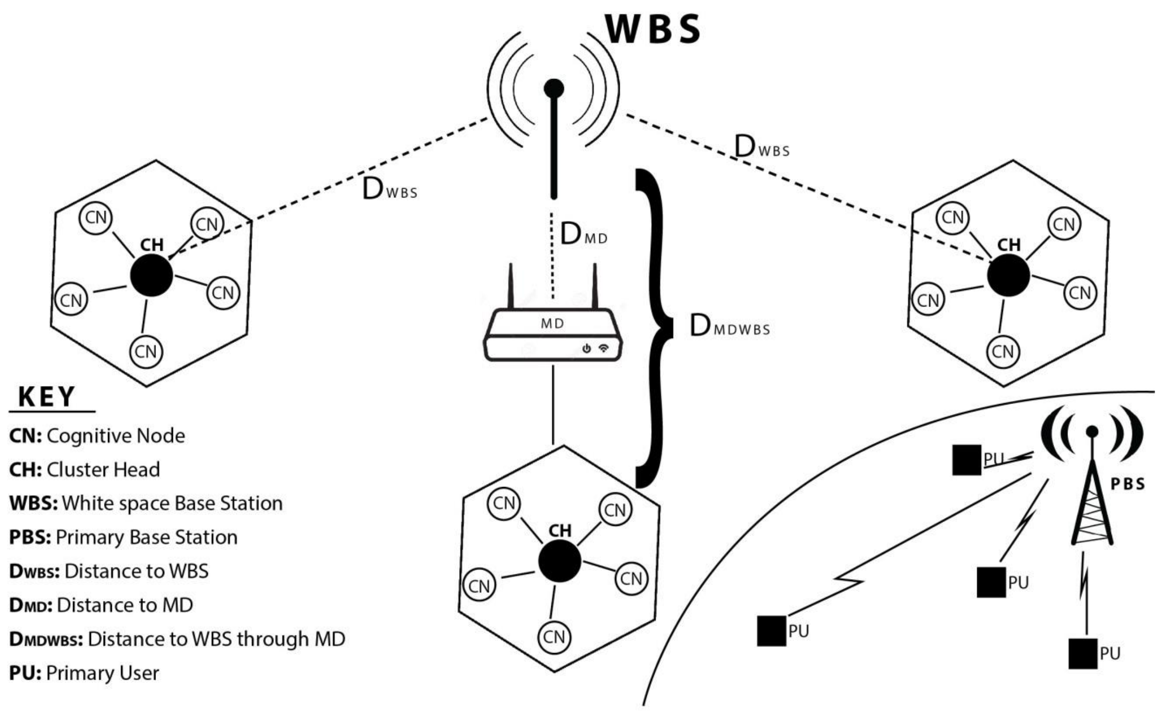

Figure 3.8: Set Up architecture Test bed for TVWS.

The testbed is mainly based on white space base station SLB802ODU which is a modular wireless cognitive node platform and a number of sensing nodes. In this typical white space network, a white space communications link is established between the white space base station and fixed cognitive nodes equipment allowing the secondary client-side devices to connect without interfering with primary users. In figure 3.8, a typical white space base station that can serve a maximum of 512 client devices as far away as 20 km can be used in the physical implementation of the proposed protocol along with other cognitive sensor nodes.

Figure 3.9: White space base station SLB802ODU **[15].**

4. CHAPTER FOUR: RESULTS AND DISCUSSION

4.1. Available TVWS in Kenya (Nanyuki and Kalema) and its potential

In this research, the available frequency channels were investigated by consulting a state-controlled organization, the Communication Authority of Kenya, CA. The aim of this investigation was to assess the available allowed range of the frequencies allocated to secondary users in a given area where TVWS trials have been conducted in Kenya namely Nanyuki, Laikipia County and Kalema, Kajiado County. These locations were chosen for the trials because they are less congested as compared to urban areas.

In Kenya, regulators enabled the use of TVWS by designating the 470-694MHz band as an interleaved or shared spectrum. Prior to the completion of the digital migration, vacant spectrum was made available for shared use; this shared spectrum goes from 694MHz-790MHz. With the need for network connectivity increasing steadily, this has become both a social and economic issue in Kenya that needs to be addressed.

4.2. Simulation and comparison of metrics

The simulation results of the conventional LEACH and LEACH-C alongside COST-LEACH protocol are analyzed. Simple energy detection in every CR simulation is done as well, considering that the primary user signal is a real Gaussian signal and the noise associated with PU signal is Additive Gaussian energy. The receiver characteristics namely; probability of detection against the probability of false alarm for energy detection is plotted. The COST-LEACH protocol performance is compared to LEACH and LEACH-C using MatLab. The comparison metrics include the network lifetime, throughput and energy consumption.

4.3. Network model and energy detection parameters

To analyze the proposed protocol performance, Matlab r2014b software installed in an Intel(R) core™ i5 5300U CPU 2.30GHzis computer used. To study the energy detection probability of false alarm and the probability of detection, parameters taken into account include signal to noise ratio (SNR), the number of samples; as it is crucial in determining the targets on detection as well as false alarm probabilities and the set energy threshold to determine if the primary user signal is present or not. One hundred (100) cognitive nodes with the total energy of 5 joules are deployed randomly in 1000 m *1000 m area. The white base station is positioned at 1000 m*1000 XY coordinates, whereas modem is deployed at 500 m*500 m XY coordinates as indicated in the table 4.1. Transmissions are handled by the first order radio model and its parameters are discussed in subsection 3.3.2. Packet data to be transmitted are of 4000 bits size. All the parameters were set to get the optimum result in the proposed network system for simulation. In the figure 4.1, a plot of the probability of energy detection by cognitive nodes against false alarm is shown.

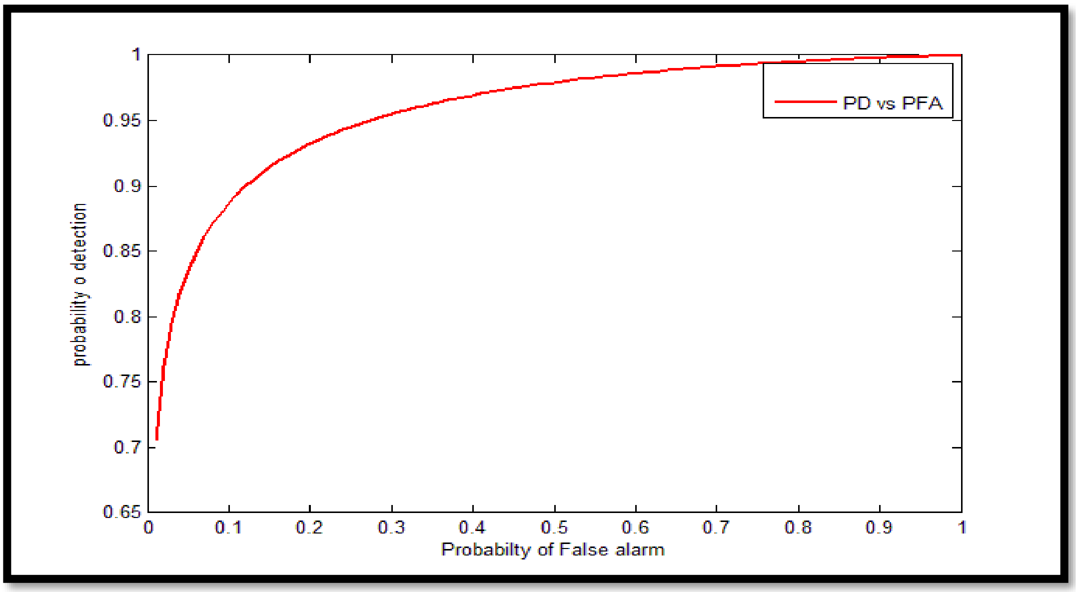

Figure 4.1: Probability of detection against probability of false alarm in 20000 samples

Table 4.1: Network model parameters

Parameter	**Values**
Network area in meters	1000*1000
Number for Cognitive nodes	100
Probability of a node to become cluster head	0.1
Probability of false alarm	0.1
WBS position in network	1000*1000 (X, Y coordinates)
Modem position in network	500*500 (X, Y coordinates)
E_{da}(Data aggregation energy)	5pJ/bit
E_{elec}(Radio electronic energy)	5nJ/bit
E_{fs}(Radio free space)	10pJ/bit/m^2
E_0(Initial energy)	5j

E_{amp}(Radio amplifier energy)	0.0013pJ/bit/m^4
Message size	4000 bits

a. Throughput

The network throughput or aggregate throughput is the sum of the data rates that are transmitted to all sensor nodes in a wireless network. The amount of data received directly by the white base station or through modem show the network lifetime and the throughput of the network are improved in the COST-LEACH protocol as it is shown in the table 4.2. In Figures 4.2 and 4.3, the throughput of the network is calculated using average packets per time slots or bits per second sent directly to BS or through the modem. Comparison of throughput metrics of conventional LEACH protocol and LEACH-C with COST-LEACH protocol shows that the proposed protocol outperforms the Conventional LEACH and LEACH-C. To assess the throughput, it is assumed that cluster heads communicate freely with the base station or the deployed central modem depending on the proximity of sensors nodes.

