MODELING OF ENERGY EFFICIENT MAC PROTOCOLS IN WIRELESS SENSOR NETWORKS

Thesis submitted to the Jawaharlal Nehru University
in partial fulfillment of the requirements
for the award of the degree of

DOCTOR OF PHILOSOPHY
IN
COMPUTER SCIENCE AND TECHNOLOGY

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CERTIFICATE

This is to certify that the thesis entitled **“*Modeling of Energy Efficient MAC Protocols in Wireless Sensor Networks*”**, being submitted by ***Mr. Mahendra Ram*** to the **School of Computer and Systems Sciences, Jawaharlal Nehru University, New Delhi**, in partial fulfillment of the requirement for the award of the **Degree of Doctor of Philosophy in Computer Science and Technology**, is a bonafide research work carried out by him under the guidance of ***Dr. Sushil Kumar***.

This research work embodied in the thesis is original and has not been submitted for the award of any other Degree.

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DECLARATION

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Mahendra Ram

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ABBREVIATIONS

Abbreviations	**Descriptions**
ADC	Analog-to-Digital Converter
ANFCA	Adaptive Neuro Fuzzy Clustering Algorithm
ACK	Acknowledgment
BO	Back Off
BE	Binary Exponential
BS	Base Station
B-MAC	Berkeley Medium Access Control
CTS	Clear to Send
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier-sense multiple access with collision avoidance
CCA	Clear Channel Assessment
CM	Cluster Member
CH	Cluster Head
DSSS	Direct-Sequence Spread Spectrum
D-MAC	Data Gathering Medium Access Control
dB	Decibels
DCF	Distributed Coordination Function
E-CLD2P	Energy Oriented Cross Layer Data Dissemination Path
EECS	Energy Efficient Clustering System
EERP	Energy Efficient Routing Protocol
E-TORA	Energy aware temporary ordered routing algorithm
EXT	Expected transmission count
EEPI	Energy Efficient Path Information
EESCI	Energy Efficient Sectoring and Clustering Information
EBM	Energy Balanced Model

FDMA	Frequency-division multiple access
FRTS	Future-Request-To-Send
GPS	Global Positioning System
GEAR	Geographic and Energy Aware Routing
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ID	Identification
iid	Independently and Identically Distributed
LEACH	Low-Energy Adaptive Clustering Hierarchy
LA	Local Aggregators
MA	Master Aggregators
MAC	Medium Access Control
MACA	Multiple Access with Collision Avoidance)
MACAW	Multiple Access with Collision Avoidance for Wireless
NAMA	Node Activation Multiple Access
ns-2	Network Simulator-2
OMAC	Optimized MAC
OTcl	Object-oriented Tcl
PCMAC	Power Control Medium Access Control
PAMAS	Power-Aware Multi-Access Protocol with Signaling
PMAC	Pattern Medium Access Control
PCF	Point Coordination Function
PETF	Pattern Exchange Time Frame
PEGASIS	Power-efficient gathering in sensor information systems
QoS	Quality of Service
RoI	Region of Interest
RFID	Radio Frequency Identification
RRCT	Random Radius Clustering Technique
RMAC	Reliable Medium Access Control
RTS	Request to Send

RX	Receive
RTR	Ready To Receive
STR	Scheduling and Traffic Redirection
SIFS	Short Interframe Space
S-MAC	Sensor Medium Access Control
SMP	Sensor Management Protocol
SQDDP	Sensor Query and Data Dissemination Protocol
SQTL	Sensor Query and Data Dissemination Protocol
SYNC	Synchronization
SMACS	Self Organizing Medium Access Control for Sensor Networks
STD	Standard
T-MAC	Timeout Medium Access Control
TADAP	Task Assignment and Data Advertisement Protocol
TCP	Transmission Control Protocol
TDMA	Time-division multiple access
TRAMA	Traffic Adaptive Medium Access
TX	Transmit
UDP	User Datagram Protocol
VGA	Virtualization centric Genetic Algorithm
WSN	Wireless Sensor Network
Wi-Fi	Wireless Fidelity
ZMAC	Zebra Medium Access Control
n	Number of sensor nodes
W	Contention window size
P	Probability
$\Pi_{(.)}$	State probability
k	Positive integer
P_{TR}	Probability of transmission
P_{ST}	Probability of successful transmission
P_{COL}	Probability of collision

E_{ST}	Energy consumption in successful transmission
E_{ID}	Idle energy
E_{COL}	Collision energy
E_{SL}	Sleeping energy
E	Whole network energy
P_{ID}	Probability of idle
P_{SL}	Probability of sleeping
R_{sam}	Sampling rate in µs
S	Throughput
T_{sam}	Sampling time in µs
T_s	Average transmission time
T_{COL}	Collision time
T_{ID}	Idle time
T_{SL}	Sleep time
T_{ST}	Successful transmission time
T_1	Missing transmission time
T_2	Time taken by the node for not capturing the channel
T_3	Time taken due to the back off procedure
T_4	Transmission time
T_{cl}	Duration of a cycle
T_A	Threshold
τ	Time slot

LIST OF PUBLICATIONS

Journals

1. **Mahendra Ram ,** Sushil Kumar, et al. " Enabling Green Wireless Sensor Networks: Energy Efficient T-MAC Using Markov Chain Based Optimization Model", Electronics 2019, 8(5), 534;doi:10.3390/electronics8050534, MDPI, (**SCI Impact Factor: 2.397**).
1. **Mahendra Ram ,** Sushil Kumar, " Green Computing for Industrial Wireless Sensor Networks: Energy oriented Cross Layer Modelling", Recent Patents on Engineering, 2021,9(2), Vol. 15, No. 1;doi:10.2174/1872212115666210917093436, Bentham Science (**Scopus**).

Conferences

1. **Mahendra Ram** and Sushil Kumar, "Analytical Energy Consumption Model for MAC Protocols in Wireless Sensor Networks," International Conference on Signal Processing & Integrated Networks, DOI: 10.1109/SPIN.2014.6776994, SPIN-14, IEEE, 2014.
2. **Mahendra Ram**, Sushil Kumar et al., "Estimation of Energy Consumption in Wireless Sensor Networks Using Random Radius Clustering Technique," 1st International Conference on Networks and Cryptology (NetCrypt-2019).

ABSTRACT

Due to the rapidly growing sensor-enabled connected world around us, with the continuously decreasing size of sensors from smaller to tiny, energy efficiency in wireless sensor networks has drawn ample consideration in both academia as well as in industries' R&D. The literature of energy efficiency in wireless sensor networks (WSNs) is focused on the three layers of wireless communication, namely the physical, Medium Access Control (MAC) and network layers. Physical layer-centric energy efficiency techniques have limited capabilities due to hardware designs and size considerations. Network layer-centric energy efficiency approaches have been constrained, in view of network dynamics and available network infrastructures. However, energy efficiency at the MAC layer requires a traffic cooperative transmission control. In this context, this thesis presents a one-dimensional discrete-time Markov chain analytical model of the Timeout Medium Access Control (T-MAC) protocol. Specifically, an analytical model is derived for T-MAC focusing on an analysis of service delay, throughput, energy consumption and power efficiency under unsaturated traffic conditions. The service delay model calculates the average service delay using the adaptive sleep wakeup schedules. The component models include a queuing theory-based throughput analysis model, a cycle probability-based analytical model for computing the probabilities of a successful transmission, collision, and the idle state of a sensor, as well as an energy consumption model for the sensor's life cycle. A fair performance assessment of the proposed T-MAC analytical model attests to the energy efficiency of the model when compared to that of state-of-the-art techniques, in terms of better power saving, a higher throughput and a lower energy consumption under various traffic loads.

Since sensor nodes are powered by battery and in most situations, they are deployed in a hostile environment, where it is very difficult to change or recharge their batteries in Wireless Sensor Networks (WSNs). So energy efficiency is a central challenge in WSNs. The radio is a major contributor to overall energy consumption of nodes. Due to limited energy supplies, reducing energy consumption is an important goal in WSNs. In this thesis, a mathematical energy model to evaluate the energy consumption, based on current traffic conditions is presented. We analysed the performance of different Medium Access Control (MAC) protocols IEEE802.15.4, and Data–Gathering Medium Access Control (D-MAC) with Radio Frequency Identification (RFID) Impulse using the proposed mathematical energy model under variable data rates. Analytical results show that RFID Impulse gives lower energy consumption in comparison of IEEE802.15.4 and D-MAC in low traffic scenario.

Energy is the critical resource in the wireless sensor networks and it should be used in very prcise way. Clustering is one of the methods for using the energy in efficient manner. In this thesis, a novel analytical model for energy consumption based on random radius clustering technique (RRCT) is presented that evaluates the energy consumption for a multi-hop wireless sensor networks (WSNs). We have analysed the performance of our proposed model with energy efficient clustering system (EECS) protocol. The experimental analysis and analytical results show that the proposed RRCT analytical model saves more energy in comparison of EECS protocol and so the novel analytical model prolongs the network lifetime.

Enabling industrial environment with automation is growing trends due to the recent developments as industry 4.0 centric productions. The industrial wireless sensor network environments have number of constrains including dense deployed nodes, delay constraint for mechanical operation, and access constraints due to node position within instruments. The related literature have applied existing models of wireless sensor network in industrial environment without appropriate updating in the different layers of communication, which results performance degradation in realistic industrial scenario. Towards this end, this thesis presents a framework for Energy Oriented Cross Layer Data Dissemination Path (E-CLD2P) towards enabling green computing in industrial wireless sensor network environments. It is a cross-layer design approach considering deployment of sensors at physical layer up to data dissemination at network layer and smart services at application layer. In particular, an energy centric virtual circular deployment visualization model is presented focusing on physical layer signal transmission characteristics in industrial WSNs scenario. A delay

centric angular striping is designed for cluster based angular transmission to support deadline constrained industrial operation in WSNs environments. Algorithms for energy centric delivery path formulation and node's role transfer are developed to support green computing in restricted access industrial WSNs scenario. The green computing framework is implemented to evaluate the performance in realistic industrial WSNs environment. The performance evaluation attests the benefits in terms of number of metrics in realistic industrial constrained environments.

All the above proposed mathematical models and algorithms of MAC layer and Cross layer have been studied for energy efficiency analysis in WSN. Further, the existing MAC protocol models are deeply examined analytically as well as through simulation for different environment. Algorithms for MAC protocol and cross layer are tested and validated by conducting simulations by using programs implemented in MATLAB. In general, it is observed that the mathematical model and algorithms presented in this work outperform the existing related model and algorithms in the literature. It also provides a framework for developing new mathematical models and algorithms for MAC layer as well as cross layer in WSNs.

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Chapter 1

Introduction to Wireless Sensor Networks (WSNs)

1.1 Overview

WSNs is becoming a big area of research in recent years. It is prepared by a huge amount of very minor devices. These minor devices are called sensors. The computing and processing resources [1] are limited in sensors. Sensors are used to scan different environmental circumstances to consolidate and accumulate information to some locality.

The physical circumstances humidity, pressure, temperature, direction and speed, sound, chemical components, vibrations, and pollutant levels, etc, are detected and measured by sensors with the growing technology, sensor networks are accomplished by tiny, low power, low cost, multi-functional circulated sensors [2]. The sensed, measured, and collected data from different environments by the sensors are transmitted to the operator. WSNs involve more numeral of sensors; these sensors are to be engineered or pre-determined for their position [3]. Every sensor can execute a restricted amount of efficiency.

Sensors are battery-operated and these battery power are fixed. Sometimes solar cells are used as secondary power to give the power to sensor nodes. Sensors are heavily deployed in the intended region. There are huge numbers of sensors in WSNs. These sensors are heavily located near or inside of the incident. The sensor nodes are consist of the following parts (1) power sources (2) memory storage (3) processor (4) transceiver, GPS is the basic constituent of sensor nodes are the power source, memory storage, processor, transceiver, GPS (cf. Figure 1.1). The work of the processor is that the processor executes tasks like handling information and controls the tasks of other constituents in sensor nodes. Transceiver collects commands from the base station and transmits information to the processer or stations [2]. It is a combination of both radio transceiver and receiver, wireless communication media has a probable choice they have radio frequency (RF), photosensitive communication (laser), and electromagnetic (infrared).

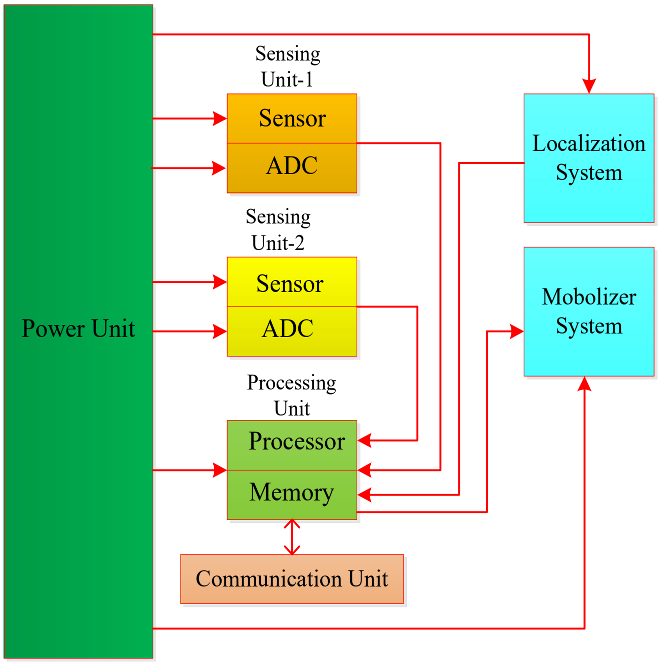

Figure 1.1 Architecture of a Sensor

User memory and program memory are two memories: (a) User memory is used for stock personal information or application related. (b) Program memory is used to identify data if it exists. In a power source, either power is deposited in batteries or capacitors. The rechargeable and un-rechargeable batteries are the main sources of power supply to sensors. The structured sensor and unstructured sensor are two kinds of sensors in WSNs. In an unstructured (ad hoc) manner, the sensors are distributed unsystematically to the intended zone that is thrown down by the plan [4]. Structured or pre-planned manner considers optimum assignment, net assignment, and 2-Dimensional and 3-Dimensional assignment models. The benefits of a pre-planned node are lesser sensor node is set up with low network care and managing cost [5]. Many applications are developed using sensor networks, most of them are custom made with basic architecture and standardization in protocols that can be used for communication [6].

1.2 Various types of WSNs

WSNs are developed on land, Underwater, and Underground. According to the environment in the sensor networks, it faces different tasks and restrictions. Sensor networks are of different kinds [5, 7].

1.2.1 Terrestrial WSNs

Terrestrial WSNs contain 100s or 1000s wireless sensors in structured (pre-planned) and unstructured (ad hoc) fashion. The distributions of sensors are unsystematic in an unstructured (ad hoc) manner to the intended region that is thrown down by the plan [7]. The structured or pre-planned mode considers optimal assignment, net assignment, 2-Dimensional and 3-Dimensional assignment models. Sensor node must communicate successfully with the base station in terrestrial WSN; the power of the battery is limited cannot be recharge, however, the battery is prepared with secondary power cells called solar cells [5], [7]. It is necessary for solar cells to preserve energy. The conservation of energy for terrestrial WSNs is obtained with the help of multi-hop optimum transmitting, small transmission range, and eliminating data redundancy, data collection in the network, delay minimization, and by the use of low duty cycle operation [5].

1.2.2 Underground WSNs

There are underground sensor nodes for underground WSN. These sensors are connected wirelessly. The communications between such sensors are through the soil, the rock, the water and other mineral contents [7]. The underground sensors are used to detecting and monitoring underground situations [6]. Sensor nodes transmit the information to the base station by sink node [7]. Underground WSNs are costlier than terrestrial WSNs [5], [7] in terms of apparatus, development and repairs. They are very problematic to recharge; the sensor node has a limited battery life and is hard to recharge. The reliable communications between the sensors are through the soil, water and other mineral contents [7] in underground WSNs. So genuine machinery or building blocks are selected for communication. Hence the costs of the underground sensor nodes are much higher. To increase network lifetime underground WSNs should plan energy and cost-efficient.

1.2.3 Underwater WSNs

Underwater WSN consists of a numeral of sensor nodes and vans that are expanded into the water [5]. Underwater sensor nodes are much costly and less dense [7] as compared to terrestrial WSNs. Sensors failure, bandwidth and long propagation delay are big challenges for acoustic communication in underwater WSN. Underwater WSN cannot be recharged or replaced because they have a limited battery. Underwater sensor node has many potential applications they are [4]: basaltic monitoring, apparatus monitoring and management and brood of underwater robots. Emerging efficient underwater infrastructures and networking procedures involve energy conservation issues for underwater WSNs.

1.2.4 Multi-media WSNs

It is used to enable monitoring and event tracking in terms of multi-media [5]. It interconnects a brilliant mechanism that permits recapture video, audio, still photographs and scalar sensor testimony [6]. The camera and microphone are the low-cost sensor nodes equipped by the multimedia WSNs [7]. Information compression, information retrieving and connection sensor nodes are linked to each other with wireless connection. The challenges with the multimedia WSN include the consumption of higher energy, requirements of higher bandwidth, quality of services (QoS), processing of information and compression methods and cross-layer scheme [5], [7]. Video stream needs high bandwidth to deliver the content. So, the energy consumption of energy is higher if the rate of data is higher [5]. Processing, as well as delivery of process, is improved by the interaction of cross-layer between layers.

1.2.5 Mobile WSNs

Such a network consists of movable sensors. The movable sensors move from one place to another place [5]. Mobile nodes communicate, compute, and sense. Mobile nodes can organize themselves and change their position within the network [7]. Mobile WSNs start with the preliminary state and sensor nodes will spread out to collect data [7]. If the mobile nodes are within the range then they can communicate to each other and transfer the collected information [5, 7]. These networks can be easily interfaced with the environment. The challenges with the mobile WSN are [5]: deployment, self-organization, localization, energy, direction finding and control, repairs, coverage, and information process. Target tracking, environmental monitoring, exploration and rescue, and hazardous real-time monitoring are applications for mobile WSNs [7]. These mobile networks are versatile compared with other static sensor network systems.

1.3 Architecture of WSNs for Communication

The architecture of WSNs for communication is shown in Figure 1.2. It contains sensor nodes, internet, sensor field and user. Sensor node works as a battery in maximum circumstances in a WSN.

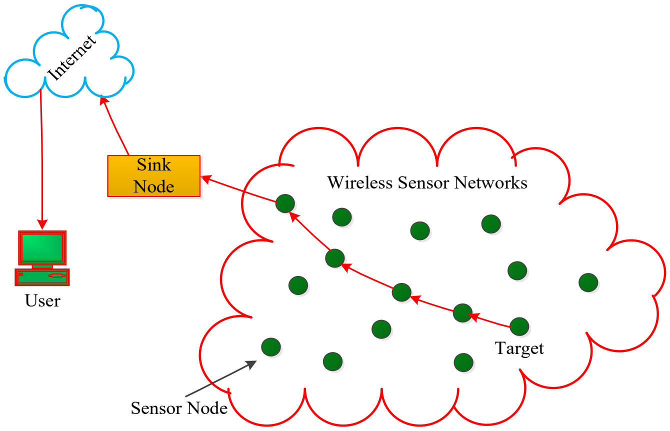

Figure 1.2 Sensor Network Communication Architecture

They are capable to gather information and path data rear to the sink and to the finishing point user. A network can have 100 or 1000 nodes, depending upon the application. The sink node sends data by Multi-hop infrastructure-less structural design [3] back to the final user. The originating node or sink communicates with the task manager node via the internets & satellite [2]. To succeed more lifetime of the network, sensor nodes must modify their actions in an energy-efficient way so unusual energy backs are recycled very efficiently [3]. Each sensor node communicates to one another and to sink by using a protocol stack (cf.Figure1.3). In the way of communication and effective work through manifold sensor nodes, protocol stack must be worked energy efficiently. Protocol stack consists of seven layers; physical layer, data link layer, network layer, transport layer application layer, power management plan, mobility management plan, and task management plan [3]. The protocol incorporate information and network protocol and supports a helpful effect of sensor nodes [2, 3]. The stack of sensor network protocol is shown in Figure1.3 below.

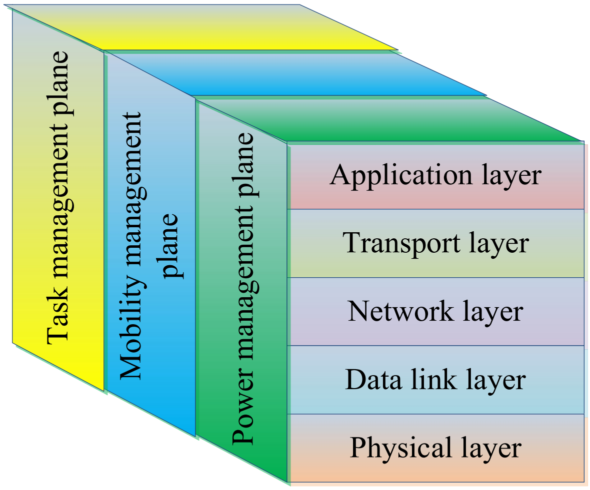

Figure 1.3 Different layers in a wireless sensor networks

1.3.1 Application Layer

SMP, TADAP, SQDDP [3] are three protocols of the application layer. Application layer is responsible to make available software for various applications that predictably transform the information or send requests to get definite data and to maintain traffic management. There are three protocols for the application layer they are:

1.3.1.1 SMP

Sensor networks and system administrators interact with help of SMP protocol [2]. Sensor network applications [3] are controlled by software transparent and lower layers hardware with the help of SMP. The software will execute administrative tasks [3].

1.3.1.2 TADAP

One of the significant procedures of sensor networks is awareness diffusion and the user sends their awareness to a sensor, a subsection on the whole network, or a node [2]. An alternative single is the announcement of existing information where the sensor nodes announce the existing data to operators and operator question data in which they are interested [2, 3].

1.3.1.3 SQTL

This protocol provides the user interface for the applications to raise questions, reply to questions and gather arriving responses [3]. Queries are not supplied for the nodes instead; location or attributes-based identification is chosen [2]. SQTL [2, 3] is an application planned to deliver even a large set of services. There are three events: receive, every and expire. Receive is defined as when the sensor nodes receive a message then it creates events. Everyone is defined as the information comes periodically because of the timer's time-out. Expiration is defined as information come when the time has been expired [2, 3]. SQTL supports these events.

1.3.2 Transport Layer

Reliability and quality of information on the source node and sink node are provided by transport layer function. For different applications, this layer should provide variable packet reliability [5]. The data packets are recovered by two types of approach one is hop-by-hop other is end-to-end [5]. The transport layer helps the system to access the plans via the internet or external networks [3]. The connections between the sensor node and sink are created by TCP, the user communicates with the sink node via internet or satellite by UDP or TCP [2]. Transport layers are used in a different-2 way to grip the issues such as consumption of power, scalability, and characteristics like data-centric routing.

1.3.3 Network Layer

Routing is a major function of the network layer. Network layer grips routing of information over a network from source to destination [5]. By meeting these protocol limitations like restricted energy, transmission bandwidth, and memory and consumption efficiency can prolong the network's lifetime [5]. Energy profitable path, testimony significant routing, and information gathering are some of the important tasks performed by network layer which grant internal-networking with exterior networks like internet and rule and management schemes [2].

1.3.4 Data Link Layer

This layer is accountable for multiplexing information flows, information frame recognition, error regulator and MAC, which guarantees the reliability of point-to-point or point-to-multiple point [3]. MAC would have the subsequent characteristics are energy efficiency, bandwidth utilization, frame synchronization, flow control, error control and scalable to node density for data communication [5]. Wireless multi-hop sensor network must complete two objectives: 1) Formation of network frame: MAC should begin communication links for the information transmission which provides the self-organizing capability to the sensor network, since 1000 of sensor nodes may be heavily dispersed in a sensor field. 2) The second is effectively and fairly share communication assets among sensor nodes.

1.3.5 Physical Layer

The importance of this layer is for a rate of recurrence selection, signal detection, modulation, transferor rate of recurrence formation, and statistics encryption [3]. It interacts with the MAC layer, executing diffusion, reception and inflection. The rate of the error at the physical layer is more and times changing in the wireless transmission, to detection and correction errors MAC layer interrelates with a physical layer [5].

1.3.6 Power Management Plan

This plan is used to manage the power of a sensor node [3]. If the sensor power level is low, it stops participating in routing and broadcasts the low power status to the neighbor [2]. To get duplicate messages sensor node can be turned off their reception message from their neighbors [2].

1.3.7 Mobility Management Plan

Movements of sensor nodes are registered and detected by the mobility management plan [2, 8]. Results way rear to the manipulator are preserved. So, that the sensor node can maintain records that stable their job usage and power.

1.3.8 Task Management Plan

The sensing task is scheduled by task management plan to a particular area [8]. This task management plan is required for route information in a moveable sensor network; sensor nodes can be worked composed in a power resourceful way and share assets among sensor nodes [2].

1.4 Characteristics of Wireless Sensor Networks

WSN’s characteristics contain the following.

- Power depletion restrictions of a node within batteries.
- If the node fails, it can grip.
- Nodes movement and heterogeneity.
- Expandability to the enormous scale of scattering.
- Ability to guarantee harsh environmental situations.
- Humble to usage.
- Cross-layer strategy.

1.5 Advantages of Wireless Sensor Networks

WSN’s advantages are the following

- Network provisions can be accepted obtainable without immobile infrastructure.
- Suitable for those places which are not reachable like deep forests, mountains, rural areas, and sea.
- It is flexible for casual circumstances if there is a need for an additional workstation.
- Execution valuing is cheap.
- It escapes adequately of cabling.
- It might offer accommodations for the novel devices at any phase.
- Centralized monitoring can be used to open it.

