Waseda University
Doctoral Dissertation

Study on Energy Consumption and Reliability Issues
in Multi-hop Wireless Sensor Networks

マルチホップ無線センサネットワークにおける
電力消費と信頼性に関する研究

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Graduate School of Global Information and Telecommunication Studies, Waseda University

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Muhammad Tariq

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Dedicated to my beloved wife Dr. Zainab Umar
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ACK  Acknowledgment frame
BPSK  Binary Phase Shift Keying
$b_c$  Control bits
$b_d$  Data bits
BO  Beacon Order
BI  Beacon Interval
CCA  Clear Channel Assessment
CC2420  Chipcon 2420
CCI  Chip Correlation Indicator
CSMA/CA:  Carrier Sense Multiple Access /Collision Avoidance
CTS  Clear To Send
dBm  deci Bell meter
DCM:  Distributed Communication Model
DPV  Default Parameter Value
DSSS  Direct Sequence Spread Spectrum
$d_{ss}$  Distance of a source node $k$ to the sink
$E_{comm}(k)$  Energy consumed by a sensor $k$ during communication process
$E_{comm_{rx}}(h)$  Total energy consumption for receiving via $h$ hop
$E_{comm_{tx}}(h)$  Total energy consumption for transmitting via $h$ hop
$E_{comm_{idle}}(h)$  Total energy consumption for idle listening via $h$ hop
$E_{idle_{1}}$  Single hop energy consumption during idle listening
ETX  Expected Transmission Count
$E_{m_{comm}(h_{2})}$  Energy consumption for 2 hop communication
$E_{m_{comm}}$  Energy consumption for multiple hop communication
$E_{s_{comm}}$  Energy consumption for single hop communication
$E_{tx_{1}}$  Single hop energy consumption during transmitting
$FRR_{th}$  Frame reception rate defined threshold value
FFD  Fully Function Device
$FLR_{current}$  Frame loss rate current value
Frame loss rate defined threshold
Frame reception rate current value
Giga Hertz
General Packet Radio Service
Guaranteed Time Slot
Number of hop
Hybrid-Adaptive Parameter Tuning Based Estimation
A sensor node
Length of frame
Length of a side of square sensing field
Length of ACK frame
Loss rate of frame
Frame loss rate of reply frame
Frame loss rate of query frame
Low Rate-Wireless Personal Area Network
Loss rate of symbol
Logical Quality Estimator
Link Quality Indicator
Medium Access Control
Maximum CSMA backoff value
Minimum CSMA backoff value
Maximum number of frame retries
Minimum value of backoff exponent
Maximum value of backoff exponent
Micro Electro Mechanical Systems
Mega Hertz
Maximum Parameter Value
Number of query frame
Number of reply frame
Offset Quadrature Phase Shift Keying
Personal Area Network
$P_c$ Probability of collision

$P_{CCA1}$ Probability of clear channel assessment 1

$P_{CCA2}$ Probability of clear channel assessment 2

$\pi_{comm}$ Average power dissipation for packet transmission

$p_{ch\_sens}$ Power dissipation during channel sensing

$\bar{p}_{ch\_sens}$ Total power dissipation during channel sensing

$P_{cs}$ Probability of carrier sensing

PHY Physical

$p_{idle}$ Power dissipation during idle state

$P_{min}$ Minimum transmit power level

PQE Physical Quality Estimator

$p_{tx}$ Transmission power

$p_{rx}$ Receiver power

$Pr_{ktr}$ Probability of frame loss and retransmission of frames

$p_{sleep}$ Power dissipation during idle listening mode

PSR Packet Success Rate

$q$ Query frame

$r$ Reply frame

$r_c$ Communication/Radio range of a node

$r_f$ Reception rate of a frame

$RF$ Radio Frequency

RFD Reduced Function Device

RFID Radio Frequency Identification

RNP Required Number of Packets

RTS Request To Send

RSSI Radio Signal Strength Indicator

SECDED Single Error Correction and Double Bit Error Detection

SNR Signal to Noise Ratio

SO Super-frame Order

$|S_{src}|$ Number of neighboring nodes in communication range

$|S|$ Total Number of sensor nodes
$t$ moment of time
$t_1$ Time waiting for an empty channel
$t_2$ Time waiting for a control frame
TDMA Time Division Multiple Access
WSNs: Wireless Sensor Networks
4B Four-Bit
$\mathcal{E}_{kq}$ Energy consumed through transmitted and receiving a query frame
$\mathcal{E}_{kr}$ Energy consumed through transmitted and receiving a reply frame
$\gamma_{kr}$ Number of transmission times for reply frame
$\gamma_{kq}$ Number of transmission times for query frame
$\lambda_k$ Data rate
$\alpha$ Duty Cycle
$\rho$ Node Density
$\mathcal{E}_{amp}$ Power due to Amplifier
$\beta$ Path loss exponent
$\eta$ Energy efficiency gain
Summary

Micro Electro Mechanical Systems (MEMS), which is a technology of the low power micro sensors, integrated circuits, and wireless technologies, has led to the expansion of Wireless Sensor Networks (WSNs). WSNs has shown tremendous progress in the last decade due to its significant contribution in a variety of promising solutions in the diverse application scenarios. The scale of WSNs deployments for real life applications has rapidly increased in last few years and it is expected to rise significantly in the near future.

The deployment of WSNs is believed to be very useful in critical situations like emergency response and the disaster area management, where deployment of sensor nodes is random. In disaster areas, sometimes it may be impossible to enter in the affected zones due to the severe circumstances. In such a case, WSNs will be an alternative technology to be utilized in the scenarios, such as monitoring an area, which is polluted with the nuclear radiation, where human intervention can lead to serious health issues. In the course of such real life implementation, all sensor nodes cannot communicate directly with a centralized sink node. Due to the short communication range of an individual sensor node, the information has to be routed through the intermediate nodes to be delivered to the sink node. It has been observed during the experiments that a WSNs that operates in an error-prone multi-hop network environment and where deployment of sensor nodes is random, suffers from serious reliability issues, which result in the decrease of the energy resources of a node. The network environment becomes error-prone due to the noisy wireless channel and due to the failure probability of the sensor nodes, which lead to the data loss.

With the involvement of WSNs in the energy-hungry applications and the error-prone network environments, the energy conservation, efficient utilization of the resources and the reliable communication, are becoming the critical research issues. Therefore, it is important to design a communication model, which can estimate the overall energy consumption for a specific duration and at the same time estimate the accurate lifetime of the whole network. In addition, to reduce the latency and energy consumption in the error-prone environment, it is necessary to use a good channel quality estimation technique for selecting the best link to route data.

In Chapter 1, introduction about WSNs, various applications, and challenges that are being faced in real deployment of sensor nodes, are explained in detail. It has been found that energy
estimation and reliability are the two important research issues in real deployment of WSNs recently. In order to address both the energy estimation and reliability issues, the thesis is logically divided into two parts; the energy consumption/estimation and the lifetime modeling of the whole network, are discussed in Chapter 2, 3, while the reliability issues in multi-hop WSNs are introduced in Chapter 4.

In **Chapter 2**, in order to estimate the energy consumption of an individual sensor node and ultimately the lifetime of the whole WSNs, a Distributed Communication Model (DCM) is introduced that can accurately determine the energy consumption through data communication from a source to a destination node in the error-prone multi-hop network. The energy consumption is affected with the quality of link, which is affected by interference, wave reflection, wave diffraction, and the multipath effects. Link quality is characterized by symmetry, directivity, instability, and irregularity of the communication range of a sensor node. Due to the weak communication links, significant data loss occurs that affects the overall energy consumption of a node and ultimately the lifetime of the whole network. While other proposed energy models are unable to determine energy consumption due to lossy links in the error-prone network environments, DCM can be used to accurately estimate the energy consumption in such environments. The analysis performed using DCM, is validated through rigorous simulations and practical implementation. Both simulations and experimental results show that DCM outperforms all the other energy models designed for data communications in WSNs, in terms of accuracy and diversity of the environments.

In **Chapter 3**, by using the idea of DCM, a detailed analysis of the power dissipation through various factors involved in WSNs communications using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), based on IEEE 802.15.4 Medium Access Control (MAC) protocol is performed. It is observed that most of the MAC protocols designed in WSNs are based on the CSMA access mechanism. However, energy estimation models designed for WSNs, mostly consider Time Division Multiple Access (TDMA) protocols for energy analysis. A major drawback with TDMA based protocols is that such protocols need a good centralized synchronization scheme. For distributed WSNs, CSMA based protocols are the ultimate solution. In the power dissipation analysis using IEEE 802.15.4 CSMA/CA MAC protocol, the loss rate of frames, neighbor nodes density in the communication range of a sensor node, number of hops, distance of source to the sink, and the density of the network, are taken into account. To assess the true nature of the MAC protocol predictability, the random nature of the parameters of CSMA/CA protocol is used in both analyses and simulations. A comprehensive analysis of the
affects of these factors on the energy consumption along with the overheads caused by message routing through multi-hop distributed networks is performed. The accuracy of the analysis is then verified through Monte Carlo simulations. Results from both analysis and simulations show that the power dissipation analysis is more realistic compared to other proposed models in terms of accuracy and complexity of the network environment.

In Chapter 4, channel quality estimation in error-prone multi-hop WSNs is addressed. To route data on the lossy links in the error-prone networks, the selection of a good quality channel is very important. To tackle this issue, a channel estimation technique, called Hybrid Adaptive Parameter Tuning based Estimation (HAPTE) is introduced. HAPTE estimates the current channel conditions using cross-layered approach, and then utilizes this information to change the MAC protocol parameters adaptively. The HAPTE, designed for IEEE 802.15.4 MAC protocol utilizes the four bits concept of 4-Bits (4B) hybrid channel quality estimation, by adaptively tuning MAC protocol parameters for required level of reliability, while maintaining layered networking abstractions. Comparison of HAPTE in the IEEE 802.15.4 multi-hop networks in error-prone environments is drawn with the physical, logical, and hybrid channel quality estimators. Simulation results show that the HAPTE outperforms all the physical, logical, and hybrid channel quality estimators in terms of energy consumption, delay, and end to end packets delivery rate, using the same surrounding conditions.

Finally, in Chapter 5, conclusions of all the research findings, which have been introduced in this thesis, are drawn. On the basis of the research findings, some directions toward the future works and the research collaboration plans have been proposed at the end of the chapter.
Chapter 1

Wireless Sensor Networks: An Overview

1.1. Introduction

Recent development in the Micro Electro Mechanical Systems (MEMS), which is a technology of low power micro sensors, integrated circuits, and wireless technologies, has led to the expansion of Wireless Sensor Networks (WSNs) in a diverse real life applications. WSNs is playing a major role in different aspects of human society through applications like home automation, consumer electronics, military application, agriculture, smart grid, environmental monitoring, and human health probing. Usually sensor devices, which are used in different applications, are small and inexpensive, so that they can be produced and deployed in large numbers in different situations and application scenarios. For example, in the military and environmental monitoring applications, hundred to thousand of sensor nodes operate in the strategic locations for a long duration of time, in order to gather the required information about the surrounding environment. Similarly, in the disaster area management, sensor nodes in large number can be deployed for a limited duration to gather critical information in order to reduce the human loss to the minimum [1-4].

The resources of these tiny sensor nodes, such as energy, bandwidth, processing speed, and memory are very limited. Due to limited resources, energy consumption and efficient utilization are the crucial design factors for WSNs hardware and software developers, and the designers. Therefore, it is important to design a WSNs in such a way that it can maximize the overall network lifetime expectancy. For that purpose, power management is considered as a core issue in designing WSNs. In addition, when mobile nodes are embedded with static nodes, a set of issues has to be undertaken in terms of cost and energy for locomotion along with sensing, processing, and communication. These factors make the WSNs technology an active research area in the wireless communication, signal processing, and networking communities.
WSNs is capable of collecting useful information, processing and dissemination of that information, in diverse and hostile surrounding environments. Due to certain factors such as simplicity, cost effectiveness, self-healing, self-maintenance, and self-organization capabilities, the WSNs has distinctive advantages over other existing wireless networks, which make WSNs appropriate for many real life applications.

1.1.1. Potential Application Areas of Wireless Sensor Networks

As explained earlier, WSNs play a major role in many aspects of the society such as disaster area management and emergency response, home automation, consumer electronics, military applications, agriculture, human health probe, and environmental monitoring.

1.1.1.1. Disaster Area Management and Emergency Response

WSNs possesses huge potentials in the field of emergency response and disaster area management. For disaster area management and emergency services, such as post earthquake relief efforts, flood affected areas, tsunami hit coastal zones, and forest fire outbreak, the timely reporting and responding are of critical significance in order to minimize the number of casualties, injuries, and property damages from the catastrophes. In the worst situation of such calamities, the existing communication infrastructure might not be operational. This makes it difficult to gather even rough information about the incident, and then to respond to the incident quickly and appropriately. In such situations, WSNs can tackle these problems by randomly deploying the sensor nodes, which can actively monitor and timely report to the disaster management and monitoring cell, in order to save and minimize the precious human lives, as can be seen in Fig. 1.1. Although WSNs is not a de-facto technology in disaster management, it lays a huge potential in such applications due to the cost effectiveness and simplicity in the deployment and operation.
1.1.1.2. Environmental Monitoring

Environment monitoring is one of the typical examples of WSNs, where sensor nodes are deployed in a large unattended area for long term monitoring of various environmental phenomena, such as temperature, pressure, pollution, humidity, and nuclear radiation. The gathered information is routed to the monitoring center, where this information is utilized for multi-purposes. For example, when partial meltdown occurred on March 11, 2011 at Fukushima nuclear power plant, a radiation sensor board was developed by Libelium [6] to check the radiation level. The motive behind this development was to
help the nuclear plant authorities and Japanese security forces to measure the level of radiation of the affected zones without compromising on the life of the plant workers. For this reason, Libelium created an autonomous battery powered Geiger Counter (Fig. 1.3), which can read the radiation levels automatically and send the information in real time using wireless technologies like ZigBee [7] using IEEE 802.15.4 standard [8] and General Packet Radio Services (GPRS). With this technology, radiation measurements can be determined in the real time without deploying the power plant workers to be inside the security perimeter in order to activate the Geiger counters. The information can be extracted automatically and sent wirelessly to the gateway/sink node.

![Figure 1.3: A radiation sensor board developed by Libelium [6] to check the radiation level at Fukushima nuclear power plant.](image)

1.1.1.3. Military Applications

WSNs systems have useful applications in military installment and surveillance systems [3]. Various complex WSNs systems have been installed on the national borders for military surveillance and monitoring of illegal entrance across porous and complex border territories. In addition, the measuring of dangerous gas leakage, underwater surveillance, and on ground target detection, are few other examples out of many applications in military and defense systems.

1.1.1.4. Habitat Monitoring and Medical Applications
Another important potential application area of WSNs is habitat monitoring of animals and wildlife. Habitat monitoring allows scrutinizing various activities of wildlife without intervention of human. In addition, it can be further used for monitoring various aspects related to the health status of wildlife, which helps to prevent untimed death of precious animals and species.

Research on the human mass probes has been of particular interest recently [5], especially measurements of the human health status monitoring at large events, such as religious gathering like the annual Muslim Pilgrimage (The Hujj) in Makkah, where every individual pilgrim is provided with a Radio Frequency Identification (RFID) tag, which passes on all the health related information to the centralized health monitoring centre. In this way, on time first aid service can be provided to each individual pilgrim with less efforts and more convenience. Similarly, the health of elderly people who are living alone can be monitored directly from a family hospital and health services can be provided whenever any health parameter exceeds the specified limit.

1.1.1.5. Industrial Applications

In industries, various machines are installed for long purpose activities. It is important to check whether a machine is working properly without human intervention, which can save not only time but capital of an industry as well. Monitoring of a machine health and operation can improve the performance and maintainability of a machine and thus prolong the overall lifetime span of a machine and indirectly the whole industry. Wireless communication using WSNs is necessary for potentially hazardous industrial zones with inaccessibility or low accessibility.