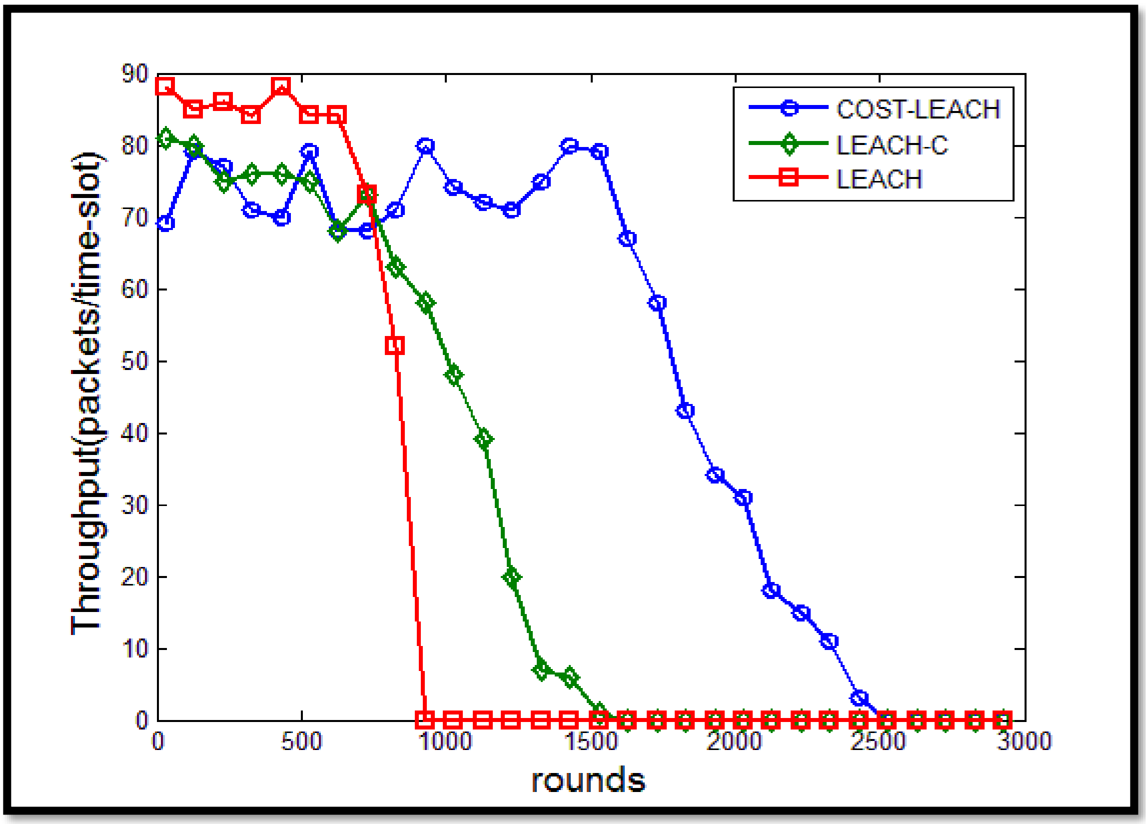

Figure 4.2: Analysis of throughput (Packets/time slot against rounds)

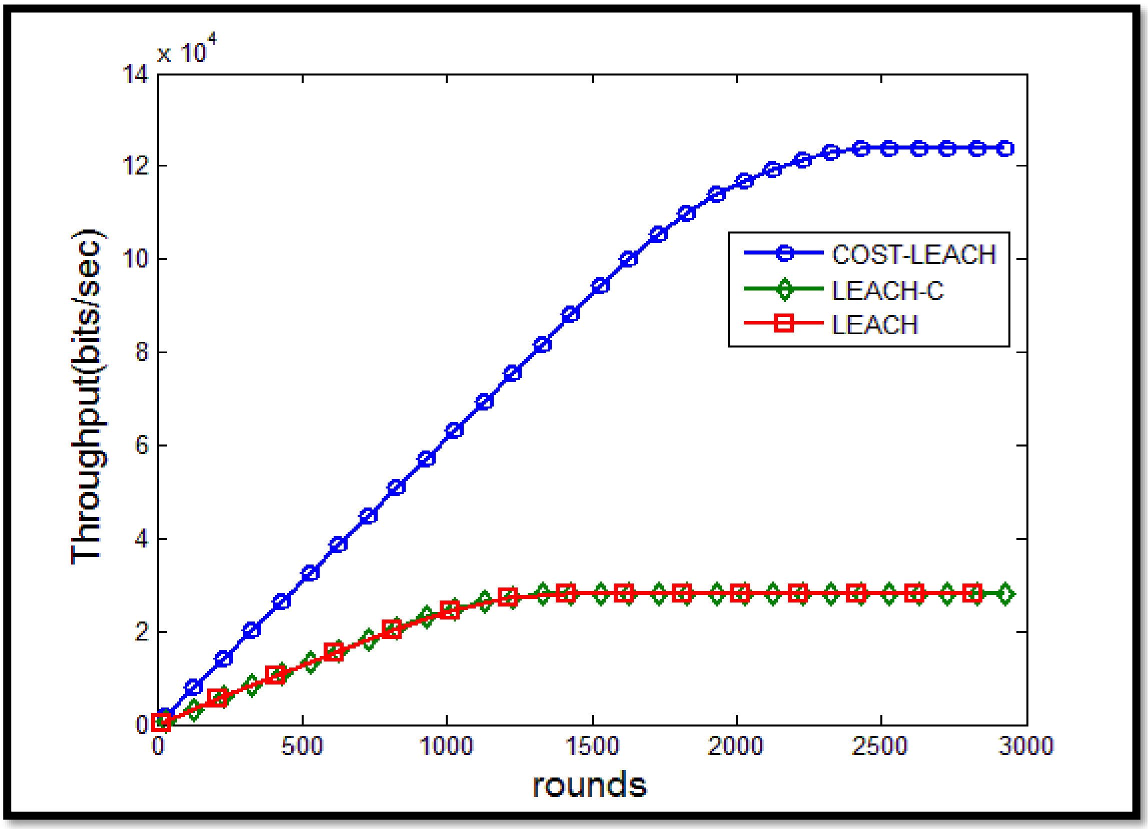

Figure 4.3: Analysis of throughput (bits per second against rounds)

Table 4.2: Comparison of throughputs metrics

Rounds	Number of packets in conventional LEACH	Number of Packets in LEACH-C	Number of packets in COST-LEACH	Bits per second in conventional LEACH	Bits per second in LEACH-C	Bits per second in COST-LEACH
1st	92	80	70	0	0	0
500th	85	75	70	12600	12600	30430
1000th	0	65	78	24390	24390	61080
1500th	0	1	75	28260	28260	92490
2000th	0	0	25	28260	28260	114800
2500th	0	0	2	-	-	121600
3000th	0	0	0	-	-	-

It is clear that from Table 4.2 and Figures 4.2 and 4.3 that COST-LEACH protocol outperforms the conventional LEACH as well as LEACH-C taking network throughput metrics into account. The number of packets in LEACH and LEACH-C drops drastically at 500th round and 1000th round respectively, whereas in COST-LEACH it remains fairly constant and drops at 2000th round. For transmitted bits per second from the 500th up to

2000th round COST-LEACH transmits more than three times bits compared to LEACH and LEACH-C.

b. Network life time

Network lifetime is a key characteristic for assessing sensor networks in an application-specific way. Even quality of service (QoS) measures can be reduced to lifetime considerations. The network lifetime T ends as soon as the first sensor node fails, thus:

$$\boldsymbol{T} = \mathbf{min}\,\boldsymbol{T_s} \quad \text{Where } \boldsymbol{s}, \in \ \boldsymbol{S} \tag{4.1}$$

T_s is the lifetime of node s and S a set of sensor nodes. A number of algorithms and methods have been proposed to increase the lifetime of a sensor network, but in this thesis, an improved protocol of LEACH is proposed to increase the white space sensor network.

