Fixed Chain-Based Wireless Sensor Network for Intelligent Transportation Systems

Jalawi Alshudukhi

Department of Computing and Communication Technologies
Oxford Brookes University

A thesis submitted in partial fulfilment of the requirements of Oxford Brookes University for the degree of
Doctor of Philosophy

September 2016

I would like to dedicate this thesis . . .

To my late Father, God bless his soul
To my Mother and her unlimited support and patience
To my Wife and her generous love and continuous encouragement

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 40,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Jalawi Alshudukhi
September 2016

Acknowledgements

I would like to thank my primary supervisor, Dr. Shumao Ou, for his sustained support throughout the course of conducting this research. His enthusiasm, insight and guidance were invaluable assets which encouraged me to proceed well beyond my initial ideas. I am deeply grateful to my second supervisor Dr. Peter Ball for providing useful feedback and positive criticisms which deepened the results of the study. Special thanks also go to Prof. Nigel Crook Head of Computing and Communication Technologies Department in Brookes University for generous encouragement and financial support to present my work in a respected conference. Many thanks are for Prof. Liqiang Zhao and his students due to their warm reception and hospitality during my research trip to China. I am grateful to the coordinator of my study, Professor Khaled Hayatleh, for providing unlimited support and mentoring. I would also like to acknowledge the kind assistance offered by Dr. Tjeerd Scheper as PhD tutor. I would greatly thank my wife, Ohud Alowaidi, for her continuous love and encouragement, particularly in the very stressful moments. I would like to thank my family, especially my mother, for their selfless love and support. Above all, I thank God for giving me the perseverance required to ensure that the good work I started was completed.

Abstract

Wireless Sensor Networks (WSNs) are distributed and interconnected wirelessly sensors that are used in a variety of fields of our daily life, such as the manufacturing, utility operations and traffic monitoring. Many WSN applications come with some technical weaknesses and issues, especially when they are used in Intelligent Transportation Systems (ITS). For ITS applications that use a fixed chain topology which contains road studs deployed at ground level, there are some challenges related to radio propagation, energy constraints and the Media Access Control (MAC) protocol. This thesis develops a ground level radio propagation model for communication between road studs, and energy efficiency metrics to manage the resources to overcome the energy constraints, as well as a MAC protocol compatible with chain topology and ground level communication.

For the challenges of the physical layer, this thesis investigates the use of a WSN for communicating between road-based nodes. These nodes are situated at ground level, and two-way wireless communication is required between the nodes and from the nodes to a roadside control unit. Field measurements have been carried out to examine the propagation close to the ground to determine the maximum distance between road-based nodes as a function of the antenna height. The results show that for a frequency of 2.4 GHz, a range of up to 8m is achievable with 2mW equivalent isotropically radiated power (EIRP). An empirical near-ground level radio propagation model has been derived, and the predicted results from this model are shown to match closely to the measured results.

Since wireless sensor networks have power constraints, green energy efficiency metrics have been proposed for low-power wireless sensors operating at ground level. A numerical analysis is carried out to investigate the utilisation of the green energy efficiency metrics for ground level communication in wireless sensor networks. The proposed metrics have been developed to calculate the optimal sensor deployment, antenna height and energy efficiency level for the near ground wireless sensor. As an application of the proposed metrics, the relationship between the energy efficiency and the spacing between the wireless sensor nodes has been studied. The results provide guidance for energy efficient deployment of near ground level wireless sensors.

To manage the communication between large numbers of nodes deployed on a chain topology, this research presents a time division multiple access (TDMA) MAC protocol that is specifically designed for applications requiring periodic sensing of the sensor field. Numerical analysis has been conducted to investigate the optimum transmission scheduling based on the signal-to-interference-plus-noise-ratio (SINR) for ground level propagation model applied on wireless chain topology. The optimised transmission schedule considers the SINR value to enable simultaneous transmission from multiple nodes. The most significant advantages of this approach are reduced delay and improved Packet Received Ratio (PRR). Simulation is performed to evaluate the proposed protocol for intelligent transport system applications. The simulation results validate the MAC protocol for a fixed chain topology compared with similar protocols.