1.6 Application of WSNs

WSNs are widely used in controlling and monitoring different physical environments. The introduction of wireless sensors has reduced the physical presence of humans in monitoring several situations. Now a day availability of sensors is not difficult for anyone. People can easily buy such sensors. These sensors can be used to measure a variety of phenomena. For example location, distance, acceleration, motion, and temperature, etc. [9]. WSNs can be applied in the automation of various applications like [10]

1. Defense
2. Environmental monitoring
3. Logistics
4. Human-centric applications
5. Robotics.

1.6.1 Defense Surveillance Applications

The concept of wireless sensor networks is developed for requirements in the defense sector to reduce the human involvement and automation of military applications. In the fields of security and surveillance, there is huge potential for WSNs. In military applications, motes are mainly used in border surveillance, tracking, and classification of enemy activities. Proximity sensors are used to monitor and detects the motion of land and mines that are considered dangerous for a human being to access. WSNs are also used in homeland security, border portal, and property protection, etc [10].

1.6.2 Robotic Applications

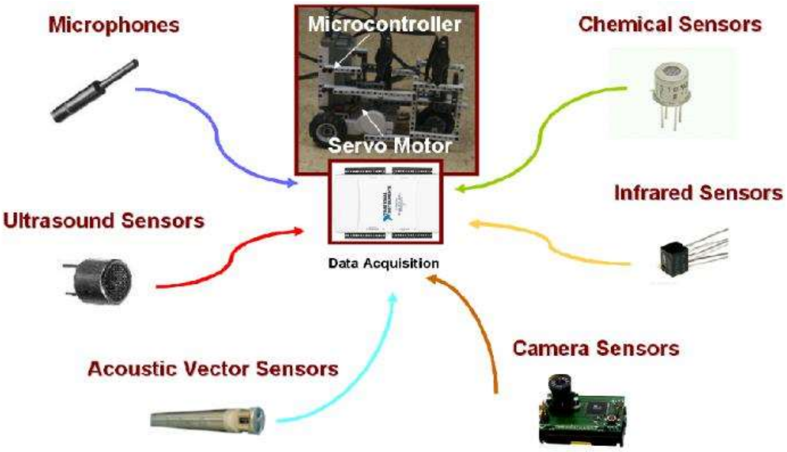

Figure 1.4 Examples of robotic sensors [10]

Now a day there is an advanced development in robotics. Robots are equipped with multiple sensors that can solve different problems humans face every day [10]. Wireless sensors play an important role in these robots by gathering the information, processing, and providing output to the user. USC developed rob mote, it is like a robot. Figure 1.4 shows various robotic sensors. Each of the robotic sensors shown in Figure 1.4 has its individual functions that perform various operations also they can easily incorporate with other devices. These sensors are easy to produce and cost-efficient. They can be programmed to perform certain actions with a particular time frame that helps people to easily trace different actions and situations.

1.6.3 Environmental Monitoring applications

It is one of the obvious applications of WSNs [11]. For instance:

1.6.3.1 Air monitoring

A good example for air monitoring is using air quality sensors for measuring the level of air pollution in major cities to let the people know the level of pollution and take proper measures to control air pollution.

1.6.3.2 Water monitoring

A lot of government agencies are involved in monitoring the national waters to determine the water quality, finding problems like water pollution and pollution control efforts, and responding to emergencies. Some of the popular examples of environmental monitoring are great duck, glacier, zebra net, etc.

1.6.4 Other Applications

WSNs are used in commercial applications such as detection of a vehicle and its tracking, intensive care material weakness, constructing virtual keyboards, handling inventory, monitoring manufactured goods feature, building, controlling in office buildings eco-friendly, factory process regulator, mechanization, observing disaster zone, smooth constructions with sensor nodes immovable inside. It is used to detect car thefts and its monitoring. An application of sensor networks to civil engineering is the idea of smart buildings. To improve alive circumstances and dropping the energy consumption, for the occasion by calculating airflow and temperature, wireless sensor devices and actuator networks could be incorporated inside buildings [12 - 16].

1.7 Design Issues of WSNs

In WSNs, sensor nodes are self-organized and form a network using a self-motivated topology. The sensor nodes are very large in numbers for a typical sensor network and condensed distribution is commonly required to guarantee coverage and connectivity. Due to the reasons, the low-cost sensors are to be considered. Each sensor is equipped with limited battery power which makes them more failure-prone. Sensors form random topology due to depletion of energy and volatile nature of the channel. Power-efficient, inexpensive, fault tolerance, reliable to maximize network lifetime, scalable, facilitation of information gathering, and minimum maintenance are the prime characteristics of a sensor network hardware that makes sensor network applicable and robust.

1.7.1 Lifetime

The power sources cannot be replaced in most of the application scenarios. Therefore, the lifespan of a sensor strongly is influenced by the battery life. Now a day researchers are doing research like power-aware self-organizing connectivity and other protocols. They also focused on developing low-power communication and node processing. Another important task is the requirement for the prolonged sequential operation of sensors, despite a restricted power supply. The main operations of a sensor to detect an event in the sensing field are sensing communication and data processing which all consume power. Low power depletion is the main issue in ensuring the longevity of WSNs. Other performance metrics are throughput and power efficiency, quality of surveillance [13, 17, 18]. Hence the protocols and algorithms for these critical applications can be developed appropriately by tradeoff.

1.7.2 Fault tolerance

The reason for to failure of sensors in WSNs is either power depletion or physical damage or environmental interference. The functioning of WSNs as a whole should not be threatened by the unexpected failure of sensors. Self-evolving algorithms and protocols need to be developed which guarantee the successful operations of sensor networks without human interaction. Physical phenomena like temperature, humidity are monitored by low fault levels. The sensors which are deployed to monitor such phenomena can’t be broken or affected within environmental factors. The fault tolerance is high for battlefield surveillance applications. Because hostile actions [18] can damage sensor nodes and detected data threats to the life of sensors.

1.7.3 Coverage and Connectivity

The density of sensor nodes in WSNs is determined by the application for which the sensor nodes are being positioned to study a phenomenon. Some applications may require a high density of sensors and others require low density. For example, a home might have lots of home applications holding sensors. For military surveillance applications, 5000 sensors may be deployed in an area of 1000x1000 km^2. WSNs must be flexible and capable to energetically get used to the changes in the density of node and topology. Any change in the location, reachability, accessible energy, broken and job information of sensors result in the change of topology. The node density changes are due to the need for deploying additional sensors by replacing the broken sensor nodes or due to change in task changing aspects [13]. For example, in surveillance applications, most of the sensors may remain passive state as long as naught motivating occurs. Sensors get activated as and when intended events occur. To deliver a interruption assured service for control applications, the response time is very critical [17]. Sensor networks have to also be robust to modifications in their topology due to energy depletion or destruction of sensor nodes. In individual, greater connectivity and desired coverage is all the time required. Connectivity is succeeded if the base station is able to get hold of any node. For surveillance applications, complete coverage is highly desired.

1.7.4 Data gathering

Data gathering in WSNs is directly linked to network coverage and connectivity. Quality and quantity of gathered information are the direct measures of coverage. The data which is being sensed is transferred to a base station, nevertheless, this central approach may shorten the lifetime of the network, and generate non-uniform power consumption patterns. The clustering technique is the best choice to minimize the non-uniformity in power consumption. Sensor nodes form clusters and transfer the data to their cluster heads, which process data to reduce the redundancy and forward it to the sink [13].

1.7.5 Hardware constraints

Basic hardware constraints are basic components of sensors like sensing, processing, communication, and power unit shown in Figure 1.1. Other application-based modules are the position discovery system and mobilizer that makes a sensor more intelligent. The sensing unit contains two subunits; analog-to-digital converters (ADCs) and sensors. ADC transformed the observed analog form data into digital form after that data comes into the processing unit. Now, processing unit performs the operations which make easier to transform allocated sensing task from one sensor node to another sensor node. The communications between sensors to the network are performed by communication units. The sensor node has ultimate significant components known as a power unit. This unit is sustained by power hunting units like solar cells. Location finding subunit estimates the location of other sensors or targets with high accuracy that is required for routing and sensing. A mobilizer moves sensor nodes when it is essential to carry out the allocated task. All of these subunits can necessary to fit into a small size node and it is nimble sufficient to persist suspended in the air. These nodes must eat very low power, function in great volumetric densities, consume small manufacture price, and self-organize to form a network [12].

1.7.6 Environments

Sensors are deployed in huge quantities to measure the local environment situations or other phenomena. Therefore, they are anticipated to work in an unattended and inaccessible geographical area. Nodes may be positioned in severe, unfriendly, or broadly spread environments. For example, in a battlefield beyond the enemy line, at the bottommost of a sea, in a biological or chemically polluted area, attached to the animal, and fast-moving vehicle, etc. Such an environment offers several challenges in management mechanisms.

1.8 Energy Issues in MAC

In MAC layer [19, 20] many factors affect energy and delay. Some of the factors are explained below that are linked to the radio mode, service time, and medium access technique.

Overhearing

When a sensor node transmits packets to receive the intended sensor node then other nodes which are in transmission range received these packets that were meant for other nodes [21]. Therefore, energy is wasted due to other nodes receiving packets.

Over-emitting

If the destination node is not ready to receive the data when the source node sends data, it may result in extra delay [22].

Collisions

When two nodes transmit packets at the same time it occurs collision and interferes transmission with each other. Retransmission of the data may increase energy consumption. Furthermore, due to collisions latency increases too [20].

Control Packets Overhead

Since the control packets SYNC, RTS, CTS, ACK are used by sensor nodes before sending data packets. These control packets help to regulate access to the transmission channel. Due to control packets receiving and sending of a sensor node incur some delay.

Idle Listening

If the sensor nodes are in an idle state then there will still be wasted energy of the sensor node. Thus minimizing energy wastage is the main goal of MAC protocol due to these above factors.

1.9 Motivation

The energy optimization on WSNs is typically done on the three layers of the wireless communication architecture, which include the physical, MAC and network layers. Energy optimization at physical layer requires direct manipulation at the hardware level, and this has very limited scope [62]. At Network layer, energy optimization considered the network dynamics [63]. In effect, energy optimization at the MAC layer provides an opportunity for energy saving without the aforementioned shortcomings with the former two layers. Many T-MAC [66] achieves better energy saving than S-MAC[65] by avoiding idle listening during the active time. The sensor goes into sleep mode, as there is no event happening for a certain time of idle listening. The analytical model presented in [67] to study the impact of the sleep mode for the S-MAC protocol is not suitable for the T-MAC because it allows a variable burst length of traffic in the active mode. Since the lifetime of sensors is fully depends on its battery lifetime and the battery has limited energy. Hence the energy conservation is the most important factor for any protocol in WSNs. Thus, protocols should have fewer few of transmissions. Thus, propose schemes should be able to make a node, consume less power so that network lifetime can be increased. There should not be transmitted unnecessary control packet overhead causing extra energy wastage.

1.10 Problem Statement and Objectives

Energy conservation in WSNs is a very critical issue since nodes have limited battery power. The lifetime of the network is completely depends on how the propose protocols/approaches at MAC layer functioned. There are many factors such as overhearing, over-emitting, collisions and control packets overheads consume extra energy of the nodes in WSNs. Considering the above energy efficiency standpoint of view, new energy efficiency optimization approaches need to develop to improve the lifetime of the networks.

Objective

To develop energy-efficient MAC protocols following objectives have been identified.

- To develop new analytical model for energy optimization for T-MAC protocol focusing on an analysis of service delay, throughput, energy consumption and power efficiency under unsaturated traffic conditions.
- Mathematical models for proposed energy-efficient MAC protocols will be developed to analyzed delay, throughput, and energy consumption using Markov chain and queuing.
- The collision and overhearing problem will be solved by proposing efficient approaches.
- If the nodes allow a sleeping mode for long period when no transmission is there and the time taken by the node is minimized if the node goes into sleep mode and wakes up from sleep mode.
- Proposed models will be simulated using Matlab.

1.11 Accomplishment and Contribution

Everybody of work carried out as doctoral thesis must contribute to the knowledge in the area of research. Further, it must accomplish some of the work as objectives of the thesis. Therefore, the following describes the contribution to the knowledge by accomplishing the work in the thesis.

- A one-dimensional discrete-time Markov chain analytical model of the Timeout Medium Access Control (TMAC) protocol is proposed. Specifically, an analytical model is derived for TMAC focusing on an analysis of service delay, throughput, energy consumption and power efficiency under unsaturated traffic conditions. The service delay model computes the average service delay using the adaptive sleep wakeup schedules. The constituent models contain a queuing theory-based throughput analysis model, a cycle probability-based analytical model for computing the probabilities of a successful transmission, collision, and the idle state of a sensor, as well as an energy consumption model for the sensor’s life cycle. A fair performance valuation of the proposed TMAC analytical model attests to the energy efficiency of the model when compared to that of state-of-the-art techniques, in terms of better power saving, a higher throughput and a lower energy consumption under various traffic loads.
- A mathematical energy model to evaluate the energy consumption, based on current traffic conditions is presented. We analyzed the performance of different Medium Access Control (MAC) protocols IEEE 802.15.4, and Data Gathering Medium Access Control (DMAC) with Radio Frequency Identification (RFID) Impulse using the proposed mathematical energy model under variable data rates. Analytical results show that RFID Impulse gives lower energy consumption in comparison of IEEE 802.15.4 and DMAC in low traffic scenarios.
- A novel analytical model for energy consumption based on random radius clustering technique (RRCT) is presented that evaluates the energy consumption for a multi-hop wireless sensor networks (WSNs). We have analyzed the performance of our proposed model with energy efficient clustering system (EECS) protocol. The experimental analysis and analytical results show that the proposed RRCT analytical model saves

more energy in comparison of the EECS protocol and so the novel analytical model prolongs the network lifetime.

- A framework for Energy Oriented Cross Layer Data Dissemination Path (E-CLD2P) towards enabling green computing in industrial wireless sensor network environments is proposed. It is a cross-layer design methodology considering deployment of sensors at the physical layer up to data dissemination at the network layer and smart services at the application layer. In particular, an energy-centric virtual circular deployment visualization model is presented focusing on physical layer signal transmission characteristics in industrial WSNs scenario. A delay centric angular striping is designed for cluster-based angular transmission to support deadline constrained industrial operation in WSNs environments. Algorithms for energy centric delivery path formulation and node's role transfer are developed to support green computing in restricted access industrial WSNs scenarios. The green computing framework is implemented to evaluate the performance in a realistic industrial WSNs environment. The performance evaluation attests to the benefits in terms of a number of metrics in realistic industrial constrained environments.

1.12 Organization of thesis

This thesis comprises six chapters and following the introduction, the thesis is organized as the following fashion:

Chapter 2 explains a review of progress made in literature so far in the area of MAC layer in WSNs. Since energy-efficient MAC protocol designing is one of the approaches which increase life time of WSNs so for energy efficient mathematical modeling is proposed in chapter 3. In chapter 4, energy mathematical model is presented. This modeling is based on current traffic conditions and it evaluates energy consumption. Further a novel mathematical model based on RRCT is presented in chapter 4. This model analyzes the energy consumption for WSNs. In chapter 5, an energy centric virtual circular deployment visualization model is presented focusing on physical layer signal transmission characteristics in industrial WSNs scenarios. Finally, the conclusion with its future research scope enhancement presents chapter 6.

Chapter 2

MAC Protocols for Wireless Sensor Networks (WSNs): A Survey

WSNs are a deep area of research. The WSNs dwell on huge quantity of teeny devices named sensors. These sensors are mechanized by battery and the battery has fixed power. Since the sensors are positioned in horse or hostile area or non-approachable area where if the battery power is depleted then node becomes dead and the communication of nodes fails. So there is a requirement of techniques to optimize the WSNs. Therefore WSNs has turned up as one of the prevailing technology which has potential use in yielding and logical applications. WSNs are used for many determinations like target tracking, wildlife habitat monitoring, intrusion detection, climate control disaster management, and climate control [23]. Typically, a device in the WSN is made up of a sensor, transmitter/receiver chip, memory, ingrained processor. Normally, sensors are powered by the battery and they synchronize between themselves to execute a natural job. These WSNs have harsh source inhibits and energy care is very crucial. The momentous bulk of the energy is drained on the radio of the sensor node in WSNs. Massive research has been ended on the architecture of lesser influence electrical devices thus the energy depletion of these sensor nodes is reduced. Furthermore, due to the hardware constraint energy productivity can be gain over the architecture of energy efficient conversation protocols. MAC is a significant approach that establishes prosperous action of network. Sensors nodes become collision-free from nosey nodes is an important goal of MAC protocol. In IEEE 802.11 MAC protocol the huge amount of energy wastage during idle listening for wireless local area networks. Designing the energy efficient MAC protocol is one of the approaches to increase lifetime of WSNs. Some mathematical models are proposed by many authors that analyzed the performance of MAC protocols like S-MAC, B-MAC, D-MAC, T-MAC, DYNAMIC MAC, Power Control MAC (PC-MAC), X-MAC, WISEMAC, etc. The comparative study of energy efficient

MAC protocol for WSNs is carried out in this chapter. Service delay, throughput, energy conservation, power efficiency, collision probability, idle probability, sleep mode probability have been evaluated to measure the performance of these MAC protocol.

Break of the chapter is follows as: examine challenges in the architecture of MAC protocol, aspects of efficient MAC protocol, big causes of energy wastage, MAC performance matrices, discusses the various scheduled MAC protocols pointing out their strength and weakness where it is possible, future research directions and conclusions.

2.1 MAC Protocol Architecture Challenges

The MAC protocol is categorized into four parts for WSNs. Part one is contention-based MAC protocols like CSMA/CA, MACA, MACAW, PAMAS, B-MAC, S-MAC, T-MAC, R-MAC, X-MAC. The second part is scheduled-based MAC protocols like TDMA/FDMA, NAMA [34], LAMA, PAMA, TRAMA, MMAC, SMACS, TDMA-W, and LEACH. Part three is hybrid like IEEE STD 802.15.4, Wise-MAC, D-MAC, Z-MAC. The last and fourth part is Consensus-based. The MAC creates a structure for the sensor node in WSNs. Since the huge amount of sensor nodes are positioned in the intended area and so, the communication link among sensor nodes is created by the MAC scheme in WSNs. An efficient and equal communication module is contributed for sensor nodes.

2.2 Aspects of Efficient MAC Protocol

Energy efficiency, latency, throughput, and fairness are the aspects [24] of an efficient MAC protocol for WSNs.

2.2.1 Energy Efficiency

Energy efficiency is the first aspect of efficient MAC protocol. The sensor has fixed battery power and this is usually very problematic to alteration/renew for sensors. Occasionally it is valuable to change the sensors instead of renewing them.

2.2.2 Latency

Latency depends on the utilizations of WSNs. In Latency utilizations of WSNs, collected data transfer to sink and leads; instant action will be taken in real-time efficiently.

2.2.3 Throughput

It varies with various utilization. Some WSNs applications sample the data with an attractive physical settlement. In such WSNs applications, it is good to achieve major data by sink node.

2.2.4 Fairness

The sink nodes receive data from all other sensors fairly, when bandwidth is limited in WSNs applications.

Among all the above four, the major aspects are energy efficiency and throughput for efficient MAC protocol. Minimization of energy consumption improves energy efficiency.

2.3 Big Causes of Energy Wastage

Four factors Collision, overhearing, packet overhead and idle listening are big causes of energy wastage for WSNs [24, 25].

2.3.1 Collision

Collision is one of the energy wastage factors for sensors in WSNs that shows in Figure 2.1. If there is an interference in the data transmission then the transmitted packet has corrupted and so it has to be discarded. The discarded data packet needs to be retransmissions. So retransmissions of data packet increase energy consumption. Latency is also increased by collision.

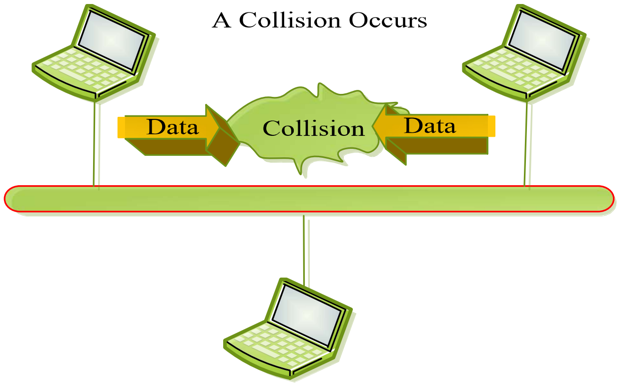

Figure 2.1 Collision

2.3.2 Overhearing

Overhearing is the second factor of energy wastage for sensor node in wireless sensor networks. In overhearing, nodes receive data packets that were meant for other nodes shown in Figure 2.2.

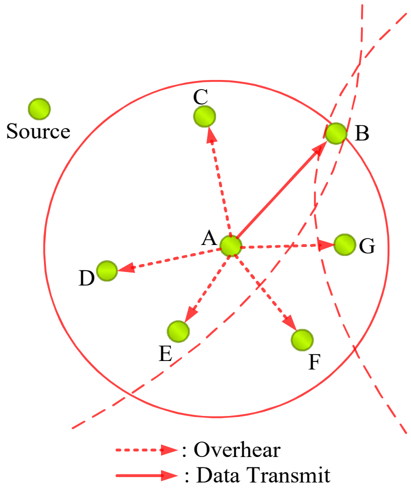

Figure 2.2 Overhearing

2.3.3 Packet Overhead

The third cause of the energy wastage is the control packet overhead. Due to control packets sending and receiving, sensor nodes consume additional energy. It results, lesser worthwhile data transmitted.

2.3.4 Idle listening

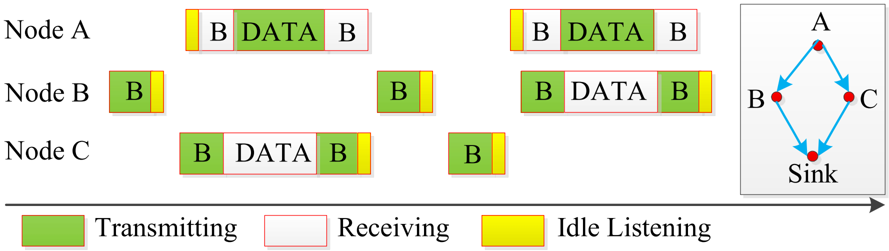

Figure 2.3 Idle listening

Idle listening is the big factor of energy wastage shown in Figure 2.3. Idle listening collects the probable traffic flows that are not sent. In various WSNs applications, particularly it is true. Sensor nodes are in an idle state for a long period if nothing is sensed. Minimization of energy wastage for idle listening, overhearing and collision are the main goal of MAC protocol for WSNs.

2.4 MAC Performance Matrices

Matrices that are used by researchers to measure and evaluate energy efficient over MAC protocol are energy consumption per bit, average delivery packet ratio, average packet latency and network throughput.

2.4.1 Energy Consumption per bit

$\text{Energy efficiency} = \frac{\text{Total consumption energy}}{\text{Total transmitted bit}}$ Joules/bit. The efficiency of protocol will be superior if a lesser number in transmitting the data in the network. Idle listening, collisions, control packet overhead and overhearing are a big cause of energy wastage. Due to this performance matrices are affected.

2.4.2 Average Delivery Ratio of Packet

$\text{Average delivery packet ratio} = \frac{Total\ number\ of\ packet\ received}{Total\ number\ of\ packet\ sent}$. This ratio is averaged over all the sensors.

2.4.3 Average Packet Latency

The average time during which packets reached to sink node is known as average packet latency.

2.4.4 Network Throughput

Network throughput is a total number of packets sent to the sink node per unit time.

2.5 MAC Protocols

Many MAC protocols are pronounced briefly by testifying crucial performance of the protocols wherever potential significantly for WSNs. The MAC protocols for WSNs are categorized broadly into two parts: The first part is contention based MAC protocol and the second part is schedule based MAC protocol. Those protocols which are based on scheduling avoids Collisions, overhearing and idle listening by scheduled transmission & listen time but there is a requirement of strict time synchronization. Contention-based protocols have relaxed time synchronization. As new nodes come in network, topology has been changed easily by relaxing time synchronization whenever other nodes may die after few years of deployment. These protocols are CSMA based protocols.

2.5.1 IEEE802.11 MAC Protocol

The IEEE 802.11MAC protocol [26] optimizes network lifetime by using DCF. This protocol is based on contention. Carrier sensing and a random back-off mechanism are used to avoid collision in IEEE802.11 MAC protocol. It also reduces idle listening by intermittently to sensor nodes going to sleep mode. IEEE802.11 MAC protocol modeling has been developed by authors under saturated traffic conditions that are data has been taken continuous fashion. Many authors have been used Markov chain mathematical modeling to analyzes IEEE802.11 MAC in terms of throughput, collision, idle listening, successful transmission, delay, energy consumption, and power efficiency.

2.5.2 S-MAC Protocol

S-MAC protocol is known as sensor MAC [27]. IEEE802.11 is not considering the irregular data traffic so there is a loss of energy of a sensor node and redundancy is created. So in this protocol, this redundancy has been removed because of considering the unsaturated traffic condition. S-MAC decreases energy consumption during overhearing, idle listening, and collision. It has used sleep state and active state in a cycle. S-MAC is based on contention. S-MAC is an improved protocol of IEEE 802.11 MAC. It was constructed for WSNs in 2002. In this protocol sensor node has a fixed periodic listen and sleep duty cycle. A cycle is divided into two equal parts in S-MAC protocol one is the listening period and the other is the sleeping period. SYNC, RTS, CTS and ACK called control packets are transmitted by a sensor node to other sensor nodes in a listening period. All neighboring sensors are coordinate with each-other by exchanging SYNC packets. A sensor node is ready to send data to the intended sensor node with the help of RTS and CTS control packet exchanging. S-MAC transmission scheme shows Figure 2.4(a) and Figure 2.4(b). In the listen time period, massive energy is consumed in S-MAC. Sensors are active in listening time even they are not receiving or transmitting packets. To reduce the energy consumption many authors have been developed a mathematical model based on a discrete time Markov chain. In this developed mathematical model of S-MAC protocol delay, throughput, energy consumption, power efficiency has been calculated.

Advantages: The power saving is increased due to sleep schedules. S-MAC is an easy to the mechanism. Message passing method is used for long data frame transmission efficiently.