1.1.1.6. Smart Grid

A new concept of next generation electric power system, called smart grid has emerged recently, where WSNs is used to upgrade the existing 100 years old electrical infrastructure by bringing the Information Technology and Communications (ICT) concepts. The components of the traditional power grid are near to the end of their potential life. The electrical power grid has been outdated, while the demand for electricity has been gradually increasing throughout the world. The U.S. Department of
Energy has reported that the demand and consumption for electricity in the U.S. have increased by 2.5% annually over the last 20 years [66].

Today’s electric power distribution system is very complex and to say the least, not suitable for the needs of the 21st Century. Among the deficiencies of the existing system include the lack of automated analysis, poor visibility, mechanical switches causing slow response times, lack of situational awareness whenever power outage or blackout happened [67]. As a result, a new grid infrastructure is urgently needed to address these challenges. To realize these potentials, the smart grid has emerged as an alternative electric power system, which can elegantly use WSNs technology for automation of power distribution and automatic meter reading [68].

1.2. Current Research Areas and Prospective Research Issues in Wireless Sensor Networks

Some active areas of recent research in WSNs include energy consumption and power management, localization and tracking, distributed detection and estimation, data fusion, node scheduling, node connectivity, the reliability of data communication through weak channels, and the network security. In this thesis, we address several challenges in terms of the energy estimation and power dissipation, network lifetime, and the reliability with respect to data communication in distributed and multi-hop communications in error-prone environment.

The Significance of WSNs has been reinforced by the introduction of the IEEE 802.15.4 standard for the physical (PHY) and Medium Access Control (MAC) layers and the ZigBee standard for the network and application layers. In this thesis, the focus is mainly on the IEEE 802.15.4 standard in multi-hop WSNs communication. Therefore, different research problems and prospective research issues related with IEEE 802.15.4 multi-hop network in terms of the energy efficiency and reliability are being considered. Before going into the details of research issues, an overview of the IEEE 802.15.4 standard is required.
1.2.1. An Overview of the IEEE 802.15.4 Standard

The IEEE 802.15.4 standard [8] defines the characteristics of the PHY and MAC layers for Low-Rate Wireless Personal Area Networks (LR-WPAN) as shown in Fig. 1.4. While maintaining a flexible but simple protocol stack, the advantages of an LR-WPAN are the reliable transfer of data, simplicity of installation, short range communication, cost effectiveness, and a relatively longer battery lifetime.

1.2.1.1. The PHY Layer

In IEEE 802.15.4 standard, the PHY layer supports three frequency bands: a 2.4 GHz having 16 channels, a 915 MHz having 10 channels and 868 MHz band having 1 channel. They all use the Direct Sequence Spread Spectrum (DSSS) access mode. The 868 and 915 MHz bands rely on Binary Phase Shift Keying (BPSK), while 2.4 GHz band employs Offset Quadrature Phase Shift Keying (O-QPSK) for modulation. Besides radio on/off operation, the PHY layer supports various functionalities, such as channel selection, energy detection measurement, link quality assessment, and Clear Channel Assessment (CCA).

1.2.1.2. The MAC layer

In IEEE 802.15.4 standard, the MAC layer specifies two types of nodes:
Reduced Function Devices (RFDs)

Full Function Devices (FFDs).

RFDs can only function as the end devices and are equipped with sensors like transducers, light switches, etc. It is possible they may only interact with a one FFD. FFDs are equipped with a full set of MAC layer functions, which enables them to act both as a network coordinator and a network end device.

Two main types of network topology are considered in IEEE 802.15.4, i.e.

- The star topology
- The peer-to-peer (or multi-hop) topology

In the former, a master/slave type network model is adopted, where a FFD takes up the role of Personal Area Network (PAN) coordinator; the rest of the nodes can be either RFDs or FFDs, and will only communicate with the PAN coordinator. In the multi-hop network scenario, a FFD can communicate with other FFDs within its radio range and can pass on messages to other FFDs outside of its radio range via a relay FFD, forming a multi-hop network as shown in Fig. 1.5. A PAN coordinator is selected as an
administrator network operation. The PAN coordinator may operate its PAN with superframe or without superframe. In the first case it starts the superframe with a beacon, which is used for synchronization purposes as well as to describe the superframe structure and send control information to the PAN coordinator.

The PAN coordinator is ready to receive data from an end device and it is always on while data transfer in the other direction is on poll based, i.e. the end device periodically wakes up and polls the coordinator for pending messages. The coordinator then sends these messages of unavailability. In addition, the coordinator-coordinator communication creates no problem as both of them are active all the time. In addition to data transfer, the MAC layer possesses channel scan and association and disassociation functionalities. The scan procedure involves scanning several logical channels by sending a beacon request message and listening, i.e. active scan, for FFDs or just listening i.e. passive scan, for RFDs, for beacons to locate existing PANs and coordinators in the network.

1.2.2. IEEE 802.15.4 Standard Based Energy Efficiency

There are various features of IEEE 802.15.4 standard [1] that combined together result in a considerable energy savings. However, there is a trade-off between achieving a desired data rate and maximizing the lifetime of the individual sensor nodes. These are the goals, which are the subject of ongoing WSNs research. The Carrier Sense Multiple Access-Collision Avoidance (CSMA/CA) scheme employed in IEEE 802.15.4 does not involve Request to Send/Clear to Send (RTS/CTS) exchanges unlike IEEE 802.11. As a result, unslotted CSMA/CA, which is used in beaconless mode, is enabled to achieve higher channel utilization compared to the slotted CSMA/CA, which is used in beacon-enabled mode. It allows self-organization and scalability; however, it suffers from the hidden terminal problem in multi-hop network environments.

There are some application with timing constraints, delivery in time may be more important than energy saving. The Guaranteed Time Slot (GTS) protocol mode is one potential candidate to achieve predictable real time performance for LR-WPAN. This mode offers the possibility of allocating and de-allocating time slots in a superframe and provides predictable minimum service guarantees. From the time allocation point of view,
the concept of a GTS allocation is similar to a Time Division Multiple Access (TDMA) time slot allocation. Here, a fixed amount of bandwidth is granted for a given data flow periodically, whereas, the amount of bandwidth is determined by the periodicity and duration of the time slot.

The IEEE 802.15.4 GTS mechanism is more flexible than traditional TDMA because the GTS duration may be dynamically adjusted through some MAC parameters. Information from the higher layers of the protocol stack can be combined with MAC layer approaches to achieve higher energy savings. The network and the application layers in particular have much better information on actual communication patterns, multi-hop data routes, and associated data rates. This information can be utilized to gain better radio activation schedules.

1.2.3. IEEE 802.15.4 Standard Based Reliability

One of the key issues of WSNs is reliability. Nodes are battery powered and communications are radio based, which means nodes can fail temporary or permanent disconnections could occur. The measurements collected by individual nodes are rarely crucial. Reliable communication in WSNs is not focused on each single end-to-end delivery but is of a more general nature, encircling network-wide significance. In order to improve on the reliability and limited scope of the PHY and MAC layers, the network and higher layers must deal with this issue. Failure of an individual node or link may prevent correct routing to some nodes but does not usually compromise the whole network. Periodic refreshing through an algorithm reruns helps maintain acceptable levels for the associated supporting functions.

Energy efficiency and reliability are the key issues in WSNs, which are required to be efficiently managed for a realistic deployment of sensor nodes. It has been observed that a WSNs that operates in such an environment usually suffers from serious reliability issues [9], [10]. Quality of a communication link that is established between two neighboring nodes in the IEEE 802.15.4 multi-hop networks is a critical factor for reliable data transfer, which in turn is provided by the channel quality estimation metrics. There are various channel quality estimators that have been proposed to cope with the
unpredictability of the communication channel. These channel quality estimators can be divided into three broad categories, i.e. physical, logical, and hybrid.

In physical channel quality estimation, the channel quality assessment is provided by the radio hardware, which is based on the signal strength of a received packet, such as Signal to Noise Ratio (SNR), Received Signal Strength Indicator (RSSI), and Chip Correlation Indicator (CCI) [11]. In WSNs, the real sensor nodes, such as Telos and MICAz [12] motes use Chipcon CC2420 radio [13]. On the other hand logical channel quality estimators, assess the channel quality by keeping track of packet loss, such as Expected Transmission Count (ETX) [14], i.e. the number of transmissions required to successfully transmit a packet, the Required Number of Packets (RNP), and the Packet Success Rate (PSR).

Hybrid channel quality estimators are the combination of both physical and logical channel quality estimators by exploiting the characteristics of both estimators to assess the channel quality. Example of hybrid estimation is Four-Bit (4B) estimator [15], which uses cross layer approach by utilizing information from physical (white bit), link layer (ack bit), and network layer (compare and pin bits). The logical channel estimator, i.e. 4B exploits the radio channel quality information from PHY layer, the Link Quality Indicator (LQI) information from link layer by combining it with the estimation of ETX, and the information from the network layer for better path quality estimation.

1.3. Major Contributions in the Dissertation

There are three major contributions in this thesis, which is briefly introduced as below.

1.3.1. Realistic Analysis of Energy Consumption in Distributed Error-Prone Environment

As explained earlier, the resources of the sensor nodes, such as energy, bandwidth, processing speed, and memory are very limited. Due to limited resources, energy consumption and efficient utilization are the crucial design factors for both WSNs hardware and software designers. Therefore, it is highly desired to design a system that is
aiming for maximizing the overall lifetime of the WSNs thereby reducing the energy consumption [16], [17].

It is found in the related works that most of the analysis model related to energy consumption measurement for data communication considers error-free environments [18], [21], [22], [23], where no packet loss is considered. However, in practical WSNs applications, such as disaster areas management, remote harsh fields, contaminated urban regions, search and rescue operations, active volcanic areas, and the forest fire outbreak, the environment may be error-prone and unstable at times. In such situations, significant packet loss can be experienced. Due to packet retransmission, a considerable amount of energy will be wasted, which will affect the overall energy consumption and ultimately affect the lifetime of the whole network. Consequently, a model which does not consider packet loss will most probably end up in wrong lifetime estimation in practical network scenarios. Therefore, in order to determine accurate energy consumption and predict accurate lifetime of WSNs, energy consumption due to packet retransmission via lossy link must be considered.

In order to deal with this issue, we design and thoroughly analyze an energy consumption model called Distributed Communication Model (DCM) that takes loss rate of packets into account. In addition, various factors, such as duty cycle, neighbor nodes in communication range of a source node, number of hops, distance of a source to the sink, data rate, and density of the network, are taken into account in DCM. We evaluate the impact of these factors on energy consumption due to data communication through variety of viewpoints. Lastly, we analyze the impact of overheads due to message routing over multi-hop links that causes considerable amount of energy loss.

1.3.2. Power Dissipation Analysis of IEEE 802.15.4 Multi-hop Wireless Sensor Networks In Error-Prone Environment

While the power dissipation analysis of single-hop IEEE 802.15.4 networks is well investigated, there is not yet a clear perceptive of the power dissipation over multi-hop WSNs. From a literature review, it is observed that the proposed energy models for
WSNs do not consider power dissipation through distributed multi-hop communication. In addition, none of these energy models show the clear impact of frame loss rate, network density, neighbor sensors density, and the overheads caused by multi-hops communication, on the overall power dissipation of a sensor.

By surveying the MAC protocols, which are designed for WSNs, it is found that most of the protocols are based on a CSMA access mechanism. However, energy estimation models like the one proposed in [18], considers TDMA protocols only for energy analysis. A major drawback with TDMA based protocols is that such protocols need a good centralized synchronization scheme. Such schemes are not easy to implement in dynamic networks like distributed WSNs. It is necessary to determine the power dissipation model for CSMA/CA based MAC protocols that take the states like back-off, carrier sensing, idle listening, sleeping, and data transmission in power dissipation analysis into account.

For this purpose, we propose and thoroughly analyze a power dissipation model for slotted CSMA/CA based IEEE 802.15.4 distributed multi-hop WSNs. It investigates the effect of frame loss rate, neighbor sensors density in communication range of a sensor node, distance of a source to the sink, density of the network, and the overheads caused by multi-hop communication. We evaluate the impact of these factors on power dissipation due to data communication via a variety of viewpoints.

1.3.3. Adaptive Hybrid Link Quality Estimation in IEEE 802.15.4 Multi-hop Wireless Sensor Networks in Error-Prone Environment

Energy efficiency is an important factor in WSNs as sensor nodes are typically powered by batteries, which have limited energy resources. In most of the applications, sensor nodes cannot be replaced nor recharged due to the nature of environment or cost constraints. While the energy consumption analysis of single-hop IEEE 802.15.4 networks is well explored, there is not yet a clear insight about the energy consumption with reference to reliability in the multi-hop networks.
Quality of a communication link that is established between two neighboring nodes in the IEEE 802.15.4 multi-hop networks is an important factor for reliable routing of packets in the network, which in turn can be provided by the channel quality estimation metrics. There are various channel quality estimators that have been proposed to cope with the unpredictability of the communication channel. These channel quality estimators can be divided into three categories, i.e. physical, logical, and hybrid.

In physical channel quality estimators, the channel quality assessment is provided by the radio hardware, which is based on the signal strength of a received packet, such as SNR, RSSI, and CCI.

As mentioned earlier, the logical channel quality estimators, assess the channel quality by keeping track of packet loss, such as ETX, i.e. the number of transmissions required to successfully transmit a packet, the RNP and the PSR. Hybrid channel quality estimators are the combination of both physical and logical channel quality estimators by exploiting the characteristics of both to assess the channel quality. Example of hybrid is 4B estimator, which uses cross layer approach by utilizing information from physical (white bit), link layer (Ack bit), and network layer (compare and pin bits). 4B exploits the radio channel quality information from physical layer LQI and combines it with the estimation of ETX and information from the network layer for better path quality estimation.

In order to better estimate the channel quality, we design another type of channel quality estimation metric, called Hybrid Adaptive Parameter Tuning based Estimation (HAPTE), which estimates the current channel conditions precisely, and changes MAC parameters adaptively according to the required level of reliability by considering physical, logical, and hybrid channel quality estimators. HAPTE outperforms all other channel estimation approaches in terms of accuracy, energy consumption, end to end delivery, and delay.

1.4. Conclusion

In this chapter, a detailed overview about the WSNs technologies and their utilization in real life applications has been provided. A brief introduction about various research
issues involved in WSNs has been provided. In addition, introduction about WSNs research issues like energy consumption/estimation, lifetime modeling of the whole network and reliability issues in packet routing using error-prone network environment has also been provided. At the end, a brief summary of the main contribution of this dissertation has been introduced, which will be explained in details in the upcoming chapters.
Chapter 2

A Realistic Communication Model for Distributed Error-Prone Wireless Sensor Networks

2.1. Introduction

As explained in Chapter 1, Wireless Sensor Network (WSNs) is receiving significant attention recently in real life applications, such as, military application, search and rescue operations, home automation, consumer electronics, agriculture and environmental monitoring, and human health examination. Almost all WSNs consist of tiny sensor motes that are usually battery driven. The vision of researchers to create smart environments over past few years is becoming a reality today with the deployment of hundreds to thousands of sensor nodes, each with a short communication range. These nodes are capable of detecting surrounding conditions such as temperature, movement, sound, and atmospheric pressure in the real network scenarios [3].

Different sensor motes developed by different vendors, which can be used for different purposes, depends on the applications for which they are being developed. Various types of sensor nodes can be seen in Fig. 2.1. In this chapter, for analysis, simulation, and then for experiments, MICAz motes are considered, which is developed by Crossbow systems.
Figure 2.1: Different available sensor motes available in the Market.