Table of contents

List of Figures

List of Tables

List of Abbreviation

Roman Symbols

2G	Second-generation of Cellular systems
ACM	Adaptive Coding and Modulation
AEA	Adaptive Election Algorithm
ARQ	Automatic Repeat Request
BEB	Binary Exponential Back-off
C++	C Plus Plus is middle-level programming language
C2CCC	Car2Car Communication Consortium
CM	Control Message
CR	Communication Request
CS	Carrier Sensing process
CSMA	Carrier sense multiple access
CTS	Clear To Send
CW	Contention Window
DCE	Data centre efficiency
DiS-MAC	Directional Scheduled MAC protocol
DM	Data Message
ECR	Energy Consumption Rating

List of Abbreviation

ECR-VL	Energy Consumption Rating-Variable Load
EEM	Energy Efficiency Metric
EIRP	Equivalent Isotropically Radiated Power
EMACS	The EYES MAC protocol
ETSI	European Telecommunications Standards Institute
FOM	Free Space Outdoor Model
FS	Free Space
FSPL	Free Space Path Loss
GLPM	Ground Level radio Propagation Level
GR	Ground Reflection
GSM	Global System for Mobile Communications
ITS	Intelligent Transportation Systems
LEACH	Low Energy Adaptive Clustering Hierarchy
LED	Light-emitting Diode
LMAC	Lightweight Medium Access Control
LOS	Line of Sight propagation
LPLM	Long-distance Path Loss Model
MAC	Media Access Control
MACAW	Multiple Access with Collision Avoidance for Wireless
MIMO	Multiple-Input and Multiple-Output
NLOS	Non-line-of-sight propagation
NoW	Network on Wheels project
NP	Neighbour Protocol
np-CSMA	non persistent CSMA

NS-3	Discrete-event network simulator
OFDM	Orthogonal Frequency-Division Multiplexing
PE	Plane-Earth propagation
PRR	Packet Received Ratio
PUE	Power usage efficiency
QoS	Quality of Services
R-T-I-T-R-I	receive-transmit-idle-transmit-receive-idle
RCS	Radar Cross-Section model
RF	Radio frequency
RS	Road Stud
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
RSU	Road Side Unite
RTS	Request To Send
S-MAC	Sensor-MAC protocol
SEP	Schedule Exchange Protocol
SIFT	Contention-Based MAC protocol
SINR	Signal-to-Interference-plus-Noise-Ratio
SIR	Signal Interference Ratio
SNR	Signal Noise Ratio
STDMA	Spatial Time Division Multiple Access
SYNC	Synchronisation process
T-MAC	Timeout-MAC protocol
TA	Time threshold in T-MAC protocol

List of Abbreviation

TC	Traffic Control
TCC	Traffic Control Center
TCCs	Traffic Control Centres
TDMA	Time Division Multiple Access
TEEER	Telecommunications Equipment Energy Efficiency Rating
TEER	Telecommunications Energy Efficiency Ratio
TENU	Thermal noise Energy Unit
TGG	The Green Grid
TRAMA	Traffic-Adaptive Medium Access
V2I	Vehicle To Infrastructure
V2V	Vehicle TO Vehicle
VANET	Vehicular Ad hoc Networks systems
VII	Vehicle Infrastructure Integration
WAVE	Wireless Access for Vehicular Environment standard
WiseMAC	Wireless Sensor MAC protocol
WiWi	Wireless Wire
WSNs	Wireless Sensor Networks
X-CTU	Software used for configuring RF module

List of Publications

- J. Alshudukhi, S. Ou, and P. Ball, "A ground level radio propagation model for road-based wireless sensor networks," in *Communication Systems, Networks & Digital Signal Processing (CSNDSP), 2014 9th International Symposium on*. IEEE, Conference Proceedings, pp. 146–151
- J. Alshudukhi, S. Ou, P. Ball, L. Zhao, and G. Zhao, "Energy efficiency metrics for low-power near ground level wireless sensors," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2015 IEEE 11th International Conference on*. IEEE, Conference Proceedings, pp. 329–335
- J. Alshudukhi, S. Ou, and P. Ball, "A mac protocol for wireless sensors in a fixed chain topology," in *Multimedia and Broadcasting (APMediaCast), 2016 Asia Pacific Conference (Accepted)*. IEEE, 2016