In Figures 4.4 and 4.5, the first dead node appears at 1500th rounds in the proposed scheduling; where as in LEACH-C is at 1000th round and in conventional LEACH is at 600th. Every sensor node has 0.5 joules energy; this means that sensor nodes are inactive after the exhaustion of 0.5J of its energy; in Figures 4.4 and 4.5, the first dead node and the last alive node were assessed. The fair distributing of energy in the COST-LEACH protocol results in the longest wireless sensor network lifetime compared to the conventional LEACH and LEACH-C as it I shown in the comparison table 4.3.

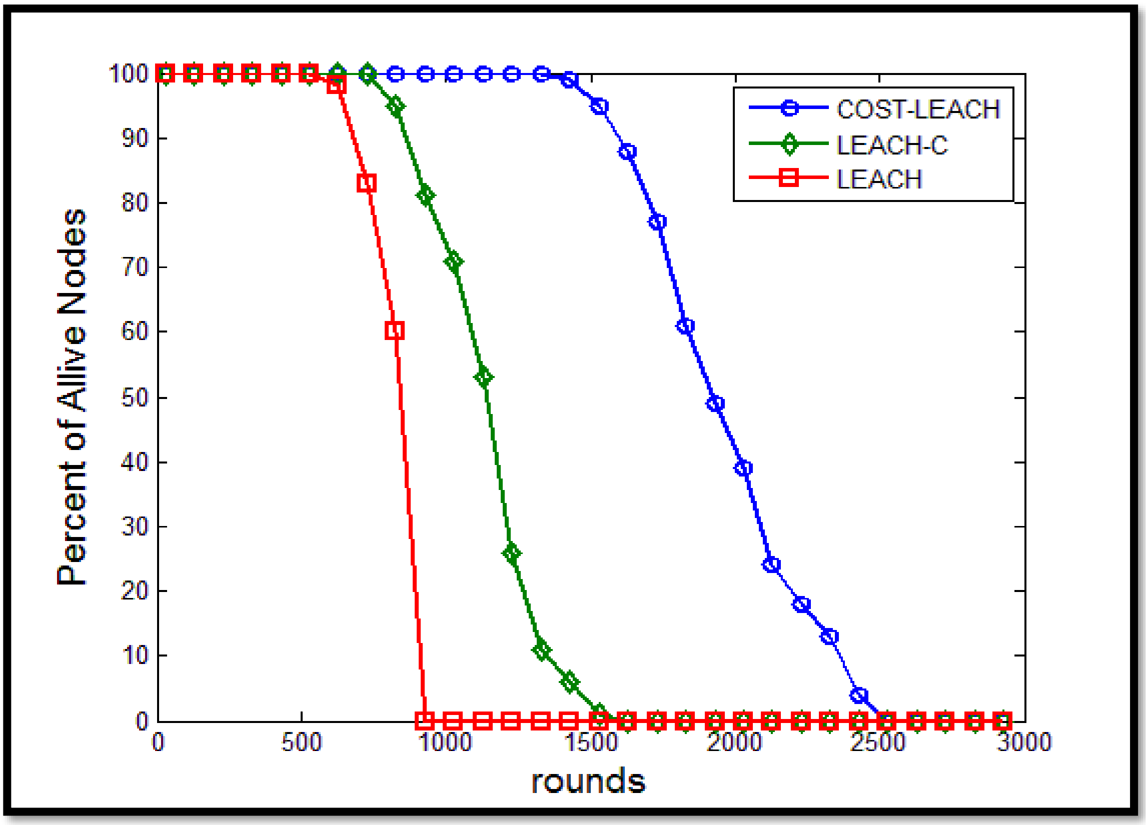

Figure 4.4: Alive nodes against rounds

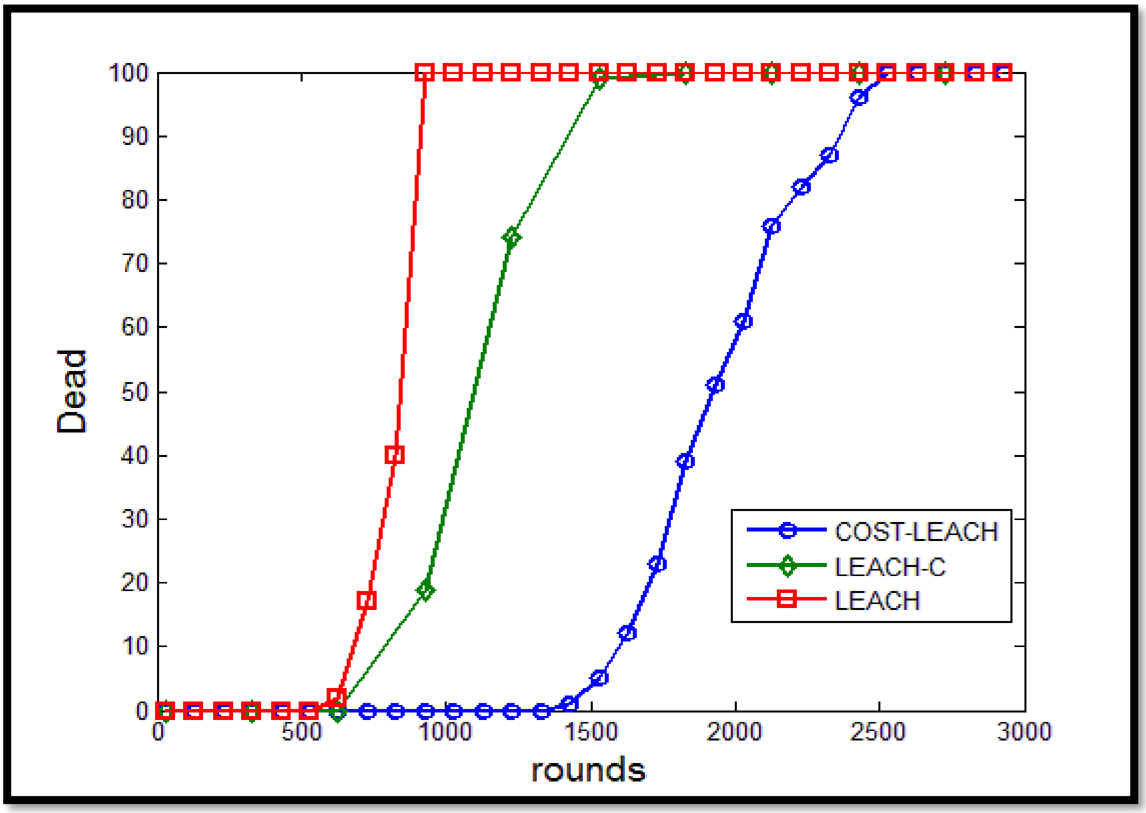

Figure 4.5: Dead nodes against rounds

Table 4.3: Comparison of the metrics alive nodes and dead nodes

Rounds	Alive nodes in conventional LEACH	Alive nodes in LEACH-C	Alive nodes in COST-LEACH	Dead nodes in conventional LEACH	Dead nodes in LEACH-C	Dead nodes in COST-LEACH
1^{st}	100	100	100	0	0	0
500^{th}	100	100	100	0	0	0
1000^{th}	0	76	100	100	24	0
1500^{th}	0	0	94	100	100	6
2000^{th}	0	0	38	100	100	62
2500^{th}	0	0	0	100	100	100
3000^{th}	0	0	0	100	100	100

From Figures 4.4 and 4.5, it is deduced that COST-LEACH protocol outperforms the conventional LEACH and LEACH-C in terms of the network life performance metric.

c. Energy consumption

Reducing energy consumption to extend the lifetime of the network is the main research challenge in any WSNs. After nodes are deployed in the area, the number of alive nodes diminishes and the functionality of the network exponentially reduce as time passes. Network architecture composed of sensor nodes, a white base station situated in the sensor nodes field and modem deployed at the center of the sensor network area is proposed.

Also, the division of wireless sensor network field into logical areas in a bid to reduce energy consumption is proposed; hence increasing the lifetime of the network. The results for the efficiency of the proposed protocol are presented in Figure 4.6 and compared in table 4.5. The remaining energy in the COST-LEACH protocol is much more at every round compared to the energy in the convention LEACH, $S(i).E \ > S(i)E_{BS}$; hence our protocol has much longer network life time. The overall comparison of the proposed technique with others is shown in the table 4.5.