The main characteristic of sensor motes is that the resources of these tiny devices, such as energy, bandwidth, processing speed, and memory are very limited. Due to limited resources, energy consumption and efficient utilization are the crucial design factors for WSNs hardware and software developers, and the designers. Therefore, it is highly desired to design a system that is aiming at maximizing the lifetime of WSNs [16], [17].

The energy conservation and efficient utilization have become a growing research issues in WSNs as global importance on energy and environmental management continue to mature. The issue of resources allocation within such networks in a distributed fashion becomes more of a design and implementation concern. This is especially true in such networks where the allocation involves distributed collections of resources rather than just a single resource, and where this allocation must be performed in real time [19], [20].

In literature, it is found that most of the research works related to energy consumption measurement for data communication considers error-free environments [18], [21], [23] where frame loss is not taken into consideration. However, when we see the practical WSNs applications such as disaster areas management, remote harsh fields, contaminated urban regions, active volcanic areas, and the forest fire outburst, the environment is usually error-prone and unstable at different times. In such situations, significant packet loss can be experienced. Due to packet retransmission, a considerable
amount of energy will be wasted, which will affect the overall energy consumption and ultimately affect the lifetime of the whole network. Consequently, a model which does not consider packet loss will most probably end up in wrong lifetime estimation in practical network scenarios. In order to determine accurate energy consumption and predict accurate lifetime of WSNs, energy consumption due to packet loss/retransmission via lossy link must be considered.

In this chapter, an energy consumption model called Distributed Communication Model (DCM) is designed and thoroughly analyzed that takes loss rate of packets in multi-hop communication into account. In addition, various factors, such as duty cycle, neighbor nodes in communication range of a source node, number of hops, distance of source to the sink, data rate, and density of the network are taken into account in DCM. The impact of these factors on energy consumption due to data communication through variety of viewpoints are evaluated. Lastly, the impact of overheads due to message routing over multi-hop links that cause considerable amount of energy loss is also analyzed.

The remainder of the chapter is organized as follows. Section 2.2 describes related works. Section 2.3 introduces DCM in details. Section 2.4 discusses the performance evaluation of DCM through both simulations and experimentations. Conclusions are then provided in Sect. 2.5.

2.2. Related Works

Various research works have been conducted to determine energy consumption and efficient data transmission in WSNs. Initially, one research group proposed a model for the energy consumption of communication module for WSNs in [21]. In this model, the energy consumption is calculated based on power consumption through transceiver, amplifier and the distance between the source and destination node. Another research group extended the work done in [23] with a notable change of increasing the path loss exponent i.e. $\beta$ value is increased from 2 to 4.

In literature, it is found that most of the energy models designed for communication in WSNs are based on the model defined in [21] and [23]. A research group used the energy
model to study energy efficient routing protocols in WSNs [24]. In [25], the author used the model to determine the optimal transmission range for topology management in WSNs. The authors in [26] used the energy model to derive a cross layer design. In [27], the author utilized the energy model to study the problem of maximizing network lifetime through balancing energy consumption for uniformly deployed nodes for data gathering in WSNs. One exception is found in [22], where the authors designed their own energy model that derive the conditions for minimum sensor networks power consumption for sensor data from source to destination. A notable difference between the model designed in [21], [23] and the one in [22] is that, power consumption through transmitter and receiver are slightly different in different Radio Frequency (RF) band in [22] compared to [21], [23], where the power dissipation per bit are taken same as $50\text{pJ/bit/m}^2$.

By analyzing the related works, it is observed that none of the models or extended work of those models elaborated about the packet loss due to lossy links. In practical WSNs applications, a network will not be stable all the time, and packet loss may occur which causes the packet retransmission that ultimately affects the overall energy consumption. It is observed that most of the research works are fundamentally based on centralized approach, which is usually not energy efficient in long term prospective. In addition, none of the relations show the clear impact of neighbor nodes density in the communication range of a sensor node, the overall network density, the effect of communication range and the number of hops from the source to the sink, on the overall energy consumption through data propagation.

In this chapter, a distributed energy model for data propagation in distributed multi-hop WSNs that includes all the above factors into account is proposed. In the end, the integrity of the model through both simulations and real time experiments is validated.
2.3. Energy Consumption Analysis in Distributed Error-prone Wireless Sensor Networks

In this section, an energy consumption model based on the following assumptions is proposed.

2.3.1. Assumptions

- All sensor nodes are supposed to be homogenous; having same physical capacity such as communication range and sensing range.
- Sensor nodes are distributed in a square sensing field area randomly according to a homogeneous Poisson process.
- Location information of each node can be determined through Global Positioning Systems or through other localization techniques that are mentioned in [28].
- A node will only communicate with peers, which are in the communication range due to limited power. Therefore, multi-hop communication is required to communicate with remote nodes.

2.3.2. Distributed Communication Model

In unstable environment, it is a known fact that the quality of link may degrade, which results in the retransmission of packets and ultimately affect the energy expenditure due to the increasing loss rate of packets. First, we determine the impact of the loss rate on energy consumption in the error-prone network environment based on the quality of the link.

For chip communication, such as CC2420 [13], data are transmitted in the form of frames, which are composed of bytes. Each byte is divided into two symbols during the communication process. The chip sequence is transmitted using Offset Quadrature Phase Shift Keying (O-QPSK) modulation. The CC2420 decodes the received symbol by correlating it with all 16 different possible symbols. This process is shown in Fig. 2.2.
2.3.2.1. Basic Model

DCM is based on the basic energy model proposed in [21].

The energy consumed by a node $k$ by sending a query frame $q$ to the sink and getting a reply frame $r$ in a square sensing field having length of a side equal to $l$, is given by:

$$
E_{\text{comm}}(k) = \alpha \left( e_{ktr} N_{ktr} r_{ktr} + e_{ktq} N_{ktq} r_{ktq} \right) d_{kts} l_{k}
$$

(2.1)

Where, $e_{ktq}$ is energy consumed through transmitting and receiving a query frame $q$, $N_{ktq}$ is the number of query frames and $r_{ktq}$ is the number of retransmission times for query frames, through a node $k$ at moment $t$. Similarly, $e_{ktr}$ is energy consumed through transmitting and receiving a reply frame $r$, $N_{ktr}$ is the number of reply frames, and $r_{ktr}$ is the number of retransmission time for reply frames, through a node $k$ at moment $t$. Here,

$$
e_{ktq} = e_{ktr} = \left( p_{rx} + p_{tx} + e_{\text{amp}} r_{c}^\beta \right)
$$

(2.2)

Where, $\alpha$ is the duty cycle of Medium Access Control (MAC) protocol, which is defined as the proportion of the radio awaking time to the entire cycle time of a node. $p_{rx}$ and $p_{tx}$ are the amount of energy consumed for transmitting a single bit by receiver and transmitter circuits, respectively. $e_{\text{amp}}$ is the amount of energy consumed by amplifier. $r_{c}$ is the communication range of a node with path loss exponent $\beta$. $d_{kts}$ is the average random distance from any node $k$ to the sink at moment $t$ with the condition that the sensing area will be square. The details of calculating $d_{kts}$ can be found in the previous work for error-free energy estimation and lifetime modeling [29], which is given by:
\[ d_{kls} = \left( \frac{0.521 I}{r_c} + 0.5 \right) \]  

\( \lambda_k \) is the data rate of a node \( k \) that varies, depending on the RF band, i.e. the low band and high band. The low band adopts Binary Phase Shift Keying (BPSK) modulation that operates in the 868 MHz band, offering one channel with a raw data rate up to maximum of 20 Kbps in Europe, and in the 915 MHz ISM band, offering 10 channels with a raw data rate of up to 40 Kbps in North America. The high frequency band adopts O-QPSK modulation that operates in 2.4 GHz to 2.483 GHz. It has 16 channels with channel spacing of 5 MHz having a maximum data rate of 250 Kbps.

2.3.2.2. Link Quality Assessment

Next, suppose the frame loss rate is \( l_f \), then the number of

![Diagram](Figure 2.3: Chain of error from the chip sequence to the packet.)
Figure 2.4: Chip Correlation Indicator versus perceived packet reception and frame loss rates. Here, CC2420@2.4 GHz with data rate ($\lambda$) = 250 Kbps.

Frame retransmission times due to lossy links will be:

$$P_{rtx} = l_f + 2l_f(1-l_f) + 3l_f^2(1-l_f) + 4l_f^3(1-l_f) + ... = \frac{1}{1-l_f} \quad (2.4)$$

Where

$$l_f = 1 - (1 - l_s)^{2fl} \quad (2.5)$$

$l_s$ is the symbol error rate and $fl$ is the frame length. The frame reception rate ($r_f$) will be equal to:

$$r_f = 1 - l_f \quad (2.6)$$

$$r_f = (1-l_s)^{2\beta} \quad (2.7)$$

Frame loss is the only cause of packet loss under the case of perceived packet loss. It means that both frame loss and perceived packet loss will be equal. Hence, we use frame loss and packet loss interchangeably throughout this chapter. The process through which
a packet loss occurs is shown in Fig. 2.4. Perceived packet loss means that a receiver has successfully perceived the synchronization head; but there are some wrong symbols in the frame length field or MAC data unit field or both of them [15]. From the above analysis, it indicates that if the frame length is fixed, \( r_f \) is only influenced by \( l_s \), which is influenced from chip error rate.

The CC2420 provides two pieces of metadata about received packets. The first is its Received Signal Strength indicator (RSSI), which is the received RF signal strength in \( dBm \) over the first eight symbols after the start of a frame. The second is the chip correlation indicator (CCI). Instead of RSSI, we use the CCI as a measurement of chip error rate due to its accuracy. We can determine the relationship between CCI and the frame reception rate if we know the relationship between CCI and \( l_s \), which is the key issue. This relationship is determined in [11], which is given by:

\[
I_s = \begin{cases} 
0 & \text{CCI} \geq 100 \\
331.182023 \times e^{(-0.0147655 \times \text{CCI})} & \text{CCI} < 100
\end{cases} \tag{2.8}
\]

By taking the frame length as 23 bytes, frame loss rate can be determined from (2.5) and (2.7) as:

\[
l_f = 1 - (1 - I_s)^{46} \tag{2.9}
\]

Fig. 2.4 shows the relationship between CCI with frame loss rate and perceived packet loss rate. The relationship between CCI and frame loss rate is determined from (2.5), (2.8), and (2.9), while the relationship between CCI and perceived packet loss rate is determined through analysis that is verified through experiments in [11]. CCI can be considered as a measurement of chip error rate, which is used as an indicator for frame loss rate in the analysis of the model. It is shown in Fig. 2.4 that frame loss rate will be approximately 100% if CCI < 50 and will be 0% if CCI > 100. It indicates that a network will be stable if CCI value is around 100 or above. In Section 2.4, we use the frame loss rate as an indicator to determine the effects on the energy consumption of a sensor node in both simulations and experiments on MICAz motes.

Link quality is affected by the characteristics like symmetry, directivity, instability,
and irregularity of the communication range of a sensor node. The quality of a link is not the same in different directions. It may be good in one direction while it may be very weak in other direction. Practically, the shape of communication range is not sphere but it is irregular in different directions. There are various factors that caused failure of data frame transmission such as, wave reflection and diffraction, multi-path effects, and the interference from the surrounding environment. These factors will cause the change in the chip sequence. The changed chip sequence will make comparator to select other chip sequence instead of the one transmitted by sender. Therefore, the wrong selection will result in the mapping error in the chip sequence to symbol mapping phase that will lead to the failure of transmitted frame. This chain of data frame error is shown in Fig. 2.3.

Average energy consumption due to data communication with the probability that frames may loss and retransmission may occur; the energy consumption model in (2.1) can be reduced to:

\[
E_{\text{comm}}(k) = a \left( \frac{\varepsilon_{kr} \Pr_{kr} + \varepsilon_{kq} |S_{rc}|}{1 - l_{fkr}} \right) d_{kis} \lambda_k
\]

(2.10)

Here, \(|S_{rc}|\) shows the number of neighbor nodes in the communication range of a source node \(k\) as shown in Fig. 2.5. \(l_{fkr}\) and \(l_{fkr}\) are the loss rates of query and reply frames at moment \(t\) for a node \(k\), respectively. For long terms view, the loss rate of query and reply frames should be kept same, i.e. \(l_{fkr} = l_{fkr} = l_f\). Here, \(Pr_{kr}\) is the probability that the frame will go through the node \(k\) at moment \(t\), which is given by:

\[
Pr_{kr} = \left( \frac{1}{(1-l_f)\pi r_c^2 \rho} \right) \frac{|S|-\pi \rho d_{kis}^2}{2d_{kis}^2}
\]

(2.11)

The shape of communication range changes with the change of conditions. However, for simplicity, we assume that the communication range of a node as spherical shape. With the increase of communication range, more neighbor nodes come in the radio range of a corresponding node as shown in Fig. 2.5.

In (2.9), \(\rho\) represents the density of the network, which is determined in [30], as:
\[ \rho = \frac{|S|}{l \times l} \]  

(2.12)

2.3.2.3. Energy Consumption Estimation

From (2.2), (2.3), (2.10), and (2.11), energy consumption due to data communication for a node \( k \) can be calculated as:

\[
E_{\text{comm}}(k) = \alpha \left( \frac{\rho}{\eta(1-L_c)\pi r_c^2} \left[ |S| - \pi \rho \left( \frac{0.521L}{r_c} + 0.5 \right)^2 \right] + \frac{\rho}{2 \left( \frac{0.521L}{r_c} + 0.5 \right)} \right) \lambda_k \]  

(2.13)

The energy consumption for the whole network with the assumption that none of the nodes totally depleted energy out of the nodes deployed in the sensing field, by taking the individual node energy consumption as average of the total \(|S|\) nodes, is given by:

\[
E_{\text{comm}} = \sum_{k=1}^{\|S\|} E_{\text{comm}}(k) \]  

(2.14)

2.3.3. Analysis of the Factors Impacting on DCM

From (2.13), we can draw very useful conclusions that can be very handy for the researchers, especially for those who are dealing with the energy estimation and lifetime modeling for different WSNs systems. It can be deduced from (2.13) that by keeping the rest of parameters as constant, the energy consumption is increased with the increase of frame loss rate, i.e.

\[
E_{\text{comm}}(k) \propto \frac{1}{1-L_f} \]

From (2.13), it can be further deduced that:

\[
E_{\text{comm}}(k) \propto \alpha \]

It shows that energy consumption is increased with the increase of duty cycle of the MAC protocol used by a node \( k \). Similarly, more the neighbor nodes in the communication range of a sensor node the more energy
Figure 2.5: The effect of variation in the communication range of a corresponding sensor node on the nodes in the surrounding.

will be dissipated, i.e.

\[ E_{\text{comm}}(k) \propto |S_{rc}| \]

However, it must be kept in mind that the energy consumption varies with the topology, and different MAC and data propagation protocols. Likewise, it can also be inferred from (2.13) that:

\[ E_{\text{comm}}(k) \propto \lambda_k \]

This implies that the energy consumption by data propagation has direct relationship with data rate.

Energy consumption by data communication affects by the distance from the corresponding source node to the sink as well as by the communication range of a node. For efficient topology management, the selection of optimal communication range for a node is important. The optimal communication range for a given data rate can be calculated from [25].

We can conclude that any application based on IEEE 802.15.4 standard and MICAz motes can be studied to demonstrate the capability of DCM. This is a general model
which can be easily extended to different type of sensor nodes if the electrical characteristics of the hardware components are available.

2.3.4. Impact of Overheads on the Energy Consumption

The ultimate goals of the algorithms, designed for WSNs are to decrease idle listening time, route discovery, and efficient data routing. Fundamental aim is to reduce the total energy consumption and increase the lifetime of the network. However, these algorithms caused significant overheads. The energy consumption due to overheads must be properly analyzed to validate the actual efficiency gained by applying the algorithms.