Chapter 1

Introduction

1.1 Overview

Wireless Sensor Network (WSN) is a group of low-power wireless devices which communicate with each other through radio communication facilities [5]. These devices are restricted in terms of resources such as processing speed, communication bandwidth, storage capacity and battery life [5]. Recently, WSNs have been widely used in a number of different applications for a various tasks such as to sensing area, gathering data, surveillance, monitoring conditions or other objects. Thus, WSNs can potentially be used in various systems such as utilities, automation, hospital/patient management systems and transportation such as to build Intelligent Transportation System [6, 7]. The design considerations for WSNs include location, topology, and propagation, scheduling, routeing and power consumption. These requirements should be taken into account in order to assist these sensors to transmit and exchange data effectively [8].

Intelligent Traffic/Transport Systems and Services is the integration of information and communications technology with transport infrastructure, vehicles, and users [7]. This integration aims to improve safety and provide useful information for transportation users. WSN-based technologies have been integrated with transport infrastructure and vehicles in order to build effective ITS systems. Thus, ITS systems have attracted the attention of governments and research centres to focus on developing and funding ITS projects [9], for example the InternetITS Consortium has been introduced in Japan, the Vehicle Infrastructure Integration (VII) in the USA [10], the Car2Car Communication Consortium (C2CCC) in Europe [11] and the Network on Wheels project (NoW) in Germany [12]. As a result, two common approaches have been used to design ITS systems: Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I). Both approaches aim to increase road traffic safety by, for example wrong way warnings, red light violations, intersection collision warnings and emergency brake warnings. Despite recent advances in technology and the proposed and implemented ITS, there are still some inadequacies and issues related to WSNs technology which is used in ITS systems. These inadequacies are related to physical layers such as propagation model and the appropriate topology, and the MAC layer such as the scheduling and power consumption.

Several proposed ITS systems have been built based on either Vehicle to Vehicle or Vehicle to Infrastructure. The first approach is V2V which relies mainly on exchange traffic information between vehicles. Several proposed systems have been built on this approach and have exploited the concept of multi hops communication, to produce and deliver significant data about the road to the driver. The second approach is V2I ITS systems which employ the existing transportation infrastructure to monitor and collect information about the state of the road and then sends it to vehicle drivers. Some proposed approaches have tried to combine the two approaches V2V and V2I in order to reduce the cost and increase the reliability. As In [13] the author proposes a combination of V2V and V2I communication in (VANETs) Vehicular Ad hoc Networks systems. In order to reduce the total cost of access point installation, the IEEE 802.11p/WAVE Wireless Access for Vehicular Environment standard has been improved to support multi hops communication.

Despite these considerations WSNs seem to be the preferred technology since these have many advantages over the traditional technologies, including flexibility in deployment, scalability and convenient maintenance [14]. A networked wireless sensor system may be even more powerful since it can be used to collect and process real-time information in a distributed and coordinated fashion.

1.2 Motivation

Despite recent advances in the field of developing WSNs, some gaps remain. These gaps are related to the usability in some types of environments such as motorway which use road studs placed on the ground. Thus WSNs is not implementable to perform its functions and achieve the target of the ITS systems. Thus, the communication aspects need more investigation and in depth studies to solve the problem and then introduce practical solutions that suit these unique environments. The communication aspects are represented in Radio Propagation on the Ground level where the transmitter and receiver are on the same level of height. This area has not yet been investigated, thus there is no specific radio propagation model designed to suit this case. Also at MAC layer , it is important to design an appropriate MAC Protocol where the topology and the technical capabilities are considered.

The motivation in ITS is that there is an opportunity to use WSNs technology in ITS systems and take advantage of it in order to overcome the existing challenges in current ITS systems. Several systems proposed to use road studs that are deployed on the road surface, to monitor traffic as shown in Figure 1.1. These works were mainly focused on the road stud design as in [15], or improving the detection systems as proposed in [16, 17]. At the same time, previous systems using the existing radio propagation model such as the free space propagation model and MAC protocols were not particularly designed for ground level communication and they do not consider the topology and the technical capabilities of road studs. Therefore, this work was motivated by designing technical solutions that consider the road bed environment, the road stud capability, the topology and the required protocol and then introduce it as a solution to the road studs used in ITS systems.