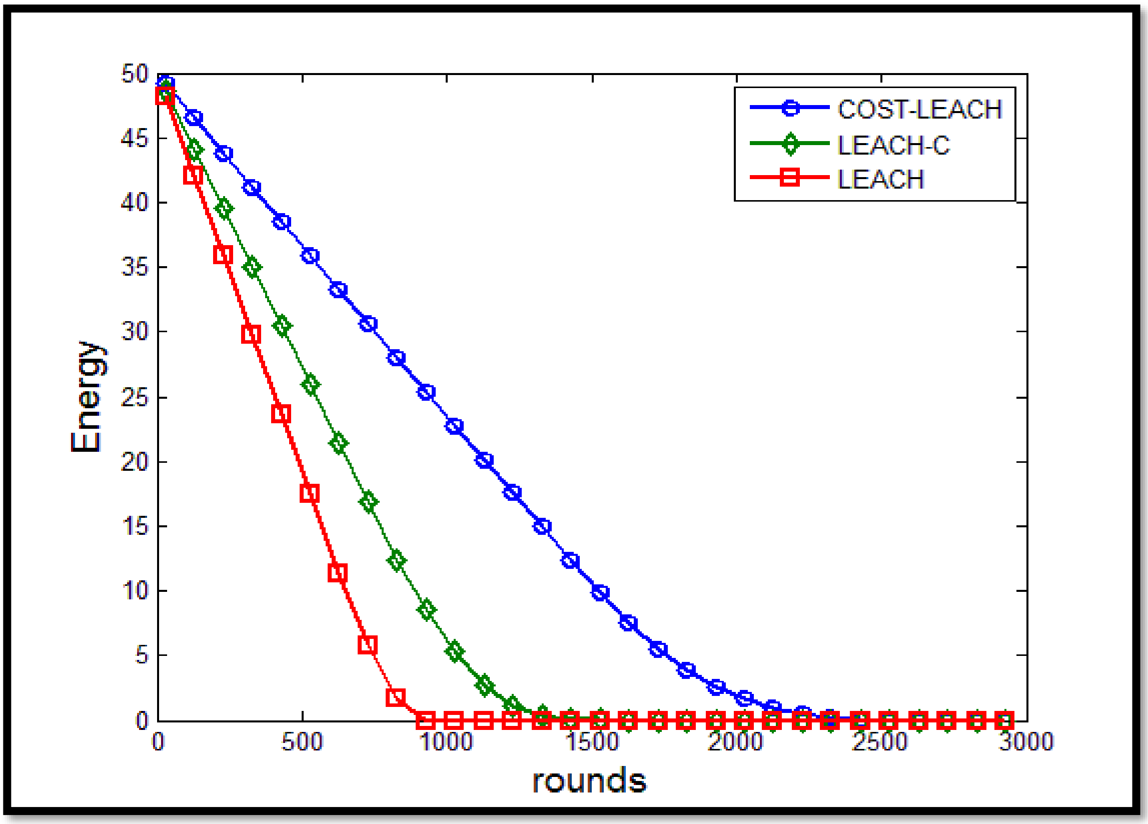

Figure 4.6: Remaining energy against rounds

Table 4.4: Comparison of remaining energy metrics

Rounds	Remaining energy in conventional LEACH in joules	Remaining Energy in LEACH-C protocol in joules	Remaining energy In COST-LEACH
1st	50	50	50
500th	18.61	26.80	36.30
1000th	0	5.90	23.10
1500th	0	0	10
1500th	0	0	1.70
2500th	0	0	0

In Table 4.4, it is shown that the proposed protocol consumes less energy compared to the conventional LEACH and the centralized LEACH, LEACH-C.

4.4. Comparison summary

In table 4.5 all the main parameters namely Threshold, Energy, clustering approach, Mobility, transmission channel, components and primary user detection are compared.

Table 4.5: Overall comparison LEACH, LEACH-C and COST-LEACH

Parameters	COST-LEACH	LEACH-C	Conventional LEACH
Threshold	Based on probability and remaining energy $\frac{p}{1-p\left(rmod\left(\frac{1}{p}\right)\right)*\left(S(i).\frac{E}{E_{tot}}\right)}$	Based on probability $\frac{p}{1-p\left(rmod\left(\frac{1}{p}\right)\right)}$	Based on probability $\frac{p}{1-p\left(rmod\left(\frac{1}{p}\right)\right)}$
Total Energy	$E_{tot} = n.E_o + E_{MD}$	$E_{tot} = n.E_o$	$E_{tot} = n.E_o$
Remaining Energy	Remaining energy in sensor node and in the modem $S(i).E = S(i).E_{\mathrm{MD}} - E_{RXWBS-elec}(k)$	Remaining energy in sensor node $\boldsymbol{S(i).E_{BS} = E_{TX}(k,d) - E_{RX}(k,d)}$	Remaining energy in sensor node $\boldsymbol{S(i).E_{BS} = E_{TX}(k,d) - E_{RX}(k,d)}$
Clustering approach	Centralized and opportunistic	Centralized	Distributed
Mobility	Stationary MD, Stationary WBS	Stationary BS	Stationary BS
Transmission channel	Direct to WBS or MD based on energy detection	Direct transmission Base station	Direct transmission to BS
Components	White space base station, Modem, cognitive Nodes	Base station, Sensor nodes	Base station, Sensor nodes
Primary user detection	Energy detection approach	——	——

5. CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

In this research, an improved wireless network life time, high throughput and less energy consumption compared with other wireless sensor network protocols namely conventional LEACH and LEACH-C has been achieved. Hence, the improved LEACH can be adapted for wireless networking in TVWS and is able to offer high throughput without interfering with primary users. When all cognitive nodes are deployed in their respective clusters and areas, each Cluster head creates time division multiple accesses taking into account time slots for its member nodes and each cognitive node evaluate if primary users are present or absent by using energy detection approach.

The amalgamated cognitive nodes send their sensed data to the cluster head in their own allocated time slot. This proposed protocol guarantees uniform distribution of cluster head nodes as the election is based on probability and remaining energy. A WBS is deployed in the sensing area to ensure efficient use of energy by cognitive nodes and relatively reduce the interference between primary users and cognitive.

The proposed centralized scheduling protocol uses cognitive nodes in dynamic and adaptive manner for cluster heads election and uses energy detection approach to determine the presence of PUs. Therefore, looking at the above results and the comparison of metrics, conclusion is drawn that the proposed protocol outperforms the conventional LEACH and LEACH-C protocols. It is therefore proposed for use as a centralized scheduling technique for wireless networks working over TVWS spectrum band, as it offers a longer network life, higher throughput and more efficient energy use.

5.2. Recommendation and future work

The work done in this research is based on low energy adaptive clustering method to provide a centralized opportunistic scheduling of TVWS with efficient energy consumption. In line with the study done, further studies are suggested in order to get the best of TVWS resources in physical implementation. The incorporation of technologies such as: Artificial Neural networks for cognitive radios that can observe the internal and external parameters of the network are recommended to minimize the transmission latencies. Also, a system analysis/ audit can be done to ascertain the actual complexity introduced in the network by the improved performance metrics witnessed in this research.

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APPENDIX 1: Published Journal Abstract

Publisher: International Journal of Science and Technology Research

Title: Centralized Opportunistic Scheduling technique based on LEACH (COST-LEACH) for TVWS (Accepted, to be published in July 2021)

Abstract

There is a drastic increase in demand of spectrum as result of growth of Internet of Things (IoT) and associated wireless sensor networks. Television White Space (TVWS) is considered to be a good solution in satisfying the growing need of wireless broadband. However wireless network working in TVWS face challenges such as short network life time and untimely energy exhaustion. A Centralized Opportunistic Scheduling Technique based on Low Energy Adaptive Clustering Hierarchy (COST-LEACH) using a modem is proposed in this paper. Performance analysis of metrics such as throughput, network lifetime and energy consumption show that COST-LEACH protocol outperforms the conventional LEACH and Centralized LEACH.