In this section, we analyze energy consumption due to overheads caused by synchronous idle listening and sleeping schedule, centralized single hop communication and distributed multi-hop scheme. We investigate the algorithm according to a simplified CSMA/CA protocol defined by IEEE 802.15.4 standard. For the purpose of the analysis, we take the time spent in waiting for an empty channel as \( t_1 \), the time spent in listening for an RTS as \( t_2 \), the length of control frames as \( b_c \) bits, while that of all data frames (having same size) is \( b_d \) bits.

2.3.4.1. Energy Consumption via Multi-hop Communication Overheads

In the following analysis, we use \( E_{\text{comm}}(h) \) to denote the total energy consumption for sending data from source to destination via \( h \) hops. The energy consumption due to data transmissions via \( h \) hops can be calculated as:

\[
E_{\text{comm}}(h) = E_{\text{comm\_rx}}(h) + E_{\text{comm\_tx}}(h) + E_{\text{comm\_idle}}(h)
\]

\[
E_{\text{comm}}(h) = (h - 1)E_{\text{rx\_1}} + hE_{\text{tx\_1}} + h(h - 2)E_{\text{idle\_1}}
\]

Here, \( E_{\text{comm\_rx}}(h) \), \( E_{\text{comm\_tx}}(h) \), and \( E_{\text{comm\_idle}}(h) \) denote the total energy consumption for receiving, transmitting, and idle listening via \( h \) hops, respectively. \( E_{\text{rx\_1}} \), \( E_{\text{tx\_1}} \), and \( E_{\text{idle\_1}} \) denote the single hop energy consumption during receiving, transmitting, and idle listening, respectively. In order to send a data frame from source to the sink, we need \( h \) units of energy in transmission mode, \( h - 1 \) units of energy in receiving mode. If there are \( h \) duty cycles in total, then in each duty cycle, \( h - 2 \) nodes will be in idle listening mode.
Hence, in idle listening mode, the entire network consumes \( h(h - 2) \) units of energy. The energy consumption for idle listening mode in a unit time is denoted by \( E_{idle} \), and the energy consumption for receiving one bit is denoted as \( E_{rx} \), and the energy consumption for transmitting one bit via \( h \) hops is denoted as \( E_{tx}(h) \). Then the energy consumption via multi-hop communication is given by:

\[
E_{m\_comm}(h) = (h - 1)(E_{rx}(b_c + b_d) + E_{tx}(h)(b_c + b_d) + E_{idle}t_2) + h(E_{rx}(b_c + b_d)) + E_{tx}(h)(b_c + b_d) + E_{idle}t_1 + h(h - 2)(E_{idle}t_2)
\]  

(2.16)

2.3.4.2. Energy Consumption via Single Hop Communications

Energy consumption for a centralized single hop network can be determined as:

\[
E_{s\_comm} = E_{rx}b_c + E_{tx}(h_1)b_d + E_{idle}t_1
\]  

(2.17)

For single hop communication, sleeping schedule is not required. Therefore, power consumption of the source node is required only. Source node senses for an empty channel over the interval \( t_1 \), transmits \( b_d \) bits of a data frame, and receives \( b_c \) bits of an ACK frame. In the above equation, \( E_{tx}(h_1) \) denote the energy consumption for transmitting one bit from source to the sink directly.

2.3.4.3. Single Hop versus Distributed Multi-hop Energy Consumption Comparison

Comparing \( E_{s\_comm} \) and \( E_{m\_comm}(h) \), it is clear that \( E_{s\_comm} < E_{m\_comm}(h_1) \). Consequently, it can be deduced that if \( E_{s\_comm} < E_{m\_comm}(h_2) \) then \( E_{s\_comm} < E_{comm}(h) \), where \( h > 2 \). Hence, we can simplify the analysis by comparing a single hop network with a 2-hop network only. We have to find the minimum transmit power level, which can satisfy \( E_{s\_comm} < E_{m\_comm}(h_2) \).

From (2.16) and (2.17) we have,

\[
E_{m\_comm}(h_2) - E_{s\_comm} = E_{rx}(4b_c + b_d) + E_{tx}(h_2)(4b_c + b_d) - E_{tx}(h_1)b_d + E_{idle}(t_1 + t_2)
\]  

(2.18)

We assume that the time for waiting empty channel is relatively short, i.e. the time waiting for RTS is equal to one time unit and the time to transmit a single control frame
can also be defined as one time unit. Then \( t_1 = 0 \) and \( t_2 \) will be equal to the time taken for transmitting \( b_c \) bits [22]. For transceivers, usually \( p_{idle} = p_{rx} \). Therefore,

\[
E_{idle}t = E_{rx}b_c
\]  
(2.19)

By utilizing the idea of (2.19), (2.18) can be rewritten as:

\[
E_{m\_comm}(h_2) - E_{s\_comm} = E_{rx}(5b_c + b_d) + E_{tx}(h_2)(4b_c + 2b_d) - E_{tx}(h_1)b_d
\]  
(2.20)

The minimum transmit power level \( P_{min} \), which can satisfy \( E_{s\_comm} < E_{m\_comm}(h_2) \) with optimal communication range \( r_c \), having constant data rate is:

\[
P_{min}(r_c) \leq \min \left\{ P_{max}, \alpha \left[ \frac{p_{rx}(4b_c + b_d) + p_{tx}(5b_c + b_d) + \epsilon_{amp}r_c^\beta}{(b_c + b_d)(1-l_f)\pi r_c^2 \rho \frac{|S| - \pi \rho d_k^2}{2d_{kts}}} \right] \right\}
\]  
(2.21)

2.3.4.4. Energy Efficiency Gain

Fig. 2.6 shows the IEEE 802.15.4 standard frame types. Here, we assume that the address field and the payload for control frames are equal to 4 bytes. The payload size will be equal to 114 bytes. Therefore, \( b_c \) and \( b_d \) will be 19 and 133 bytes, respectively. From [21] it is shown that \( p_{rx} = p_{tx} = \epsilon \), then,

\[
P_{min}(r_c) \leq \alpha \left[ \frac{(9b_c + 2b_d)\epsilon + \epsilon_{amp}r_c^\beta}{(b_c + b_d)(1-l_f)\pi r_c^2 \rho \frac{|S| - \pi \rho d_k^2}{2d_{kts}}} \right] + \left[ \frac{(9b_c + 2b_d)\epsilon + \epsilon_{amp}r_c^\beta}{(b_c + b_d)(1-l_f)\pi r_c^2 \rho \frac{|S| - \pi \rho d_k^2}{2d_{kts}}} \right] \lambda_k
\]

\[
P_{min}(r_c) \leq \left( \frac{(9b_c + 2b_d)\epsilon + \epsilon_{amp}r_c^\beta}{(b_c + b_d)(2\epsilon + \epsilon_{amp}r_c^\beta)} \right) E_{comm}
\]  
(2.22)

It indicates that the overheads of the multi-hop communication of an IEEE 802.15.4 standard frame will increase the power consumption by a factor of:
Figure 2.6: Four basic frame types defined in 802.15.4: Data, ACK, MAC command, and Beacon.

Equation (2.22) specifies that the sleeping schedule of multi-hop causes to increase the $E_{comm}$ by 2.8 times compared to the sleepless single hop communication. It implies that single hop communication is about 180% more energy efficient than multi-hop in terms of sleeping schedule. However, the centralized approach in WSNs is useful and energy efficient only in small networks. For large networks, which aim for longer lasting, the distributed approach is the ultimate solution.

To analyze the impact of overheads on energy consumption due to multi-hop communication, we denote the efficiency of communication energy for the $h$ hop such that $h>2$ as $1/\eta(h)$. $\eta(h)$ can be calculated as:

$$\eta(h) = \frac{E_{comm}(h)b_d}{E_{m\_comm}(h)}$$  \hspace{1cm} (2.23)

By putting the values of $E_{comm}(h)$ and $E_{m\_comm}(h)$ in (2.23), we have:
For $h>2$, $\eta(h)$ will be equal to:

$$\eta(h) = \left( \frac{2h-1}{{\lambda}_d}c + \varepsilon + \varepsilon_{amp} r_c^\beta \right) \left( \frac{E}{2b_c + b_d} \varepsilon + \varepsilon_{amp} r_c^\beta \right)$$

(2.24)

For $h=2$, $\eta(2)$ will be equal to:

$$\eta(2) = \frac{b_d \varepsilon + \varepsilon_{amp} r_c^\beta}{2b_c + b_d} \varepsilon + \varepsilon_{amp} r_c^\beta$$

(2.25)

The total average energy consumption with multi-hop communication overheads, by sending data from a source node $k$ to the sink via $h$ hops at normalized data rate $\lambda_d$, can be calculated as:

$$E(h) = \frac{E_{comm}(k)}{\eta(h)}$$

(2.26)

It can be deduced from the analysis above that if sleeping schedule of the nodes and multi-hop network are considered, the energy consumption with overheads will be increased, compared to the single hop sleepless network. The rate of energy consumption due to overheads depends on the number of hops and on the sleeping scheduled algorithms.
2.4. Performance Evaluation

In this section, we evaluate the performance of the energy consumption model through simulations and then through experimentations using MICAz motes. In order to determine energy consumption in propagating data from source to the sink in multi-hop environment, we use a simple protocol, called GOSSIP [31], in order to avoid the routing complicacy which is usually used in energy efficient routing schemes. GOSSIP is a simple probabilistic flooding based scheme. It is a broadcasting scheme where a source node broadcasts a message to all its neighbors. Whenever a neighbor node receives a message, it has not generated, it tosses a coin and, with probability $p$, it retransmits the broadcast message to all of its neighbors except the neighbor from which it received the message. It remains silent with probability $(1-p)$.

In order to understand the 802.15.4 frame delivery performance, the delivery mechanism at both PHY and MAC layers is explained as below.

2.4.1. IEEE 802.15.4 Frame Delivery Performance

In this section, we explain the frame delivery at PHY and MAC layers.

2.4.1.1. IEEE 802.15.4 Frame Delivery at Physical Layer

The PHY layer has two functions, i.e. bit error detection/correction and framing. These functions are affected by many factors as explained earlier in Fig. 2.3. In addition to these factors, some minor variations in receiver and transmitter circuitry and battery levels can considerably affect those two functions of the PHY layer.

In chip communication, such as CC2420, data are transmitted in the form of frames, which are composed of bytes. Each byte is divided into two symbols during the communication process. Then from a local symbol-to-chip mapping table, each symbol is mapped into chip sequence. Finally, the chip sequence is transmitted through O-QPSK modulation. This process is shown in Fig. 2.7.

To measure 802.15.4 frame delivery at the PHY layer, we placed 15 MICAz motes in a chain topology each 0.5m apart. A source node sends a message periodically, while all
the other nodes receive the message. In Fig 2.7, it is shown that if an application from a source node is interested to send a message, then it issues a send event along with the message pointer. This is indicated by thick solid line in the figure. The lower layers (MAC and PHY) receive this message pointer and send an ACK to the higher layers indicating that the message was successfully accepted. This is indicated by the simple arrow in the figure. Once the PHY layer sends the message on the medium, a send done event is issued by the MAC layer, which ultimately notifies all the above layers. This is shown by the thick dashed line in the figure. If the MAC layer is programmed to wait for an ACK from its peer receiver, then the send done event is given after reception of the ACK. In case the ACK does not reach within the allotted time, the MAC issues the send done event, with failure notice. The thin dark line between the PHY and the MAC layers represents a bi-directional communications.

2.4.1.2. IEEE 802.15.4 Frame Delivery at MAC Layer

The MAC layer is responsible for transmission and reception of data frames and ACKs. It has a buffer that is responsible for receiving data frames from the PHY layer as shown in Fig. 2.7. In addition to the factors that impact the PHY layer, there are two factors that
affect the MAC layer. First is the application workload, i.e. to determine the traffic generated by nodes and second is the network topology. The basic metric for the frame delivery performance is the frame loss: the fraction of frames that are not successfully delivered within some time constraint. We measure frame loss by analyzing the sequence numbers received at the sink. Initially, we discuss a very gross measure of overall frame delivery performance and then measure the energy consumption of the node when experiencing frame loss. Instead of calculating frame loss at each node, we calculate frame loss based on the successful delivery of transmitted frames at the sink. We consider that a frame is lost if the link layer recovery fails to deliver the frame. Frame losses could occur due to collisions or corruption at the PHY layer. Packet delivery at the MAC layer from a source to a relay sensor node can also be seen in Fig. 2.7.

2.4.2. Simulations

All the results in this section are based on the analyses that are validated by rigorous simulations. We performed thorough simulations to verify the effectiveness of DCM on
Castalia 3.0 simulator, which is based on OMNeT++ 4.0 platform [32]. In both analysis and simulations we used the basic frame types of IEEE 802.15.4 standard as shown in Fig. 2.5. The CSMA/CA MAC parameters were set as: length of data frame ($L = 7$), length of ACK frame ($L_{ack} = 2$), back-off exponents ($macMaxCSMABackoff = 4$), and ($macMinBE = 3$). All the parameter values used for both analysis and simulation are listed in Table 2.1. All the radio parameters are taken from and CC2420 datasheet. The hardware parameter values are set according to MICAz motes. The channel bandwidth was set to 1 $Mb/s$. We assumed that each node reports data once every 300 $ms$ ($t = 0.3 s$). All simulations were run independently with each result is averaged under 10 different seeds.

Fig. 2.8 shows the average energy consumption comparison of a node $E_{comm}(k)$ with different loss rates. Initially, we deployed 50 homogeneous nodes randomly in a sensing field of area $100\times100m^2$ with each node having communication range of 10 $m$. Then we varied the number of nodes from 50 to 300 with fixed field area. We also increased the communication range gradually from 10 $m$ to 50 $m$ to see the impact. It is obvious from the figure that energy consumption is increased with the increase of communication range. One of the reasons is that with fixed area size, the neighbor nodes in the communication range of a source node will increase, which will results in more energy consumption due to packet forwarding. It is also clear that higher the frame loss rate, more the energy will be consumed.

Fig. 2.9 shows the comparison of average energy consumption of a node with overheads caused by multi-hop communications. We analyzed the results with different packet loss rates. It is clear from the figure that a node will consume more energy with the increase of communication range. Similarly, more energy is consumed with the increase in the number of hops from source to the sink during data propagation. However,
Table 2.1 Analysis and simulation parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial energy of node</td>
<td>3000 Joules (MICAz mote)</td>
</tr>
<tr>
<td>Sleep power ($P_{sleep}$)</td>
<td>0.016 (mW)</td>
</tr>
<tr>
<td>Idle power ($P_{idle}$)</td>
<td>12.36 (mW)</td>
</tr>
<tr>
<td>Transmit amplifier energy ($\varepsilon_{amp}$)</td>
<td></td>
</tr>
<tr>
<td>Data rate ($\lambda$)</td>
<td>100 pJ/bit/m²</td>
</tr>
<tr>
<td>Communication range ($r_c$)</td>
<td>0.6 to 250 Kbps</td>
</tr>
<tr>
<td>Network size ($</td>
<td>S</td>
</tr>
<tr>
<td>Frame loss rate ($f_l$)</td>
<td>50 to 300</td>
</tr>
<tr>
<td>Network area ($A$)</td>
<td>0 to 50%</td>
</tr>
<tr>
<td>Simulation time ($t$)</td>
<td>(100×100) m²</td>
</tr>
<tr>
<td>Frame size</td>
<td>(200 to 1000) seconds</td>
</tr>
<tr>
<td>Supply voltage to node ($V_s$)</td>
<td>2.7V</td>
</tr>
<tr>
<td></td>
<td>133 bytes (Data) 19 bytes (Control)</td>
</tr>
</tbody>
</table>
Figure 2.8: Average energy consumption $E_{\text{comm}}(k)$ versus different loss rate of frames ($l_f$), here, duty cycle ($\alpha$) = 1, $l_f = 100$ m, and $\lambda$ = 1 Kbps.