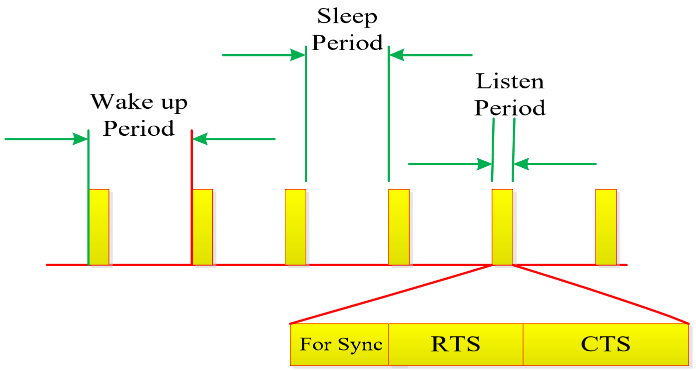

Figure 2.4(a) Basics of S-MAC Scheme

Disadvantages: Sleep and wake-up time are fixed in a cycle for S-MAC. Therefore variable traffic load makes the efficient algorithm.

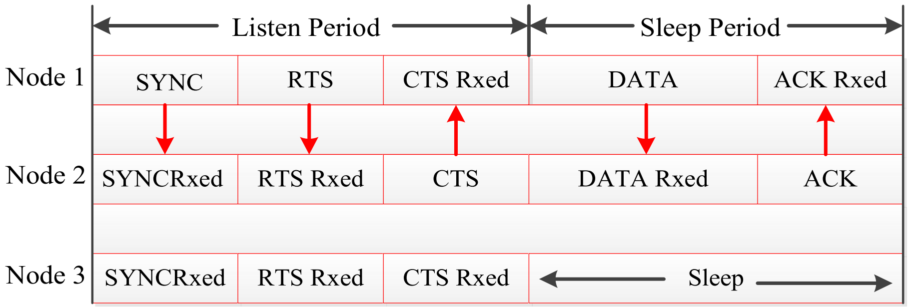

Figure 2.4(b) Basic S-MAC Scheme, Node 1 Transmits Data to Node 2

2.5.3 T-MAC Protocol

In this protocol, the authors considered a dynamic duty cycle. There is a threshold that represents the minimum listening time between the active and sleeps time in the dynamic duty cycle. The minimum listening time is a time in which a sensor node made in wake mode coming for data if data are not coming for this period then node goes into sleep mode dynamically. T-MAC protocol [25] improves over S-MAC protocol. Because in S-

MAC protocol duty cycle is fixed. Due to a fixed dynamic duty cycle, if data is not coming then the node is also in active mode or data is coming but the node is in sleep mode due to this shortcoming either data losses or wastage of energy. For the removal of this shortcoming, the authors have been proposed T-MAC protocol, in this protocol, a mathematical modelling has been developed. This mathematical modeling analyzed the performance of T-MAC protocol by measuring the following factors: delay, throughput, energy consumption, power efficiency. In Figure 2.5, 'TA' is the threshold for minimum time for an ideal listening period per data frame. If TCi, TRt, TTa, TCt represent contention interval length, RTS packet length, turn-around time, CTS packet length then the minimum duration for ideal listening to each data frame is the interval as TA is greater than the sum of TCi , TRt , TTa and TCt. Energy consumed in S-MAC is greater than in T-MAC. But latency is low in S-MAC as compared to T-MAC.

Advantages: Variable traffic loads are easy to handle in T-MAC because of variable duty cycles or due to dynamic sleeping schedule.

Disadvantages: Early sleep problem. In long messages, data get lost due to early goes into the sleep mode of sensors.

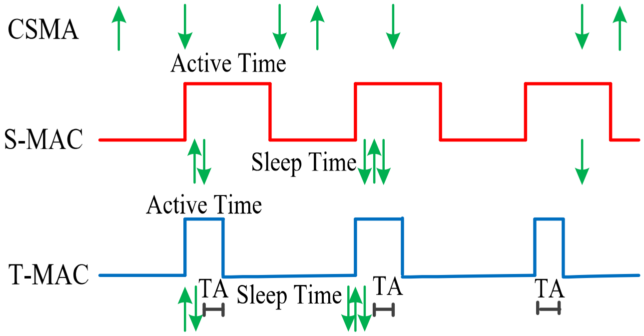

Figure 2.5 Basics of T-MAC

2.5.4 X-MAC Protocol

X-MAC protocol is like Time-out MAC protocol. In this protocol, there is also an adaption of dynamic duty cycle in this protocol the duty cycle is adjusted by varying duty cycle time. Due to varying duty cycle under unsaturated traffic conditions it is more efficient because sometimes data has come and sometimes not for this dynamic duty cycle is more efficient. For this protocol, authors have been developed mathematical modeling by using discrete-time Markov chain with Queueing theory. In this model, a variable traffic load has been considered. By obtaining a transmission probability of a state, the author's calculated throughput, delay, energy consumption, and power efficiency for the performance of X-MAC protocol.

2.5.5 IEEE802.15.4 MAC Protocol

In this type of MAC protocol [28], the authors firstly have been proposed a linear discrete-time Markov chain after that generalized their mathematical modeling for more than two attempts and it becomes three-dimensional discrete time Markov chain. In this modeling the data has been attempted one times, second times, third times and so on. Back off time, slot time and retransmission of ACK packet are considered in the mathematical modeling.

This protocol is a universal standard for lower traffic and for lower energy depletion. This MAC protocol has been structured time slotted mode. In time-slotted mode, for the identification of networks, a controller sends a beacon packet periodically so that sensor nodes are synchronized. Supper frames are started with beacon packets which follow an optimal wake-up and sleep time. In IEEE802.15.4 MAC protocol, authors have been proposed a mathematical modeling to analyze the performance of IEEE802.15.4 MAC protocol [29]. In this mathematical, a Markov chain has been proposed shows in Figure 2.6(a) and Figure 2.6(b). This model consider the following factors(i) Node state models (ii) channel state models (iii) Metrics formulation which is explained bellow:

(i) Node state model

The node behavior, for each class-1 node,…,class- q node is explained by discrete-time Markov chain. The node in class q is remained in idle state until there is no packet receives for transmission with probability $p^{n,q} = \frac{\lambda_q}{N_q}$ where N_q represents the backoff slot in which class-q node receive the arriving packets with Poisson arrival rate λ_q. If a node which is in class q ,willing to send the packet, it first goes back off state BO_1 a random number of back off slots X_1 according to a geometric distribution with probability $P[X_1 = k] = (1-p)^k \, p_1$, where $k = 0,1,2, \ldots \infty$ and parameter's numeric value is ${}^{1}/_{4.5}$, due to setting this value, the mean number of back-off slots for corresponding random distribution and its counterpart IEEE802.15.4 uniform back-off distribution, i.e. 3.5 [30] are equal. The node after leaving the backoff BO_1 goes into the state CS_{11} this performs the first channel back off count access CCA. Suppose channel is idle in CCA. The probability that channel becomes idle is p_i^c and class -1 node transmit stateTX. During N_1 back off slot, class-1 node transmits its packet. Similarly, class-2 node goes into CS_{12} state and transmits their packet in back off slot N_2 as preceding the process up to class-q node for back off slot N_q and transmits their packets in this back off duration.

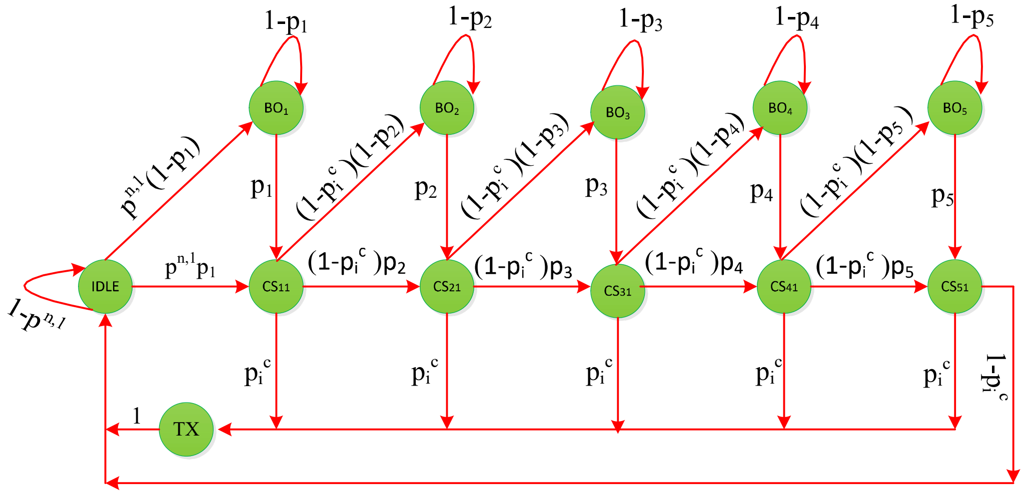

Figure 2.6(a) Embedded Markov chain model for a class-1 sensing node

(ii) Channel state model

Channel behavior is defined with the help of discrete time Markov chain. If it is supposed to be CCA span is maximum for two adjacent backoff corresponding to contention window CW=2 for nodes which is in class 2. This results that channel is idle in the current back off from busy state. Next cycle the single success full transmission if the two nodes have the same priority to transmit a packet of same length N to a single success full transmission or the failure in the same single channel.

(iii) Metrics Formulation

There are three relevant metrics measurement; channel access probability, aggregate channel throughput, and average frame service time

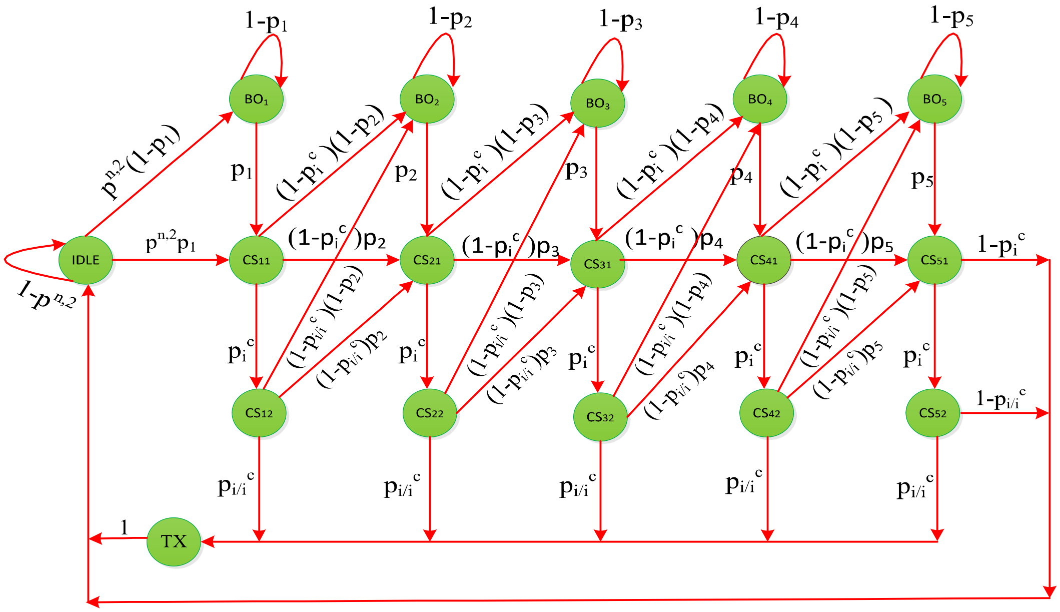

Figure 2.6 (b) Embedded Markov chain model for a class-2 sensing node

2.5.5.1 Markov Chain model

Markov chain having state {s(t), c(t)} for a back off time t. The s(t)=-1 represents the transmission stage for a given time slot t , s(t)=-2 represents the ACK stage and the backoff and CCA stages for s(t) € {0,…, M} . This state represents the state of the Markov chain process. By the help of Markov chin process, the authors explain the behaviour of the sensor nodes in the cycle that a channel has been captured by sensor nodes. After acquiring, the channel by nodes, it may be ready for sending data. It also has been explain the node behaviour for the state of the model in the idle state of the channel in model.

2.5.5.2 Calculation of the Markov chain parameters

It is assumed that the steady state probability of {i, k} state is $b_{i,k}$ and it is

$b_{i,k} = lim_{t\to\infty} P\{s(t) = i, c(t) = k\}$.

The probability of the randomly chosen slot to perform CCA1 can be expressed as

$$\emptyset = \sum_{j=0}^{M} b_{i,k} = \frac{1-(1-y)^{M+1}}{y} b_{0,0} \qquad (2.1)$$

and busy channel probability is expressed as

$$\alpha = [L + L_{ack}\,(1 - p_{c*})][1 - (1 - \emptyset)^{(N-1)}]y \qquad (2.2)$$

Now the probability that the channel is busy when it consider

$$\beta = \left[1 - \frac{2-p_{c*}}{2-p_{c*} + \frac{1}{1-(1-\emptyset)^N}}\right](1 - (1 - \emptyset)^{N-1}) + \frac{1-p_{c*}}{2-p_{c*}+\frac{1}{1-(1-\emptyset)^N}} \qquad (2.3)$$

Where the value of $\emptyset, \alpha, \beta$ can be determined by the following normalizing condition given as

$$\sum_i \sum_k b_{i,k} = 1 \qquad (2.4)$$

By substituting the value of $b_{0,0}$ we get the above parameter value from equation (2.4) and we get the value of this parameter.

In this mathematical modeling, authors have maximized the energy for IEEE802.15.4 MAC protocol with variable sleeping time for a node when the data is not coming in the transmission queue. After normalizing equation (2.4) authors have seen that energy consumption in IEEE802.15.4 is lesser than S-MAC and T-MAC.

2.5.6 D-MAC Protocol

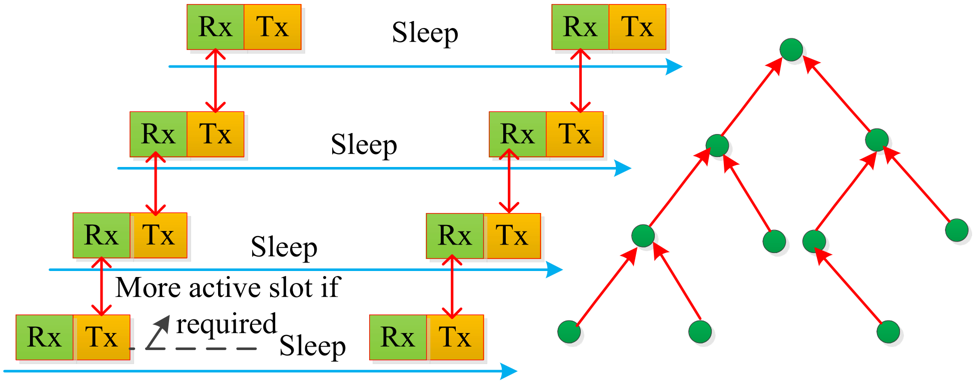

Figure 2.7 D-MAC Protocol

In D-MAC [31], there is a tree based process in which a sensor node scheduled their process by scheduling the sensor node synchronization by the adjustment of duty cycle. In this process data is taken from lover child level to the higher root level. Tree based structure have taken the transmitting data from root level to the child level and receiving data has taken from the child level to the root level. D-MAC protocol mainly focused on minimizes latency and maximizes energy conservation. Time is divided into minor slots in D-MAC protocol. It uses CSMA with ACK to send and collect single data in every minor time slots. The sequence of periodic execution for D-MAC protocol is 1 transmission, 1 receiving, and n sleeping slots. If k be the depth of tree then for a single packet the delay is the k times of the slot from source to sink. This delay is much small. Figure 2.7 shows tree building of D-MAC. The performance of this protocol is evaluated by making the mathematical modeling. This mathematical model is based on discrete time Markov chain and queuing theory. The authors have been calculated the delay, throughput, energy efficiency, power efficiency with the help of this model.

2.5.7 B-MAC Protocol

B-MAC [32] is based on contention. It is known as Berkeley media access control. This protocol is the same as Aloha with Preamble Sample [33]. In aloha, sensors turned on or off their radios frequently without losing their data. But in B-MAC, preamble length is provided that as factor to the higher layer. This delivers optimum trade-off among energy conservation and latency or throughput. Many authors have been presented a mathematical model for monitoring use to calculate delay, throughput, energy efficiency, power efficiency for the performance of B-MAC. The investigational outcomes show that B-MAC has better performance as compared to S-MAC.

2.5.8 Power Control Time Out Medium Access Control (PCMAC) protocol

In this protocol, the authors have been proposed an analytical model in which there is a combination of features of S-MAC and T-MAC protocol and generate new protocol named as Power Control Time Out Medium Access Control protocol. In this mathematical modeling, the authors calculate the active time. After calculating the active time the duration of sleep time is calculated. So that, energy consumed by node is reduced and hence network lifetime is increased. The proposed mathematical modeling expression can be expressed as

$$P(T) = T_k * P_t + R_k * P_r + \beta_t * p_r + \big(1 - (\alpha + \beta)\big)T * P_s$$

Where $P(T)$, T_k , P_t , β_t , p_r , α, β, T , P_s are the overall power , number of sent messages, power consumed by a sensor for sending messages, the idle time of a node, the power consumed in receiving message, power consumed in sleep mode receiving power. The above expression gives the power consumed at which the sensor is in the wake up mode.

2.5.9 Power Aware Multi-Access Signaling (PAMAS)

This protocol is based on contention. The main goal of designing PAMAS [35] protocol is the power saving that is energy efficiency. Sensors turned “OFF” their radios in the case when they are not transmitting or receiving data packets so that energy consumption is reduced. There are two separate channels in PAMAS protocol for data packet transmission and control packets. Due to two separate channels, each sensor node has two radios of different frequency bandwidth. In PAMAS, therefore, the price of sensors, dimension of sensors and scheme density increased. But the power consumption is more significant due to unreasonably switch between sleep and active mode.

2.5.10 Pattern Medium Access Control (PMAC)

PMAC [36] protocol is an adaptive energy efficient MAC protocol for WSNs. In PMAC, mathematical modelling is based on discrete time Markov chain in which binary bit representation is shown by Markov state. S-MAC has a fixed dynamic duty cycle. S-MAC and T-MAC both have small duration of the active period. In this duration the group communication has occurred. D-MAC protocol is also based on an adaptive duty cycle. It delivers the lower latency in converging cast communication by signifying the wake-up time of converge cast tree. It provides low latency to node to sink. While D-MAC beats S-MAC in comparison to latency, throughput, and energy efficiency. The PMAC protocol achieves high throughput in heavy traffic load in comparison of S-MAC and conserves more energy than S-MAC protocol in low traffic loads.

2.5.10.1 Overview of PMAC Protocol

In this model, the sleep wakeup pattern has been scheduled in several slot time. In which the bit pattern is followed. In bit pattern the 0 number represents the sleep mode of the node and bit 1 represents the wakeup mode of a node in the pattern generation Pj= 01 represents the first bit pattern and if N=5 then the plan of for time slot N=5 is 01010 that is the node is in sleep mode in the duration 1, 3, 5 and remaining time slot 2 and 4 the node is in the wake up mode.

(a) Pattern Exchange

In this PMAC protocol the sleep and wakeup mode of node is scheduled by itself and their neighbours. The time slot is divided into the super time frame. Each supper frame consists of two sub frames. STF's 2nd sub frame is called the pattern exchange time frame. In this duration, new patterns are exchanged between neighbours. PETF is also divided into numerous times of slots. In the period of PRTF, the latest created pattern becomes the next PRTF frame. Let us assumed that in the ith period the pattern of a sensor node is 001. Node a repeats their pattern during PRTF.

(b) Analytical model

Authors study the power saving under light traffic loads. Let us assumed that a node is empty with steady probability p. It is assumed that p is constant over all the time. Markov chain model is shown in Figure 2.8.

From the Markov chain average number or the mean number of 0 bits can be expressed as

$$E(0) = \sum_{i=0}^{M}(2^i P_{2^i}) \tag{2.5}$$

If the traffic becomes heavy then p goes to 1. For PMAC protocol let us assumed that the time

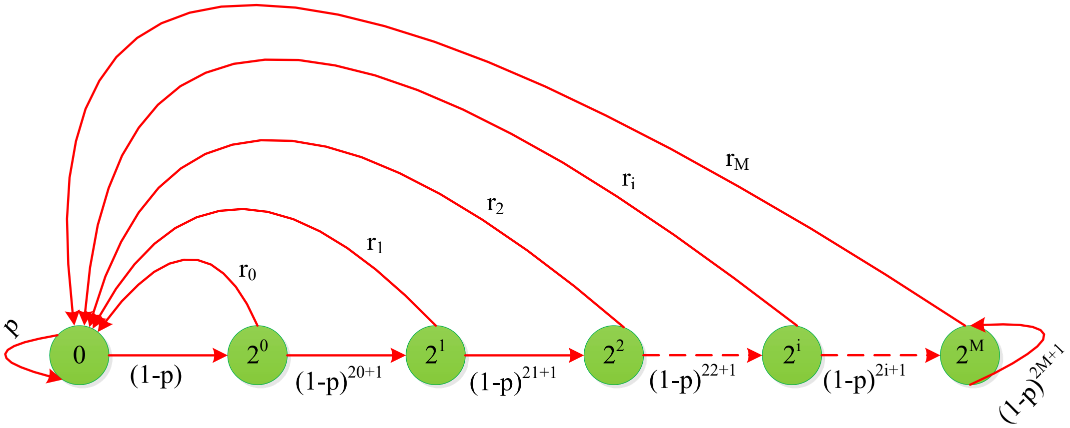

Figure 2.8 Linear Markov Chain

Now with the help of this Markov chain, the authors have been calculated probability of transmission and it is

$$P_0 = \frac{1}{1 + \sum_{i=0}^{M-1} (1-p)^{(2^i+1) + \frac{(1-p)^{(2^M+M)}}{1-(1-p)^{(2^{M+1})}}}}$$

Again, E (0) represents average number of 0 bits given by

$$E(0) = \sum_{i=0}^{M} (2^i P_{2^i})$$

Probability goes to 1 for heavy traffic. So, $P_0 \rightarrow 1$ and $E(0) \rightarrow 0$ for heavy traffic in above expression. Probability goes to 0 for light traffic that is $p \rightarrow 0$ and P_{2^M} is tending to 1 and thus E (0) is near to 2^M Now, the authors considers an interval of time length E(0)*T_R for PMAC protocol to a particular nodes. Where T_R is the time slot in PMAC and it seen that over the entire interval the sensor node are in sleep mode. Again for S-MAC protocol, let us assume T and d represent frame duration and duty cycle respectively. Then duration $\frac{\mathrm{E(0)}*T_R}{T} * d$ will be wakeup time in same interval of time length E(0)*T_R for a sensor node in S-MAC protocol. Hence the amount of energy saved in PMAC protocol over S-MAC protocol can be given as

$$E_{save} = \frac{E(0) * T_R * d * P_{idle}}{T}$$

Where P_{idle} is power consumed by sensor in idle state. Consider, number of sensor that is not involved in data gathering or relaying process be S. Then saved energy of sensors in idle listening for WSNs in PMAC during interval of length E(0)*T_R will be

$$E_{save}^{total} = S * \frac{E(0) * T_R * d * P_{idle}}{T}$$

With the help of this above expression, there is a comparison between PMAC and S-MAC protocol for various sensors in heavy traffic load. For the comparison of above, these two protocol authors calculated energy consumption, delay, throughput, power consumption, and power efficiency. After comparing these components for the two MAC protocol PMAC and S-MAC it is found that PMAC protocols perform better than S-MAC protocol.

2.5.11 Optimized MAC (OMAC)

The duty cycle can be changed as traffic load varies for WSNs in OMAC protocol [37] that is duty cycle high as traffic load high and duty cycle low as traffic load low. Traffic load of sensor network is measured by a number of pending messages in queue. In this protocol the overhead of the control packets can be reduced by decreasing the size and number of control packets in comparison to S-MAC. OMAC protocol can be used for those applications where needed to be low latency and energy efficient networks.

2.5.12 Traffic Adaptive Medium Access Protocol (TRAMA)

TRAMA [38] is based on the TDMA. The architecture of this protocol is in such a way which makes the collision free medium and energy efficiency for WSNs. This protocol reduces the power consumption due to collision free transmission. Also, node switches at low power idle mode when no data packets receiving or sending. The TRMA protocol has three main fragments: (i) The sensor node in the first fragment is used to collect data from neighbours. (ii) The second fragment is used for schedule exchange. In this protocol neighbor interchange their data in two-hop and schedule. (iii) Third fragment is the adaptive selection algorithm. This algorithm decides the nodes for transmission and reception of data packets with the help of neighbor and scheduling current slot. Supplementary node goes to low power mode in the same time slot. TRAMA performance is superior to S-MAC protocol because energy efficiency is more and throughput is higher in TRMA protocol as compare to S-MAC protocol. But the latency for TRAMA protocol is higher in comparison of some other MAC protocols based on contention like S-MAC and IEEE 802.11 protocol. The results of the analytical model show that NAMA [39] has a lesser delay as compare to TRMA. The TRMA protocol is used suitably in those sensor networks where it needs higher throughput and more energy efficiency but the delay is not thoughtful.

2.5.13 Self-Organizing Medium Access Control for Sensor Networks (SMACS)

The schedule-based SMACS [40] is integral of TDMA and FDMA or CDMA to access channels.

Drawback: When the sensor node has no data packets for the transmission to the intended receiving sensor node then the time slots are wasted.

2.5.14 Aloha with Preamble Sampling

This technique is explained in [41]. It is proposed in [33]. Energy wastage during idle listening is the main drawback in Carrier Sense Multiple Access (CSMA). The low power listening technique is proposed in [33] by El-Hoiydi. The low power listening schedules the duty cycle based on radio efficiency. Methodology is based on PHY Header. PHY works at physical layer The Header twitches through Preamble intimates the receiver of future messages. The receivers turned on their radio periodically to sample for the incoming messages. The receivers continuously listen to the normal message transfer if it detects preamble. The receivers turned off their radio if the preamble is not detected till the next sample shown in Figure 2.9 that appropriates for low traffic WSNs applications.