Figure. 1.1 Road stud

1.3 Aim and Objectives

The main aim of this project is to design a wireless sensor network where the sensors are embedded in solar powered road studs. The sensors can monitor road conditions and traffic passing over the sensors and can be used to provide traffic and safety information to both drivers and traffic management systems. Data from the sensors can be relayed to neighbouring road studs and to roadside units (RSUs). Data from the RSUs will be backhauled to a Traffic Control Centres (TCCs) where the data will be analysed. Traffic control signals can also be sent from TCCs to road studs through the RSUs in order to control the traffics.

The key challenges for this system are: I) managing the transmission at ground level where the road surface interrupts the radio path as shown in Figure 1.2; II) minimising the power consumption as the road studs are solar powered which limits the energy available; III) minimising the amount of infrastructure needed to support the data collection and distribution; IV) effectively and efficiently transmitting information bi-directionally.

Figure. 1.2 Road stud deployed on ground level

1.4 Contributions

1.4.1 Ground-Level Radio Propagation model

A novel ground level radio propagation model has been developed that considers the effect of antenna height on the transmission distance. The reverse engineering method has been used to design this model. Thus, real measurements conducted to measure the transmission range between two nodes located at ground level and measure the effect of antenna height on the signal attenuation were used. As a result, the new equation proposed is capable of calculating the signal attenuation and predicting the path loss for different antenna heights.

1.4.2 Energy Efficiency Metric

A new energy efficiency metric has been introduced that is built based on physical layer properties. The proposed energy efficiency metric measures the amount of transmitted information (data bits) successfully within the available resource constraints over a certain distance to the receiver. This metric is designed specifically for wireless sensors located near ground level, and a numerical analysis has been used to validate the proposed metric. The contribution of new energy efficiency metric provides a useful tool that allows optimisation of antenna height and energy efficiency levels within available resources for the near ground wireless sensor networks.

1.4.3 MAC protocol for Wireless Sensors in Chain Topology

A new time division multiple access MAC protocol is presented that is specifically designed for applications requiring periodic sensing of the sensor field. Numerical analysis has been conducted to investigate the optimum transmission scheduling based on the signal to interference- noise-ratio (SINR) for a wireless chain topology. The optimised transmission schedule considers the SINR value to enable simultaneous transmission from multiple nodes. The most significant advantages of this approach are reduced delay and increased throughput. Simulation has been performed to evaluate the proposed protocol for intelligent transport system applications. The simulation results validate the MAC protocol for a fixed chain topology.

1.5 Thesis Structure

Chapter One

In the first chapter, an overview of ITS is introduced and the research context is described. Firstly, we meant to start with overview of ITS systems to describe the research context and present the field of this investigation. The motivations driving this research are outlined in the second section. In the third section, the aims and objectives of this research are discussed, these objectives and aims reflect the research direction. Lastly, the contributions made by this research have been listed, including contributions at the physical layer and at the MAC layer.

Chapter Two

This chapter contains three subsections; the propagation models, energy efficiency metrics and WSNs MAC protocols. The related work of radio propagation models have been reviewed in the first subsection, especially near-ground radio propagation models. Then, the relevant energy efficiency metrics are studied in the second subsection, particularly those have been proposed for wireless sensor networks. The third subsection investigates the most recent MAC protocols proposed for wireless sensor networks. These protocols have been classified as contention-based, schedule-based or schedule-based for chain topology, and then a comparison has been performed to review the advantages and disadvantages for each type.

Chapter Three

In chapter three, signal behaviour and propagation phenomena are discussed, and then the proposed radio propagation model is introduced. As a preface to studying ground level propagation, it is important to review the propagation phenomenon and study how signals act in different environments and different scenarios. Thus, the three main phenomena of propagation are reviewed here: these are reflection, diffraction and scattering. Then, the ground level radio propagation model is introduced, which includes the signal behaviour, the measurement plan, the measurement challenges and the proposed radio propagation model. Lastly, a mathematical model is used to prove the results of the conducted measurements, and this model is then validated and compared with other radio propagation models.