Figure 2.9: Comparison of average energy consumption including multi-hop overheads $E(h)$ with different $l_f$, here, $\alpha$=1, $|S|$=100, and $l$=100 m.
maximum communication range must be maintained according to the threshold analysis for optimal communicating range for a sensor node [25].

Fig. 2.10 shows the comparison of DCM with the energy model proposed in [18]. The energy model in [18] considered fixed clusters with single hop transmission. For comparison, we set all the parameter values similar to the parameter values in [18]. It is shown in the figure that the single hop network is more efficient compared to the multi-hop network. The energy consumption is increased with the increase of communication range of a node. It is also shown that with fixed network field size, the energy consumption is increased with the increase in the density of the network.

Fig. 2.11 shows comparison of the average lifetime versus sleeping time schedule of a node using DCM, with the models proposed in [18], [33], [34]. We set all the parameters same as used in [18] for lifetime analysis of a node. For DCM, we kept the packet loss rate to 10% of the total packet transmitted. For lifetime analysis, we also considered the energy consumption through a sensor processing, logging, sensing, and actuation along with the energy consumption due to data communication. It is indicated in the figure that
the overall lifetime of a node will be decreased with the increase in the packet loss rate. Therefore, if packet loss rate does not take into account, just like in previous energy models, then the measurement of the lifetime of a node will be over estimated. Consequently, it indicates that the packet loss rate is fundamental issue to consider while precisely estimating the lifetime of the network.

Fig. 2.12 shows the average energy consumption for a packet that is successfully delivered at the sink node. Simulation was performed by sending 300 packets to the sink with total simulation time as 1000 seconds. The result is based on the number of packets delivered at the sink. It is shown that the average energy consumption per packet in both GOSSIP and Directed Diffusion [36] routing techniques is slightly decreased with the increase in the packet delivery ratio.

Fig. 2.13 shows the comparison of energy efficiency by varying the number of hops and communication range of a node. It is shown in the figure that a network will be nearly 100% efficient, if nodes are directly connected with each other. However, due to limited communication range, a node has to communicate with the sink via multiple hops. It is shown in the figure that energy efficiency is gradually decreased with the increase of number of hops from source to the sink. Similarly, the energy efficiency can be achieved with the decrease of communication range with the condition that communication range must maintain the upper limit of optimum range. It means that multi-hop communication is less efficient in terms of energy compared to single hop when the source is in the
Figure 2.11: Lifetime (in days) versus sleeping time of a node with different energy models having AA Alkaline batteries (1500 mAh), here, $|S|=100$, $l=100$ m, $I_f$ for DCM = 10%.

Figure 2.12: Successful delivery of packets versus average energy consumption per packet using GOSSIP and Directed Diffusion.
communication range of the sink.

2.4.3. Experimental Setup

In order to further verify the analysis of energy consumption of a sensor node in error prone network environments, we conducted experiments in a laboratory environment. The IEEE 802.15.4 protocol is already implemented in the TinyOS [37] for the MICAz motes. We used 15 MICAz motes running TinyOS where IEEE 802.15.4 protocol was implemented. The parameter values of IEEE 802.15.4 were taken as default values. Networking stack of TinyOS includes a default PHY layer that supports Single Error Correction and Double Bit Error Detection (SECDED) capabilities. The default MAC layer of TinyOS implements a simple CSMA/CA scheme along with link layer ACKs. Each node was deployed in such a way that at least one node have another node in its radio range. We studied the effect of packet losses on the energy resources of a node. For each experiment, we plotted the distribution of frame loss within a one hour frame, i.e. 3600 transmitted frames across all the nodes on the way to the sink.

In the experiment, we determine the packet loss rate on the basis of packet loss.
During experiments, we found an interesting observation regarding the radio range of a sensor node. We observed that the communication range of a sensor node is approximately 2 m when it is on the ground, while about 5 m and 8 m when left above the ground for 1 m and 2 m, respectively. In Fig. 2.14, I determined the packet loss rate on the basis of these three scenarios. It is shown in Fig. 2.14 that the packet loss rate is increased with the increase of intermediate relay nodes.

Fig. 2.15 shows the comparison of energy consumption of a sensor node in the environment, where packet loss is conceived. We conducted the experiment by placing sensor nodes on the ground ($r_c = 2$ m approx.) and 2 m above the ground ($r_c = 8$ m approx.) Resemblance of energy consumption of a node considering link quality in experimental results with the theoretical analysis shows that the analysis is concrete and accurate.

![Figure 2.14: Packet loss rate with increasing no. of hops.](image-url)
Figure 2.15: Comparison of avg. energy consumption through analysis and experimentations, here, \(|S|=10, l=15 \text{ m.}\)

Figure 2.16: Lifetime (in days) versus sleeping time of a node having AA alkaline batteries (1500 \(mAh\)), here, \(|S|=10, l=15 \text{ m.}\)

Finally, in Fig. 2.16, we determined the average lifetime of a node when packet loss rate is around 5% and 15%. Average lifetime of sensor node with these error rates shows
similar trend in both theoretical analysis and experimental setup. Minor difference in results can be further accommodated by including the phenomena of latency, delay, and similar factors due to surrounding environments. From this similar trend, we conclude that the energy consumption analysis of a sensor node is comprehensive and realistic.

2.5. Conclusion

In this chapter, a comprehensive distributed communication model for WSNs has proposed that takes into account variety of parameters such as packet loss rate due to the weak links, duty cycle, and the density of the network, number of neighbors in the radio range of a node, and the data rate in multi-hop communication. It has verified that the quality of link, which is affected by characteristics like symmetry, directivity, instability, and irregularity of the radio range, has direct impact on the overall energy consumption of a sensor node. In addition, the effects of packet loss rate on the energy consumption due to data propagation accurately determined. It has also proved that the link quality has direct impact on the lifetime of a network. The model was verified through simulations and experiments on MICAz motes. To the best of our knowledge, this is the first energy model that takes the link quality into considerations. We believe that the model will be helpful to accurately design different network strategies for estimating energy consumption due to data propagation in the error-prone environments, where there is possibility of significant packet loss.
Chapter 3

Power Dissipation Analysis of IEEE 802.15.4 Distributed Multi-hop Wireless Sensor Networks

3.1. Introduction

The world of distributed systems has been revolutionized through Wireless Sensor Networks (WSNs) due to the diverse roles of WSNs in our society. In Chapter 2, a general energy estimation model called Distributed Communication Model (DCM) was introduced, which considered different factors that are associated with multi-hop networks in a network environment where packet loss is expected. DCM can be used for any kind of MAC protocol. In this chapter, power dissipation of these parameters is analyzed, specifically taking into consideration, the Zigbee Alliance [7] and IEEE 802.15.4 standard [8], where the Medium Access Control (MAC) parameters behave in an unpredictable way. The probability to estimate power dissipation during such unpredictability of different MAC protocol parameters is analyzed in this chapter.

As explained in Chapter 1, the IEEE 802.15.4 standard is specifically designed to meet the requirement of Low Rate Wireless Personal Area Networks (LR-WPAN) that enable a variety of WSNs applications. This standard specifies Medium Access Control (MAC) and physical (PHY) layers. The IEEE 802.15.4 networks can operate in either a non-beacon or beacon enabled mode. In the non-beacon mode, sensor nodes in the Personal Area Networks (PAN) communicate with each other through un-slotted Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) protocol. On the other hand, in the beacon enabled mode, sensor nodes communicate with each other according to a slotted CSMA/CA protocol based on a super-frame structure whose behavior is explained in Chapter 1.
It can be inferred from related works that the power dissipation analysis of single-hop IEEE 802.15.4 networks is a well thought-out subject; however, there is very little focus on the power dissipation over multi-hop WSNs. From the literature, it is observed that the proposed energy models [37]-[40] for WSNs do not consider power dissipation through distributed multi-hop communication.

By surveying the MAC protocols designed for WSNs, it is shown that most of the protocols are based on a CSMA access mechanism. However, energy estimation models like the one proposed in [18], considers TDMA protocols only for energy analysis. A major drawback with TDMA based protocols is that such protocols need a good centralized synchronization scheme. Such schemes are not easy to implement in dynamic networks like distributed WSNs. It is necessary to determine the power dissipation model for CSMA/CA based MAC protocols that take the states like back-off, carrier sensing, idle listening, sleeping, and data transmission in power dissipation analysis into account.

In this chapter, power dissipation for slotted CSMA/CA based IEEE 802.15.4 distributed multi-hop WSNs is thoroughly analyzed. The model investigates the effect of frame loss rate, neighbor nodes density in communication range of a node, distance of source to the sink, density of the network, and overheads caused by multi-hop communication. In addition, the impact of these factors on power dissipation due to data communication via a variety of viewpoints using IEEE 802.15.4 as MAC protocol is evaluated here.

The remainder of the chapter is organized as follows. Section 3.2 describes related works. Section 3.3 introduces the power dissipation model along with overheads analysis in WSNs. Section 3.4 discusses the analysis and simulation of the proposed model. Conclusions are then provided in Sect. 3.5.

3.2. Related Works

Significant research works have been conducted to determine energy consumption or in other words, power dissipation of a sensor node in WSNs. Most of these research works are based on the assumption of single hop communication. Initially, one research group in
[21] proposed a model for the energy consumption of communication module for WSNs. In this model, the energy consumption was calculated based on power dissipation through transceiver, amplifier and the distance between the source and destination. Another research group in [23] extended the work done in [21] with a notable change of increasing the path loss exponent $\beta$.

It is found that most of the energy models proposed for WSNs are based on the model defined in [21] and [23]. For example, the authors in [40] deduced the upper limit of centralized, single hop distance between source and destination. Another group [41] used the energy model to study energy efficient routing protocols in WSNs. The authors in [42] utilized the energy model to study the problem of maximizing network lifetime through balancing energy consumption of uniformly deployed sensor nodes for data gathering in WSNs. Ref. [22] is an exception, where the authors proposed their own energy model that derives the conditions for minimum sensor networks power consumption for sensor node data from source to destination.

The most comprehensive energy consumption model was claimed in [18], where the authors considered seven different energy consumption factors. However, this model does not take link quality and packet loss rate into account. In addition, this model is specifically designed for Time Division Multiple Access (TDMA) based MAC protocols that require centralized synchronization. It is observed that most of effective MAC protocols for WSNs are based on CSMA based protocols, which are not dependent on centralized approach and thus ideal for distributed systems. The authors in [37] proposed an analytical Markov Chain model for the slotted CSMA /CA of IEEE 802.15.4 standard of WSNs for energy estimation. However, the model only considered the energy consumption in single hop communication. Several simulation based studies such as [43], [44], and analytical works, such as [45–47], investigated energy consumption of IEEE 802.15.4 in addition to delay and throughput.

### 3.3. Power Dissipation in Distributed Multi-hop WSNs

The power dissipation model is based on the basic energy model proposed in [21].
3.3.1. Basic Model

The power dissipated by a node $k$ sending a query frame $q$ to the sink and getting a reply frame $r$ in a square sensor field with side length $l$, is given by:

$$ P_{\text{comm}} = \left( \epsilon_{ktr} N_{ktr} R_{ktr} + \epsilon_{ktq} N_{ktq} R_{ktq} \right) d_{kts} $$  \hspace{1cm} (3.1)

where, $\epsilon_{ktr}$ is power dissipated through transmitting and receiving a reply frame $r$, $N_{ktr}$ is the number of reply frames, and $R_{ktr}$ is the number of retransmission times for reply frames, through node $k$ at moment $t$. Similarly, $\epsilon_{ktq}$ is power dissipated through transmitting and receiving a query frame $q$, $N_{ktq}$ is the number of query frames, and $R_{ktq}$ is the number of retransmission times for query frames, through node $k$ at moment $t$. Here,

$$ \epsilon_{ktq} = \epsilon_{ktr} = \left( p_{rx} + p_{tx} + \epsilon_{\text{amp}} r_{c}^{\beta} \right) $$ \hspace{1cm} (3.2)

where, $p_{rx}$ and $p_{tx}$ are the amounts of power dissipated for transmitting a single bit by receiver and transmitter circuits, respectively. $\epsilon_{\text{amp}}$ is the amount of power dissipated by amplifier. $r_{c}$ is the communication range of a node with path loss exponent value $\beta$ that varies from 2 to 4. Finally in (3.1), $d_{kts}$ is the average random distance from any node $k$ to the sink at moment $t$ with the condition that the node area will have square type shape. The details of calculating $d_{kts}$ can be found in previous work for error free energy estimation and lifetime modeling [48], which is given by:

$$ d_{kts} = \left( \frac{0.521l}{r_{c}} + 0.5 \right) $$ \hspace{1cm} (3.3)

In CC2420 chip communication, data are transmitted in the form of frames, which are composed of bytes. Each byte is divided into two symbols during the communication process. Next, each symbol is mapped into chip sequence from a local symbol to chip mapping table. Finally, the chip sequence is transmitted through an Offset Quadrature Phase Shift keying (O-QPSK) modulation [49]. This process is shown in Fig. 3.1.

The CC2420 is a low cost, highly integrated and a true single chip 2.4 GHz IEEE
802.15.4 compliant Radio Frequency (RF) transceiver designed for low power wireless applications. It provides extensive hardware support for data buffering, data authentication, burst transmissions, data encryption, clear channel assessment, packet handling, packet timing information, and link quality indication.

![Data transmission process using IEEE 802.15.4 standard.](image)

3.3.2. Link Quality Evaluation

Suppose that the frame loss rate is denoted by $l_f$. Then the number of frame retransmission times due to weak links will be:

$$P_{\text{rtx}} = l_f + 2l_f(1-l_f) + 3l_f^2(1-l_f) + 4l_f^3(1-l_f) + \ldots = \frac{1}{1-l_f}$$  \hspace{1cm} (3.4)

where, $l_f = 1 - (1 - l_s)^{2/\lambda}$  \hspace{1cm} (3.5)

Here, $l_s$ is the symbol error rate and $\lambda l$ is the frame length. The frame reception rate ($r_f$) will be equal to:

$$r_f = 1 - l_f$$  \hspace{1cm} (3.6)

$$r_f = (1 - l_s)^{2/\lambda}$$  \hspace{1cm} (3.7)

In WSNs, frame loss is the only reason to cause packet loss under the case of perceived packet loss. It means that both frame loss and perceived packet loss will be equal. Perceived packet loss means that a receiver has successfully perceived the synchronization head; but there are some incorrect symbols in the frame length field or MAC data unit field or both of them. The above analysis indicates that if the frame length is fixed, $r_f$ will be influenced by $l_s$ only, which is influenced by chip error rate. According to the CC2420 datasheet, Chip Correlation Indicator (CCI) can be considered as a measurement of chip error rate. We can draw the relationship between CCI and $r_f$ when
the relationship between CCI and $l_s$ is available, which is the key issue here.

There are various factors that cause failure of data frame transmission such as, multi-path effects, wave reflection and diffraction, and the interference from the surrounding environment. These factors will cause the change in the chip sequence. The changed chip sequence will make comparator to select other chip sequence instead of the one transmitted by sender. Therefore, the wrong selection will result in the mapping error in the chip sequence to symbol mapping phase that will lead to the failure of transmitted frames.