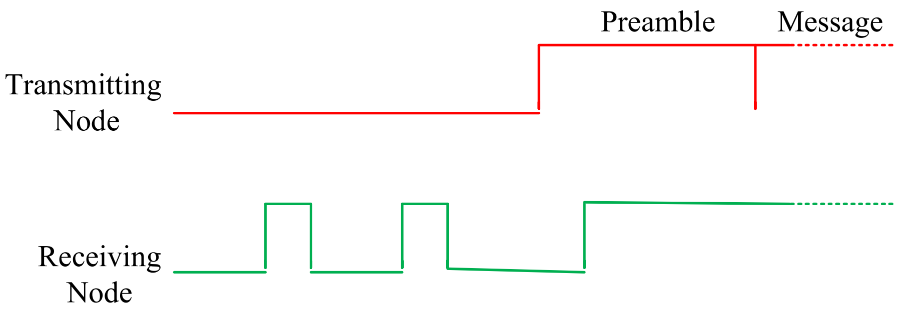

Figure 2.9 Preamble Sampling and Low Power Listening

2.5.15 Wise MAC

The Wise MAC [42] protocol has been established for the application of “Wise NET” WSNs. Wise MAC protocol has similarly with Spatial TDMA and CSMA with Preamble Sampling protocol [43]. All the sensor devices have two transmission channel as the first channel is used to access the data packet by TDMA and second channel is used to access control packets by CSMA. However, Wise MAC [42] protocol is used a single channel also uses non-persistent CSMA with preamble sampling technique to save the power in idle listening period. Wise MAC protocol usages smallest size preamble based on the data packets sampling scheme of its direct neighbor nodes. In each data transmission, the sleep schemes for the neighbor nodes are updated by the acknowledgement packet (ACK). Wise MAC is an adoptive MAC protocol for the network's traffic load. It provides minimum power consumption in low traffic and the efficiency of the energy is high in high traffic. The Wise MAC protocol outperforms SMAC protocol.

2.5.16 Energy Aware TDMA Based MAC

This MAC protocol [44] makes clusters in WSNs. Gateway helps to sensor node succeeded in every cluster. Gateways collect data from other sensors within the cluster and makes the union of collected data, transmit to an-other gateways. Finally, data get into control center. Gateways assign slots to sensors in its cluster. Whenever Gateways listen about the time slot form a sensor nodes notify other sensors about this slot to transmit their own information. Energy Aware TDMA based MAC protocol has four stages: information transmission, restore, the incident triggered rerouting and refresh-based rerouting. The information transmission stage stands for transferring information in its assigned time slot. All through the state of the sensors like state, level of energy, position, etc, are restored in the gateway at the time of replenish stage. The gateway requires the state data of this sensor to perform rerouting when events triggered rerouting. After the refresh stage, the rerouting called refresh based rerouting happens periodically. During both the rerouting stage, the gateway gives the new rout of the sensor nodes after executing the routing algorithms. The assignment of the slot which is based on the graph parsing strategy has two approaches first one is BFS known as Breadth First Search and the second one is DFS called Depth First Search. In BFS, the numbering of assignment of time slot are started from outermost sensor nodes by giving adjoining time slots. But in DFS, the time slot called adjoining time slots assigned to that sensors which are on route in-between outermost sensor node and gateway. The consumption of energy is saved being the state on-off in BFS. Hence the lifetime of sensors is high. The buffering capacity is needed to be enough for sensor nodes in BFS. In DFS the buffering overflow problem is avoided but it is not saved the consumption of energy in changing the state on-off. The latency is low but throughput is high in DFS as compared to BFS.

Lately, authors have developed several MAC protocols for WSNs. But no any protocol MAC protocol has been considered as standard MAC protocol among all these developed MAC protocols because MAC protocols are application-based. Therefore no any MAC protocol will be perfect for WSNs [45]. For example, TDMA is scheduling protocol. It access the medium collision free but the synchronization is critical. Besides, there is no possibility to change the network topology because the sensor node can’t be replaced. Even though Carrier Sense Multiple Access (CSMA) protocol is suffering from collision but latency in CSMA is low and throughput is high. The medium access by FDMA scheme is free from a collision. But FDMA needs an additional electrical system to connect with other various radio channels energetically. So, it increases sensor’s cost. It is a drawback of FDMA for wireless sensor networks. Also, the medium access by Code Division Multiple Access (CDMA) scheme is free from the collision. There is more energy conservation and lower computational complexity for the sensor network.

2.6 Summary

This chapter explains a survey of existing MAC protocols and algorithms that solve the duty cycle, wakeup sleep, idle listening, and collisions issues in WSNs. This chapter first introduced elementary awareness of MAC protocol briefly. Second, architecture challenges, aspects, matrices of MAC protocols and their types are given. The existing MAC protocol is categorized under the types of protocols are discussed. The issue and its related algorithms are also discussed. At last, challenges related to energy wastage are identified and presented.

Chapter 3

Modeling of Energy Efficient T-MAC Using Markov Chain

This chapter presents a one-dimensional discrete-time Markov chain analytical model of the Timeout Medium Access Control (T-MAC) protocol. Specifically, an analytical model is derived for T-MAC focusing on an analysis of service delay, throughput, energy consumption and power efficiency under unsaturated traffic conditions. The service delay model calculates the average service delay using the adaptive sleep wakeup schedules. The component models include a queuing theory-based throughput analysis model, a cycle probability-based analytical model for computing the probabilities of a successful transmission, collision, and the idle state of a sensor, as well as an energy consumption model for the sensor's life cycle. A fair performance assessment of the proposed T-MAC analytical model attests to the energy efficiency of the model when compared to that of state-of-the-art techniques, in terms of better power saving, a higher throughput and a lower energy consumption under various traffic loads.

3.1 Introduction

WSNs have various real-life applications in various fields, such as precision agriculture [48], patient healthcare [49], target tracking, homeland security, environmental monitoring, surveillance [50], vehicular traffic management [51, 52], and electric vehicle charging recommendation [53, 54]. WSNs' role is significant in the emergence of the Internet of Things (IoT) [55, 56]. Sensor nodes are deployed in WSNs in large amounts in a geographical area. There are basically two different ways of deploying the sensor nodes: planned and random. For example, sensors are deployed in a well-calculated style in an approachable area where humans can travel [57]. On the other hand, an ad-hoc method approach is used in a hostile environment, as it is very difficult to deploy the nodes there manually [58]. Typically, these sensor nodes are battery-run with constrained power and are left unattended after being deployed in the hostile environment. Additionally, if the number of nodes is higher, as is the case with typical IoT applications, changing the batteries on the nodes after they run out of power is not feasible [59]. Furthermore, because of the low cost, changing the entire network might be more viable than changing individual batteries. Hence, elongating the network lifetime by optimizing the available energy in the sensor nodes seems comprehensible [60]. As such, energy optimization in the sensor nodes to prolong the network lifetime has attracted massive research interest [61].

The energy optimization on WSNs is typically done on the three layers of the wireless communication architecture, which include the physical, MAC and network layers. In the physical layer optimization, the optimization of modulation techniques or changes in antenna schemes is performed [62]. Since this requires direct manipulation at the hardware level, energy optimization on the physical layer is generally limited. Network layer optimization requires a consideration of the network dynamics and the network infrastructure; therefore, any changes to the network dynamics can have negative effects on the network [63]. In effect, parameter optimization at the MAC layer provides an opportunity for energy optimization without the aforementioned shortcomings with the former two layers. Many MAC protocols have been designed for WSNs in order to use the limited energy efficiently by placing the sensor nodes in sleep mode [64]. Some of the existing MAC protocols that adopted this technique are S-MAC [65] and T-MAC [66]. These reduce the energy waste by introducing an active and sleep time into the time cycle of IEEE 802.11. T-MAC achieves better energy saving than S-MAC by avoiding idle listening during the active time. The sensor goes into sleep mode, as there is no event happening for a certain time of idle listening. The analytical model presented in [67] to study the impact of the sleep mode for the S-MAC protocol is not suitable for the T-MAC because it allows a variable burst length of traffic in the active mode. To the best of our knowledge, the performance analysis of the T-MAC protocol for energy efficiency, throughput and delay has not yet been done in view of unsaturated traffic conditions or environments.

A new discrete-time Markov chain analytical model is developed that appropriately determines the performance of the T-MAC protocol under unsaturated traffic conditions for sensor-enabled wireless network environments. The proposed analytical model utilizes the

Markov chain analysis, considering the back-off procedure of the T-MAC protocol. The novelty of the method is emphasized by the co-operative use of the discrete-time Markov chain with the T-MAC protocol. This chapter is summarized below:

- We derive an analytical model for T-MAC, applying a discrete-time Markov chain focusing on throughput, energy consumption, power efficiency and service energy under unsaturated traffic conditions.
- A node behavior model is presented with a transmission probability, which reviews the back-off mechanism in the T-MAC protocol using the Markov chain. Moreover, the probabilities of a successful transmission, collision, and idle state of a node are computed in a cycle probability model, which is also illustrated.
- A system model, based on the M/M/1/∞ queuing model, is presented to analyses the throughput under unsaturated traffic conditions, and a service delay model is illustrated to calculate the average service delay using the adaptive sleep wakeup schedules.
- A comparative performance analysis is done with the aid of a simulation to assess the energy efficiency of the suggested model, as compared to the state-of-the-art S-MAC and X-MAC based techniques, in view of various metrics.

The break of this chapter is systematized as follows: In section 3.2 critically analyses the existing associated literatures on the MAC-based WSN energy optimization. The details of the proposed discrete-time Markov chain analytical model of the T-MAC protocol are presented in section 3.3. The analytical and experimental results, with the comparative performance evaluation, are discussed in section 3.4, which is later followed by summary in section 3.5.

Table (3.1) Notations

Notation	Description	Notation	Description
n	Number of sensor nodes	E_{SL}	Sleeping energy
W	Contention window size	P_{SL}	Probability of sleeping
p	Probability	T_{COL}	Collision time

$\Pi_{(.)}$	State probability	T_{ID}	Idle time
k	Positive integer	T_{SL}	Sleep time
P_{TR}	Probability of transmission	T_{ST}	Successful transmission time
P_{ST}	Probability of successful transmission	T_1	Missing transmission time
P_{COL}	Probability of collision	T_2	Time taken by the node for not capturing the channel
P_{ID}	Probability of idle	T_3	Time taken due to the back off procedure
τ	Time slot	T_4	Transmission time
E_{ST}	Energy consumption in successful transmission	T_{cl}	Duration of a cycle
E_{ID}	Idle energy	T_A	Threshold
E_{COL}	Collision energy	E	Whole network energy
T_{sam}	Sampling time in μs	S	Throughput
T_s	Average transmission time	R_{sam}	Sampling rate in μs

3.2 Background

3.2.1 MAC Orientated Green Communication

In recent years, the focus has been on developing energy efficient MAC protocols for WSNs. The sleep and wake-up time cycle has been incorporated in the IEEE 802.11-distributed coordination function to conserve the energy of a sensor node. Various protocols are proposed in WSNs, like S-MAC, T-MAC, X-MAC and IEE 802.15, which are variants of IEEE 802.11, to conserve the energy at the MAC layer. In the past, there have been some analytical models that are proposed for the analysis of the performance of these MAC protocols on the basis of sleeping nodes. In [67], a mathematical model has been proposed for the S-MAC protocol to evaluate the throughput, delay and energy consumption under unsaturated traffic conditions. The authors considered the various factors together, including the active and sleep time cycle, the back off method, and the different traffic patterns for the S-MAC protocol. The modelling of the states of a node is done using a discrete time Markov chain, and the M/G/1/∞ queueing theory has been applied to compute the service delay, throughput, and energy consumption under unsaturated traffic conditions. A Markov queuing model has been proposed for the S-MAC and X-MAC protocols to calculate the throughput, delay, and energy consumption of both the synchronized duty-cycled S-MAC protocol and the asynchronous duty-cycled X-MAC protocol in [68]. The synchronous and asynchronous duty-cycled nodes queueing behaviour is studied using the Markov queueing model, as suggested by some authors. The performance evaluation of the synchronized duty-cycled S-MAC and asynchronous duty-cycled X-MAC protocols is calculated for the stationary probabilities of the packet transmission.

In [69], the authors evaluated the performance of the IEEE802.15.4 protocol, which takes retransmission and acknowledgements under unsaturated traffic conditions as parameters using a Markov chain model. In this analytical model, the network performance has been measured in terms of the frame delivery ratio, average power consumption of a node, channel throughput and frame discard ratio. The authors in [70] modelled the IEEE 802.15.4 MAC layer as a non-persistence CSMA with a back off to compute the throughput and energy efficiency of the contention access period, and they proved that switching the radio into sleep mode between transmissions conserves the energy of the MAC layer. In [71], the performance of the IEEE 802.15.4 MAC protocol was dispensed within the terms of energy and throughput, in view of the right channel conditions under saturated and unsaturated traffic conditions. In [72], the authors estimated the delay and energy consumption of the IEEE 802.15.4 MAC layer, showing that the overall performance of the proposed model depends on the collision probability. In [73], an energy model is proposed to compute the power consumption, using the time-slotted channel hoping scheme that is the core of the IEEE 802.15.4e-2012 amendment of the IEEE 802.15.4-2011 standard.

3.2.2 Routing Orientated Green Communication

An approach for green computing has been proposed in [74] using Huffman coding-based ant colony optimization for a randomly distributed wireless sensor network. In particular, ant colony optimization is used to explore multiple paths, and Huffman coding is used to select the best path in view of the impact of two parameters on the energy consumption; namely, the path length and residual energy of each node. Green computing is performed in [75] by equalizing the energy consumption of all the sensors in the networks. A distributed forward search space was introduced to reduce the unnecessary transmission. Furthermore, four parameters, residual energy, node degree, distance and angle, have been used to construct the next forwarder selection function to select the next hop to route the packets. In [76], an energy balanced model was proposed to realize an equal distribution of energy consumption among all of the sensors in the network. New methods are proposed for the sensors to adjust the transmission range, adaptive sensing and density control to achieve a fair equalization of the energy consumption. Additionally, algorithms are presented for the annulus formation, connectivity ensured routing and coverage preserved scheduling, for the realization of a proposed energy balanced model. In [77], a new approach for green computing was presented, as lifetime maximization based on balanced tree node switching. Two methods of shifting the nodes to achieve the balance tree of the node in the network, in terms of energy, were proposed. The author in [78] proposed a fault tolerance optimization method to minimize any end-to-end communication delay and fault tolerance in WSNs. An adaptive non-dominated sorting based genetic algorithm was used to solve the optimization problem. An analytical model of the T-MAC protocol was proposed in [79]. The authors in [79], estimated the length of the active and sleep time of a cycle time assuming that the occurrence of events follows the Poisson distribution. In this model, the energy consumption has been evaluated in terms of transmitting and receiving packets during the active time of a node. However, this model could not consider the back off mechanism. Furthermore, this analytical model could not calculate the service delay, throughput and power efficiency. Therefore, an analytical model that considers the back off mechanism, delay, throughput, and power efficiency under unsaturated traffic conditions needs to be developed.

3.3 Analytical Model of T-MAC Protocol

Here, we present a one-dimensional discrete time Markov queuing model of T-MAC for duty-cycled nodes with a variable cycle length. We consider the service delay, throughput, energy consumption and power efficiency for a node, according to the following assumptions: a) a large number of arrivals of packets at each node are independent and discrete; therefore, the arrival of packets follows the Poisson distribution, b) A large number of data packets is buffered by each node, c) the packet retransmission is not endorsed here,

d) the channel is considered perfect (no fading), and e) the deployment of sensor nodes follows the geometric distribution.

3.3.1 Node Behaviour Model

In this analytical model, a single hop WSN is considered, with *n* number of identical sensor nodes. The change of the node's back off (BO) period is represented using the stochastic process. As per the T-MAC protocol, the back off timer is cancelled by the node if it fails to seize the channel in a cycle time, after which it will set a new BO timer for the next cycle. Hence, the stochastic process can be demonstrated with the discrete time Markov chain, as shown in Figure 3.1.

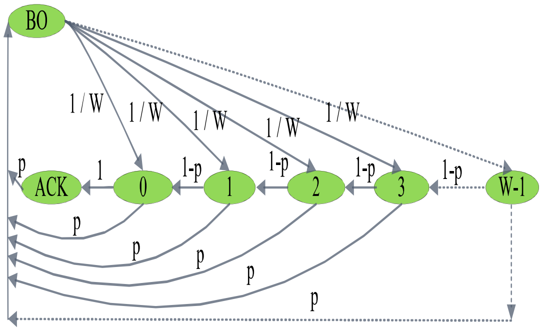

Figure 3.1 Discrete time Markov Chain of T-MAC Protocol

Consider that the proposed Markov chain has a finite number of states that are equal to the size W of the contention window. These states are numbered 0, 1, 2, 3 …, W−1, representing the status of the nodes. The parameters are considered in the model, as shown in Table (3.1). The random back off timer is less than or equal to the current time slot. The transmission begins as soon as the back off period reaches zero. The back off period is chosen randomly in the range of [0, W−1] for each transmission. All of the sensor nodes sense the medium with an equal probability 1/W to capture the channel. If the channel is found to be idle, then a node contains the particular time slot which is equal to the current back off timer. The node continuously senses, with a probability (1-p), until the back off duration becomes zero, and it also ensures that no one is transmitting on the channel, after which it starts transmitting with probability 1. After the completion of the packet transmission, the node receives an acknowledgment (ACK) packet and then goes for back off duration with probability p. In the event that the channel seems busy, the node goes to back off duration with probability p. Again, the same process is repeated to capture the channel. The steady state equations of the discrete-time Markov chain are expressed as:

$$\Pi_0 \ = \ (1/\mathrm{W})\ \Pi_{BO} \ + \ (1-\mathrm{p})\Pi_1 \tag{3.1}$$

$$\Pi_1 \ = \ (1/\mathrm{W})\ \Pi_{BO} \ + \ (1-p)\Pi_2. \tag{3.2}$$

Similarly, for the kth state, the balance equation is given by Equation (3.3):

$$\Pi_k \ = \ (1\ /\ \mathrm{W})\ \Pi_{BO} \ + \ (1-p)\Pi_{k+1} \tag{3.3}$$

$$\Pi_{BO} = \ \mathrm{p}\ \Pi_{ACK} \ + p\Pi_0 + \ \mathrm{p}\ \Pi_1 + \cdots + \mathrm{p}\Pi_{W-1} \tag{3.4}$$

$$\Pi_{ACK} = \Pi_0 \tag{3.5}$$

$$\Pi_{ACK} + \Pi_{BO} + \sum_{k=0}^{W-1} \Pi_k = 1, \tag{3.6}$$

where k takes the positive integer value from 0 to W−1, and $\Pi_{(.)}$ represents the state probability. Upon solving the above equations, we have:

$$\Pi_0 = \ (1/\mathrm{W})\Pi_{BO} \ + \ (1-\mathrm{p})[(1/\mathrm{W})\Pi_{BO} \ + \ (1-\mathrm{p})\Pi_2]$$

$$= \ (2-\mathrm{p})(1/\mathrm{W})\Pi_{BO} \ + \ (1-\mathrm{p})^2\ \Pi_2$$

$$= \ (2-\mathrm{p})(1/\mathrm{W})\Pi_{BO} + \ + (1-\mathrm{p})^2(1/\mathrm{W})\ \Pi_{BO} + \cdots (1-\mathrm{p})^{\mathrm{k}}\ \Pi_k$$

$$= \left(\frac{1}{\mathrm{W}}\right)\Pi_{BO}\left[(2-\mathrm{p}) + (1-\mathrm{p})^2 + \cdots + (1-\mathrm{p})^{\mathrm{k}-1}\right] + (1-\mathrm{p})^{\mathrm{k}}\ \Pi_k$$

$$= \left(\frac{1}{\mathrm{W}}\right)\Pi_{BO}\left[1 + (1-\mathrm{p}) + (1-\mathrm{p})^2 + \cdots (1-\mathrm{p})^{\mathrm{k}-1}\right]$$

$$+ (1-\mathrm{p})^{\mathrm{k}}\ \Pi_k = \left(\frac{1}{\mathrm{W}}\right)\Pi_{BO} + \left[\frac{1-(1-\mathrm{p})^{\mathrm{k}-1}}{\mathrm{p}}\right] + \ (1-\mathrm{p})^{\mathrm{k}}\ \Pi_k$$

$$\Pi_k = \ [\Pi_0 - \left(\frac{1}{\mathrm{W}}\right)\Pi_{BO}\{\frac{1-(1-\mathrm{p})^{\mathrm{k}-1}}{\mathrm{p}}\}]\frac{1}{(1-\mathrm{p})^{\mathrm{k}}}$$

$$\Pi_k(1-\mathrm{p})^{\mathrm{k}} = \ \Pi_0 \ - \ \left(\frac{1}{\mathrm{W}}\right)\Pi_{BO}\ \{\frac{1-(1-\mathrm{p})^{\mathrm{k}-1}}{\mathrm{p}}\}. \tag{3.7}$$

To normalize, we solve Equations (3.6) and (3.7), which is to say we put the value of Π_{BO} from Equation (3.6) into Equation (3.7), and we get:

$$\Pi_k(1-\mathrm{p})^{\mathrm{k}} = \ \Pi_0 - \left(\frac{1}{\mathrm{W}}\right)\{1 - \textstyle\sum_{\mathrm{k}=0}^{\mathrm{W}-1}\Pi_k\}\{\frac{1-(1-\mathrm{p})^{\mathrm{k}-1}}{\mathrm{p}}\}$$

$$\Pi_k(1-\mathrm{p})^{\mathrm{k}} = \Pi_0\{1+\left(\frac{1}{\mathrm{W}}\right)\{\frac{1-(1-\mathrm{p})^{\mathrm{k}-1}}{\mathrm{p}}\}-\left(\frac{1}{\mathrm{W}}\right)\{1\sum_{\mathrm{k}=0}^{\mathrm{W}-1}\Pi_k\}\{\frac{1-(1-\mathrm{p})^{\mathrm{k}-1}}{\mathrm{p}}\}$$

$$\Pi_0 = \frac{\Pi(state\ k)+\left(\frac{1}{W}\right)\{1-\sum_{k=0}^{W-1}\Pi_k\}\{\frac{1-(1-p)^{k-1}}{p}\}}{1+\{\frac{1-(1-p)^{k-1}}{Wp}\}}$$

$$= \frac{\frac{1}{\mathrm{W}}+\left(\frac{1}{\mathrm{W}}\right)\{1-\sum_{\mathrm{k}=0}^{\mathrm{W}-1}\left(\frac{1}{\mathrm{W}}\right)\}\{\frac{1-(1-\mathrm{p})^{\mathrm{W}-1-1}}{\mathrm{p}}\}}{1+\{\frac{1-(1-\mathrm{p})^{\mathrm{W}-1-1}}{\mathrm{Wp}}\}}$$

$$= \frac{\frac{1}{\mathrm{W}}+\left(\frac{1}{\mathrm{W}}\right)\{1-\left(\frac{1}{\mathrm{W}}\right)\sum_{\mathrm{k}=0}^{\mathrm{W}-1}(1)\}\{\frac{1-(1-\mathrm{p})^{\mathrm{W}-2}}{\mathrm{p}}\}}{1+\{\frac{1-(1-\mathrm{p})^{\mathrm{W}-2}}{\mathrm{Wp}}\}}$$

$$= \frac{\frac{1}{\mathrm{W}}+\left(\frac{1}{\mathrm{W}}\right)\{1-\left(\frac{1}{\mathrm{W}}\right)(\mathrm{W}-1)\}\{\frac{1-(1-\mathrm{p})^{\mathrm{W}-2}}{\mathrm{p}}\}}{1+\{\frac{1-(1-\mathrm{p})^{\mathrm{W}-2}}{\mathrm{Wp}}\}}$$

$$= \frac{\mathrm{p}+\left(\frac{1}{\mathrm{W}}\right)\{\frac{1-(1-\mathrm{p})^{\mathrm{W}-2}}{\mathrm{p}}\}}{1+\{\frac{1-(1-\mathrm{p})^{\mathrm{W}-2}}{\mathrm{Wp}}\}}.$$

The transmission probability is given by:

$$\Pi_0 = \frac{\mathrm{p}+\left(\frac{1}{\mathrm{W}}\right)\{1-(1-\mathrm{p})^{\mathrm{W}-2}\}}{1+\mathrm{p}-(1-\mathrm{p})^{\mathrm{W}-2}}, \tag{3.8}$$

where p represents the probability that among the remaining *n−1* sensor nodes, at least one will transmit in a time slot given by $p = 1-(1-\Pi_0)^{n-1}$.

3.3.2. Cycle Probability Model

A cycle can be characterized by the event that happens within the cycle. The events are an idle cycle, a successful transmission cycle, and an unsuccessful transmission cycle/collision cycle. When the sensors have no packet to transmit, it is termed an idle cycle. On the other hand, when one of the sensors, having a packet which requires transmission, attains the channel and transmits the packet successfully, it is called a successful transmission cycle; furthermore, when more than one sensor selects the same back off period and causes an RTS collision, it is termed a collision cycle. We assume that P_{TR} is the probability of at least one transmission of n active sensor nodes in a time slot, P_{ST} is the probability that a transmission is successful, P_{COL} is the collision probability, P_{ID} is the idle probability and P_{SL} is the sleeping probability; these are given as:

$$P_{TR} = 1 - (1 - \Pi_0)^n \tag{3.9}$$

$$P_{ST} = \frac{n\,\Pi_0 (1 - \Pi_0)^{n-1}}{P_{TR}} \tag{3.10}$$

$$P_{COL} = (1 - \Pi_0)^n \sum_{k=0}^{n} \binom{n}{k} (P_{TR})^k (1 - P_{TR})^{n-k} \tag{3.11}$$

$$P_{ID} = \frac{\Pi_0}{P_{ST}} \tag{3.12}$$

$$P_{SL} = (1 - P_{TR})(1 - P_{ID}) \tag{3.13}$$

3.3.3. Throughput Analysis

The throughput *S* is defined as the total time to the time when the channel was used for transmitting the payload bits successfully. The time for the collision, sleeping time, time for the successful transmission and idle time are four fractions of the time when a slot of some random time is chosen. Thus, the throughput expression *S* is given by:

$$S = \frac{P_{tr} P_{ST} E[P]}{(1 - P_{TR}P_{ST} - P_{COL}) + P_{TR}P_{ST}T_{ST} + P_{COL}T_{COL} + P_{SL}T_{SL} + P_{ID}T_{ID}}, \tag{3.14}$$

where E[P] is represented by the average packet payload size. The times T_{COL}, T_{ID}, T_{SL} and T_{ST} are the times for the collision, idle, sleep and successful transmissions for the busy channel, respectively.