Chapter Four

In this chapter, new energy efficiency metrics for low-powered ground level wireless sensors has been introduced. This chapter defines the main concept of energy efficiency metrics and how these metrics are applied in the existing systems. After this, the main concept and the purpose of the proposed metrics are described. More technical details about the proposed energy efficiency metrics are given in this chapter covering the components and the effective factors. To reach a deep level of understanding of the proposed metrics, a mathematical model is explained and is then followed by some numerical results. At the end of this chapter, one of the applications of the proposed energy efficiency metrics is given to show that these metrics provide accurate guidance for wireless sensor deployment and achieve energy efficiency within available resources.

Chapter Five

The main focus of chapter five is the proposed spatial TDMA MAC protocol for Fixed-chain WSNs. The first section of this chapter briefly highlights the two main categories of the schedule-based protocol: the TDMA and STDMA. Then the existing challenges to the design of the spatial TDMA MAC protocol is discussed which include the topology, the interference, the delay and the throughput. After this, the main part of this chapter “the system model of the proposed MAC” is presented in detail to include the physical layer properties, the interference model, the spatial reuse technique, the time slot allocation scheme, the protocol specification and algorithm and the MAC protocol design. The main section is followed by the simulation section that describes the simulator used, the requirement, the scenarios, the parameters used and the results. To evaluate the proposed protocol, the final section of this chapter shows the results of the proposed protocol compared with other similar protocols.

Chapter Six

Chapter six is the conclusion that summarises the entire research. It starts by identifying the research context and the key issues for this research, and then the main contributions of this research are presented. For each chapter, the results and findings are reviewed and their originality discussed. Then the significance of these results is deeply deliberated to identify how they can be implemented in reality. This chapter finalised by future work section which describe the expected future works.

Chapter 2

Related Works

In recent developments in modern cities, ITS solutions have become essential in many urban areas, especially when this coincides with the rapid rise in the number of vehicles. ITS solutions consist of various elements, such as monitoring traffic, highway management, information on traffic conditions, detecting areas of congestion and so on. These elements are based on the road conditions which are represented mainly by traffic volume, velocity and lane occupancy[14]. There are several traditional traffic monitoring systems which have been introduced recently; these systems rely on different technologies such as camera detection and inductive loop. However, these systems can not meet the requirements of convenient deployment, detection accuracy and overall cost. Furthermore, current traffic monitoring systems are usually wired which increases the cost of the implementation and the maintenance of the system. Thus, to reduce the implementation cost, several systems have been proposed using the existing infrastructure on the road such as road studs that is integrated with wireless technology to introduce new ITS systems for monitoring and traffic control. However, the proposed technical solution for a road stud-based ITS system comes with some technical issues. These issues related to the communication aspects (particularly communication between the road studs) and the power constraints and these issues need to be solved to redesign a new road stud-based ITS system effectively.

Traffic sensing and monitoring plays an important role in ITSs. Utilizing road studs(RS) and RSUs for wireless sensing and traffic monitoring has become a hot research topic [5]. Since the road studs are installed on the ground and they are normally battery powered (for example by integrated solar batteries), providing reliable wireless communication between studs and between the studs and the RSU is very challenging. Signal propagation for the sensors on the ground will experience more reflection and interference, due to the rough surface , blocked propagation path, and passing vehicles [18]. As a result, the road stud sensors should be more carefully designed to cope with the tough operating environments.

In terms of the localization, road stud sensors are fixed on the road. This presents a unique fixed chain-based networking topology. In addition to the physical layer radio propagation, the MAC layer is equally challenging. Because of, a few MAC protocol have been designed for linear wireless sensor network application [19], so effective and efficient MAC layer mechanisms and scheduling algorithms for chain topology are needed for bi-directional communications between the road studs sensors and RSUs [20]. The wireless communication includes uploading the sense data and also transmitting control information down to the road studs (for example, to change the colour or flashing pattern of the studs).
To solve the current technical issues, whether in road stud-based systems, physical layer issues (ground propagation and energy efficiency) or MAC layer protocol, these issues should be deeply investigated. The next three subsections review the recent propagation models that have been designed for near ground communication, to assess whether they are implementable using road stud or not. In addition, on the level of the physical layer, we have illustrated the most recent energy efficiency metrics that have been proposed for wireless communication. Most of the current energy efficiency metrics have been designed for cellular systems and a few for WSNs. However, we have tried to study the energy efficiency metrics designed for WSNs. Finally, the third subsection reviews the related WSN MAC protocols that were previously proposed for WSNs. This investigation aims to find out the strengths and weak points of these protocols. This investigation could result in good understanding and efficient knowledge by which to design an algorithm which suit road studs deployed as a chain topology.