APPENDIX 2: Matlab Codes

```
%**********************************************************************
%
% COST-LEACH BJD
% STUDENT OF MSC ELECTRICAL AND ELECTRONICS ENGINEERING
%**********************************************************************
legendsize=18;
xylabel=14;
xm = 1000 ; % perimeter of the field
ym = 1000 ;
p = 0.1 ;
WBS.x = 1000; % position of white base station
WBS.y = 1000 ;
n = 100 ;
modem.x = 500 ; % Position of the modem
modem.y = 500 ;
Eo = 5 ; %initial energy
ETX=50*0.000000001; % transmission energy
ERX=50*0.000000001; % receiver energy
Efs=10*0.000000000001;
Emp=0.0013*0.000000000001;
EDA=5*0.000000001;
do=sqrt(Efs/Emp);
U = 1000; %number of samples
snr_dB = -10; % SNR in decibels
snr = 10.^(snr_dB./10); % Linear Value of SNR
Pf = 0.01:0.01:1; % Pf = Probability of False Alarm
rmax = 3000;
allive  = n;
```

```
first_dead_dir=0;
teenth_dead_dir=0;
all_dead_dir=0;
dead_dir=0;
first_dead_dir=0;
teenth_dead_dir=0;
all_dead_dir=0;
first_dead_c1=0 ;
all_dead_c1=0;
dead_c1=0;
first_dead_c1=0;
all_dead_c1=0;
first_dead_c2=0;
all_dead_c2=0;
dead_c2=0;
first_dead_c2=0;
teenth_dead_c2=0;
all_dead_c2=0;
first_dead_dir_modem=0;
all_dead_dir_modem=0;
dead_dir_modem=0;
first_dead_dir_modem=0;
all_dead_dir_modem=0;
packets_to_wbs = 0;
packets_to_ch = 0;
packets_to_modem = 0;
%**********************************************************************
    %          LEACH
%**********************************************************************
xm1=1000;
```

```
ym1=1000;
WBS1.x=1000;
WBS1.y=1000;
nl = 100;
pl=0.1;
El1= 0;
Eint=5;
Etl =0 ;
for i=1:1:nl
   Sl(i).xd=rand(1,1)*xm1;
   XR(i)=Sl(i).xd;
   Sl(i).yd=rand(1,1)*ym1;
   YR(i)=Sl(i).yd;
   Sl(i).id = i;
   Sl(i).G=0;
   Sl(i).E=Eint;
   Sl(i).type='N';
end
Sl(n+1).xd=WBS.x;
Sl(n+1).yd=WBS.y;
countCHsl=0;
clusterl=1;
first_deadl=0;
teenth_deadl=0;
all_deadl=0;
deadl=0;
first_deadl=0;
teenth_deadl=0;
all_deadl=0;
allivel=nl;
```

```
packets_TO_WBSl=0;
packets_TO_CHl=0;
%*******************************************************************
%C-LEACH
%*******************************************************************
xm2=1000;
ym2=1000;
WBS2.x=1000;
WBS2.y=1000;
nb = 100;
pb=0.1;
Eb2= 0;
Eint=5;
Etb =0 ;
for i=1:1:nb
   Sb(i).xd=rand(1,1)*xm2;
   XR(i)=Sb(i).xd;
   Sb(i).yd=rand(1,1)*ym2;
   YR(i)=Sb(i).yd;
   Sb(i).id = i;
   Sb(i).G=0;
   Sb(i).E=Eint;

   Sb(i).type='R';
end

Sb(n+1).xd=BS.x;
Sb(n+1).yd=BS.y;
countCHsb=0;
clusterb=1;
```

```
first_deadb=0;
teenth_deadb=0;
all_deadb=0;

deadb=0;
first_deadb=0;
teenth_deadb=0;
all_deadb=0;

alliveb=nb;
packets_TO_WBSb=0;
packets_TO_CHb=0;


%--------------------------------------------------------------------------
for i = 1 : 1 :n
   S(i).xd = rand(1,1)*xm ;
   S(i).yd = rand (1,1)*ym ;
   xd(i) = S(i).xd ;
   yd(i) = S(i).yd ;
   S(i).id = i;
   S(i).type = 0;
   S(i).g = 0 ;
   S(i).E = Eo ;
   S(i).type = 0 ;
       plot(S(i).xd, S(i).yd , 'o' )
       plot (WBS.x , WBS.y , '+r')
       plot( modem.x, modem.y, '*r' )
       grid off ;
       hold on ;
```

```
    figure(1);
end
a0 = 1 ;
count_dir = 0;
x0 = [];
for i = 1:1:n
  if ((S(i).xd >= 0) && (S(i).xd <=1000) && (S(i).yd >= 800) && (S(i).yd <= 1000))
     x0{a0} = S(i).id ;
     count_dir = count_dir+1 ;
     S0(a0).id = S(i).id;
     S0(a0).E = Eo ;
     S0(i).id = i;
     S0(a0).type = 0 ;
     S0(a0).xd = S(i).xd ;
     S0(a0).yd = S(i).yd ;
     a0 = a0+1 ;
  end
end
a = 1 ;
count_dir_modem = 0 ;
x1 = [];
for i = 1:1:n
  if ((S(i).xd >= 300) && (S(i).xd <=700) && (S(i).yd >= 300) && (S(i).yd <= 700))
     x1{a} = S(i).id ;
     count_dir_modem = count_dir_modem + 1 ;
     g1(a).id = S(i).id;
     g1(a).E = Eo ;
     g(i).id = i;
     g1(a).g = 0;
     g1(a).xd = S(i).xd ;
```

```
        g1(a).yd = S(i).yd ;
        g1(a).type = 0;
        a=a+1;
      end
    end
    b = 1 ;
    x2 = [];
    countr1 = 0;
    for i = 1:1:n
       if( (S(i).xd >= 0) && (S(i).xd <300) && (S(i).yd >= 0) && (S(i).yd < 800)||(S(i).xd > 300) &&
(S(i).xd <=500) && (S(i).yd >= 0) && (S(i).yd < 300)||(S(i).xd > 300) && (S(i).xd <= 500)&&(S(i).yd >
700) && (S(i).yd < 800))

        x2{b} = S(i).id ;
        countr1 = countr1+1 ;
         S2(b).id = S(i).id;
         S2(b).E = Eo ;
         S2(i).id = i;
         S2(b).xd = S(i).xd ;
         S2(b).yd = S(i).yd ;
         S2(b).type = 0;
        b=b+1;
       end
    end
    c0 = 1 ;
    x3 = [];
    countr2 = 0;
    for i = 1:1:n
      if ( (S(i).xd > 500) && (S(i).xd <700) && (S(i).yd >= 0) && (S(i).yd < 300)|| (S(i).xd > 700) &&
(S(i).xd <=1000) && (S(i).yd >= 0) && (S(i).yd < 800)||(S(i).xd > 500) && (S(i).xd < 700)&&(S(i).yd >
700) && (S(i).yd < 800))
```

```
        x3{c0} = S(i).id ;
        countr2 = countr2+1 ;
        S3(c0).id = S(i).id;
        S3(c0).E = Eo ;
        S3(i).id = i;
        S3(c0).g = 0;
        S3(c0).xd = S(i).xd ;
        S3(c0).yd = S(i).yd ;
        S3(c0).type = 0;
        c0=c0+1;
    end
end


for r= 0:1:rmax
    r
     if(mod(r, round(1/p) )==0)
         for i = 1:1:length(x2)
             S2(i).type = 0;
             S3(i).type = 0;
         end
     end
     if(mod(r, round(1/pl) )==0)
        for i=1:1:nl
            Sl(i).G=0;
        end
    end

    Etl=0;
```

```
deadl=0;
for i=1:1:nl

   if (Sl(i).E<=0)
      deadl=deadl+1;

      if (deadl==1)
         if(first_deadl==0)
            first_deadl=r;
            first_deadl=1;
         end
      end
      if(deadl==0.1*nl)
         if(teenth_deadl==0)
            teenth_deadl=r;
            teenth_deadl=1;
         end
      end
      if(deadl==n)
         if(all_deadl==0)
            all_deadl=r;
            all_deadl=1;
         end
      end
   end
   if Sl(i).E>0
      Sl(i).type='N';
      Etl = Etl+Sl(i).E ;
   end
end
```

```
   STATISTICS.El(r+1)=Etl;
   STATISTICS.DEADl(r+1)=deadl;
   STATISTICS.ALLIVEl(r+1)=allivel-deadl;
   alive1l = allivel-deadl ;
   received_packsl =0;
%-----------------------------------------------
%C-LEACH DEAD
%====================================================
  if(mod(r, round(1/pb) )==0)
      for i=1:1:nb
          Sb(i).G=0;
      end
   end
   Etb=0;
   deadb=0;
   for i=1:1:nb
      if (Sb(i).E<=0)
          deadb=deadb+1;
          if (deadb==1)
              if(first_deadb==0)
                  first_deadb=r;
                  first_deadb=1;
              end
          end
          if(deadb==0.1*nb)
              if(teenth_deadb==0)
                  teenth_deadb=r;
                  teenth_deadb=1;
              end
          end
```

```
          if(deadb==n)