3.3.4. Service Delay Analysis

The service delay is a significant measurement in low-rate traffic. The time from the arrival of the packet to the reception of the packet is termed the service delay or packet service time. We show all time consumption in terms of the back off period, which has the following components: 1) T_1, represented as the time taken due to missing the transmission opportunity as a result of sleeping; 2) T_2, represented as the time taken by the node for not capturing the channel and for not being able to successfully transmit during the cycle; 3) T_3, represented as the time taken due to the back off procedure for the successful transmission in a cycle; and 4) T_4 is the time required for a represented transmission. It is assumed that the duration of a cycle is denoted by T_{CL}, the time slot by τ; furthermore, the minimum idle time (threshold) to change the states of the sensor from active to sleep is denoted by T_{A}. Following this, the sleep time of a node can be represented as:

$$T_{SL} = \mathrm{T}_{\mathrm{CL}} - (\mathrm{T}_{\mathrm{TR}} + \mathrm{T}_{\mathrm{A}}). \tag{3.15}$$

Let us define *G*(*z*) as a probability generating function (PGF) of the packet service time:

$$G(z) = \sum_{i=0}^{W-1} P_{TR}\ Z^i + \sum_{i=0}^{T_{ST}} P_{ST}\ Z^i + \sum_{i=0}^{T_{ID}} P_{ID}\ Z^i + \sum_{i=0}^{T_{SL}} P_{SL}\ Z^i \tag{3.16}$$

$$\frac{dG(z)}{dz} = \sum_{i=0}^{W-1} P_{TR}\ i\,Z^{i-1} + \sum_{i=0}^{T_{ST}} P_{ST}\, i\, Z^{i-1} + \sum_{i=0}^{T_{ID}} P_{ID}\, i\, Z^{i-1} + \sum_{i=0}^{T_{SL}} P_{SL}\ i\, Z^{i-1} \tag{3.17}$$

Therefore, the average service delay is given as:

$$\begin{aligned} \mathrm{E}\,(G) = \left.\frac{dG(z)}{dz}\right|_{Z=1} &= \frac{1}{2}[P_{TR}\, W(W-1) + \\ P_{ST}\, T_{ST}(T_{ST}+1) + P_{ID}\, T_{ID}(T_{ID}+1) &+ P_{SL}T_{SL}\,(T_{SL}+1)] \end{aligned} \tag{3.18}$$

3.3.5. Energy Consumption and Power Efficiency

The whole network energy consumption during a cycle is given as:

$$\mathrm{E} = E_{ST}P_{ST} + E_{ID}P_{ID} + E_{COL}\,\mathrm{P}_{\mathrm{COL}} + E_{SL}P_{SL} \tag{3.19}$$

On substituting the values of P_{ST}, P_{ID}, P_{COL} and P_{SL} from Equations (3.10), (3.11), (3.12) and (3.13) in (3.19), the energy consumption E for the whole network can be determined. E_{ST}, E_{ID}, E_{COL} and E_{SL} are the energy consumption in a successful transmission cycle, in the idle state, in collision, and in the sleep state, respectively. The throughput attained per unit of energy consumed is termed as power efficiency and is represented as:

$$Power\ efficiency = \frac{Throughput}{Total\ energy\ consumption} = \frac{S}{E} \tag{3.20}$$

3.4 Experimental Results and Analysis

The analytical results obtained for the proposed analytical model of T-MAC are presented and compared with those of the analytical model of the S-MAC and X-MAC protocols. Furthermore, the analytical results of T-MAC have been validated by conducting the simulation for the T-MAC protocol. The nodes are randomly deployed in the network field, which has an area of 200 × 200 m^2. The number of sensors deployed for this simulation is 50. The radio range of the sensor is assumed to be 50 m. The data packet size is taken to be 512 bits. The packet arrival rate follows the Poison process. The results provide an analysis for the probabilities of a successful transmission cycle, energy consumption, idle cycle, average service delay, throughput, collision cycle, and power efficiency for the different packet arrival rates λ. It is assumed that there are $n = 4$ sensors, contending for the channel access, with a contention window size of $W = 16$. The energy consumed per unit of time for a successful transmission, idle state, collision, and sleep state is assumed to be $E_{ST} = 5$ mJ, $E_{ID} = 0.2$ mJ, $E_{COL} = 7$ mJ and $E_{SL} = 0.04$ mJ, respectively. The time is divided into a number of slots of length $\tau = 10$ s. The cycle length is assumed to be $T_{cl} = 30$ µs. The sensor goes into sleep mode if no event occurred for a certain time of idle listening that assumed to be $T_A = 1$ µs. The average transmission time of the sensors is assumed to be $T_s = 5$ µs. The signal sampling time and rate are assumed to be $T_{sam} = 5$ µs and $R_{sam} = 2$ µs.

Figure 3.2 shows the comparison of the idle probability in a cycle with respect to the different packet arrival rates for the T-MAC, S-MAC and X-MAC protocols. It is observed that for T-MAC, with the increase of the packet arrival rate, the idle probability of a sensor increases very slowly; however, for S-MAC, it decreases sharply. This is due to the fact that the idle listening time for the T-MAC protocol is fixed, which is to say it avoids idle listening during the active time, and the sensor goes to sleep mode if there is no event happening for a certain time of idle listening. In other words, due to the lower idle listening time, the T-MAC protocol has lower energy consumption when compared to the S-MAC protocol. It is seen that the ideal probability of the sensor is lower than that of S-MAC and X-MAC. For example, for the packet arrival rate $\lambda = 0.4$, the idle probability P_{ID} is 0.05 for T-MAC, whereas for X-MAC and S-MAC it is 0.09 and 0.5, respectively.

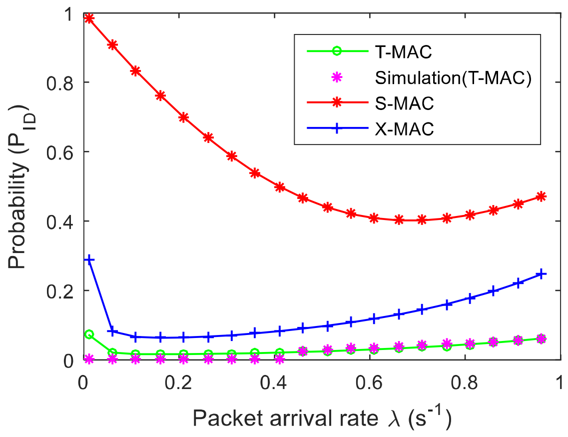

Figure 3.2 The idle probability P_{ID} in a cycle versus the packet arrival rate ⋋ for the T-MAC, S-MAC and X-MAC protocols

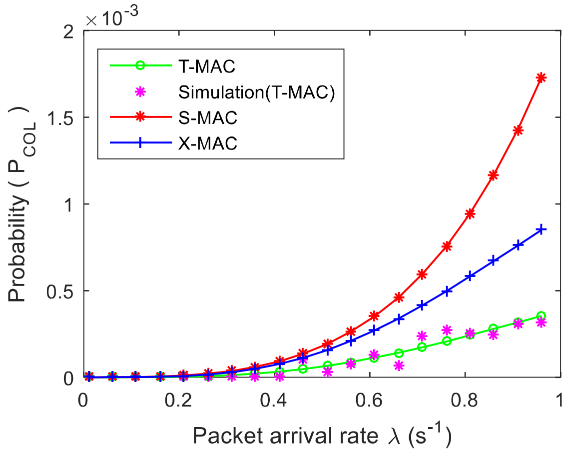

Figure 3.3 The collision probability P_{COL} in a cycle versus the packet arrival rate ⋋ for the T-MAC, S-MAC and X-MAC protocols

Figure 3.3 shows the comparison of the collision probability P_{COL}, with respect to the packet arrival rate ⋋ for the T-MAC, S-MAC and X-MAC protocols. It is perceived that, with the increase in the arrival rate, the collision probability packet also increases for all of the protocols considered for comparison. The collision probability of the T-MAC protocol is much less when compared to the S-MAC and X-MAC protocols. For example, for the packet arrival rate ⋋ = 0.8, the collision probability for T-MAC is 0.00025, whereas for S-MAC and X-MAC, it is 0.001 and 0.00075, respectively. This is due to the fact that for a high packet arrival rate, the active time for T-MAC becomes longer than that of S-MAC and X-MAC. T-MAC sends more data in a successful cycle time, whereas a higher number of successful cycles for S-MAC is required to send the same amount of data. In other words, the number of trials to reserve the medium for S-MAC and X-MAC is higher than for T-MAC.

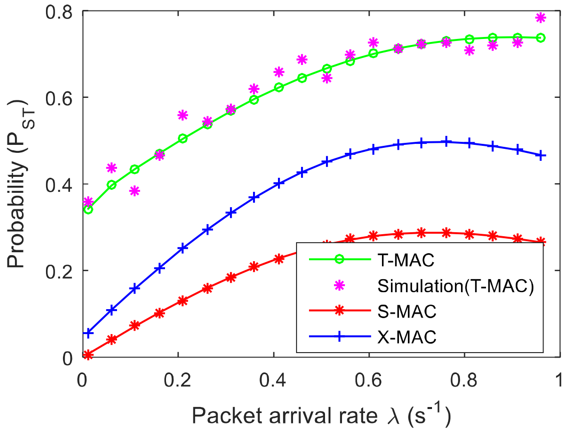

Figure 3.4 The successful transmission probability, P_{ST}, in a cycle versus different packet arrival rates ⋋, for the T-MAC, S-MAC and X-MAC protocols

Figure 3.4 shows the comparison of the successful transmission probability P_{ST}, with respect to the packet arrival rate ⋋ for the T-MAC, S-MAC and X-MAC protocols. The probability of a successful transmission for both of the protocols is directly proportional to the packet arrival rate. The rate of increments in the successful transmissions for T-MAC is higher than that of S-MAC and X-MAC. For example, for the packet arrival rate ⋋ = 0.2, the successful transmission probability for T-MAC is 0.5, whereas for S-MAC and X-MAC it is 0.1 and 0.25, respectively. Similarly, for the packet arrival rate ⋋ = 0.6, the successful transmission probability for T-MAC is 0.7, whereas for SMAC and X-MAC it is 0.23 and0.48, respectively. This is due to the fact that T-MAC transmits a higher number of packets in the active time than S-MAC does.

Figure 3.5 shows the comparison of the T-MAC, S-MAC and X-MAX protocols for the average service delay with respect to different packet arrival rates ⋋ for the T-MAC, S-MAC and X-MAC protocols. It is witnessed in the protocols that the average service delay of T-MAC increases slower when compared with that of the S-MAC and X-MAX protocols for an increasing packet arrival rate λ. For example, for the packet arrival rate $\lambda = 0.2$, the average service delay for T-MAC is 20 s, whereas for S-MAC and X-MAC it is 30 and 125 s, respectively. Similarly, for the packet arrival rate $\lambda = 0.6$, the average service delay for T-MAC is 75 s, whereas for S-MAC and X-MAC it is 110 and 150 s, respectively. This is due to the following reason: the increment in the packet arrival rate increases the active time of a cycle for T-MAC, which ultimately increases the transmission of the packets. Therefore, the average service delay is lower than for S-MAC and X-MAC.

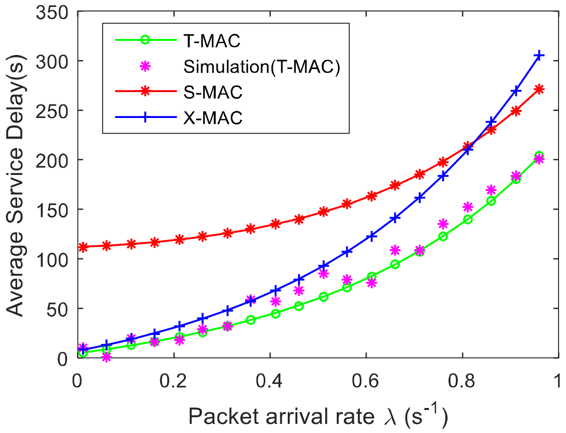

Figure 3.5 The average service delay with respect to the packet arrival rate λ for the T-MAC, S-MAC and X-MAC protocols

Figure 3.6 shows the throughput with respect to the different packet arrival rates for the T-MAC, S-MAC and X-MAC protocols. It is witnessed that before the node becomes saturated for the T-MAC, S-MAC and X-MAC protocols, the overall throughput increments linearly with the packet arrival rate up to 0.2. Thereafter, the throughputs for all of the protocols start decreasing with an increasing packet arrival rate. The throughput of the T-MAC protocol is better than that of the S-MAC and X-MAC protocols. For example, for the packet arrival rate $\lambda = 0.2$, the throughput for T-MAC is 0.25, whereas for S-MAC and X-MAC it is 0.04 and 0.12, respectively. Similarly, for the packet arrival rate $\lambda = 0.6$, the throughput for T-MAC is 0.2, whereas for S-MAC and X-MAC it is 0.09 and 0.12, respectively. This is due to the fact that a higher packet arrival rate increases the active time of a cycle for the T-MAC.

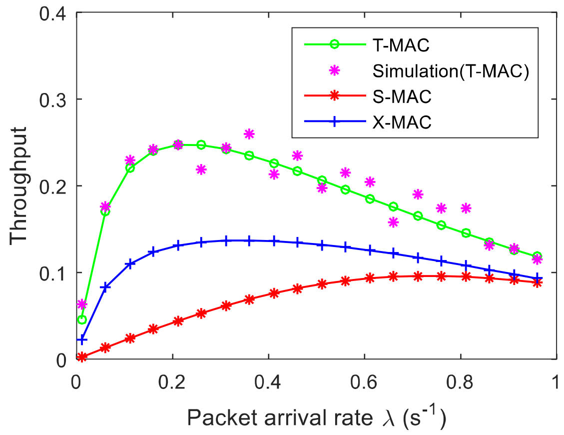

Figure 3.6 The throughput versus packet arrival rate λ for the T-MAC, S-MAC and X-MAC protocols

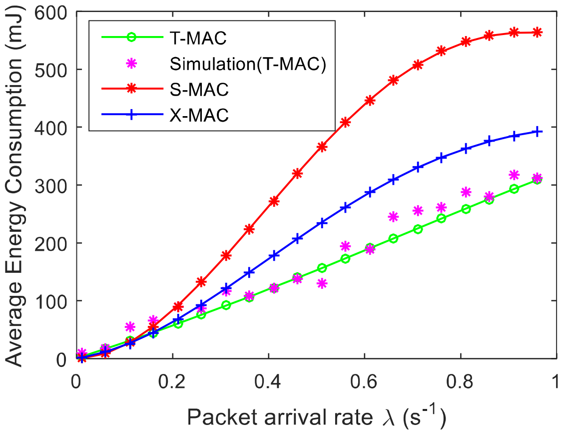

Figure 3.7 The average energy consumption versus packet arrival rate for the T-MAC, S-MAC and X-MAC protocols

Figure 3.7 demonstrates the correlation of the average energy consumption with respect to the packet arrival rate λ for the T-MAC, S-MAC and X-MAC protocols. From Figure 3.7, it is seen that a higher traffic load has induced a larger energy consumption for all of the protocols. However, the T-MAC protocol consumes less energy that S-MAC and X-MAC do. For example, for the packet arrival rate λ = 0.4, the average energy consumption for T-

MAC is 100 mJ, whereas for S-MAC and X-MAC it is 280 mJ and 190 mJ, respectively. Similarly, for the packet arrival rate λ = 0.6, the average energy consumption for T-MAC is 170 mJ, whereas for S-MAC and X-MAC it is 425 mJ and 300 mJ, respectively. This is because the sensors in S-MAC sense the channel throughout the active duration in each idle cycle, which consumes a lot of the protocol's energy. In T-MAC, the idle listening varies with the packet arrival rate. If the packet arrival rate is high, the sensor nodes remain alert in order to deal with the packets.

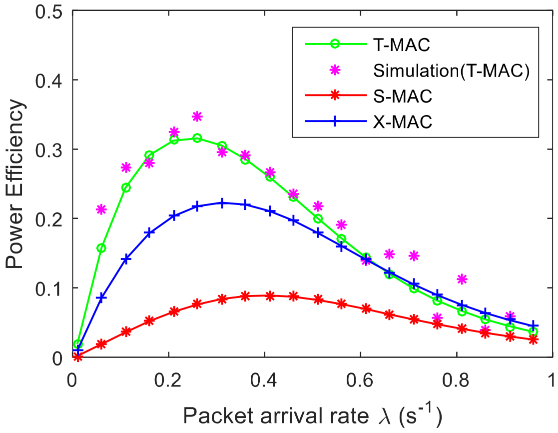

Figure 3.8 The power efficiency for T-MAC, S-MAC and X-MAC protocols versus packet arrival rate

Figure 3.8 shows the comparison of the power efficiency with respect to the packet arrival rate λ for the T-MAC, S-MAC and X-MAC protocols. It is observed in Figure 3.8 that the power efficiency for the T-MAC protocol is better than for the S-MAC and X-MAC protocols. The overall power efficiency increases linearly with the packet arrival rate, up to 0.24. Thereafter, the power efficiencies for all of the protocols start decreasing with an increasing packet arrival rate. The power efficiency of the T-MAC protocol is better than that of the S-MAC and X-MAC protocols. For example, for the packet arrival rate λ = 0.2, the power efficiency for T-MAC is 0.3, whereas for S-MAC and X-MAC it is 0.06 and 0.2, respectively. Similarly, for the packet arrival rate λ = 0.6, the power efficiency for T-MAC is 0.17, and it also equal to that of X-MAC. On the other hand, the power efficiency for S-MAC is 0.08. The power efficiency for all of the three protocols converges to 0.05 for a packet arrival rate of 1. This is because a higher number of packets arriving in the network increases the collisions and consumes more of the nodes' energy in order to reserve the channel. Hence, T-MAC saves more power in comparison to the S-MAC and X-MAC protocols.

3.5. Summary

An analytical model is proposed in this chapter to analyze the performance of the T-MAC protocol under unsaturated traffic conditions. The proposed analytical model is also validated by conducting a simulation. Furthermore, a one-dimensional discrete time Markov queueing model has been presented in order to represent the back-off process of duty-cycled sensor nodes. The probabilities of a successful transmission, collision, and idle state of a sensor node are computed. The $M/M/1/\infty$ model is proposed to analyse the throughput of the T-MAC protocol under unsaturated traffic conditions. The energy consumption model has been presented, using the probabilities of a successful transmission, collision, and idle state of a sensor node. The proposed analytical model is matched with the existing analytical model of the S-MAC and X-MAC protocols. Our analysis shows that the proposed model of T-MAC achieves a healthier throughput and saves more energy than the existing model of the S-MAC and X-MAC protocols.

Chapter 4

Designing Analytical Models for Energy Efficiency Analysis of MAC Protocols

In this chapter, a mathematical model for energy efficacy analysis for different MCA protocols based on current traffic conditions is presented. Specially, we analyzed the performance of different Medium Access Control (MAC) protocols IEEE 802.15.4, and D-MAC with Radio Frequency Identification (RFID) Impulse using the proposed mathematical energy model under variable data rates. Analytical results show that RFID Impulse gives lower energy consumption in comparison to IEEE 802.15.4 and D-MAC in low traffic scenarios.

Further, a novel analytical model for energy consumption based on random radius clustering technique (RRCT) is presented that evaluates the energy consumption for multi-hop WSNs. This chapter analyzed the performance of the proposed model with an energy-efficient clustering system (EECS) protocol. The experimental analysis and analytical results show that the proposed RRCT analytical model saves more energy in comparison to the EECS protocol and so the novel analytical model prolongs the network lifetime.

4.1 Analytical Energy Consumption Model for RFID

4.1.1 Introduction

The efficiency of energy is a crucial task for WSNs as it is very difficult to change the battery and may cost in non-reachable places. Authors have several efforts to make energy-efficient MAC protocols for WSNs, such as low-power wake-up radio protocols [80], and routing protocols [81]. In this chapter, we have introduced; First: The mathematical energy model; Second: Evaluate power consumption of IEEE 802.15.4 and D-MAC with RFID Impulse; Third: Evaluate energy consumption of IEEE 802.15.4 and D-

MAC with RFID Impulse. In the whole energy consumption for every sensor, the major energy consumption component is the radio. So, if a radio is to put in sleep mode during data is not receiving or sending. This leads to energy consumption is reduced. Current MAC used this methodology in which radio sleep mode is static low power mode and it involves energy. But adaptive radio low power is dynamic. It dynamically changes as current traffic conditions in WSNs. Adaptive sleep radio low power mode incorporated with RFID Impulse [82, 83]. The performance is compared with IEEE 802.15.4 and D-MAC. Radio energy consumption, receiving, transmitting, listening, and sleeping excluding switching energy components [84] are evaluated in RFID Impulse. This is appreciable for any protocol that switches nodes between active and sleep modes in low traffic conditions. So proposed mathematical model includes switching energy under adaptive low power current traffic conditions in WSNs. The model improves existing models [85], can be generalized for any MAC. This model evaluates energy consumption for sleep mode configurations under given traffic loads. Analyzed performance of three protocols for sleep mode configuration and determine optimal protocol. Comparison is done with different traffic loads for picking the right MAC. Optimal radio low power mode with RFID Impulse is also determined as data rate varies.

4.1.2 Background

4.1.2.1 MAC

Here, we have studied the three protocols which are IEEE 802.15.4, D-MAC, and RFID Impulse. Taking a combination of these protocols and found out which protocol is better to optimize the energy using low power sleep mode for a given scenario of WSNs. Physical and MAC layers are defined in IEEE 802.15.4[86] for specifying low traffic and energy-efficient WSNs. Since beacon and non-beacon-enabled mode are considered in the MAC layer. In long-standing intensive care applications, beacon enabled mode does not perform well and is overkill. So the focus is only on non-beacon enabled mode. Beacons packets are not broadcasted when we choose only non-beacon enabled this results in IEEE 802.15.4 being reduced to plain CSMA/CA. BE represents several slots in each backoff. BE is binary exponential. Sensors used a back-off mechanism that reduced collisions with variable BE. Initially, the BE of during first 2^{BE}-1=7 time slots to send data. During the time slot R_1 a node performs CCA. Sensor node considers channel is free from carriers if there is no activity in the channel. Now, the sensor node conquer channel for this slot R_1. But, if there is an activity in a channel that is channel is found busy then the node backs off and increases BE by 1 that is BE=3+1. Now the case when the channel is busy, the sensor node selects R_2 time slot randomly during the next 2^4-1=15 time slots. Repeating CCA process if R_2 is also busy, node repeats the process for BE = 5 to select R_3. If R_3 is free, then the node sends its data during the time slot R_3 Otherwise, it falls packet.

In Lu et al [87], the goal of D-MAC is the efficiency of energy and low latency. It is tree-based structured data gathering. In this protocol, time is divided into small slots and runs CSMA with ACK within each slot to transmit/receive one packet. The sensor node periodically executes the basic sequence of ‘1’ transmit, ‘1’ receive, and ‘n’ sleep slots. In the sleeping period, a node turns off its radio to save energy.

4.1.2.2 RFID Impulse

An RFID system consists of two main components: tags and readers. A tag has an identification (ID) number and memory. The readers can read and/or write data to tag via wireless transmission. The communication between tags and readers is of two types one is inductive coupling done by antenna structures, other is propagation coupling done by propagating electromagnetic waves [88]. In the application of RFID, tags are attached with objects that are required to be identified. The RFID is integrated with WSNs. The RFID tags and integrated sensors are attached to the same objects to perform both detecting and sensing tasks. The main goal in designing RFID tags are to lower, power consumption and cost. Tags are usually implemented in hardware. MAC address of a sensor node can be treated and utilized as an ID. But the use of tag IDs instead of MAC addresses is an efficient solution for wireless sensor nodes. When data packets are not sending or receiving then radios, voltage regulators and oscillator are turned off by all sensors in RFID impulse as long as. When the sender receives ACK from the receiver then it initiates the transmission. Once the sender finishes its packet transmissions, it turned off the radio and the receiver also turned off its radio. If the sender does not receive ACK from the receiver then the sender considers that the tag is not detected by signal or signal is very low. So again, the sender sends an RFID wake-up signal, with a maximum of three retries. If any one of three retries is received by the receiver then the sender transmits the data packet. Otherwise, the sender stops its attempts to use RFID wake-up signals to this receiver.

4.1.3 Mathematical Modeling for Energy Evaluation

All energy components are considered to calculate overall energy consumption for MAC (D-MAC, IEEE 802.15.4) and RFID Impulse at sensors Consider all sensors sampled periodically and send data to the base station. Energy consumption was evaluated for a single sampling period.

4.1.3.1 Transmission Energy

Energy spent on the transmission during time T is called transmission energy (E_t). It is directly proportional to the power (P_t) and to the length of the transmission packet (K_t). Hence it is given by equation (4.1)

$$E_t = P_t * K_t \tag{4.1}$$

But, transmission power (P) is given by equation (4.2)

$$P_t = I_t * V \tag{4.2}$$

And, length of the packet (K_t) is given by equation (4.3)

$$K_t = P_{sent} * P_{lengt} \quad * T \tag{4.3}$$

Now, solving three equations (4.2), (4.3) & (4.1) we get:

$$E_t = I_t * V * P_{sent} * P_{lengt} \quad * T \tag{4.4}$$

Where I_t represents is currently drawn by radio in transmitting mode, V indicates voltage, T represents a time for sending one byte on radio, P_{sent} represents packet sent by node and P_{lengt} represents packet length in bytes.