2.1 Literature Review of Radio Propagation Models

In the communication field, several experiments have been performed to study propagation characteristics to understand signal behaviour. These proposed propagations aim to find an empirical model which can be used to calculate the path loss and signal attenuation in different environments with different scenarios. However, since these previous studies considered the free space environment, a few considered antenna height to be an important factor. As a result, the importance of antenna height increases when the propagation is located near or at ground level. The effects of antenna height on path loss propagation near to the ground have been investigated in [21–26].

In[25], Stoyanova et al carried out some measurements in an outdoor environment with sensors deployed at heights of 12 cm, 70 cm, 150 cm and 197 cm for both the transmitter and the receiver. The sensors used were Tmote Sky sensor nodes, which have 2.4GHz CC2420 radio modules with internal omnidirectional antennas. The results of this study show that when the antenna height decreases, the path loss increases. The paper proposes a propagation model based on combining the free-space path loss and the plane earth propagation models and including factors to account for ground reflection and antenna pattern irregularity:

$$\overline{P_R}(d) = P_T \left(\frac{\lambda}{4\pi d}\right)^2 \left(K_1^2 + K_2^2\Gamma^2 + 2K_2\Gamma\cos\left(\frac{2\pi}{\lambda}\Delta L\right)\right) \tag{2.1}$$

where P_R is the received power, P_T is the transmission power, d is distance between the transmitter and receiver, λ is the wavelength, L includes transmission lines and antenna losses, ΔL is the path difference between the direct and the reflected rays, K_1 and K_2 represent the antenna gain and Γ is the ground reflection coefficient.

$$P_R(d) = \overline{P_R}(d) + X_{\sigma(\overline{P_R})} \tag{2.2}$$

Equation 2.2 shows the Received Signal Strength (RSS) distribution as a Gaussian random variable X with standard deviation σ .
Equation 2.1 is a combination of the Free Space (FS) and Ground Reflection (GR) models. The results are compared with the Free Space Outdoor Model (FOM) and the Long-distance Path Loss Model (LPLM). They found that FOM is capable of predicting the received signal strength (RSS) as a function of distance with greater accuracy than LPLM [25]. The results showed that the maximum range for FOM and LPLM for antenna heights of 0.12 m, 0.70 m and 1.50 m are 30 m, 65 m and 70 m respectively [25].
A comprehensive study is shown here tried to include all technical, physical factors that affect the Path Loss as a function of antenna height. The proposed propagation model combined with a free space model and applied on a reasonable antenna height near ground level that was located between 197 ~ 12 cm. However, this study did not consider the communication at ground level where the antenna height ≈ 0 cm. In this scenario the propagation become unable to predict an accurate estimation of Path loss, especially when the antenna pattern was significantly affected by the ground.

Janek et al [26] investigated the RF propagation for a WSN designed to operate in agricultural crop fields to collect aggregate data composed of subsurface soil moisture and soil temperature. This study shows that the effect of antenna placement close to the ground (within 10 cm) significantly changes the omnidirectional transmission pattern. A propagation model is proposed that includes an environmental propagation factor, the value of which is obtained by measurements in different environments, to test the reflection and absorption with

and without obstacles. The proposed method takes into account environmental properties for the RF communication range based on the height of nodes and gateways. To study the separation space between transmitter and receiver, it concentrates on the Fresnel zone effect for sensors located close to ground level. As the sensor gets closer to the ground, the propagated wave is affected by ground obstacles which lead to reflection and diffraction. These effects have been studied and analysed to produce a model that is able to predict the loss close to the ground surface.
This model considers a factor for each environment to be calculated with a modified Friis equation which considers antenna height by using Golio and Goldsmith analytical treatments [26].