             if(all_deadb==0)
                all_deadb=r;
                all_deadb=1;
             end
          end
       end
       if Sb(i).E>0
          Sb(i).type='R';
          Etb = Etb+Sb(i).E ;
       end
    end
    STATISTICS.Eb(r+1)=Etb;
    STATISTICS.DEADb(r+1)=deadb;
    STATISTICS.ALLIVEb(r+1)=allivel-deadb;
    alive1b = alliveb-deadb ;
    received_packsb =0;
%---------------------------------------------------------------------
%*********************************************************************
pb = 0.26;
rb = 0.25;
total_packsb =  alive1b;
checkb = 100;
goodb = 1;
packetsb = [];
sizeb = 1;
while sizeb <= total_packsb
if goodb == 1
    packetsb = [packetsb goodb];
    goodb = rand(1) > p;
```

```
elseif goodb == 0
   packetsb = [packetsb goodb];
   goodb = rand(1) > pb;
else
   break;
end
sizeb = sizeb + 1;
end
received_packsb = nnz(packetsb);
theo_pack_loss_rateb = 1 - rb / (pb+rb);
act_pack_loss_rateb = 1 - received_packsb/total_packsb;
checkb = abs(theo_pack_loss_rateb - act_pack_loss_rateb) / theo_pack_loss_rateb * 100;
packetsb;
theo_pack_loss_rateb = pb / (pb+rb);
act_pack_loss_rateb = 1 - received_packsb/total_packsb;
received_pac = received_packsb;
%    %__________________________________________________________________________
   STATISTICS.recievedb(r+1)=received_pac ;
  %}
   countCHsb=0;
   clusterl=b;
   for i=1:1:nb
      if(Sl(i).E>0)
         temp_randl=rand;
         if ( (Sl(i).G)<=0)
            if(temp_randl<= (pb/(1-pb*mod(r,round(1/pb)))))
               countCHsb=countCHsb+1;
               packets_TO_WBSb=packets_TO_WBSb+1;
               PACKETS_TO_WBSb(r+1)=packets_TO_WBSb;
               Sb(i).type='C';
```

```
                Sb(i).G=round(1/pb)-1;
                Cb(clusterb).xd=Sb(i).xd;
                Cb(clusterb).yd=Sb(i).yd;
                distanceb=sqrt( (Sb(i).xd-(Sb(n+1).xd) )^2 + (Sb(i).yd-(Sb(n+1).yd) )^2 );
                Cb(clusterb).distance=distanceb;
                Cb(clusterb).id=i;
                X(clusterb)=Sb(i).xd;
                Y(clusterb)=Sb(i).yd;
                clusterb=clusterb+1;
                distanceb;
                if (distanceb>do)
                    Sb(i).E=Sb(i).E- ( (ETX+EDA)*(4000) +
Emp*4000*(distanceb*distanceb*distanceb*distanceb ));
                end
                if (distanceb<=do)
                    Sb(i).E=Sb(i).E- ( (ETX+EDA)*(4000)  + Efs*4000*(distanceb * distanceb ));
                end
            end
        end
    end
end
STATISTICS.COUNTCHS(r+1)=countCHsb;
for i=1:1:nb
    if ( Sb(i).type=='R' && Sb(i).E>0 )
        if(clusterb-1>=1)
            min_disb=Inf;
            min_dis_clusterb=0;
            for cb=1:1:clusterb-1
                tempb=min(min_disb,sqrt( (Sb(i).xd-Cb(cb).xd)^2 + (Sb(i).yd-Cb(cb).yd)^2 ) );
                if ( tempb<min_disb )
```

```
                    min_disb=tempb;
                    min_dis_clusterb=cb;
                end
            end
            min_disb;
            if (min_disb>do)
                Sb(i).E=Sb(i).E- ( ETX*(4000) + Emp*4000*( min_disb *min_disb * min_disb *
min_disb));
            end
            if (min_disb<=do)
                Sb(i).E=Sb(i).E- ( ETX*(4000) + Efs*4000*( min_disb * min_disb));
            end
            Sb(Cb(min_dis_clusterb).id).E =Sb(Cb(min_dis_clusterb).id).E- ( (ERX + EDA)*4000 );

            Sb(Cb(min_dis_clusterb).id).E =Sb(Cb(min_dis_clusterb).id).E- ( (ERX + EDA)*4000 );
            packets_TO_CHb=packets_TO_CHb+1;
            Sb(i).min_disb=min_disb;
            Sb(i).min_dis_clusterb=min_dis_clusterb;
          else
            min_disb=sqrt( (Sb(i).xd-Sb(n+1).xd)^2 + (Sb(i).yd-Sb(n+1).yd)^2 );
            if (min_disb>do)
                Sb(i).E=Sb(i).E- ( ETX*(4000) + Emp*4000*( min_disb *min_disb * min_disb *
min_disb));
            end
            if (min_disb<=do)
                Sb(i).E=Sb(i).E- ( ETX*(4000) + Efs*4000*( min_disb * min_disb));
            end
            packets_TO_WBSb=packets_TO_WBSb+1;
          end
        end
      end
```

```
   STATISTICS.PACKETS_TO_WBSb(r+1)=packets_TO_WBSb;
pl = 0.26;
rl = 0.25;
total_packsl =  alive1l;
checkl = 100;
goodl = 1;
packetsl = [];
sizel = 1;
while sizel <= total_packsl
if goodl == 1
   packetsl = [packetsl goodl];
   goodl = rand(1) > pl;
elseif goodl == 0
   packetsl = [packetsl goodl];
   goodl = rand(1) > pl;
else
   break;
end
sizel = sizel + 1;
end
received_packsl = nnz(packetsl);
theo_pack_loss_ratel = 1 - rl / (pl+rl);
act_pack_loss_ratel = 1 - received_packsl/total_packsl;
checkl = abs(theo_pack_loss_ratel - act_pack_loss_ratel) / theo_pack_loss_ratel * 100;
%end
packetsl;
theo_pack_loss_ratel = pl / (pl+rl);
act_pack_loss_ratel = 1 - received_packsl/total_packsl;
received_pac = received_packsl;
%    %_____________________________________________________________________
```

```
    STATISTICS.recievedl(r+1)=received_pac ;
   %}
    countCHsl=0;
    clusterl=1;

    for i=1:1:nl
      if(Sl(i).E>0)
        temp_randl=rand;
        if ( (Sl(i).G)<=0)
          if(temp_randl<= (pl/(1-pl*mod(r,round(1/pl)))))
            countCHsl=countCHsl+1;
            packets_TO_WBSl=packets_TO_WBSl+1;
            PACKETS_TO_WBSl(r+1)=packets_TO_WBSl;
            Sl(i).type='C';
            Sl(i).G=round(1/pl)-1;
            Cl(clusterl).xd=Sl(i).xd;
            Cl(clusterl).yd=Sl(i).yd;
            distancel=sqrt( (Sl(i).xd-(Sl(n+1).xd) )^2 + (Sl(i).yd-(Sl(n+1).yd) )^2 );
            Cl(clusterl).distance=distancel;
            Cl(clusterl).id=i;
            X(clusterl)=Sl(i).xd;
            Y(clusterl)=Sl(i).yd;
            clusterl=clusterl+1;
            distancel;
            if (distancel>do)
              Sl(i).E=Sl(i).E- ( (ETX+EDA)*(4000) +
Emp*4000*(distancel*distancel*distancel*distancel ));
            end
            if (distancel<=do)
              Sl(i).E=Sl(i).E- ( (ETX+EDA)*(4000)  + Efs*4000*(distancel * distancel ));
```

```
            end
          end
        end
      end
    end
STATISTICS.COUNTCHS(r+1)=countCHsl;
for i=1:1:nl
  if ( Sl(i).type=='N' && Sl(i).E>0 )
    if(clusterl-1>=1)
      min_disl=Inf;
      min_dis_clusterl=0;
      for cl=1:1:clusterl-1
        templ=min(min_disl,sqrt( (Sl(i).xd-Cl(cl).xd)^2 + (Sl(i).yd-Cl(cl).yd)^2 ) );
        if ( templ<min_disl )
          min_disl=templ;
          min_dis_clusterl=cl;
        end
      end
      min_disl;
      if (min_disl>do)
        Sl(i).E=Sl(i).E- ( ETX*(4000) + Emp*4000*( min_disl *min_disl * min_disl * min_disl));
      end
      if (min_disl<=do)