4.1.3.2 Receiving Energy

Energy for packet reception during time T is called receiving energy (E_r). It is directly proportional to the reception power (P_r) and to the length of the packet (K_r). Hence it is given by equation (4.5)

$$E_r = P_r * K_r \tag{4.5}$$

But, reception power (P) is given by equation (4.6)

$$P_r = I_r * V \tag{4.6}$$

And, length of the packet (K) is given by equation (4.7)

$$K_r = P_{recv} * P_{length} * T \tag{4.7}$$

Now, solving equations (4.6), (4.7) & (4.5) we get:

$$E_r = I_r * V * P_{recv} * P_{length} * T \tag{4.8}$$

Where I_r represents current drawn by the radio in receiving mode, P_{recv} represents packet received by the sensor node.

4.1.3.3 Listening Energy

Energy for checking the channel is called listening energy (E_l). In listening mode, the radio will be active even data is not sending or receiving. Listening energy is directly proportional to the sampling interval (S), to the power (P_l) consumed by the radio in listening mode and inversely proportional to the check interval (CK) and time (T_{CK}) during sensor awakes in each cycle. Hence it is given by equation (4.9)

$$E_l = S * \frac{1}{CK} * T_{CK} * P_l \tag{4.9}$$

But, the power (P_l) consumed by the radio in listening mode is given by equation (4.10)

$$P_l = I_l * V \tag{4.10}$$

Now, solving equations (4.10) & (4.9) we get:

$$E_l = S * \frac{1}{CK} * T_{CK} * I_l * V \tag{4.11}$$

Where I_l represents current drawn by radio in listening mode and T_{CK} is time during sensor awakes in each cycle.

4.1.3.4 Switching Energy

Energy for the radio switching from the sleep mode to active mode and active mode to sleep mode is called switching energy (E_{swich}) [9]. Switching energy is given by equation (4.12)

$$E_{swich} = \frac{P_{swich}}{2} * T_{sleep\ mode\ to\ active\ mode} \tag{4.12}$$

But, the power (P_{swic}) consumed from the sleep mode to active mode and the active mode to sleep mode is given by equation (4.13)

$$P_{swic} = \left(I_{active} - I_{sleep}\right) * V \tag{4.13}$$

Solving equation (4.12)&(4.13) we get:

$$E_{swich} = \frac{(I_{active} - I_{sleep}) * V * T_{sleep\ mode\ to\ active\ mode}}{2} \tag{4.14}$$

4.1.3.5 Sleeping Energy

Energy consumed while the node is in a sleep mode is called sleeping energy (E_{sleep}). Sleeping energy is given by equation (4.15)

$$E_{sleep} = P_{sleep} * T_{off} \tag{4.15}$$

But, the power (P_{sleep}) when the node goes into sleep mode is given by equation (4.16)

$$P_{sleep} = I_{sleep} * V \tag{4.16}$$

Putting equation (16) in equation (15) we get equation (4.17)

$$E_{sleep} = I_{sleep} * V * T_{off} \tag{4.17}$$

4.1.3.6 Overall Energy

Summation of all the above energy results in overall energy consumption (E). Hence it is given by equation (4.18)

$$E = E_t + E_r + E_l + E_{swich} + E_{sleep} \tag{4.18}$$

Putting the value of E_t , E_r , E_l , E_{swich} and $E_{sleep}$from equation (4.4), (4.8), (4.11), (4.14), (4.17) in equation (4.18) we get equation (4.19)

$$E = \left(I_t * V * P_{sent} * P_{lengt} \ * T\right) + \left(I_r * V * P_{recv} * P_{length} * T\right) + \left(S * \frac{1}{CK} * T_{CK} * I_l * V\right) + \frac{(I_{active} - I_{sleep}) * V * T_{sleep\ mode\ to\ active\ mode}}{2} + I_{sleep} * V * T_{off} \tag{4.19}$$

Equation (4.19) represents whole energy consumption by a sensor node.

4.1.4 Results and Analysis

Now, we compare the result of RFID impulse with the result of IEEE802.15.4 and the D-MAC protocol created for WSNs. We use simulator MATLAB for WSNs. We consider Mica2 mote sensors for WSNs.

Table (4.1) Model and Simulation parameter

Parameters	Values
Nodes	100

Transmission Range	22m
Band width	350Kbps
Area	1000X500 m^2
Traffic type	CBR
Packet size	250Bytes
Time simulation	700sec

Table (4.1) represents various network parameters and the power consumption parameters of Mica2 mote sensors.

Model outcomes are obtained on the basis of convenient data rates and identify the finest performing protocol for every sensor stage and traffic load to determine the energy consumption. In Figure 4.1, the graph is plotted between the number of receivers and the power (mW). In Figure 4.1, horizontal and vertical lines represent the number of receivers and power respectively. The red, green and blue charts represent the power consumption of RFID impulse, IEEE 802.15.4 and D-MAC respectively. The blue chart shows that D-MAC takes more power for communication and the red chart shows that RFID impulse takes lesser power and green chart shows that the power consumed by IEEE 802.15.4 is in between the power consumption of RFID impulse and D-MAC. So in Figure 4.1, we see that the power consumption of RFID impulse is lesser than the IEEE 802.15.4 and D-MAC. Hence, sensor lifetime is increased.

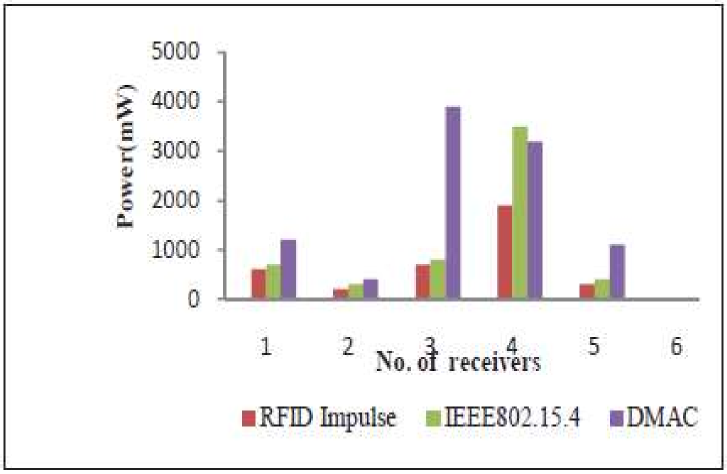

Figure 4.1 Power consumption of RFID Impulse, IEEE802.15.4 and D-MAC

In Figure 4.2, the graph is plotted between the number of receivers and the energy (joules/period). In Figure 4.2, horizontal and vertical lines represent the number of receivers and energy level respectively. The red, green and blue charts represent the energy consumption of RFID impulse, IEEE 802.15.4 and D-MAC respectively. The blue chart shows that D-MAC takes more energy for communication and red chart shows that RFID impulse takes lesser energy and green chart shows that the energy consumed by IEEE802.15.4 is in between the energy consumption of RFID impulse and D-MAC. So in Figure 4.2, we see that the energy consumption of RFID impulse is lesser than the IEEE 802.15.4 and D-MAC. Hence the network lifetime is increased.

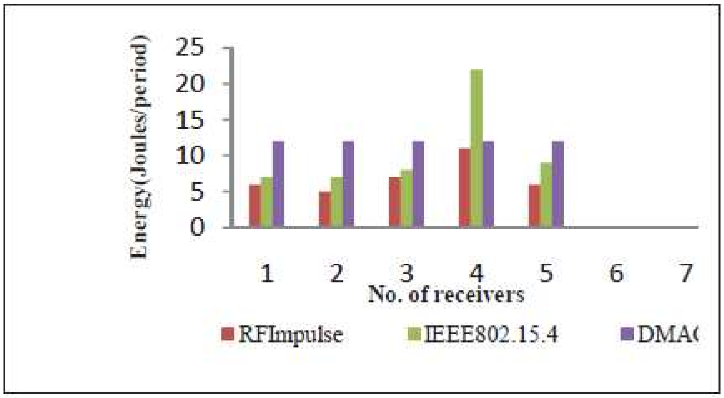

Figure 4.2 Power Consumption of RFID Impulse, IEEE802.15.4 and D-MAC

4.2 Estimation of Energy Consumption for WSNs Using Random Radius Clustering Technique

4.2.1 Background

The present advancement in the microelectronic-mechanical systems, memory, and wireless networking and communication technologies motivates new ideas in the field of wireless sensor nodes [89, 90] and their deployment. The nodes in wireless networks are tiny devices and not so expensive. Some of them are very small that is in the form of dust. It would be extremely hard to detect and destroy for enemies. They majorly comprise four components: sensing module, a processing module, communication module, and power module. There are large sensing devices in the network that are heavily expanded in a field of activity with single or numerous data sinks or base stations. Data sinks or base stations are positioned nearly or indoors the sensing field. Sensor nodes are randomly deployed. So they need self-configured [91, 92, 93]. WSNs have huge appliances in numerous fields such as natural monitoring, object capture and homeland security [94, 95], etc. Sensor nodes are deployed in two ways: planned manner and random manner. In the approachable area where a human can reach, sensors are deployed in well prepared and coordinated aspect. But it is impossible to deploy manually in adverse areas. Therefore, sensors are positioned randomly in the hostile zone [96]. These sensors are operated by limited battery power and left unattended after deployment in a hostile environment. Therefore, energy saving is the main issue to prolong the lifetime of WSNs [89].

In EECS protocol [90], the author has been used periodically data gathering and the cardinal of nodes are fixed for every cluster. There are many issues to become cluster such as the cardinal of clusters in the network, the statistic of nodes in one cluster and which node becomes cluster head in each cluster. We use those sensors as a master node in a cluster that has more surplus energy by using clustering techniques in RRCT model. In this cluster head technique, p be the equal probability for all volunteer sensors to turn out to be cluster nodes. Therefore, the lifetime of sensor node increases through balanced energy consumption. The important factors to optimal clusters are the radius of clusters and the probability with which a node becomes a master node called cluster head in a single or multi-level clustering to minimize the communication outlay for networks.

The proposed RRCT model categorized the sensors into two parts: simple sensors which are the member of clusters called cluster member (CM), cluster head node (CH) and base station (BS). The environment features are sensed by cluster member. Each member of a cluster forwards the gathered information to the CH in their own clusters. Then cluster head node (CH) sends aggregated data to BS. This section presents analytical mathematical modeling based on a clustering algorithm in which random radius technique are considered. The random radius technique optimized the energy consumption for CM, CH and BS. Therefore whole network energy has been optimized. We have compared our proposed technique with the existing technique. The energy consumption in the proposed technique is lesser than that of the existing clustering technique. Therefore our proposed analytical mathematical model outperforms the existing model. The proposed RRCT model consists of two sub-models: 1) transmission energy model, 2) receiving energy model for a sensor node and RRCT algorithm that calculates the average energy consumption in the clusters. Analytically and experimentally determination shows that the suggested analytical model prevents more energy in comparison to EECS protocol. Therefore the novel analytical model increases the network lifetime.

The break of this chapter is structured as pursue: section 4.2.2 presents related work as a review of the literature. Section 4.2.3 presents the analytical energy consumption model. The experimental work and results are included under section 4.2.5. The summary of work is concluded in section 4.3.

4.2.2 Literature Review

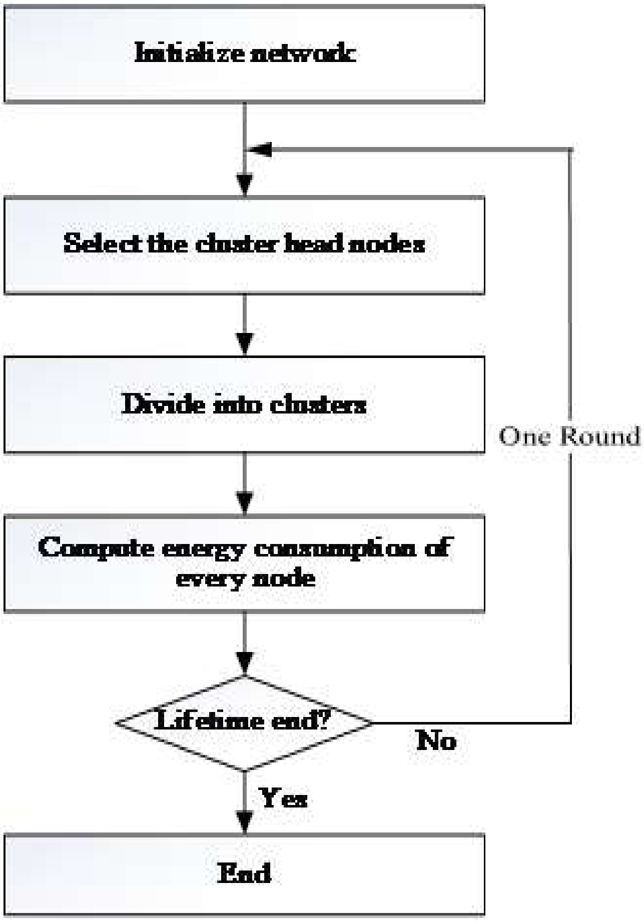

Figure 4.3 LEACH Model proposed [97]

Polastre et al. [97] proposed a protocol named LEACH in which the cluster head gathers data from the sensor device into the cluster and forwards the collected data directly to the sink node. Also, the rotation of a cluster head scheme has been proposed therefore the cluster head node is not fixed. It plays a variable role. It is rotated dynamically among all sensor devices. Therefore, the LEACH protocol improves the energy strength at a high cost because of dynamic clustering. LEACH follows a hierarchy method and arranges sensor devices into clusters. Every cluster sensor proceeds to active to be supposed for the role of a cluster head.

The communication between cluster nodes and cluster-head has been set up via TDMA in LEACH. The base station receives the data gathered by the master node in the cluster which in turn is gathered from the various members of the cluster. TDMA [98] scheme is set up by master nodes to communicate all nodes inside the cluster. TDMA scheme avoids collisions among data messages. The sensor nodes use the TDMA scheme to determine the time slots in their active period. So that the radio components of every cluster node are turned off except the cluster head during the inactive period. An assumption is made in LEACH protocol that n the cluster setup phase is begun at the same time by all master nodes so they are synchronized later. The mechanism to get synchronization is to send out SYNC pulse to nodes by the BS. The inter-cluster interference is reduced in LEACH by using a code assignment schedule based on communication. Sensors communicate to the corresponding cluster head with the help of DSSS. In DSSS, a spreading code is unique to each cluster to use. All sensors nodes forward data to the cluster head with the help of spreading code inside the cluster. Codes are based on first-in and first-served technique that used by cluster heads.

There is another requirement for sensors in the cluster that is the adjustment for their communication potential so that it reduces interference with closest clusters. The master node in the cluster accommodates the data when it receives from the cluster nodes and then forwards it to BS. The cluster head communicates with BS using DSSS code and CSMA code and vice-versa [99]. The cluster head which intends to transmit the data to the BS has to first sense the channel and make sure that the line to BS is not in use by any other cluster.

If the line is found to be busy, then the communication has to be delayed until the line becomes idle.

S-MAC protocol is proposed by authors in [100-101] to minimize energy consumption in WSNs. It uses the technique of scheduling for data transmission and avoids contention in channel. These sensor nodes use the technique of time division multiple access techniques to reduce intra collision among them. So whenever there is requirement of data transmission, these sensor nodes turn on their radio in their allocated slot after that turn off the radio known as the sleep/wakeup process. By default all the nodes in low-duty cycle mode, where sensor nodes are always in sleep state they activate only whenever the network is congested. Hence energy consumption is reduced among nodes that results in overall lifetime of WSNs being improved.

In [102] Kumar et. al proposed a method to minimize energy consumption and balanced the load. In this method, fuzzy logic and the neural network has been fused. ANFCA (adaptive neuro-fuzzy clustering algorithm) technique solves the problem of load balancing and minimizes energy consumption. ANFCA is a hybrid technique in which use fuzzy logic and neural network.

Snag Hyun et. al. [103] proposed a probabilistic routing algorithm for energy efficiency called as EEPR algorithm that is used to decrease the loss of packets and rise the lifetime of the network under the flooding condition. This algorithm (EEPR) simultaneously controls the both Expected transmission count (EXT) metric and residual node energy of each node at the same time for routing metrics. EEPROM algorithm uses the EXT metric for creating the path of routing along with good link value. The residual energy of each node is chosen as a metric for routing the path in the algorithm so that each node exhausted its energy proportionally. Kumar et. al. [104] developed an energy efficiency model used in IoT environment. Categorizations of these techniques are based on various layers of energy architecture of the internet of things. This architecture contains five layers namely sensing, local processing and storage, cloud processing, network/communication, and application layers.

Other than the above techniques there are several other techniques, some are given below Energy efficiency modulation techniques: the proposed EESAC technique minimizes the energy consumption as well as makes the network more robust by rectifying the pipeline leakage issue. The EAWCM algorithm uses the ultra-small node to optimize energy consumption. It designs the cross layer system to optimize the following perimeter carrier frequency, RF/analog/digital and node dimension. The SOT-EENGNM techniques make a relevance which itself configured, optimized, self-healed and organized based upon the network.

4.2.3 Optimal Modeling for Energy Calculation in Multi-Hop Networks

EECS model was based on single-hop network scenarios. In single-hop communication, cluster head directly sends collected data to the base station. In EECS model, every cluster head sends collected data directly to the base station. Therefore there is more energy wastage and cluster head nodes die soon in EECS model. The proposed RRCT model is based on multi-hop network scenarios. In multi-hop network scenarios, cluster head transfer the aggregated data to the next proceeding level. Finally, the cluster head in the last level which is near to base station directly sends collected data to base station. We consider the rectangular area y^2 in network scenario. BS is a base station situated at outside of networks. Let i represent levels in network scenario. Let R_1, R_2, …, R_i in level 1, 2,…, i respectively represent radii of cluster head (CH) shown in Figure 4.4.

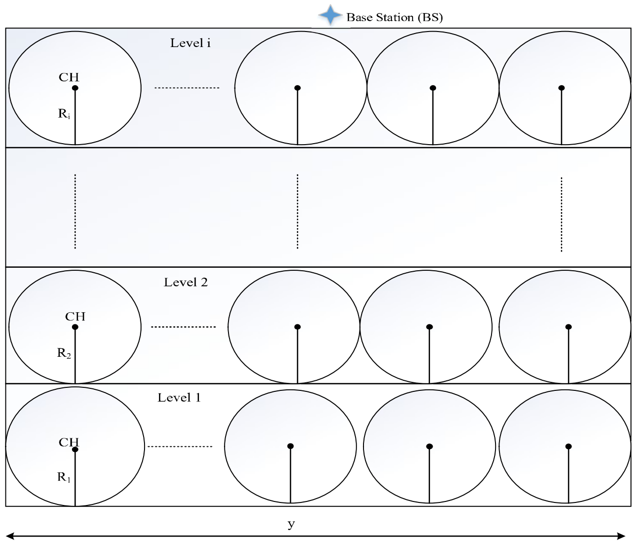

Figure 4.4 Multi-Hop Networks

4.2.3.1 Communication Energy

The energy used on communication at the time T is called communication energy (E_t). It is precisely proportional to the potential (P_t) and to the length of the communication packet (K_t) addicted in equation (4.20).

$$E_t = P_t * K_t \tag{4.20}$$

But, communication potential (P) is shown in equation (4.21)

$$P_t = I_t * V \tag{4.21}$$

And, packet length (K_t) is shown in equation (4.22)

$$K_t = P_{sent} * P_{length} * T \tag{4.22}$$

Finally, substituting the value of P_t and K_t from above equations (4.21) & (4.22) into equation (4.20) we have equation (4.23)

$$E_t = I_t * V * T * P_{sent} * P_{length} \tag{4.23}$$

Here I_t represents current peaked by the radio in communicating mode, V represents the supply voltage, T represents time for dispatching single byte at the radio, P_{sent} represents the packet emitted by node and P_{length} represents packet length in bytes.

4.2.3.2 Receiving Energy

The receiving energy is represented as E_r, consumed in reception of packet at time T. It is precisely proportional to reception potential (P_r) and to length of reception packet (K_t) addicted in equation (4.24).

$$E_r = P_r * K_r \tag{4.24}$$

But, reception potential (P_r) is shown in equation (4.25).

$$P_r = I_r * V \tag{4.25}$$

And, packet length (K_r) is shown in equation (4.26).

$$K_r = P_{recv} * P_{length} * T \tag{4.26}$$

Finally, substituting the value of P_r and K_r from above equations (4.25) & (4.26) into equation (4.24) we have equation (4.27)

$$E_r = I_r * V * T * P_{recv} * P_{lengt} \tag{4.27}$$

Here I_t represents current peaked by the radio in receiving mode, P_{recv} represents packet received by sensor node. Total cluster energy is given by

$$E_{Cluster} = E_{Cluster\ Head} + E_{Cluster\ Member} \tag{4.28}$$

Where $E_{Cluster\ Head}$ and $E_{Cluster\ Member}$ represent the energy of cluster head and cluster members nodes respectively. Let us consider ρ is the nodes density and R_i is coverage radius of the circular region for the ith level of cluster. The energy drain by the cluster head is shown in equation (4.29)

$$E_{Cluster\ Head} = \pi\rho {R_i}^2(E_r + E_t) + \mathrm{s} + \mathrm{q}d^4_{to\ Base\ Station\ or\ to\ the\ \text{next proceeding level}} \tag{4.29}$$

Where s & q are parameter constants associated to node energy bust to run the radio.

The energy consumed by the cluster member is given as:

$$E_{Cluster\ Member} = \pi\rho {R_i}^2(s + qd^2_{to\ Cluster\ Head}) \tag{4.30}$$

Putting equation (4.29) and (4.30) in (4.28) we get

$$E_{Cluster} = \pi\rho {R_i}^2(E_r + E_t) + \mathrm{s} + \mathrm{q}d^4_{to\ Base\ Station\ or\ to\ the\ \text{next proceeding level}} + \pi\rho {R_i}^2(s + qd^2_{to\ Cluster\ Head})$$

If K be the number of the cluster in each level then the energy of ith level is given by

$E^i_{level} = \mathrm{K}.E_{Cluster}$, Where $\mathrm{K} = \frac{2yR_i}{\pi R_j^2}$ has been calculated by geometry

4.2.4 RRCT Algorithm

Step 1: Initially, every node broadcasts the message among them to become cluster head with equal probability p

Step2: Once became a node cluster head the energy drain by Cluster Member in each cluster to send the aggregated data to the cluster is calculated by the the formula

$$E_{Cluster\ Member} = \pi\rho {R_i}^2(s + qd^2_{to\ Cluster\ Head})$$

Step 3: Each cluster head gathers information from all cluster members with receiving energy E_r and transfer the data to the next proceeding level(up to the i-1 the level) or to the base station(at ith level) with transmission energyE_t. Therefore the total energy consumption of a cluster head is calculated by the formula

$$E_{Cluster\ Head} = \pi\rho {R_i}^2(E_r + E_t) + \mathrm{s} + \mathrm{q}d^4_{to\ Base\ Station\ or\ to\ the\ \text{next proceeding level}}$$

Step 4: The total energy consumption of each cluster is the sum of two energy one for the cluster head and other for cluster members as given

$$E_{Cluster} = E_{Cluster\ Head} + E_{Cluster\ Member}$$

Step 5: There are K number of cluster for every level. Therefore the total energy consumption of each level is given by the expression

$$E^{i}_{level} = \mathrm{K} * E_{Cluster}$$

4.2.5 Results and Analysis

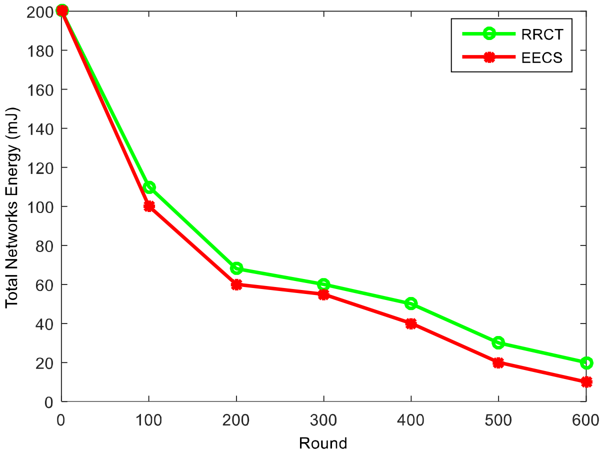

Figure 4.5 Total networks energy (400 Nodes)

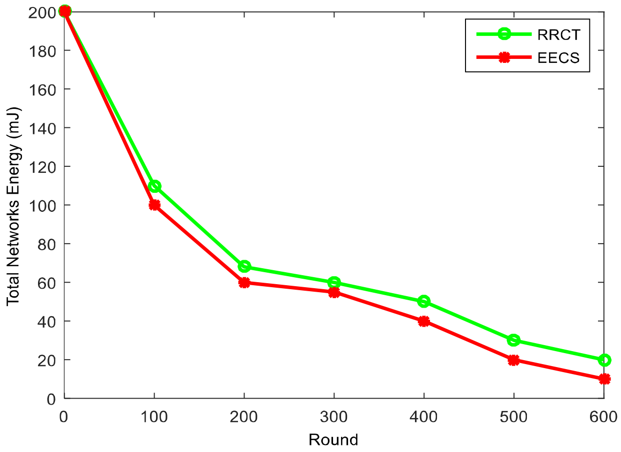

Figure 4.6 Total networks energy (800 Nodes)

The results we have obtained into two networks scenarios in which total networks energy is represented in the graphs, which are then compared and justified. Now we compare the result of RRCT with EECS that build for sensor networks. MATLAB simulator has been used for network scenarios. Mica2 mote sensors are assumed for the networks. The numerous network frameworks and the power expenditure frameworks of Mica2 mote sensor nodes are used in the simulation. Simulation frameworks: Sensors =400,800; Traffic= Constant Bit Rate: CBR; Size of packet =250B; Time=700sec.

Figure 4.5, shows that the 400nodes participating in the network scenarios. The number of rounds represents X- axis and the total networks energy represents Y- axis. The green curve shows the proposed technique RRCT, which shows the efficiency of networks in sense of sending the number of packets as well as the networks lifetime prolonging due to more network energy. Whereas red curve which represents the EECS model, due to fixing coverage radius has less network energy as shown in the comparison. So RRCT is more efficient than EECS.