By taking power dissipation due to data communication with the probability that frames may loss and retransmission may occur, (3.1) can be re-written as:

$$P_{comm} = \left( \frac{\varepsilon_{kr} P_{kr}}{1 - l_{fkr}} + \varepsilon_{ktq} |S_{rc}| \right) d_{kts}$$

(3.8)

Here, $l_{fktq}$ and $l_{fkr}$ are the loss rates of query and reply frames at moment $t$ for a node $k$, respectively. $|S_{rc}|$ is the neighbor nodedensity. For long terms view, the loss rate of query and reply frames should be kept same, i.e. $l_{fktq} = l_{fkr} = l_f$. $P_{ktr}$ is the probability that the frame will pass through the node $k$ at moment $t$, which is given by:

$$P_{ktr} = \left( |S| - \pi \rho d^2_{kts} \right) \frac{2 d_{kts} \pi r^2_c \rho}{2 d_{kts} \pi r^2_c \rho}$$

(3.9)

where, $|S|$ is total number of sensor nodes, and $r_c$ is the communication range of sensor node. For simplicity, we assume that communication range will be sphere. Here $\rho$ is the density of the network, which can be determined as:

$$\rho = \frac{|S|}{l \times l}$$

(3.10)

Average power dissipation for packet transmission including (successful transmission and collision) by using slotted CSMA/CA protocol defined by IEEE 802.15.4 standard has been determined in [3], which is given by:
\[ p_{\text{comm}} = P_{c_s} (1 - P_{\text{CCA1}}) (1 - P_{\text{CCA2}}) (p_{\text{rx}} (1 - P_c) L_{\text{ack}} + p_{\text{rx}} L + p_{\text{idle}} (1 + P_c)) \] (3.11)

where, \( P_{c_s}, P_{\text{CCA1}}, P_{\text{CCA2}}, \) and \( P_c \) are the probabilities of carrier sensing, busy Carrier Channel Assessment (CCA1), CCA2, and collision, respectively. \( L_{\text{ack}}, L, \) and \( p_{\text{idle}} \) are length of ACK frame, length of transmitted frame, and power dissipation in idle listening mode. Each of these probabilities is determined in [37], which is given by:

\[
p_{c_s} = \left( \frac{1 - x^{m+1}}{1 - x} \right) \left( \frac{1 - y^{m+1}}{1 - y} \right) b_{0,0,0} \]
(3.12)

where, \( y = P_c (1 - x^{m+1}) \)
(3.13)

\[
x = P_{\text{CCA1}} + (1 - P_{\text{CCA1}}) P_{\text{CCA2}} \]
(3.14)

\[
m = \text{macMaxCSMABackoff} \]

\[
W_0 = 2^{\text{macMinBE}} \]

Here, \( \text{macMaxCSMABackoff} \) and \( \text{macMinBE} \), are back-off exponents of CSMA/CA MAC protocols whose default values are taken as 4 and 3, respectively.

\[
P_c = 1 - (1 - P_{c_s})^{N-1} \]
(3.15)

In (3.12), \( b_{0,0,0} \) is the three dimensional per link Markov chain. The subscripts \( (0, 0, 0) \) represent back-off stage, the state of back-off counter, and the state of retransmission counter.

\[
P_{\text{CCA1}} = P_a + P_b \]
(3.16)

where,

\[
P_a = L (1 - (1 - P_{c_s})^{N-1}) (1 - P_{\text{CCA1}}) (1 - P_{\text{CCA2}}) \]
(3.17)

\[
P_b = L_{\text{ack}} \frac{NP_{c_s} (1 - P_{c_s})^{N-1}}{1 - (1 - P_{c_s})^N} (1 - (1 - P_{c_s})^{N-1}) (1 - P_{\text{CCA1}}) (1 - P_{\text{CCA2}}) \]
(3.18)

\[
P_{\text{CCA2}} = \frac{1 - (1 - P_{c_s})^{N-1} + NP_{c_s} (1 - P_{c_s})^{N-1}}{2 - (1 - P_{c_s})^N + NP_{c_s} (1 - P_{c_s})^{N-1}} \]
(3.19)

where, \( N \) is the number of sensor nodes. Using these probabilities values in (3.11), we can determine the power dissipation for multi-hop communication of a node. From (3.2),
(3.3), (3.8), and (3.9), power dissipation due to data communication for a node $k$ can be calculated as:

$$
 p_{\text{comm}} = P_{cs} (1 - P_{\text{CCA1}}) (1 - P_{\text{CCA2}}) \left( \frac{p_{\text{rx}} (1 - P_{c}) L_{\text{ack}} + p_{\text{tx}} L + e_{\text{amp}} f \beta + p_{\text{idle}} (1 + P_{c})}{(1 - \beta)^{2} \pi c^2 p} \left[ S - \pi p \left( \frac{0.52 l}{r_c} + 0.5 \right)^2 \right] \right)
 + \left[ p_{\text{rx}} (1 - P_{c}) L_{\text{ack}} + p_{\text{tx}} L + e_{\text{amp}} f \beta + p_{\text{idle}} (1 + P_{c}) \right] S_{rc} \right) \right)
$$

(3.20)

From [37], power dissipation during back-off state is given by:

$$
 p_{\text{backoff}} = \frac{P_{idle} P_{cs}}{2} \left( \frac{(1 - x) (1 - (2x)^{m+1})}{(1 - 2x)(1 - x^{m+1})} W_0 - 1 \right)
$$

(3.21)

Power dissipation for sensing a channel is given by:

$$
 \overline{p}_{\text{ch.sens}} = p_{\text{ch.sens}} (2 - P_{\text{CCA1}}) P_{cs}
$$

(3.22)

3.3.3. Total Power Dissipation

For estimating total power dissipation of a node, let's assume that average power dissipation during sleeping mode is negligible, i.e. $P_{\text{sleep}} = 0$. By summing up (3.20), (3.21), and (3.22), the average power dissipation of a node using IEEE 802.15.4 standard with CSMA/CA as MAC protocol is given by:

$$
 p_{\text{total}} = p_{\text{backoff}} + \overline{p}_{\text{ch.sens}} + p_{\text{comm}}
$$

$$
 p_{\text{total}} = \frac{P_{idle} P_{cs}}{2} \left( \frac{(1 - x) (1 - (2x)^{m+1})}{(1 - 2x)(1 - x^{m+1})} W_0 - 1 \right) + p_{\text{sc}} (2 - P_{\text{CCA1}}) P_{cs} + (1 - P_{\text{CCA1}})(1 - P_{\text{CCA2}}) P_{cs}.
$$
This is a general, but comprehensive power dissipation model for distributed multi-hop communication.

3.3.4. Overheads Impact on Power Dissipation

In this section, we analyze power dissipation due to overheads caused by centralized single hop communication, distributed multi-hop scheme, and synchronous idle listening and sleeping schedules through the model.

3.3.4.1. Power Dissipation due to Overheads of Multi-hop Communication

In the following analysis, we use $p_{\text{comm}}(h)$ to denote the total power dissipation for sending data from source to destination via $h$ hops. The power dissipation due to data transmissions via $h$ hops can be calculated as:

$$
p_{\text{comm}}(h) = p_{\text{comm\_rx}}(h) + p_{\text{comm\_tx}}(h) + p_{\text{comm\_idle}}(h)
$$

$$
p_{\text{comm}}(h) = (h-1)p_{\text{rx\_1}} + hp_{\text{tx\_1}} + h(h - 2)p_{\text{idle\_1}}
$$

(3.25)

where, $p_{\text{comm\_rx}}(h)$, $p_{\text{comm\_tx}}(h)$, and $p_{\text{comm\_idle}}(h)$ denote the total power dissipation for receiving, transmitting, and idle listening via $h$ hops, respectively. $p_{\text{rx\_1}}$, $p_{\text{tx\_1}}$, and $p_{\text{idle\_1}}$ denote the single hop power dissipation during receiving, transmitting, and idle listening, respectively. In order to send a data frame from source to the sink successfully, $h$ units of energy is required in transmission mode and $h-1$ units of energy in receiving mode. When there are $h$ duty cycles in total, then in each duty cycle, $h-2$ nodes will be in idle listening mode. Hence, in idle listening mode, the entire network consumes $h(h-2)$ units of energy.
The power dissipation for idle listening mode in a unit time is denoted by $p_{\text{idle}}$, the power dissipation for receiving one bit is denoted as $p_{\text{rx}}$, and the power dissipation for transmitting one bit via $h$ hops is denoted as $p_{\text{tx}}(h)$. Then the power dissipation via multi-hop communication is given by:

$$p_{\text{m\_comm}}(h) = (h-1)(p_{\text{rx}}(b_c + b_d) + p_{\text{tx}}(h)(b_c + b_d) + p_{\text{idle}}t_2) + h(p_{\text{rx}}(b_c + b_d) + p_{\text{tx}}(b_c + b_d) + p_{\text{idle}}t_1) + h(h-2)(p_{\text{idle}}t_2)$$

(3.26)

3.3.4.2. Power Dissipation via Single Hop Communication

Power dissipation for a single hop network can be determined as:

$$p_{\text{s\_comm}} = p_{\text{rx}}b_c + p_{\text{tx}}(h_1)b_d + p_{\text{idle}}t_1$$

(3.27)

It is obvious that sleeping schedule is not required for single hop communication. Therefore, power dissipation of the source node will be required only. Source node senses an empty channel over the interval $t_1$, transmits $b_d$ bits of a data frame, and receives $b_c$ bits of an ACK frame. In (3.27), $p_{\text{tx}}(h_1)$ denote the power dissipation for transmitting one bit from source to the sink directly.

3.3.4.3. Power Dissipation in Single Hop versus Distributed Multi-hop Communication

Comparing $p_{\text{s\_comm}}$ and $p_{\text{m\_comm}}(h)$, it is clear that $p_{\text{s\_comm}} < p_{\text{m\_comm}}(h_1)$. Consequently, it can be deduced that if $p_{\text{s\_comm}} < p_{\text{m\_comm}}(h_2)$ then $p_{\text{s\_comm}} < p_{\text{comm}}(h)$, where $h > 2$. Hence, we can simplify the analysis by comparing a single hop network with a 2-hop network only. We have to find the minimum transmit power level, which can satisfy $p_{\text{s\_comm}} < p_{\text{m\_comm}}(h_2)$. From (3.26) and (3.27) we have,

$$p_{\text{m\_comm}}(h_2) - p_{\text{s\_comm}} = p_{\text{rx}}(4b_c + b_d) + p_{\text{tx}}(h_2)(4b_c + b_d) - p_{\text{tx}}(h_1)b_d + p_{\text{idle}}(t_1 + t_2)$$

(3.28)

Lets assume that the time for waiting empty channel is relatively short, the time to transmit a single control frame can also be defined as one time unit. Then $t_1 = 0$ and $t_2$ will be equal to the time taken for transmitting $b_c$ bits. For transceivers, usually $p_{\text{idle}} = p_{\text{rx}}$. 
Figure 3.2: Four basic frame types defined in IEEE 802.15.4 MAC protocol.

Therefore,

\[ p_{idle} = p_{tx} b_c \]  \hspace{1cm} (3.29)

By utilizing the idea of (3.29), (3.28) can be rewritten as:

\[ p_{m\_comm}(h_2) - p_{s\_comm} = p_{tx}(5b_c + b_d) + p_{tx}(h_2)(4b_c + 2b_d) - p_{tx}(h_1)b_d \] \hspace{1cm} (3.30)

The minimum transmit power level \( p_{min} \), which can satisfy \( p_{s\_comm} < p_{m\_comm}(h_2) \) with optimal communication range \( r_c \) and data rate is:

\[
p_{min}(r_c) \leq \min \left[ p_{max}, \left( p_{tx}(2-P_{CCA1})P_{cs}^2 + (1-P_{CCA1})(1-P_{CCA2})P_{cs}^2 \right) \right] \cr \cr \left( \frac{p_{tx}(4b_c + b_d)(1-P_{cs})L_{ack} + p_{tx}(5b_c + b_d)L + \varepsilon_{amp}f_c^\beta + p_{idle}(1+P_{cs})}{(b_c + b_d)(1-l_f)\pi r_c^2 \rho} \right) \left\{ \frac{S - \pi d_{tx}^2}{2d_{tx}} \right\} \cr \cr + \left[ p_{tx}(4b_c + b_d)(1-P_{cs})L_{ack} + p_{tx}(5b_c + b_d)L + \varepsilon_{amp}f_c^\beta + p_{idle}(1+P_{cs}) \right] S_{re} \right] \right\} \left( \frac{b_c + b_d}{d_{tx}} \right) \right\} \cr \cr \right\} \] \hspace{1cm} (3.31)

Fig. 3.2 shows the IEEE 802.15.4 standard frame types. The maximum payload size of data frame is 114 bytes. Therefore, \( b_c \) and \( b_d \) will be 19 bytes and 133 bytes, respectively. To analyze (3.31), it is simplified that the sleeping schedule of multi-hop causes to increase the \( p_{comm} \) by approximately 2.6 times compared to the sleepless single hop.
communication. It implies that single hop communication is about 160% more energy efficient than multi-hop in terms of sleeping schedule. However, in WSNs the centralized approach is useful and energy efficient only in small networks. For large networks, which aim for longer lasting, the distributed approach is the ultimate solution.

3.4. Performance Evaluation

CSMA/CA based MAC protocols depend on the exponential back-off state, collision rate, the frame length, the carrier detect state, the network size, the inter frame gap, and the baud rate. When using multi-hop communication, various aspects such as the latency of processing of each hop must be considered. In addition, it must be checked whether the hops are stored and forwarded or when conditions permit it can cut through. After considering these factors, it is decided to perform Monte Carlo simulation to validate the analysis. The simulations are based on the specification of the IEEE 802.15.4 [8]. The CSMA/CA MAC parameters were set to $m=4$, $L=7$, and $L_{ack}=2$. In both analysis and simulations, basic frame types of IEEE 802.15.4 standard were used as shown in Fig. 3.2. All the radio parameters were taken from Chipcon CC2420 datasheet. The hardware parameter values were set according to MICAz Motes. Throughout the simulation, the sensing field area was set to $100 \times 100 \, m^2$. The channel bandwidth was set to $1 \, MHz$. It is assumed that each node reports data once every $300 \, ms$. All the simulations were implemented independently with each result was averaged under 15 different seeds.

Initially, an order to validate the concreteness of the model, i.e. to verify that the analysis results fit with simulation results, we evaluated the power dissipation of a node with frame loss rate as shown in Fig. 3.3. A network scenario was designed where 100 nodes were deployed randomly in the sensing field. It is shown in Fig. 3.3 that the power dissipation value of each node from both analysis and simulation is increased with the increase of communication range and frame loss rate, respectively. Fig. 3.3 verifies that with similar network conditions, similar results trend with both analysis and simulation is achieved. Additionally, similar result trends from both analysis and simulation can be achieved by increasing or decreasing the number of deployed nodes.

Fig. 3.4 shows the average power dissipation comparison of a node $p_{total}$ (3.24) with
frame loss rate as 0% and 50% versus communication range and number of nodes. Initially, a network scenario was designed where 50 homogeneous nodes were deployed randomly with each node having communication range of 10m. The number of nodes was increased gradually from 50 to 300 while keeping the field area as fixed. The communication range was also increased gradually from 10m to 50m. It is observed from the figure that power dissipation is increased with the increase of communication range. It is also realized that the higher the frame loss rate, the more energy will be consumed.

Fig. 3.5 shows the comparison of average power dissipation of a node with overheads caused by multi-hop communication with number of hops and communication range of each node. The results were analyzed with different frame loss rates taken as 25% and 50%. It is clear from the figure that with a fixed number of hops, more power was dissipated with the increase of communication range of a node. It is observed that in the error-prone environment, power dissipation is increased with the increase of number of hops from source to the sink having constant communication range.

Fig. 3.6 shows the comparison of the model (through both analysis and simulation) with the models proposed in [18] and [37]. The energy model proposed in [18] considered fixed clusters with single hop transmission using TDMA. While in [37], the energy model is proposed for single hop communication using CSMA/CA. For comparison, all the parameter values were set similar to the parameter values in [18]. It is shown that a single hop network is more efficient compared to a multi-hop network. The power dissipation increases with the increase of communication range of a node. In addition, with fixed network field size, the power dissipation increases with the increase
Figure 3.3: Comparison of avg. power dissipation analysis of a node (3.24) with simulation results. Here, $|S|=100$, $l=100m$, data rate = 2Kbps.

Figure 3.4: Comparison of avg. power dissipation $p_{total}$ with $l_f=0\%$ and 50\% $l = 100$ m, data rate = 1Kbps.
Figure 3.5: Comparison of average power dissipation via multi-hop communication with overheads having $l_f=25\%, 50\%, |S|=100$, $l=100m$.