        Sl(i).E=Sl(i).E- ( ETX*(4000) + Efs*4000*( min_disl * min_disl));
      end
      Sl(Cl(min_dis_clusterl).id).E =Sl(Cl(min_dis_clusterl).id).E- ( (ERX + EDA)*4000 );
      packets_TO_CHl=packets_TO_CHl+1;

      Sl(i).min_disl=min_disl;
      Sl(i).min_dis_clusterl=min_dis_clusterl;
```

```
        else
          min_disl=sqrt( (Sl(i).xd-Sl(n+1).xd)^2 + (Sl(i).yd-Sl(n+1).yd)^2 );
          if (min_disl>do)
            Sl(i).E=Sl(i).E- ( ETX*(4000) + Emp*4000*( min_dis *min_dis * min_dis * min_dis));
          end
          if (min_disl<=do)
            Sl(i).E=Sl(i).E- ( ETX*(4000) + Efs*4000*( min_disl * min_disl));
          end
          packets_TO_WBSl=packets_TO_WBSl+1;
        end
    end
end
STATISTICS.PACKETS_TO_WBSl(r+1)=packets_TO_WBSl;
dead_dir= 0;
E1 = 0;
for i = 1:1:length(x0)
    if(S0(i).E <= 0)
        dead_dir = dead_dir+1 ;
        S0(i).id = i;
        if(dead_dir==1)
          if (first_dead_dir == 0)
            first_dead_dir = r ;
            first_dead_dir = 1;
          end
        end
        if(dead_dir==length(x0))
          if(all_dead_dir==0)
            all_dead_dir=r;
            all_dead_dir=1;
          end
```

```
        end
    end
    if (S0(i).E>0)
        S0(i).type=0;
        E1 = E1+S0(i).E ;

    end
end



E2 = 0;
dead_dir_modem = 0;
for i = 1:1:length(x1)
    if(g1(i).E <= 0)
        dead_dir_modem= dead_dir_modem+1 ;
        g1(i).id = i;
        if(dead_dir_modem==1)
            if (first_dead_dir_modem == 0)
                first_dead_dir_modem = r ;
                first_dead_dir_modem = 1;
            end
        end
        if(dead_dir_modem==length(x1))
            if(all_dead_dir_modem==0)
                all_dead_dir_modem=r;
                all_dead_dir_modem=1;
            end
        end
    end
    if (g1(i).E>0)
```

```
        g1(i).type=0;
        E2= E2+g1(i).E;
    end
end



dead_c1 = 0;
E3 = 0;
for i = 1:1:length(x2)
    if(S2(i).E <= 0)
        dead_c1 = dead_c1+1 ;
        if(dead_c1==1)
            if (first_dead_c1 == 0)
                first_dead_c1 = r ;
                first_dead_c1 = 1;

            end
        end
        if(dead_c1==length(x2))
            if(all_dead_c1==0)
                all_dead_c1=r;
                all_dead_c1=1;
            end
        end
    end
    if (S2(i).E>0)
        S2(i).type=0;
        E3= E3+S2(i).E;
    end
end
```

```
dead_c2 = 0 ;
E4 = 0;
for i = 1:1:length(x3)
   if(S3(i).E <= 0)
      dead_c2 = dead_c2+1 ;
      S2(i).id = i;
      if(dead_c2==1)
         if (first_dead_c2 == 0)
            first_dead_c2 = r ;
            first_dead_c2 = 1;

         end
      end
      if(dead_c2==length(x3))
         if(all_dead_c2==0)
            all_dead_c2=r;
            all_dead_c2=1;
         end
      end
   end
   if (S3(i).E>0)
      S3(i).type=0;
      E4= E4+S3(i).E;
   end
end
STATISTICS.E(r+1)= E1+E2+E3+E4 ;
dead = dead_c1+dead_c2+dead_dir+dead_dir_modem ;
STATISTICS.DEAD(r+1)= dead_c1+dead_c2+dead_dir+dead_dir_modem ;
STATISTICS.ALLIVE(r+1)=allive-dead ;
aliven = allive-dead ;
```

```
received_packsn= 0;
pn = 0.26;
rn = 0.25;
total_packsn = aliven;
checkn = 100;
goodn = 1;
packetsn = [];
sizen = 1;
while sizen <= total_packsn
if goodn == 1
   packetsn = [packetsn goodn];
   goodn = rand(1) > pn;
elseif goodn == 0
   packetsn = [packetsn goodn];
   goodn = rand(1) > pn;
else
   break;
end
sizen = sizen + 1;
end;
received_packsn = nnz(packetsn);
theo_pack_loss_raten = 1 - rn / (pn+rn);
act_pack_loss_raten = 1 - received_packsn/total_packsn;
checkn = abs(theo_pack_loss_raten - act_pack_loss_raten) / theo_pack_loss_raten * 100;

theo_pack_loss_raten = pn / (pn+rn);
act_pack_loss_raten = 1 - received_packsn/total_packsn;
received_pacn=received_packsn;
%_____COST_LEACH________________________________________________________________
```

```
 STATISTICS.received(r+1)=received_pacn ;


for i = 1:1:length(x0)
   if(S0(i).type == 0 && S0(i).E >0)
      dist0=sqrt( (S0(i).xd-(WBS.x) )^2 + (S0(i).yd-(WBS.y) )^2 );
      if (dist0>do)
         S0(i).E= S0(i).E- ( (ETX)*(4000) + Emp*4000*(dist0*dist0*dist0*dist0 ));
      end
      if (dist0<=do)
         S0(i).E= S0(i).E- ( (ETX)*(4000)  + Efs*4000*(dist0 * dist0 ));
      end
      packets_to_wbs = packets_to_wbs+1;
      %
   end
end
for i = 1:1:length(x1)
   if(g1(i).type == 0 && g1(i).E >0)
      dist_to_modem =sqrt( (g1(i).xd-(modem.x) )^2 + (g1(i).yd-(modem.y) )^2 );
      if (dist_to_modem>do)
         g1(i).E= g1(i).E- ( (ETX)*(4000) +
Emp*4000*(dist_to_modem*dist_to_modem*dist_to_modem*dist_to_modem ));
      end
      if (dist_to_modem<=do)
         g1(i).E= g1(i).E- ( (ETX)*(4000)  + Efs*4000*(dist_to_modem * dist_to_modem, ));
      end
      packets_to_modem = packets_to_modem+1;
      packets_to_wbs = packets_to_wbs+1;
   end
end
countCHs=0;
```

```
cluster=1;

for i = 1:1:length(x2)
   if(S2(i).E >0 && S2(i).type ==0)

      temp_rand=rand;
      if(temp_rand<= (p/(1-p*mod(r,round(1/p))))*(Sl(i).E/500))
         countCHs=countCHs+1;
         packets_to_modem= packets_to_modem+1;
         packets_to_wbs = packets_to_wbs+1;
         S2(i).type=1;
         S2(i).g=round(1/p)-1;
         C(cluster).xd=S2(i).xd;
         C(cluster).yd=S2(i).yd;
         distance=sqrt((S2(i).xd-(modem.x) )^2 + (S2(i).yd-(modem.y) )^2 );
         C(cluster).distance=distance;
         C(cluster).id=i;
         X(cluster)=S(i).xd;
         Y(cluster)=S(i).yd;
         cluster=cluster+1;
         distance;
         if (distance>do)
            S2(i).E=S2(i).E- ( (ETX+EDA)*(4000) +
Emp*4000*(distance*distance*distance*distance ));
         end
         if (distance<=do)
            S2(i).E=S2(i).E- ( (ETX+EDA)*(4000)  + Efs*4000*(distance * distance ));
         end
         if(countCHs == (countr1/6))
           break ;
```

```
            end
        end
        if(countCHs == (countr1/6))
            break ;
        end
    end
    % S(i).G=S(i).G-1;
end
countCHs1=0;
cluster1=1;
for i = 1:1:length(x3)
    if(S3(i).E >0 && S3(i).type ==0)
        temp_rand1=rand;
        if(temp_rand1<= (p/(1-p*mod(r,round(1/p))))*(Sl(i).E/500))
            countCHs1=countCHs1+1;
            packets_to_modem= packets_to_modem+1;
            packets_to_wbs = packets_to_wbs+1;
            S3(i).type=1;
            S3(i).g=round(1/p)-1;
            C1(cluster1).xd=S3(i).xd;
            C1(cluster1).yd=S3(i).yd;
            distance1=sqrt((S3(i).xd-(modem.x) )^2 + (S3(i).yd-(modem.y) )^2 );
            C1(cluster1).distance1=distance1;