Figure 4.6, shows that the 400nodes participating in the network scenarios. Here also the graph behaves similar to previous one in the characteristics and also the RRCT curve is above EECS.

Overall in both figures we have to represent the network's lifetime which is depicted in the impression of number of alive sensor nodes. The figures show that RRCT has a longer lifetime in comparison to EECS. More decency in load distribution is gain in the proposed RRCT by using the random completion radii at every level. This is because of using random clusters based on their distance to Base Station. We can also see in both graphs that the Total Network Energy of RRCT is more than EECS at the same round values after some initial values of the round. So the Network lifetime is increased in RRCT.

4.3 Summary

A mathematical energy model to analyze the energy consumption of sensor nodes under variable traffic conditions is developed. In this proposed model, performances of IEEE 802.15.4, D-MAC, and RFID Impulse are analyzed. A comparative study of MAC protocols confirms that RFID impulse consumes lesser energy than IEEE 802.15.4 and D-MAC. Further, the proposed algorithm shows that the energy consumed by each master node in multi-hop networks depends on their distance to the base station at the ith level and to the next proceeding up to i-1 the level. and also on the number of cluster members. On other hand, EECS used fixed competition radii of tentative cluster head nodes which are derived as a function of the distance of a node to Base Station and the next proceeding level cluster head distance. In RRCT, at first, the optimal distance is computed for the farthest level in the network scenarios because farthest nodes died early than any other nodes because they are near to the Base station and most of the time inactivate mode. Then considering the same energy dissipation for each subsequent level, we got the optimal length of the level. The main difference between EECS and the proposed RRCT is that EECS relies on fix competitive radii for tentative nodes whereas RRCT uses the per level energy dissipation to achieve the competitive radii. The proposed RRCT makes the Network lifetime prolonged due to better energy efficiency obtained from using the inadequate clusters. The analytical works show energy consumption is reduced which causes network lifetime and accurate numbers of received data packets to be improved. This work is proposed to be extended to devise a distributed algorithm instead of a centralized algorithm, the futuristic algorithm is expected to be more scalable, fault-tolerant, and suitable for the cluster-based network, comprising of RFID-enabled smart sensors and in turn heavy data. The proposed work can contribute to the emerging field of IoT such as monitoring of battlefield using smart sensors and appliances, agriculture fields.

Chapter 5

Energy Oriented Cross Layer Modeling for Data Dissemination

In this chapter presents a framework for Energy Oriented Cross-Layer Data Dissemination Path (E-CLD2P) towards enabling green computing in industrial wireless sensor network environments. It is a cross-layer design approach considering deployment of sensors at the physical layer up to data dissemination at the network layer and smart services at the application layer. In particular, an energy-centric virtual circular deployment visualization model is presented focusing on physical layer signal transmission characteristics in industrial WSNs scenario. A delay centric angular striping is designed for cluster based angular transmission to support deadline constrained industrial operation in WSNs environments. Algorithms for energy centric delivery path formulation and node's role transfer are developed to support green computing in restricted access industrial WSNs scenario. The green computing framework is implemented to evaluate the performance in realistic industrial WSNs environment. The performance estimations demonstrate profits in terms of number of metrics in realistic industrial constrained environments.

5.1. Introduction

WSNs refer to a big number of interconnected sensors or also referred to as motes, are distributed in a large geographical area to sense and gather physical data. This data will help remote monitoring of the physical parameters under which the sensors are deployed [105]. Some of the applications include remote monitoring of temperature for forest fire detection, environmental monitoring for air pollution of a city, water level monitoring for early flood detection, water quality monitoring for water supply chain, area monitoring for military surveillance, health monitoring for body area network, etc. [106]. There are three main aspects on a typical WSN motes, i) a sensor subsystem to perform the data acquisition

ii) processing unit or microprocessor to perform some preliminary signal processing or data manipulation, and iii) communication subsystem that will send the collected and processed data to the next hop. This next hop can either be a central gateway/base station (BS) or other intermediate motes on the way to the BS [107-108].

The selection of the next hop depends on the underlying routing or scheduling algorithms that are implemented at the communication subsystem of the motes and take into consideration of various metrics including energy efficiency. Since most of these motes are not mains powered and are installed on challenging environments, it is expected that they last for as long as it is viable. When the node dies, it should have minimum impact on the overall network, such that they have self-healing capability or self-organization property. For example, when nodes die in the network, the routing path is updated automatically such that the node at the bottom of the routing chain still finds another optimum path to send the data onto the BS. Therefore, the data dissemination process is a key aspect on the performance of WSN. Careful consideration must be taken while designing the network such that the overall network energy usage is balanced [109], not only some nodes are overloaded and the overall network lifetime is as optimally maximum as possible. While selecting the next hop for a node, various factors are considered, such as location which can be obtained from global position systems (GPS) [110], the energy level at source or receiving node, hop count, interference between neighbouring nodes [108], etc. Various techniques such as cluster formation, chain formation, mobile sink approach, etc. are also employed for energy efficient WSNs [111].

Industrial sensor networks are a special form of WSNs focusing on accuracy and deadline centric communication and computing among the sensors deployed in constrained mechanical environment [112]. Industrial wireless sensor networks come with certain design challenges or issues due to the following reasons. Sensor nodes usually do not have any kind regular human intercession because they are deployed in even non-regularly accessible mechanical environments. Therefore, the sensor network must have self-organizing and parameter optimization capabilities [113]. Hence the setup and maintenance of the industrial sensor network should be autonomous as much as possible. Sensor nodes should be able to coordinate their actions with each other, so that the ordering of detected events can be performed without any uncertainty in computing and communication in industrial environments [114]. One of the critical challenges for WSN environment is the design and implementation of green computing algorithms such that the overall network utilizes absolutely minimum energy without compromising on the accuracy on the computation. This is because most of the times, the nodes are installed on harsh environments and thus powering by mains, changing batteries or recharging the batteries may not always be possible. Therefore, on such optimization algorithms, implementations should reduce any network overhead while transferring data from one node to the other, reduce computational complexities and apply lightweight cryptographic solutions without impacting accuracy in mechanical centric computations [115].

Depending on the use cases, there might be requirements to add more motes on to the network or removal of the motes for example because of node deaths. Therefore, in such circumstances, the network should be adaptable to support either the enlargement or reduction of the density of the network. The overall system and the protocols must be designed such that change in the nodes location or numbers do not ultimately have any effect on the clustering, routing or scheduling algorithms responsible for energy optimization characteristics [116]. The system should be self-adaptable to the newer topology and thus self-healing. This will provide stability to the network in terms of green communication and computing point of view. In the situation of added nodes where more data will be flowing within the network, ultimately increasing the volume of data transfer. This should be managed in such a way that intelligent data aggregation and redundancy checks are performed such that minimum number of messages needs to be exchanged collectively among the sensor nodes, and thus battery and energy are preserved prudently [117]. The communication over sensor networks must be made secure however the challenge is cryptographic since any high level of security will require energy high computation requirements. Thus, green communication and computing is one of the major challenges in industrial sensor network environments considering highly accurate and deadline driver secure communication requirements [118]. In this context, this chapter presents green computing framework for industrial wireless sensor network environments focusing on energy centric modeling for data dissemination. It is a cross layer design approach considering deployment of sensors at physical layer up to data dissemination at network layer towards smart services at application layer.

The contributions of the chapter can be summarized in following major folds.

1) Firstly, energy centric virtual circular deployment visualization model is presented focusing on physical layer signal transmission characteristics in industrial WSNs scenario.
2) Secondly, delay centric angular striping is designed for cluster based angular transmission to support deadline constrained industrial operation in WSNs environments.
3) Thirdly, algorithms for Energy Oriented Cross Layer Data Dissemination Path (E-CLD2P) formulation and Cross Layer communication oriented Data Dissemination (CLDD) have been developed towards enabling green computing in constrained access industrial WSNs scenario.
4) Finally, the green computing framework is implemented to evaluate the performance of E-CLD2P and CLDD in realistic WSNs environment and is compared with the state-of-the-art techniques.

The rest of this chapter is organized as follows. In section 5.2, background in industrial WSNs is critically explored with different communication architecture in industrial scenario. Section 5.3 details the proposed green computing framework for industrial WSNs environment focusing conceptual and mathematical modelling. The experimental discussion is presented in section 5.4, followed by summary presented in section 5.5.

5.2 Background

A channel switching based spectrum sharing strategy has been suggested for industrial networking scenario [119] It has focused on optimizing spectrum utilization considering densely deployed wireless networking devices in industrial environments. A maximum possible spectrum sharing ratio among available devices has been defined. This definition is further enabled by a set of rules for spectrum sharing as Local Equilibrium Quality for Autonomous Channel Switching (LEQ-AutoCS). Although the local industrial networking scenario centric channel sharing enhances channel utilization, yet the definition of LEQ could not be generalized for dynamic network density in industrial environments. A green industrial networking framework has been explored focusing on reducing energy consumption and delay in industrial communications [120]. Considering the dense sensor network scenario, a framework of Wireless Computing Systems (WCS) has been developed as fog nodes in industrial networking environments. These fog nodes have been utilized for energy-oriented communication and delay centric forwarding of information towards centralized cloud processing framework. A tradeoff between the energy consumption and delay has been effectively optimized for industrial networking environments. However, the green communication framework lacks data prioritization aspects particularly for processing higher valued industrial information in the edge computing environments. A security focused architecture Flexi Cast has been suggested for industrial networking considering software integrity and energy consumption [121]. The architecture has focused on the communication for software update in sensor nodes from server. Towards effectively validating these updates considering integrity and energy as major parameters, an authentication process has been developed for all nodes as network wide scalable architecture. However, the security architecture lacks the cross-layer modeling approach for dense industrial networking scenario. The Connected Target Coverage (CTC) techniques have be critically implemented in industrial networking scenarios focusing on energy consumption [122]. Specifically, greedy coverage, heuristic, overlapping target, and cover sets has been investigated considering energy efficiency centric target coverage. The analysis framework considered range of network related metrics including network lifetime, energy consumption, and coverage time, ratio of dead nodes or nodes without energy to working nodes. However, the analysis did not consider industrial network scalability or network density while evaluating the performance in industrial environments. Another green computing framework for industrial networking has been explored considering petroleum refinery environments as a case study [123]. Focusing on frame-level energy optimization, a new frame structure has been designed for optimizing energy consumption on Wireless Highway Addressable Remote Transducer (WiHART) enabled ISA100.11a protocol. It has focused on frame-level energy optimization rather than bit-level for harnessing the energy benefits in terms of real industrial network condition and compact time division multiple accesses based scheduling. Although the energy optimization has been improved for realistic petroleum refinery industry, yet the framework could not be generalized for other industrial environments due to the chip-level based frame design. In other words, the development is too domain centric advancement for petroleum industry networking environments.

Towards targeting reliability and deadline driven communication for industrial networking, flooding based routing protocol has been improved focusing on the benefits of flooding in dense sensor network scenario [124]. The protocol has specifically enhanced the network management and network maintenance focusing the industrial scenario requirements. Although the enhancement in flooding centric protocol has improved reliability and reduced the delay in communication, yet the lack of energy consideration in routing decision reduces wider application of the protocol in range of industrial scenarios. Towards Energy Efficient Routing Protocol (EERP) for application specific industrial micro-sensor networks, architecture for lower energy centric adaptive clustering with hierarchical (LEACH-C) network management has been suggested [125]. The energy efficient cluster centric routing enabled by media access control has been effectively redeveloped considering industrial micro sensor network environment and related application domains. Data aggregation has been applied for application centric performance enabling in micro sensor environments. Benefits of LEACH including distributed clustering and self-network management have been basically utilized for dense micro sensor network environments. Towards enabling green computing in mobility centric networking environments, an Energy consumption-based improvement of Temporary Ordered Routing Algorithm (E-TORA) has been explored [126]. It has focused on hop count and residual energy based green computing for sensor network environment with mobile devices and Base Stations (BS). However, the green computing framework might have reduced impact on industrial networking scenarios as the changes of hop count is very limited in densely deployed networking environment. Data aggregation centric green computing frameworks has been suggested for densely deployed sensor networking environments [127]. It has focused on reducing information to be transmitted among sensor nodes considering appropriate data aggregation points in the networks, data aggregation function and the density of nodes in the networking environments. The data aggregation-based framework has considered optimal selection of number of data aggregation points and their locations for reducing energy consumption in communication and computation in the networking environments. It has basically integrated Virtualization based networking with Genetic Algorithm (VGA) oriented optimization technique for network parameter maximization. However, the framework for data aggregation is very general without considering the quality data from sensors specific in the network as Local Aggregator (LA) and a Master Aggregator (MA). Similar green computing framework has been explored considering Power Efficient and data Gathering approach for different types of Sensor based Information Systems (PEGASIS) [128]. The specific Geographic location of sensor centric Energy Awareness in the network for information Routing (GEAR) has been investigated as another green computing framework for sensor enabled networking environments. However, these green computing frameworks lacks reliability and deadline driven communication significant for industrial networking environments. In [129], authors have suggested how to estimates the number of sensor nodes and their radio ranges to achieve full coverage. Furthermore, waiting time estimation for a sensor which is already disjoined the network to rejoin network to get good balance of energy among the sensors. In [130], authors have proposed energy efficient virtual multiple-input multiple-output for renewal of sensor battery in the present of attackers in 5G centric environment. In [131], authors proposed ant colony based security aware energy efficient secure routing (SASR) which balance the energy consumption of the sensors to improve the network lifetime. In [132], a quantum based ant colony optimization method for green communication to fairly equalized energy consumption among sensors is suggested. In [133], authors proposed energy efficient trust evaluation using game theory to detect the malicious nodes in the network. The activity-based trust dilemma game has been employed to launch the anomaly detection method which assists in alleviation of untrustworthy nodes. Author in [134] proposed an energy balanced model (EBM) which fairly equalized energy consumption of the sensors to enhance the lifetime of the sensor network in [134]. The density of the sensors are calculated which is to be deployed in the network area to provide full coverage and connectivity among the sensor.

Table (5.1) Comparison of green computing techniques in industrial WSNs

Scheme	***Category***	***Advantages***	***Drawbacks***	***Scalability***	***Mobility***	***Robust***
LEACH [124]	Green computing	Energy centric clustering	Clustering overhead	LOW	static	High
LEACH-C [125]	Green computing	Energy centric clustering and routing	Clustering and routing overhead	HIGH	static	High
E-TORA [126]	Routing	Energy centric routing	Multicasting	Medium	Dynamic	High
VGA [127]	Geographic	Network scalability and optimization	NP- hard graphical network modeling	LOW	Dynamic	low
PEGASIS [128]	Geographic	Data quality centric information gathering	Geographical networking information management overhead	HIGH	static	low
GEAR [135]	Geographic	Optimal network lifetime	Geographical networking information management overhead	Medium	static	low

5.3 Energy Oriented Cross Layer Data Dissemination for Industrial WSNs

There are many research challenges coupled with WSNs in industrial environments rising from restricted capabilities of low price sensor node hardware and the common requirement for nodes to operate for long time periods with only a small battery. The higher volume of computation with accuracy requiring in industrial scenario is also significantly challenging particularly with limited energy constraint. The untended nature of sensor nodes in potential risky sensing environments restricts battery replacement as a feasible solution in industrial WSNs environments. The distributed nature of wireless sensor networks makes energy-efficient modelling in industrial environments specifically challenging. There are unique problems attached with industrial WSNs such as self-configuration, network discovery, medium access control and multi-hop routing where microscopic study of energy utilization can be done and novel schemes can be developed for saving energy in WSNs. Energy efficient routing is one of main contributor towards the aim of efficient use of energy in wireless sensor networks which ultimately increases lifetime of the network. The proposed scheme, clustering coupled with striping and sectoring is also a step towards minimization of operational cost of industrial WSNs in terms of energy. The proposed scheme is based on following main concepts.

5.3.1 Energy Centric Virtual Circular Deployment Visualization

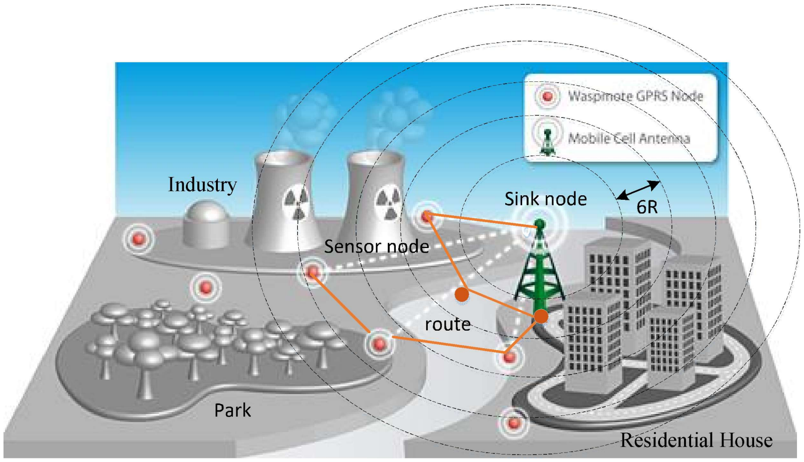

Figure 5.1 Division of RoI into circular strip

The Region of Interest (RoI) is precisely divided into number of circular strips. The width of each circular stripe is taken as six times of sensing range ie. 6R, where R is the sensing range. The aim of this division is to ensure single sensor on both sides of our aimed Energy oriented Cross Layer Data Dissemination Path (E-CLD^{2}P). This will significantly reduce the power consumption because no sensors need to forward sensory data of more than three sensors. Means that all the sensors which fall into E-CLD^{2}P or works as hope of E-CLD^{2}P, need to forward their own sensory data plus two neighbor sensors data which falls on both sides of their own. This conceptual idea can be easily visualized in the Figure 5.1.

We have analyzed the impact of circular striping in power requirement for transmission. According to two way path loss model, the received power can be calculated as

$$P_r = P_t \left[\frac{\sqrt{G_l} h_t h_r}{d^2}\right]^2 \tag{5.1}$$

where, P_r is received power, P_t is transmitted power, G_l is antenna gain, h_t is height of transmitter antenna, h_r is height of received antenna and d is the distance between transmitting and receiving devices. Suppose, we fix the received power to as minimum as required for the information exchange then the transmitted power requirement will be

$$P_t = \frac{P_r}{\left[\frac{\sqrt{G_l} h_t h_r}{d^2}\right]^2} \tag{5.2}$$

After removing the constants,

$$P_t \propto d^4 \tag{5.3}$$

Here in our circular striping concepts, we actually divide the actual distance d into number of smaller distances as $d_1, d_2, d_3 \ldots. d_n$and each $d_i \ll d$. Therefore

$$P_{ts} \ll P_t \tag{5.4}$$

Where, P_{ts} is the transmission power requirement after circular striping and P_t is the transmission power requirement in the general case. The power requirement for transmission will decrease with number of strips. In the proposed industrial WSNs scenario, the industrial region of interest is divided into circular transmission strips. The power requirement for transmission will reduce with a greater number of circular transmission strips considering the smaller width of those strips.

5.3.2 Delay centric Stripping for Cluster based Angular Transmission

The circularly striped RoI is further divided into a number of sectors. Each sector is supposed to have its own E-CLD^{2}P. The reason behind this sector division is to fulfill aimed end-to-end delay during the routing of sensory data. As soon as the number of sector will increase the end-to-end delay will decrease because with increasing number of sectors the probability of having straight E-CLD^{2}P will increase and length of E-CLD^{2}P will decrease. This conceptual idea can be easily visualized in the following Figure 5.2.

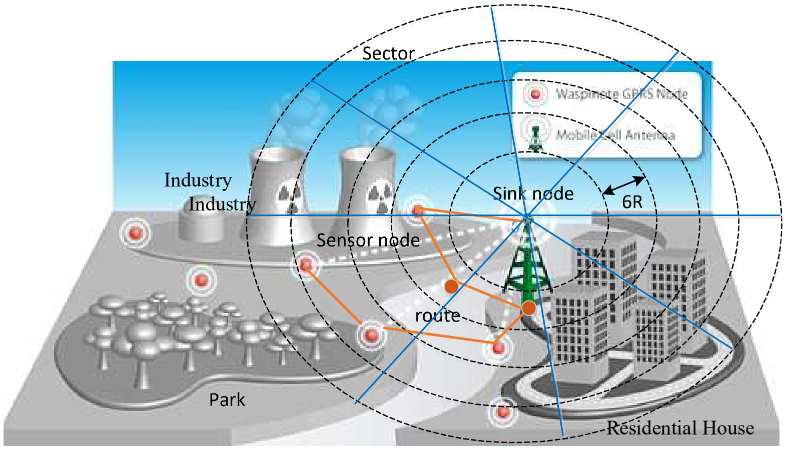

Figure 5.2 Sector composition from circularly striped RoI

We have analyzed the impact of sectoring into end-to-end delay which indirectly reduces power consumption also. Suppose we have s sensors in our RoI with total area a_t. After each sectoring step, each sector area is divided into two equal parts. It means, after Nth sectoring the complete RoI is divided into 2^N number of equal sectors.

This sector area reduction can be indirectly seen as number of sensor reduction which falls into exactly a single sector. After N^{th} sectoring the number of sensors in each individual sector will be $\frac{S}{2^N}$ which is quite smaller than S.

Let the sensors are normally distributed with average inter sensor gape g. The length of E-CLD^{2}P, l_{E} will be

$$l_{\mathrm{E}} = sg \tag{5.5}$$

After N^{th} sectoring, the length of E-CLD^{2}P after sectoring l_{ES} will be

$$l_{ES} = \frac{sg}{2^N} \tag{5.6}$$

From equation (5.5) and (5.6),

$$l_{ES} < l_E \tag{5.7}$$

Note: Length of E-CLD^{2}P will depend on number of sectoring.

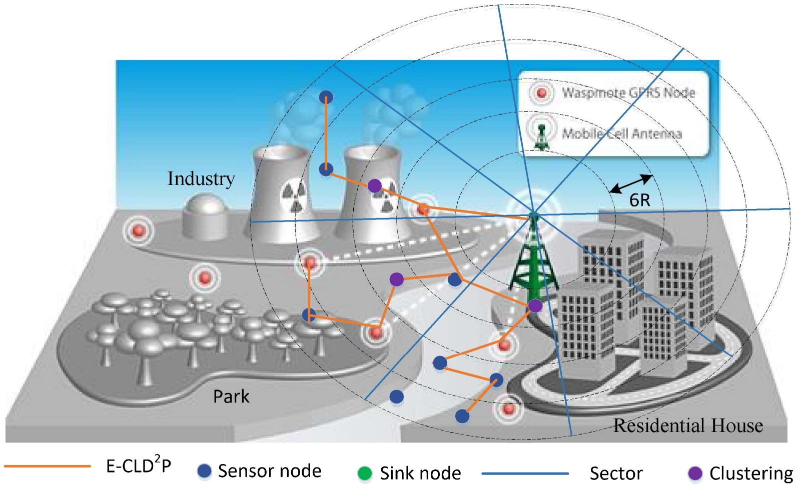

Figure 5.3 Efficient clustering of the nodes inside each sectors

Once the sectoring has been done for the networks, we proceed with clustering of sensors inside each sector. The two parameters used for clustering i.e. cluster head selection are degree of one-hop connectivity and residual energy. Degree of connectivity has been used due to the fact that the sensor having more number of neighboring sensors can be relaxed from sensing task and lesser transmission energy is required during data transmission to cluster heads. Moreover residual energy is another parameter having well known significance in cluster head selection. An example of the proposed clustering has been shown in above Figure 5.3.

5.3.3 Energy Oriented Cross Layer Data Dissemination Path Formulation

The sensors of each sector form a virtual group and are unaware of the presence of other sector's virtual group. The sink is connected through nearest single sensor of each sector. The E-CLD^{2}P starts from the sink and moves towards outer strip by strip using the density information available with each sensor. Each sensor contains the density information of its own sector only. In this way the E-CLD^{2}P is formalized and all the sensors of a particular sector have ECDP information. Whenever a sensor has sensory data, it strictly follows the E-CLD^{2}P to send it to sink. For creation of the path, the sector information is integrated with other information during neighborhood search through HELLO packets. In the following we have presented an algorithm for E-CLD^{2}P formation.