Figure 3.6: Average power dissipation of a node $p_{\text{total}}$ (3.24) with models proposed in [18] and [37]. Here, $l_f=0\%$, $l=100m$, data rate = $2Kbps$. 
Fig. 3.7 shows the comparison of energy efficiency by varying the number of hops and communication range of a node. It is observed from the figure that a network will be nearly 100% efficient, if nodes are directly connected with each other. However, due to limited communication range, a node has to communicate with the sink via multiple hops. It is also shown in the figure that with the increase of number of hops from source to the sink, the energy efficiency decreases gradually. In addition, with a fixed number of hops, the energy efficiency can be achieved with a decrease of communication range with the provision that communication range must maintain the upper limit of optimum range. It means that multi-hop communication is less energy efficient compared to single hop
Figure 3.8: Lifetime (in days) versus sleeping time of a node with the energy models. Each node has AA Alkaline batteries (1500 mAh). Here, |S|=100, l=100m.

when source node is in the communication range of the sink.

Fig. 3.8 shows a comparison of the average lifetime versus sleeping time schedule of a node using the model, with the models proposed by Halgamuge et al., Mille et al., Zhou et al., and Heinzelman et al. All the parameters values were set similar as used in [18] for lifetime comparison of a node. We determined the remaining lifetime of a node using the model with frame loss rate as 0%, 10%, 20%, and 30%, respectively. For accurate lifetime analysis, all power dissipation factors such as processing, logging, sensing, and actuation along with the power dissipation due to data communication were considered. It is shown in Fig. 3.8 that the overall lifetime of a node by using the model, is decreased with the increase in frame loss rate during transmission. In fact, the increase in frame loss rate is the main factor, which decreases the overall lifetime of a node. In other energy models, frame loss rate shows no effect on the power dissipation of a node. It indicates that if frame loss rate is ignored, the measurement of the lifetime of a node will most probably be over estimated.
3.5. Conclusion

In this chapter, a CSMA/CA based comprehensive distributed power dissipation model has proposed for IEEE 802.15.4 multi-hop WSNs. The model took into account variety of parameters such as frame loss rate, density of network, and number of neighbors in communication range of a node into consideration. It has been verified that the link quality has direct impact on the overall power dissipation of a node, which ultimately affect the lifetime of the network. Furthermore, the effects of frame loss rate on the power dissipation due to data communication along with overhead were determined. The model was then analyzed through detailed data analysis and Monte Carlo simulations. To the best of our knowledge, this is the first comprehensive multi-hop CSMA/CA based power dissipation model. We believe that the model will contribute to accurately designing the different network strategies for estimating power dissipation through multi-hop communication in distributed network environments.
Chapter 4

Hybrid Adaptive Channel Quality Estimation in IEEE 802.15.4 Multi-hop Wireless Sensor Networks in Error-Prone Environment

4.1. Introduction

Wireless Sensor Network (WSNs) has shown tremendous progress in the last decade due to its significant contribution in a variety of promising solutions in diverse application scenarios. The scale of WSNs deployments for real-life applications has rapidly increased and it is expected that most of the academic research in WSNs will be transferring into industrial research and practical implementation in the near future. The deployment of WSNs is believed to be very useful in applications like emergency responses and in disaster area management, such as the monitoring of an area polluted with nuclear radiation, where human intervention is hazardous to human health and in some situation rather impossible due to severe circumstances [3],[49],[50].

In error-prone WSNs, energy efficiency and reliability are the key issues that need to be tackled for a realistic deployment of sensor nodes. It has been observed that a WSNs that operates in such environment usually suffer from serious reliability issues. Therefore effective and efficient mechanisms should be provided to achieve reliability with low energy expenditure in such environments. For energy efficiency, the WSNs protocol stack needs to be tuned according to the actual requirements. Due to noisy wireless channel and the failure probability of sensor nodes in dynamic WSNs environment, the network can be unstable at times. In distributed WSNs, packet routing takes place through multi-hops as shown in Fig. 4.1. However, in multi-hop communications, reliability is a key factor, especially in error-prone environments where channel quality may degrades considerably with the passage of time [49-54].
Energy efficiency is an important factor in WSNs as sensor nodes are typically powered by batteries, which have limited energy resources. In most of the applications, sensor nodes cannot be replaced nor recharged due to the nature of environment or cost constraints. While the energy consumption analysis of single-hop IEEE 802.15.4 networks is well investigated, there is not yet a clear insight about the energy consumption with reference to reliability in the multi-hop networks[1],[4].

Quality of a communication link that is established between two neighboring nodes in the IEEE 802.15.4 multi-hop networks is an important factor for reliable data transfer, which in turn is provided by a channel quality estimation metrics. There are various channel quality estimators that have been proposed to cope with the unpredictability of the communication channel.

These channel quality estimators can be divided into three categories, i.e. physical, logical, and hybrid.

In physical channel quality estimators, the channel quality assessment are provided by the radio hardware, which are based on the signal strength of a received packet, such as Signal to Noise Ratio (SNR), Received Signal Strength Indicator (RSSI), and Chip
Correlation Indicator (CCI) [11]. In WSNs, the real sensor nodes, such as Telos and MICAz [12] motes use Chipcon CC2420 radio [13]. Logical channel quality estimators, assess the channel quality by keeping track of packet loss, such as Expected Transmission Count (ETX) [14], i.e. the number of transmissions required to successfully transmit a packet, the Required Number of Packets (RNP), and the Packet Success Rate (PSR). Hybrid channel quality estimators are the combination of both physical and logical channel quality estimators by exploiting the characteristics of both to assess the channel quality. Example of hybrid is Four-Bit (4B) estimator [15], which uses cross layer approach by utilizing information from physical (white bit), link layer (Ack bit), and network layer (compare and pin bits). 4B exploits the radio channel quality information from physical (PHY) layer in the form of Link Quality Indicator (LQI) and combines it with the estimation of ETX and information from the network layer for better path quality estimation.

In this chapter, we propose a hybrid and adaptive parameters tuning based channel quality estimation, which is specifically designed for IEEE 802.15.4 Medium Access Control (MAC) protocol. The proposed scheme estimates the current channel conditions, and changes MAC parameters adaptively according to the required level of reliability. It outperforms all state of the art channel estimation approaches in terms of accuracy, energy consumption, end to end delivery, and packet latency.

The remainder of the chapter is organized as follows. Section 4.2 describes the related works. Section 4.3 introduces the HAPTE and compares different channel quality estimators. Section 4.4 shows simulation results. Section 4.5 concludes the chapter.

4.2. Related Works

The performance of different channel estimation metrics has been extensively covered in literature. Conventional metrics include number of hop, round trip time and delay, normally failed to provide highly reliable and accurate path estimation in WSNs. In [14], De Couto et al. proposed ETX where they verified that a metric based on reliability can achieve better performance in terms of routing compared to the shortest hop count. In [57], Woo et al. proposed an effective design for multi-hop routing where they also
verified that the reliability based metrics like ETX are generally suitable in cost-based routing scenarios.

Initially, the link quality was assessed based on SNR. The relationship between SNR and the link quality in energy constrained WSNs is introduced in [58]. They verified that when SNR was above a defined threshold, the packet success rate would remain high regardless of the actual SNR value. However, when SNR is below the threshold, packet success rate will drop significantly. Therefore, they proposed to measure the SNR in addition to a cost based metric similar to ETX. However, they did not perform a concrete implementation to verify their proposal.

Recently, radios such as CC1000 and CC2420 that are based on IEEE 802.15 standard provide LQI and CCI to indicate the quality of a received packet at the receiver. The hybrid channel quality estimation, i.e. 4B integrates LQI with ETX to provide an interface to the routing protocol. They showed that 4B can achieve better performance compared to LQI alone by combining information from the physical layer, link information from ETX and routing information from network layer. However, they did not consider the MAC parameter values in different network scenarios. The logical estimator developed in [59] used four channel quality metrics that give a holistic assessment of the link and its dynamic behavior without specifying impact on the energy resources of a sensor node.

The reviewed literature shows that very little research has been conducted on energy expenditure of data communication in multi-hop networks using IEEE 802.15.4 protocol in error-prone environment where reliability is a key issue. In the framework of IEEE 802.15.4 based WSNs, many research works such as [60],[61] pointed out that a considerable amount of transmitted packets may be lost due to contention or congestion, especially when sensor nodes are deployed in large number and the packet size is large. Some realistic network issues have been pointed out in [62], [63], [64], [65]. In these research works, the authors evaluated a variety of aspects that were related to the IEEE 802.15.4 MAC performance. However, they did not find out limitations in the MAC protocol behavior, specifically in a situation where channel quality is very weak. In [54],
authors evaluated energy and reliability in IEEE 802.15.4/Zigbee standard. They proposed a cross-layer framework for reliable and energy-efficient data collection in WSNs. The framework involves an energy-aware adaptation module that captures the application’s reliability requirements, and autonomously configures the MAC layer based on the network topology and the traffic conditions to minimize the power consumption.

4.3. Adaptive Parameters Tuning Based Hybrid Channel Quality Estimations

In error-prone WSNs environments, such as disaster area coverage, the quality of wireless communication channels may significantly degrade with the passage of time. A sensor node can measure its own experienced reliability, in terms of the packet delivery ratio, which characterizes the packet losses due to both contention and channel errors. Each node can evaluate if a packet has been lost due to the maximum number of back-off stages ($\text{macMaxCSMABackoff}$) or the maximum number of retransmissions ($\text{macMaxFrameRetries}$) has been exceeded. In first case, the channel is sensed busy at every transmission attempt, i.e. during every Clear Channel Assessment (CCA) after the expiration time of the backoff. As a result, the packet is discarded at the MAC layer of the sender node without being transmitted through the channel.

This kind of packet loss is obviously related to contention, as it is only triggered by the channel being busy for long time occupied by other nodes. In the other case, either the message collided with transmissions by other nodes at the destination or it was corrupted owing to channel errors. IEEE 802.15.4 MAC does not provide an RTS/CTS mechanism, therefore, collisions can happen due either to the hidden node problem or actual simultaneous transmissions. With adaptively setting parameter values of IEEE 802.15.4 MAC protocol, then collisions due to hidden nodes can be neglected, and the packet loss occurred by an excessive packet retransmissions can be considered due to channel errors.

There are various factors that caused failure of a packet transmission, such as wave reflection and diffraction, multi-path effects and the interference from the surrounding environment. These factors cause the change in the chip sequence when using chip
communications such as Chipcon CC2420 radio. The changed chip sequence makes comparator to select other chip sequences instead of the one transmitted by sender node. Hence, the incorrect selection results in the mapping error in the chip sequence to symbol mapping phase that leads to the failure of transmitted packets.

Quality of a link established between two neighboring nodes in the IEEE 802.15.4 multi-hop networks is an important factor for reliable data transfer, which in turn is provided by a channel quality estimator. For choosing a relevant neighbor node in the vicinity, either short term or long term, or a combination of both is used; however, it is dependent on the nature of the application. As explained earlier, there are three different types of channel quality estimation, i.e. physical, logical, and hybrid.

4.3.1. Physical Channel Quality Estimators

In physical channel quality estimations, the channel quality indicators are provided by the radio hardware, which are based on the signal strength of a received packet, such as SNR, RSSI, and CCI.

![Figure 4.2: Chain of errors from chip to packet error.](image)

In WSNs, the real sensor nodes, such as Telos and MICAz motes use Chipcon CC2420 radio. The Chipcon CC2420 provides two pieces of metadata about received packets:

- **RSSI**: which is the received RF signal strength in $dBm$ over the first eight symbols after the start of a frame.

- **CCI**: in simulations, we use it as a physical channel quality estimator, for the measurement of chip error rate due to its accuracy. We can determine the relationship between CCI and the Frame Success Rate (FSR) if we know the relationship between
CCI and Symbol Loss Rate (SLR), which is a key issue. This relationship is determined in [11], which is given by:

\[
I_s = \begin{cases} 
0 & CCI \geq 100 \\
331.182023 \times e^{(0.147655\times CCI)} & CCI < 100 
\end{cases}
\] (4.1)

It is observed in [11] that \( l_f \) is the only reason of the packet loss under the case of perceived packet loss rate. It means both frame loss and perceived packet loss is equal. In order to determine \( l_s \), the number of frame retransmission times due to weak channels forms a Geometric series, which is given by:

\[
P_{\text{rtx}} = l_f + 2l_f(1-l_f) + 3l_f^2(1-l_f) + 4l_f^3(1-l_f) + \ldots = \frac{1}{1-l_f} \] (4.2)

Where

\[
l_f = 1 - (1-l_s)^2fl
\] (4.3)

\( l_s \) is the symbol error rate and \( fl \) is the frame length. The frame reception rate \( (r_f) \) will be equal to:

\[
r_f = 1 - l_f
\] (4.4)

\[
r_f = (1-l_s)^2fl
\] (4.5)

From (4.4), it shows that \( l_f \) is only influenced by \( l_s \), which is influenced from the chip error rate. The relationship between \( CCI \) and \( l_f \) is determined from (4.1) and (4.3), while the relationship between \( CCI \) and perceived packet loss rate is determined through analysis that is verified through experiments in [11]. \( CCI \) can be considered as a measurement of chip error rate, which is used as an indicator for frame loss rate in the analysis of the model.

**Drawback:** In spite of the fact that physical channel estimators can be utilized without any additional costs, such metrics are highly dependent on the receiver hardware.
Secondly, these metrics are available for successful received packets only. In addition research shows that physical estimators cannot predict the rate of packet reception always.

4.3.2. Logical Channel Quality Estimators

Compared to the physical channel quality estimators, logical channel estimators assess the channel quality by keeping track of packet loss, such as Expected Transmission Count (ETX), i.e. the number of transmissions required to successfully transmit a packet, the Required Number of Packet, and the Packet Success Rate. In contrast to the physical channel estimators, logical channel quality indicators like ETX are independent on specific hardware characteristics. Logical metrics correlate directly with the point of view of applications, such as successfully transmitted packets ratio. Contrary to the physical metrics, in order to update the channel quality estimates regularly, the logical metrics rely on broadcasting beacons at a regular interval.

The purpose of ETX is minimizing the number of data packets transmission. It estimates the number of transmission required to unicast a packet by measuring the PSR of beacon packets between two corresponding neighboring nodes.

**Drawback:** Logical channel quality estimators used broadcasting to update the channel quality. However, periodic broadcast of beacons consumes a considerable amount of energy and at the same time occupy the wireless channel. However, even with physical channel estimators, the measurements are conducted by the receiver, but the information of each neighboring node must be available at the sender node. Therefore, periodic information exchange is always necessary for estimating channel quality, which is only possible by dedicated broadcast.

4.3.3. Hybrid Channel Quality Estimators

Hybrid channel quality estimations integrate both physical and logical channel quality estimations. The Four Bit (4B) is the prime example of hybrid type channel quality estimation. The 4B link estimation protocol provides well-defined interfaces that combine information from the PHY, MAC, and network layers 4B uses ETX as
channel quality estimator. In 4B, the interfaces provide by four bits based on the information gathered from different layers. A *white* bit from the physical layer, which represents the low probability of decoding error in received packets. Second is an *ack* bit from the link layer to indicate whether an acknowledgment is received for a sent packet. Third is the *pin* bit and fourth is *compare* bit, which is based on the information from the network layer. Routing protocols use the *pin* bit to keep important nodes in the neighbor routing table maintained by the link estimator and the *compare* bit to measure the importance of a link.

**Drawback:** The hybrid type channel quality estimators are mainly based on default parameters of MAC protocol. However, for improved quality it is important that MAC parameter values should change adaptively according to the requirements and quality of channel.