            C1(cluster1).id=i;
            X(cluster1)=S3(i).xd;
            Y(cluster1)=S3(i).yd;
            cluster1=cluster1+1;
            distance1;
            if (distance1>do)
```

```
                S3(i).E=S3(i).E- ( (ETX+EDA)*(4000) +
Emp*4000*(distance1*distance1*distance1*distance1 ));
            end
            if (distance1<=do)
                S3(i).E=S3(i).E- ( (ETX+EDA)*(4000)  + Efs*4000*(distance1 * distance1 ));
            end
             if(countCHs1 == (countr2/6))
                break ;
            end
        end
        if(countCHs1 == (countr2/6))
            break ;
        end
    end
end
STATISTICS.cluster_heads(r+1) = countCHs ;
STATISTICS.cluster_heads1(r+1) = countCHs1
for i=1:1:length(x2)
    if ( S2(i).type==0)
       if(S2(i).E>0 )
        if(cluster-1>=1)
            min_dis=Inf;
            min_dis_cluster=0;
            for c=1:1:cluster-1
                temp=min(min_dis,sqrt( (S2(i).xd-(C(c).xd))^2 + (S2(i).yd-(C(c).yd))^2 ) );
                if ( temp<min_dis )
                    min_dis=temp;
                    min_dis_cluster=c;
                end
            end
```

```
          min_dis;
          if (min_dis>do)
             S2(i).E=S2(i).E- ( (ETX)*(4000) + Emp*4000*( min_dis *min_dis * min_dis * min_dis));
          end
          if (min_dis<=do)
             S2(i).E=S2(i).E- ( (ETX)*(4000) + Efs*4000*( min_dis * min_dis));
          end
          S2(C(min_dis_cluster).id).E =S2(C(min_dis_cluster).id).E- ( (ERX )*4000 );
          packets_to_ch=packets_to_ch+1
          S2(i).min_dis=min_dis;
          S2(i).min_dis_cluster=min_dis_cluster
       else
          min_dis=sqrt( (S2(i).xd-(modem.x))^2 + (S2(i).yd-(modem.y))^2 );
          if (min_dis>do)
             S2(i).E=S2(i).E- ( (ETX)*(4000) + Emp*4000*( min_dis *min_dis * min_dis * min_dis));
          end
          if (min_dis<=do)
             S2(i).E=S2(i).E- ( (ETX)*(4000) + Efs*4000*( min_dis * min_dis));
          end
          packets_to_modem=packets_to_modem+1;
          packets_to_wbs = packets_to_wbs+1;
       end
    end
    end
end
for i=1:1:length(x3)
    if ( S3(i).type==0 && S3(i).E>0 )
       if(cluster1-1>=1)
          min_dis1=Inf;
          min_dis_cluster1=0;
```

```
for c1=1:1:cluster1-1
    temp1=min(min_dis1,sqrt( (S3(i).xd-(C1(c1).xd))^2 + (S3(i).yd-(C1(c1).yd))^2 ) );
    if ( temp1<min_dis1 )
        min_dis1=temp1;
        min_dis_cluster1=c1;
    end
end
min_dis1;
if (min_dis1>do)
    S3(i).E=S3(i).E- ( (ETX)*(4000) + Emp*4000*( min_dis1 *min_dis1 * min_dis1 *
min_dis1));
end
if (min_dis1<=do)
    S3(i).E=S3(i).E- ( (ETX)*(4000) + Efs*4000*( min_dis1 * min_dis1));
end
S3(C1(min_dis_cluster1).id).E =S3(C1(min_dis_cluster1).id).E- ( (ERX )*4000 );
packets_to_ch=packets_to_ch+1;


S3(i).min_dis1=min_dis1;
S3(i).min_dis_cluster1=min_dis_cluster        else
min_dis1=sqrt( (S3(i).xd-(modem.x))^2 + (S3(i).yd-(modem.y))^2 );
if (min_dis1>do)
    S3(i).E=S3(i).E- ( (ETX)*(4000) + Emp*4000*( min_dis1 *min_dis1 * min_dis1 *
min_dis1));
end
if (min_dis1<=do)
    S3(i).E=S3(i).E- ( (ETX)*(4000) + Efs*4000*( min_dis1 * min_dis1));
end
packets_to_wbs=packets_to_wbs+1;
STATISTICS.PACKETS_TO_WBS(r+1)=packets_to wbs;
end
```

```
        end
    end
    STATISTICS.PACKETS_TO_WBS(r+1)=packets_to_wbs
end
for m = 1:length(Pf)
    m
    i = 0;
for MC=1:10000
 n = randn(1,U);
 s = sqrt(snr).*randn(1,U); % Gaussian PU Signal
 y = s + n; % signal detected at cognitive nodes
 energy = abs(y).^2;
 energy_fin =(1/U).*sum(energy); %
 thresh(m) = (qfuncinv(Pf(m))./sqrt(U))+ 1; %  preSet energy threshold
 if(energy_fin >= thresh(m))  % comparison of the deetected energy and threshold
     i = i+1;
 end
end
Pd(m) = i/MC;
end
plot(Pf, Pd)
hold on
thresh = (qfuncinv(Pf)./sqrt(U))+ 1;
Pd_the = qfunc(((thresh - (snr + 1)).*sqrt(U))./(sqrt(2).*(snr + 1)));
plot(Pf, Pd_the, 'r')
hold on
  warning('OFF');
[vx,vy]= voronoi(X,Y);
plot(X,Y,'r*',vx,vy,'b-');
hold on;
```

```
voronoi(X,Y);
axis([0 xm 0 ym]);


 STATISTICS.recievedl(r+1)
  STATISTICS.recievedb(r+1)
STATISTICS.El(r+1)
STATISTICS.Eb(r+1)
STATISTICS.DEADl(r+1)
STATISTICS.DEADb(r+1)
STATISTICS.ALLIVEl(r+1)
STATISTICS.ALLIVEb(r+1)
STATISTICS.PACKETS_TO_WBSl(r+1)
STATISTICS.PACKETS_TO_WBSb(r+1)
%-----------------------


STATISTICS.received(r+1)
 STATISTICS.PACKETS_TO_WBS(r+1)
 STATISTICS.DEAD(r+1)
 STATISTICS.ALLIVE(r+1)
 STATISTICS.E(r+1)
 %---------------------------------------------------------
 r=0:rmax;
  figure(2)
  plot(r(30:3000/30:3000),STATISTICS.DEAD(30:3000/30:3000),'-
o',r(30:3000/30:3000),STATISTICS.DEADl(30:3000/30:3000),'-
d',r(30:3000/30:3000),STATISTICS.DEADb(30:3000/30:3000),'-s','linewidth',2);
  xlabel('rounds','FontSize',xylabel,'FontName','Arial')
  ylabel('Dead','FontSize',xylabel,'FontName','Arial')
  legend1=legend('COST-LEACH','LEACH');
  set(legend1,'FontSize',legendsize)
   figure(3)
```

```
plot(r(30:3000/30:3000),STATISTICS.ALLIVE(30:3000/30:3000),'-o',r(30:3000/30:3000),STATISTICS.ALLIVEl(30:3000/30:3000),'-d',r(30:3000/30:3000),STATISTICS.ALLIVEb(30:3000/30:3000),'-s','linewidth',2);

xlabel('rounds','FontSize',xylabel,'FontName','Arial')

ylabel('Percent of Allive Nodes','FontSize',xylabel,'FontName','Arial')

legend1=legend('COST-LEACH','LEACH');

set(legend1,'FontSize',legendsize)

figure(4)

plot(r(30:3000/30:3000),STATISTICS.E(30:3000/30:3000),'-o',r(30:3000/30:3000),STATISTICS.El(30:3000/30:3000),'-d',r(30:3000/30:3000),STATISTICS.Eb(30:3000/30:3000),'-s','linewidth',2)

xlabel('rounds','FontSize',xylabel,'FontName','Arial')

ylabel('Energy','FontSize',xylabel,'FontName','Arial')

legend1=legend('COST-LEACH','LEACH');

set(legend1,'FontSize',legendsize)

figure(5)

plot(r(30:3000/30:3000), STATISTICS.PACKETS_TO_WBS(30:3000/30:3000),'-o',r(30:3000/30:3000),STATISTICS.PACKETS_TO_WBSl(30:3000/30:3000),'-d',r(15:3000/15:3000),STATISTICS.PACKETS_TO_WBSb(15:3000/15:3000),'-s','linewidth',2)

xlabel('rounds','FontSize',xylabel,'FontName','Arial')

ylabel('Throughput(bits/sec)','FontSize',xylabel,'FontName','Arial')

legend1=legend('COST-LEACH','LEACH') ;

set(legend1,'FontSize',legendsize)


figure(6)

plot(r(30:3000/30:3000),STATISTICS.received(30:3000/30:3000) ,'-o',r(30:3000/30:3000),STATISTICS.recievedl(30:3000/30:3000),'-d',r(30:3000/30:3000),STATISTICS.recievedb(30:3000/30:3000),'-s','linewidth',2)

xlabel('rounds','FontSize',xylabel,'FontName','Arial')

ylabel('Throughput(packets/time-slot)','FontSize',xylabel,'FontName','Arial')

legend1=legend('COST-LEACH','LEACH');

set(legend1,'FontSize',legendsize)
```