Algorithm 1: Energy Oriented Cross Layer Data Dissemination Path (E-CLD^{2}P)

Notations

NHS: Next Hope Sensor
$HELLO - SI$: Hello packet by sink
$HELL - SSS$: Hello packet by sensor integrated with sector and strip information
$REP - S$: REP packet integrated with sector number
$REP - SS$: REP packet integrated with sector number and strip number.
SEC: Sector
CST: Circular strip

Input RoI, SEC, CST

Process

```
Sink sends $HELLO - SI$ to all its neighbors
All neighbors reply by $REP - S$
For each SEC
    If(more than one $REP - S$)
        Calculates reception time of each $REP - S$
        Selects a sensor as $NHS$ which has shortest reception time
    Else
        Selects the sensor as $NHS$
    Endif
Endfor
For each $SEC$
    For each $CST$
        Sensor sends $HELLO - SSS$ to all its neighbors
        All neighboring sensor reply by $REP - SS$
```

```
15.         The sensor having maximum number of $REP - SS$ is chosen
              as $NHS$
16.     **Endfor**
17. **Endfor**
**Output** E-CLD$^2$P
```

Description of E-CLD^{2}P *Algorithm:*

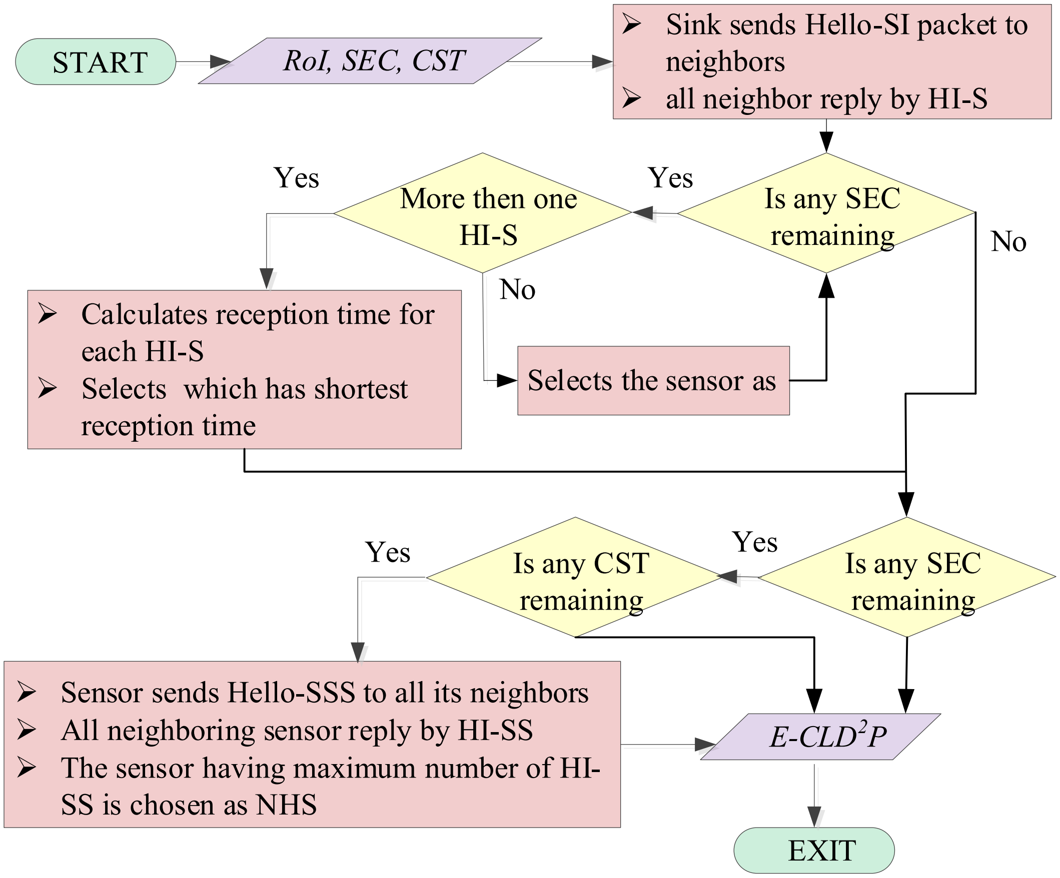

Figure 5.4 A complete flowchart of energy centric delivery path formulation

The above presented seventeen step algorithm is the formation steps of an energy efficient path. It starts from the sink node in the 1st step which sends $HELLO - SI$ to all its neighbors. In the 2nd step, all neighbor nodes of sink reply by $HI - S$ packet which is integrated with sector information. The steps 3-10 are responsible for selecting single node from each sector which is directly connected to sink node. This is done by calculating reception time for each neighboring nodes if a particular sector has more than one node near sink. The steps 11-17 are responsible for establishing E-CLD^{2}P for each strip inside each sector. This is done by sending $HELLO-SSS$ packet to all its neighbors who is replied by $HI-SS$ packets integrated with sector and strip information. At each node the sensor having maximum number of $HI-SS$ packets is chosen as NHS. In this way the complete E-CLD^{2}P is formulated.

Complexity Analysis of the Algorithm

The execution complexity of the algorithm can be done considering the number of angular sectoring m and circular stripping n. The computation in steps 1 and 2 are constant and steps 3-10 are executed in $O(m)$. Further, the execution in steps 11-17 is of $O(m \times n)$. Therefore, the overall complexity of the algorithm can be represented as $O(m \times n)$.

5.3.4 Cross Layer Communication oriented Data Dissemination using E-CLD^{2}P

After clustering has been performed in the network, the usual way of routing is through cluster heads. This way of routing has a significance drawback in terms of network failure once the cluster heads exhaust their energy. The fundamental way to handle the shortcoming is by using time slot-based cluster head selection. The time slot-based cluster head selection has its own drawback in terms of control packet overhead. In this section, we have used role transfer scheme to rotate cluster head. In cluster head role transfer scheme, once the residual energy of cluster head goes below the average residual energy of sensors in the cluster, the cluster head selects best sensor to transfer the role of cluster head. This way we maintain the residual energy of each sensor in each sector. The last functional module of this work is routing of sensed data by using either Energy Efficient Path Information (EEPI) of E-CLD^{2}P or Energy Efficient Sectoring and Clustering Information (EESCI). A complete energy efficient routing algorithm has been provided below.

Algorithm 2: Cross Layer communication oriented Data Dissemination (CLDD)

<u>Notations</u>

```
        $CFN$: Current Forwarding Node
        $SI$: Striping Information
```

SCI: Sectoring Information

CI: Clustering Information

$EEPI$: Energy Efficient Path Information

$EESCI$: Energy Efficient Sectoring and Clustering Information

SCH: Set of Cluster Head

NCH: Next Cluster Head towards sink

CH: Cluster Head

$SINK$: Sink

<u>Input</u> $SI, SCI, CI, EEPI$

<u>Process</u>

```
1.  $CFN$ receives a Data Packet  for forwarding
2.  If($CNF \in SCH$) // subset of
3.       Compute EESCI // cluster head with energy more than average of all the cluster's sensors
4.      forward Data Packet  to $NCH$ by using $EESCI$
5.  else
6.      Compute EEPI // average energy of all sensors in the path
7.      forward Data Packet  to $CH$ by using highest $EEPI$
8.  If ($NCH$ is $SINK$)
9.     exit
10. else
11.        $NCH = CFN$
12.        repeat step 1-11
13. if($CH$ is $SINK$)
14.    exit
15. else
16.    $CH = CFN$
17.     repeat step 1-17
```

Output: Data Packet reached to $SINK$

5.4 Results and Discussion

In this section, performance analysis of the proposed framework for Energy Oriented Cross Layer Data Dissemination Path (E-CLD^{2}P) towards enabling green computing in industrial wireless sensor network environments has been carried out by writing own simulation script in ns-2. We assumed the network area of size 1000x1000m^2. We deployed 100 to 500 sensors randomly in the network area where we assume 250m transmission range of the sensors. The details of specific network simulation parameter setting and their specific values are presented in Table 2. Basically, there four types of major software components in the simulator. The Tcl scipt is the main network configuration platform where the network environment has been implemented. It is enabled by the protocol implementation on different library files where the routing and green computing framework has been implemented. The library files were actually utilized in the Tcl script of simulation implementation. The results of execution were generated as output files which must be processed for data analysis and putting them as graphical results. In the simulator library, major components include scheduler for different events, objects as components and network setting modules.

Table (5.2) Basic simulation parameters with their values

Simulation Parameters	Values
Simulation Area	1-5 Km^2
Number of sensors	100-500 and 1000
Transmission Range	250m
Packet Size	512 byte
Traffic Type	CBR
MAC Protocol	802.11, DCF
Routing Protocols	D-EER
Antenna Model	Omni direction

5.4.1 Experimental Results and Performance Analysis

The results in Figure 5.5 show the energy consumption in routing as a function of number of sensors deployed in region of interest. It clearly indicates that our circular striping and sectoring concepts reduce the energy consumption significantly. This can be attributed to the fact that our striping and sectoring concepts (SS) efficiently formulate the E-CLD^{2}P that is used in forwarding. More specifically, the percentage reduction in energy consumption is 24% for the network with 100 nodes whereas the reduction further increases up to 28% for the networks with 450 nodes, and 34% for the network with 500 nodes. Therefore, it is noticed from the analysis that the proposed E-CLD^{2}P performs better energy saving as compared to the literature due to the circular scripting centric industrial WSNs framework.

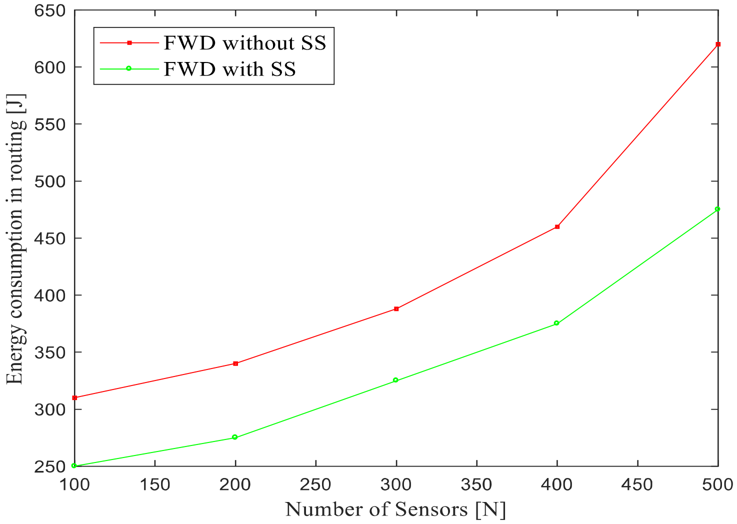

Figure 5.5 Energy consumption versus number of sensors

The results of Figure 5.6 show the energy consumption in routing as a function of number of Size of region of interest (RoI). It clearly indicates that our circular striping and sectoring concepts reduce the energy consumption significantly. This can be attributed to the fact that even with larger RoI our SS concepts perform efficiently. In particular, the percentage reduction in energy consumption is 32% for 2 Km^2 RoI whereas the reduction further increases up to 38% for 3 Km^2 RoI, and 42% for 4 Km^2 RoI. Therefore, it is evident from the analysis that the proposed E-CLD^{2}P is better in saving energy as compared to the literature considering its striping and sectoring centric industrial WSNs framework.

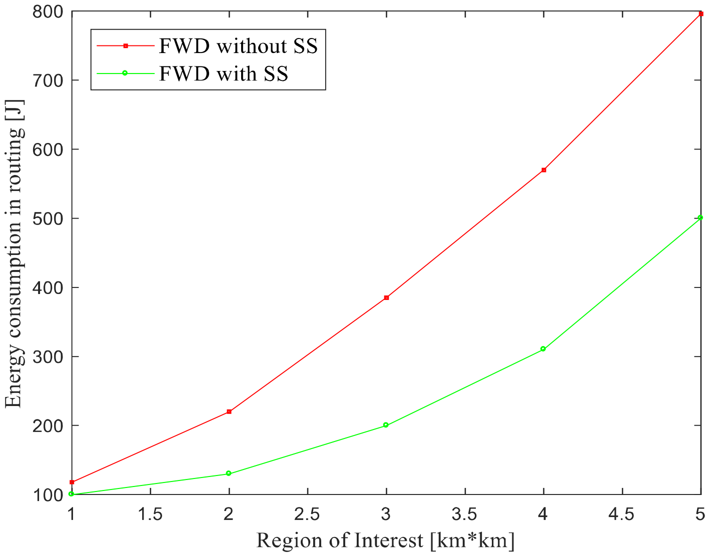

Figure 5.6 Energy consumption versus region of interest

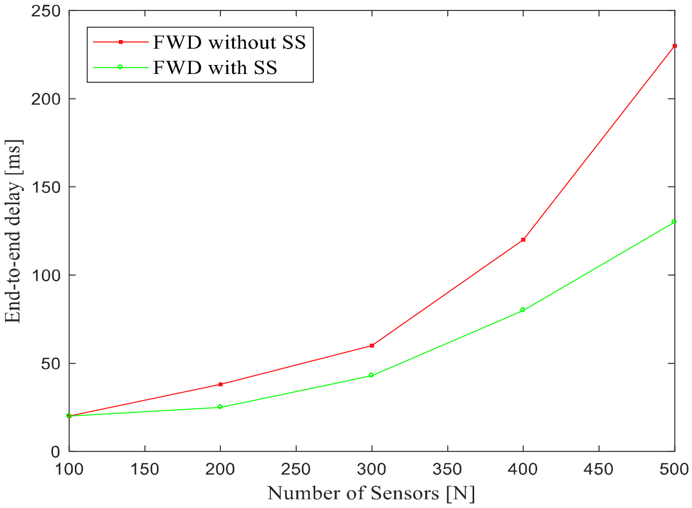

Figure 5.7 End-to-end delay versus number of sensors

The results of Figure 5.7 show the end-to-end delay as a function of number of sensors deployed in region of interest. It clearly indicates that our circular striping and sectoring concepts reduce the end-to-end delay significantly. This can be attributed to the fact that our SS concepts reduce the length of E-CLD^{2}P indirectly minimizing end-to-end delay. More specifically, the percentage reduction in end-to-end delay is 13% for the network with 200 nodes whereas the reduction further increases up to 32% for the networks with 400 nodes, and 42% for the network with 500 nodes. Therefore, it is evident from the analysis that the proposed E-CLD^{2}P outperforms the literature with lesser end-to-end delay as compared to the literature due to the angular sectorial centric industrial WSNs framework.

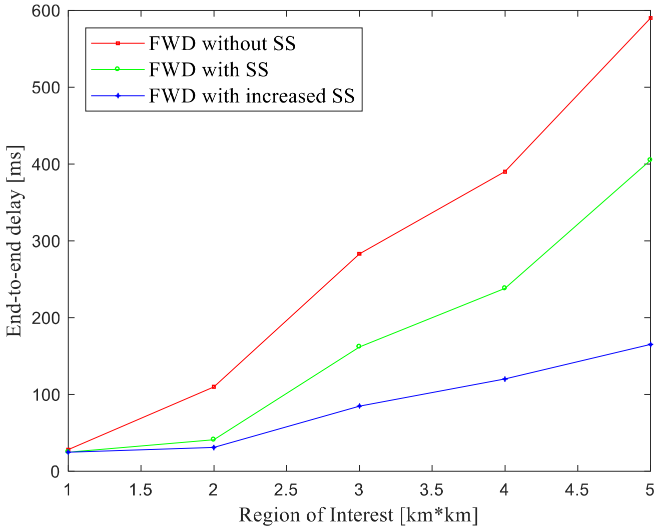

Figure 5.8 End-to-end delay versus region of interest

The results of Figure 5.8 show the end-to-end delay as a function of size of region of interest (RoI). It clearly indicates that our circular striping and sectoring concepts reduce the end-to-end delay significantly. It also reveals that when we increase the degree of SS it further minimizes end-to-end delay. This can be attributed to the fact that applying SS concepts in increasing degree makes the E-CLD^{2}P as straight line. The straightness of E-CLD^{2}P increases with increasing degree of SS. This reduces end-to-end delay. In particular, the percentage reduction in end-to-end delay is 18% for 2 Km^2 RoI whereas the reduction further increases up to 23% for 3 Km^2 RoI, and 40% for 4 Km^2 RoI. Therefore, it is clear from the analysis that the proposed E-CLD^{2}P outperforms the literature due to the sectoring centric industrial WSNs framework.

5.4.2 Performance Comparison

The simulation outcome for average energy consumption with different number of sensors is shown in Figure 5.9. It is clearly seen from the Figure 5.9 that as the number of packets transmitted through a route suggested by EBM [31], SASR [30], and the proposed E-CLD^{2}P for different network size in term of sensors, the energy consumption increases with the increase of number of packets and number of sensors. However, the EBM consumes highest energy of the sensors. The energy consumption of E-CLD^{2}P is lowest, it is because of it select the path for packet forwarding with highest average energy sector. Every time, the E-CLD^{2}P choose different route for packet transmission which better balance the energy consumption among nodes.

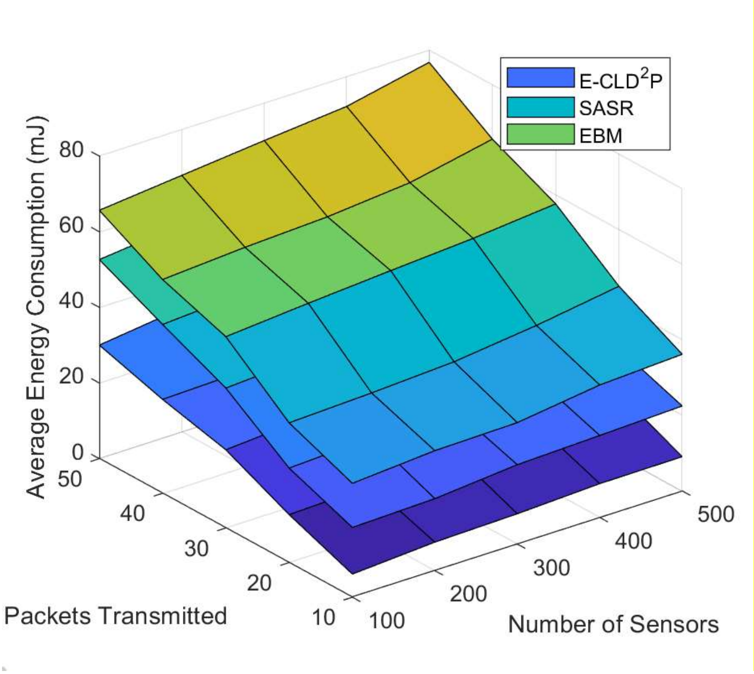

Figure 5.9 Average Energy Consumption for different number of sensors

Figure 5.10 shows the simulation results for average delay measured for different number of sensors deployed in the 1 km^2 region of interest for EBM, SASR, and the proposed E-CLD^{2}P. It is observed that the delay for the proposed E-CLD^{2}P is lowest as compare to EBM and SASR schemes. For example, for number of sensor = 100, the delay for the E-CLD^{2}P is about 60 ms, whereas about 80 ms and 88 ms are measured for SASR and EBM respectively. Furthermore, it is also observed that as number of sensors increases the delay for all the schemes are decreases, it due to fact that better and shorter routes are computed with more number of sensors.

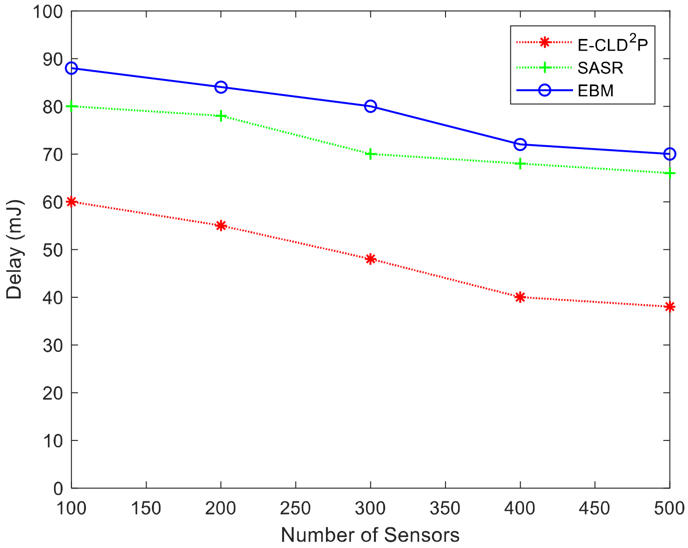

Figure 5.10 Delay for different number of sensors with 1km^2 region of interest

5.5 Summary

In this chapter, an energy efficient routing approach is presented for industrial wireless sensor network. It is named as Energy oriented Cross Layer Data Dissemination Path (E-CLD^{2}P). It is based on three main concepts. The first one is circular striping of region of interest, which reduces the distance of E-CLD^{2}P and neighboring sensor. The Second is delay based sectoring which increases the straightness of E-CLD^{2}P with increasing sectoring degree. The third concept is formulation of E-CLD^{2}P for forwarding. We have presented an algorithm for E-CLD^{2}P construction. We have also presented mathematical support for each of our concepts used in E-CLD^{2}P. Our simulation results show that our SS concept works well in saving the energy and reducing the end-to-end delay in forwarding. We compare the performance of the E-CLD^{2}P with EBM and SASR algorithms. In our current work, we have not been studied the impact of shadowing in E-CLD^{2}P.

Chapter 6

Conclusion and Future Work

The various solutions to the problem of energy efficiency in MAC protocols in WSNs are presented in the thesis. Mathematical models for the duty cycle, sleep-wake up mode have been proposed. Energy centric virtual circular deployment visualization model is presented focusing on physical layer signal transmission characteristics in industrial WSNs scenario. The performance of our proposed models is compared with the existing well known related model in WSNs. This chapter concludes work carried out in the thesis along with discussion, and future opportunities for extension of work.

6.1 Conclusion

The one-dimensional discrete-time Markov chain analytical model of T-MAC protocol, specifically, an analytical model is derived for T-MAC focusing on an analysis of service delay, throughput, energy consumption and power efficiency under unsaturated traffic conditions. The service delay model calculates the average service delay using the adaptive sleep wakeup schedules in duty cycle. The component models include a queuing theory-based throughput analysis model, a cycle probability-based analytical model for computing the probabilities of a successful transmission, collision, and the idle state of a sensor, as well as an energy consumption model for the sensor's life cycle. A fair performance assessment of the proposed T-MAC analytical model attests to the energy efficiency of the model when compared to that of existing techniques, in terms of better power saving, higher throughput and lower energy consumption under various traffic loads.

We analyzed the performance of different Medium Access Control (MAC) protocols IEEE 802.15.4, and D-MAC with Radio Frequency Identification (RFID) Impulse using the proposed mathematical energy model under variable data rates. In low traffic scenarios, analytical results show that RFID Impulse gives lower energy consumption as compared to IEEE 802.15.4 MAC and D-MAC.

Further, a novel analytical model for energy consumption based on random radius clustering technique (RRCT) is presented that evaluates energy consumption for a multi-hop WSNs. We have analyzed the performance of our proposed model with energy efficient clustering system (EECS) protocol. The experimental analysis and analytical results show that the proposed RRCT analytical model saves more energy in comparison to EECS protocol and so the novel analytical model prolongs the network lifetime.

An energy efficient routing approach is presented for industrial wireless sensor network. Simulation results show that SS concept works well in saving the energy and reducing the end-to-end delay in forwarding. We compare the performance of the E-CLD^{2}P with EBM and SASR algorithms. The proposed E-CLD^{2}P performs better energy saving as compared to the literature due to the circular scripting centric industrial WSNs framework.

6.2 Discussion

In this work, we have presented the results obtained analytically and through simulations. Mathematical models and algorithms developed for computing the required number of sensors and efficiency of energy, delay, and throughput. Simulations are made using MATLAB the setting of various parameters. After analysis of results took in this work, we observed the followings:

- It is observed that for T-MAC, with the increase of the packet arrival rate, the idle probability of a sensor increases very slowly; however, for S-MAC, it decreases sharply. This is due to the fact that the idle listening time for the T-MAC protocol is fixed, which is to say it avoids idle listening during the active time, and the sensor goes to sleep mode if there is no event happening for a certain time of idle listening. In other words, due to the lower idle listening time, the T-MAC protocol has lower energy consumption when compared to the S-MAC protocol.
- It is witnessed in the protocols that the average service delay of T-MAC increases slower when compared with that of the S-MAC and X-MAX protocols for an increasing packet arrival rate λ.

- It is witnessed that before the node becomes saturated for the T-MAC, S-MAC and X-MAC protocols, the overall throughput increments linearly with the packet arrival rate up to 0.2. Thereafter, the throughputs for all of the protocols start decreasing with an increasing packet arrival rate. Throughput for T-MAC protocol is better than S-MAC and X-MAC protocols.
- The overall power efficiency increases linearly with the packet arrival rate, up to 0.24. The power efficiencies for all of the protocols start decreasing with an increasing packet arrival rate. The power efficiency of T-MAC protocol is better than S-MAC and X-MAC protocols.
- The energy consumption of RFID impulse is lesser than the IEEE 802.15.4 and D-MAC. Hence the network lifetime is increased.
- The networks lifetime is depicted in the impression of number of alive sensor nodes. The RRCT has longer life time in comparison to EECS. More decency in load distribution is gain in proposed RRCT by using the random completion radii at every level. This is because of using random clusters on the basis of their distance to Base Station. We can also see, total network energy of RRCT is more than EECS at the same round values after some initial values of round. So network life time is increased in RRCT.
- The green computing framework is implemented to evaluate the performance of E-CLD2P and CLDD in realistic WSNs environment and is compared with existing techniques that clearly shows that as number of packets transmitted through a route suggested by EBM, SASR, and the proposed E-CLD2P for different network size in term of sensors, the energy consumption increases as increase packets and sensors in number. However, the EBM consumes highest energy of the sensors. The energy consumption of E-CLD2P is lowest. It is because of it select the path for packet forwarding with highest average energy sector. Every time, the E-CLD2P chooses different route for packet transmission which better balance the energy consumption among nodes.

6.3 Future Work

The work carried out in this thesis encompasses scope and objectives set in the proposal of the work. However, a study effort in addition to investigating and achieving its aims should always lead to inaugural up new dimensions of study yet to come. Further, no research work can be considered complete in its entirety, if it is a time bound programme, especially leading towards a degree course. Therefore, in this work, duty cycle, sleep wake up, deployment, and scheduling algorithms studied cannot be considered complete and should leave scope for further improvement and enhancement. Similarly, the models and algorithms developed in this work can be improved and enhanced additional in the following fashion.

- Cross-layer optimization.
- Cross-layer interaction.
- Robotics and embedded systems promote research in large-scale WSNs.
- Our efforts on MAC protocol are mainly focused on energy efficiency. Researchers also have to efforts on another area at MAC layer like network security, nodes mobility, evaluation on sensor platforms, real-time systems
- Authors have to be studied to protect eavesdropping and malicious behavior at MAC layer by sensor network security. Shared-key based secure MAC protocol has been developed by Karlof et al. in TinySec [46]. But still, it has to be needed additional innovative scheme to be established.
- Initially, nodes are considered to be static in WSNs. Newly there is a growing concern in medical care and adversity retort uses where moveable sensors can be devoted to the patient, clinician or first responder. Flexibility at MAC layer has been assumed in MMAC [47], still there is a huge opportunity for future study in this zone.
- Simulations are used to estimate the results of many MAC protocols in WSNs. But it has to be needed that mathematical and analytical analysis of the MAC protocol calculated in scenarios of real sensor nodes. The author needs to concentrate on research at scenarios of real sensor node stages.
- Manly the design of MAC protocol focuses on energy saving in WSNs. But in real-time it is crucial to transfer the data packet consistently for fixed schedule hazardous uses. So

the author encourages to research in the area where it requires to be worked exuberantly broadly.

- An interesting direction is to explore interdependencies between choices of node platforms, MAC protocols, routing and scheduling protocols whatever the dependencies exist.
- Researchers need to concentrate on working in the direction to study the performance of E-CLD^{2}P in a more realistic environment.

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