4.3.4. Adaptive Hybrid Channel Quality Estimator

The 4B estimator is designed for fixed parameter values of MAC protocol. Instead of fixed MAC parameters of IEEE 802.15.4 MAC protocol, in order to estimate the
reliability accurately, the adaptation module has to continuously monitor the performance of the MAC layer, and provides feedback on the current operating conditions by adaptively tuning the MAC parameters such as `macMaxFrameRetries`. Furthermore, in IEEE 802.15.4 multi-hop networks, it exploits the information about the network topology, made available by the network layer, for mapping the end-to-end reliability constraints to the link-level parameters.

In the following, we present an adaptive scheme i.e. Hybrid Adaptive Parameter Tuning based Estimation (HAPTE), which estimates the current traffic conditions, and changes MAC parameters according to the required level of reliability. HAPTE utilizes the four bit concept of 4B hybrid channel quality estimation, which contrary to 4B specifically designed for IEEE 802.15.4 MAC protocol by adaptively tuning its parameter for required level of reliability. Fig. 4.3 shows the interfaces of each layer, which are provided to a link estimator. Altogether, the three layers provide four bits of information: two bits for incoming packets and one bit each for transmitted unicast packets and link table entries. The HAPTE work as follows:

- The `macMaxFrameRetries` value is adaptively adjusted according to the information gathered from the `compare` bit interface, which takes the beacon packet received from a neighbor node and the `white` bit as inputs, and finds the neighbor, which has better quality link.

- Using the CC2420 radio, the `white` bit is set when the CCI value is in the range of 100 to 110. The range of CCI in CC2420 radio chip is from 50 to 110. A link which has CCI value greater than 100 indicates that the quality of the received frame is about 90%.

- A MAC layer provides one bit of information per transmitted packet, i.e. the `ack` bit. A link layer sets the `ack` bit on a transmit buffer when it receives a MAC layer acknowledgment for that buffer. If the `ack` bit is clear, there is still no assurance that the packet has arrived successfully.

| Pseudo-code of HAPTE Algorithm |
A link estimator requests a network layer for a compare bit on a packet. The compare bit shows whether the link provided by the sender of the packet is better than the link provided by one or more of the entries in the link table.

### 4.4. Simulation Results

We performed simulations using Castalia 3.0 simulator, which is based on the OMNeT++ 4.0 platform [32]. We used a cluster-tree based multi-hop WSNs network with maximum of 10 levels. We used the frame types defined by IEEE 802.15.4 standard. Each data frame uses 2 Bytes at application layer, 8 Bytes at network layer, 9 Bytes at MAC layer, and 8 Bytes at PHY layer headers. The ACK frame is 11 Bytes. Each node transmits 6 Bytes of sensing item, which composed of 16-bit sensor sample and 32-bit timestamp. A 33 Bytes data short frame length is used for transmitting sensing items separately from sensor nodes to cluster-tree coordinators and for transmitting downlink data. Cluster-point coordinators collect received sensing items, and utilize 105 Bytes long data frames having 12 sensing items in total.

The data aggregation requires 6 Bytes as collective header. I used the IEEE 802.15.4 beacon enabled mode, where the Beacon Interval (BI) was set to BI = 126 s (i.e. BO = 13), and the active period was set to SD = 4 s (i.e. SO = 8). Finally, we considered a WSNs where 100 nodes were randomly deployed in a (100× 100) m area.
Fig. 4.4 shows the packet delivery ratio received at a PAN coordinator of the total sent packets from different source nodes in a cluster-tree based multi-hop WSNs without using the adaptive technique used in HAPTE. We considered the cluster-tree multi-hop WSNs up to 10 levels. We compared the delivery ratio using $CCI$ as a Physical link Quality Estimator (PQE) and $PSR$ as Logical link Quality Estimator (LQE). It shows that PQE exhibits higher delivery ratio compared to LQE with both Default Parameter Values (DPV) and Maximum Parameter Values (MPV) of IEEE 802.15.4 MAC parameter values, as shown in Table 4.1. In addition, Fig. 4.4 also confirms that MPV shows higher packet delivery ratio compared to DPV.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Default parameter values</th>
<th>Maximum parameter values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$macMaxFrameRetries$</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>$macMaxCSMABackoffs$</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$macMaxBE$</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$macMinBE$</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Fig. 4.5 shows that quality of route determined through different channel quality estimators versus the average distance from a source to the sink node. Quality of the route is determined by the number of received out of the number of packets sent from a source. It is shown in the figure that physical (CCI) and logical (ETX) indicate more rapid change compared to hybrid (4B) and adaptive hybrid (HAPTE). By adaptive tuning of MAC parameters, HAPTE shows and realistic and improved quality of overall route compared to the route quality determined by other channel quality estimators.

Fig. 4.6 shows the end to end delivery rate of transmitted packets versus the number of hop used from source to the sink. It is clear from the figure that by using HAPTE, the channel quality assessment is more accurate, which results in higher delivery rate compared to all physical, logical and hybrid channel quality estimators.

Fig.4.7 shows the average energy consumption per successfully delivered packet versus the number of sensor nodes deployed in the sensor field. Due to beacon packet broadcasting, the overall energy consumption of ETX is more compared to other channel estimation metrics. By utilizing the cross layer approach and adaptive tuning of
parameters, the energy consumption using HAPTE is lower compared to others.

Fig. 4.8 shows the average energy consumption of a sensor node versus the number of hop involved in packet routing from a source to the sink. Average energy consumption of a sensor node decreased with the increase in the number of hop from source to the sink. Again by using HAPTE, the energy consumption is lower compared to all other channel assessment metrics.

Fig. 4.9 shows the overall latency in (second) that happened while routing a packet with the number of packet transmitted in beacon interval by comparing 4B (with default and maximum MAC parameter values) and HAPTE with no frame loss. Due to adaptive nature of HAPTE, the overall packet latency is lowered compared to 4B in both cases. Hence it proved that HAPTE out performed 4B in both cases.

Fig. 4.10 shows the overall latency in (second) that happened while routing a packet with the number of packet transmitted in beacon interval by comparing 4B (with default and maximum MAC parameter values) and HAPTE with frame loss rate as 10%. Again HAPTE shows improved performance compared to 4B in both cases.

Figure 4.5: Quality of route versus distance from source to the sink.
Figure 4.6: End to end packet delivery rate versus no of hop from source to the sink.

Figure 4.7: Energy consumption per successfully delivered packet versus number of deployed nodes.
Figure 4.8: Avg. energy consumption per node versus number of hop from source to the sink.

Figure 4.9: Avg. latency versus total number of packets transmitted per beacon interval.
4.5. Conclusion

In this chapter, a hybrid adaptive channel quality estimator has been introduced, which
adaptively changes the MAC protocol parameters according to the requirement of the channel. The scheme has utilized cross layer approach by taking information from the physical, link, and network layers. It has shown significant improvements in terms of end to end delivery rate, energy consumption, and packet latency over the state of the art physical, logical and hybrid channel quality estimators in multi-hop network, while maintaining layered networking abstractions. It has been verified that HAPTE is equally useful in both error free and error-prone WSNs environments. We believe that this approach will be very helpful in assessing the accurate quality of communicating links in dynamic multi-hop error-prone WSNs environments.
Chapter 5

Thesis Conclusion and Future Directions

5.1. Research Summary

Wireless Sensor Networks (WSNs) has emerged as a promising wireless network technology, which is capable of collecting useful and sensitive information, processing and dissemination of that information in diverse and often in the hostile surrounding environments. Due to certain factors such as simplicity, cost effectiveness, self-healing, self-maintenance, and self-organization capabilities, the WSNs has distinctive advantages over other existing wireless networks, which make WSNs appropriate for many real life applications, like flood affected area, emergency search and rescue operations, radiation measuring in crippled nuclear power plants.

With the deployment of WSNs in real life applications, different issues are associated with functions and maintenance of the network. When we talk about the error-prone WSNs, then the two most critical issues are considered to be the energy efficiency and reliability, which are the important problems that need to be tackled for a realistic deployment of sensor nodes. It has been observed that a WSNs that operates in such environment usually utilizes more energy resources and suffer from serious reliability issues. Therefore effective and efficient mechanisms should be provided to achieve reliability with low energy expenditure multi-hop network environments. For energy efficiency, the WSNs protocol stack needs to be tuned according to the actual requirements. Due to noisy wireless channel and the failure probability of sensor nodes in dynamic WSNs environment, the network can be unstable from time to time.

In this thesis, various issues associated with both energy consumption and reliability in WSNs are introduced.
Before bringing in the research contribution in the thesis, we gave a detailed overview of WSNs. We introduced different applications areas and potential future WSNs deployment fields in Chapter 1.

Energy estimation and lifetime modeling in WSNs is an important research topic recently. In Chapter 2, we proposed a new comprehensive Distributed Communication Model (DCM), which is distinct from different available communication model. In the new designed model, we took various parameters into account, which are fundamentally associated with error-prone WSNs using multi-hop communication, such as:

- Packet loss rate, which can be experienced through weak links in multi-hop communications.
- Duty cycle in communication model, which is used in Medium Access Control (MAC) protocols in order to preserve the energy, which otherwise can be wasted through idle listening mode.
- Density of the network and the number of neighbors in the radio range of a node using multi-hop communications.
- Data rate, which varies from one application to another application.

From analysis, simulations, and experiments on MICAz motes, we verified that the quality of link that is affected by characteristics like symmetry, directivity, instability, and irregularity of the radio range has direct impact on the overall energy consumption of a sensor node. We estimated the effects of packet loss rate on the energy consumption due to data propagation in a multi-hop communication environment. We proved that the link quality has direct impact on the lifetime of a network. We then validated the model through simulations and experiments on MICAz motes. We believe that the model will be helpful to accurately design different network strategies for estimating energy consumption due to data propagation in the error-prone environments, where there is possibility of significant packet loss.

In WSNs, most of the MAC protocols are based on a Carrier Sense Multiple Access (CSMA) access mechanism. However, energy estimation models, considers Time Division Multiple Access (TDMA) protocols only for energy analysis. A major drawback
with TDMA based protocols is that such protocols need a good centralized synchronization scheme. We know that centralized schemes are not easy to implement in dynamic networks like distributed WSNs. It is necessary to determine the power dissipation model for CSMA/CA based MAC protocols that take the states like back-off, carrier sensing, idle listening, sleeping, and data transmission in power dissipation analysis into account.

In Chapter 3, by using the idea of DCM in error-prone environment, we performed detailed analysis of power dissipation through various factors involved in WSNs communications using CSMA/CA based IEEE 802.15.4 MAC protocol. Using random nature of CSMA/CA protocol parameters in both analysis in simulations, we verified that the link quality has direct impact on the overall power dissipation of a node, which ultimately affect the lifetime of the network. We also performed overheads analysis for multi-hop communication in WSNs. We validated the model through detailed analysis and Monte Carlo simulations. We confess to the best of my knowledge that this is the first comprehensive multi-hop CSMA/CA based power dissipation model. We believe that it will contribute to accurately designing the different network strategies for estimating power dissipation through multi-hop communication in distributed network environments.

Research work related to energy consumption in error-prone WSNs will be incomplete without studying the data and network reliability. To conserve energy efficiently, an effective mechanism should be designed that can achieve reliability with low energy expenditure. To measure the reliability, the communication channel quality estimation is an important factor. For the said purpose, in Chapter 4, we introduced a hybrid adaptive channel quality estimation scheme, called as Hybrid-Adaptive Parameter Tuning Based Estimation (HAPTE) in detailed, which adaptively changes the MAC protocol parameters according to the requirement of the channel. The main characteristic of the scheme are as follow:

- It utilized the cross layer approach by taking information from the physical, link, and network layers. It has shown that significant improvements in terms of end to end delivery rate, energy consumption, and packet latency over the state of the art
physical, logical and hybrid channel quality estimators in multi-hop network, while maintaining layered networking abstractions.

- In contrast to the existing channel quality estimation techniques, which either used default or maximum parameter values, the scheme used MAC protocol parameters according to the condition and quality of the link, which is more efficient in terms of energy usage.

- We have verified that HAPTE is equally useful in both error free and error-prone WSNs environments. We believe that this approach will be very helpful in assessing the accurate quality of communicating links in dynamic multi-hop error-prone WSNs environments.

5.2. Impact of Research Findings

The purpose of conducting this research work was estimating the energy consumption and lifetime of a WSNs in error-prone network, where the deployment of sensor nodes will be random. In random deployment of nodes, the position of a sensor node will not be deterministic and energy of an individual node will be affected by various factors, such as frame loss, retransmission of frames, density of the network, number of neighbor nodes, number of hops involved in the selected route for data forwarding, and the topology management. It is clear that in manual deployment, the above factors may not have much impact, however, in random deployment these factors will affect the battery life of an individual sensor node considerably. In order to emulate the impact of these factors in the lifetime of a sensor node battery and on the overall lifetime of a network, we conducted this research.

We hope that the research output of this study will be helpful in

- estimating the lifetime of a network in random deployment in the error-prone environment.

- estimating the link quality for best route selection, in order to decrease the network delay, sensor node energy, and increase end to end packet delivery in the error-prone
network environment.

5.3. Directions towards the Future Works

Channel quality is an important factor in determining the reliable route in multi-hop communication, accurately. In addition, the more we know about the channel quality, the better we can predict which communication technique is most energy efficient and reliable. We are planning to apply HAPTE, using different available WSNs motes to verify its effectives and then use it in real life applications, which can operate in the error-prone network scenarios. Taking into account the relative lack of WSNs specific measurements, we are planning to carry out extensive channel measurements. After getting enough data from different error-prone network environments, proper channel quality selection method can show us which model to use. Integration of relevant channel estimation model which is based on cross-layer approach, such as HAPTE, in the development of higher layer protocols for routing and scheduling is vital if these are to be used efficiently and robustly under the large channel variations that WSNs can expect to encounter.

5.4. Implementation of the WSNs Based Smart Grid

In the broader prospective with the application point of view in the upcoming future, we are planning to collaborate toward applying WSNs in the smart grid. We are at the planning phase of formulating issues related with WSNs in the smart grid that may lead to the successful implantation of smart grid in the developing and energy deficient country like Pakistan which has huge potential for investment in regularizing the traditional old electric power generation and distribution systems.

Currently, developing countries are suffering from serious energy crisis, due to the electric power generation shortage, which is mainly due to the mismanagement of utilities at industrial and domestic level. This mismanagement has a direct and immediate impact on the power distribution. Smart grid implementation can save a lot of the management, capital, and distribution challenges that the local power distribution companies, are facing at the moment.
We are expecting that the implementation WSNs in smart grid can be beneficial in the following three ways:

- It will improve the overall service reliability and operational efficiency from the power generation to distribution to the end user.
- Implementing smart metering will reduce the man’s power and reduce if not eliminate the misuse and wastage of electricity.
- Without replacing the existing power system completely, it will update the existing physical power distribution infrastructure in a cost efficient way.

References


[8] IEEE 802.15.4 Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPAN), 2006


2005.


[64] G. Lu, B. Krishnamachari, and C. Raghavendra, “Performance Evaluation of the
IEEE 802.15.4 MAC for Low-rate Low power Wireless Networks,” in proceeding of the Workshop on Energy -Efficient Wireless Communications and Networks (EWCN ’04), 2004.


## List of academic achievements

<table>
<thead>
<tr>
<th>Category (Subheadings)</th>
<th>Description</th>
<th>Chapter</th>
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<tbody>
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<td>Presentations at domestic academic meetings held by study groups</td>
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Tokyo, Japan


Ochirmaa Lkhagvaa, Tariq Muhammad, Macuha Martin, and Takuro Sato, "TOA Estimation Based UWB Position Location Algorithm," IEICE General Conference, March 2011, Tokyo, Japan

Ochirmaa Lkhagvaa, Tariq Muhammad, Macuha Martin, and Takuro Sato, "Accurate Localization in Short-Range Outdoor Environment," IEICE General Conference, September 2010, Osaka, Japan