The researchers performed field measurements at a university agricultural research facility. Three different test fields were studied: bare soil (not planted or tilled), soybeans, and corn. The tests were conducted where the transmitter antenna height h_t was located at 82.5 cm, 66 cm, 50 cm, 33 cm, 16 cm and 8 cm above the ground, at a frequency of 900MHz. In terms of the receiver antenna, the antenna height was at few centimetres at all crop environments, and then the receiver antenna had to be raised. Each transmitter height was tested to find the minimum receiver height to reach maximum range on different field. For example the maximum range for a transmitter height h_t and receiver height h_r of 8 cm is 6 m, and this range increases to 30 m when h_r and h_t are 1.2m. For h_t = 88.2cm and 66 cm, the required receiver height to reach 30 m are h_r = 18 and 20 cm, respectively.
These measurements are consistent with the hypothesis that say that antenna height can significantly affect on the RF range. Furthermore, the simulation results, the anechoic chamber and the results of the field measurements reflect the fact that the antenna radiation pattern will significantly be changed as the antenna height moves closer to the ground plane. The proposed model considers the environmental factors and then uses these together with the free space model. However, the introduced model is only implementable as long as there is free space between the transmitter and receiver, whereas the focus was to consider the nearby environmental factors that can impact the received signal. Besides the environmental factors, antenna height has also been considered in order to predict the signal attenuation. Despite the new features introduced by the proposed model such as considering antenna height, it is not implementable at ground level where the distance between the transmitter and receiver is not free space.

A statistical model is proposed by Wang et al [21] for near-ground channels based on extensive measurements. One-slope and Two-slope models have been used to verify the measured results and have been compared with the generic model.

The measurements were conducted on three outdoor environments comprising a large plaza, a straight side walk, and open grassland. At each of these three sites, the same methodology was applied at the same frequency 2.4 GHz. The transmitter position was fixed with antenna heights of 3 cm and 1m, and receiver antenna heights of 1 and 2m were used. Along the straight line which was followed by the receiver, samples were collected at one-meter intervals up to a ten-meter distance from the transmitter; then, this process was repeated but at two-meter intervals until the end. The results show that the predicted values and the measured values match.

In [21], the maximum range and minimum antenna height achieved is 351m when the transmitter height is 3cm and the receiver height is 1m in the Plaza environment. The measurements confirmed that for a line-of-sight (LOS) condition and radio wave propagates near to ground level, a plane-earth (PE) model is the most accurate model to describe the path loss rather than a free space model. The plane-earth path loss model includes antenna heights and the effect of ground reflection [27]. It produces the closest results to the measured results, but it is still unable to predict the path loss accurately, especially when the antenna is at ground level. This refereed to that the conducted measurement were considering transmitter near ground level ≃ 3 cm and receiver on 1 m height, this scenario does not reflect a ground level communication where the transmitter and receiver on the same height. However, this study can be useful to estimate the path loss between the road studs and the base station, where the antenna of the base station is much higher than the road stud antenna.

In the work reported above, the minimum height of the antenna was 12cm for the measurements at 2.4 GHz and 8cm for the measurements at 900 MHz. For the road-based node network proposed in this research, antenna heights closer to the ground are needed. Therefore, a new measurement should be conducted to measure the signal attenuation for ground level communication.

2.2 Related Works in Energy Efficiency Metrics

Since the global environmental problem related to increasing energy consumption, concerns about energy efficiency in wireless communications have also been growing rapidly. To introduce energy efficiency solutions that lead to green wireless communications, numerous pieces of research and investments have been channelled into the wireless industry [28].

Several energy efficiency metrics have been introduced as solutions to improve the energy efficiency of cellular networks. These solutions have been designed on different levels such as the facility-level, equipment-level, network-level and access node level as shown in Figure 2.1 [29, 30]. The community has proposed some energy efficiency metrics [4, 31, 3, 32], which focus mainly on mobile and cellular communication systems. The objectives are mainly related to eco-sustainability, economic and also technical aspects.

Energy efficiency is one of the primary concerns in wireless ad hoc networks, since nodes in such a network normally use batteries. The energy consumption problem is more critical in wireless sensor networks as the battery of a sensor may not be charged or replaced [28]. For wireless sensor networks, the energy efficiency topic has been studied on several levels. At the access node level, green communications has received much attention from government, academia, and industry [4]. The main aim of green communications is to investigate and create innovative methods for the reduction of the total energy needed to operate wireless communication systems and to identify appropriate network architectures and radio technologies which facilitate the required power reduction [31]. While targeting generic wireless communication systems, mainly cellular systems, some work has been reported on the metrics used to determine energy efficiency and the techniques used to optimise modulation schemes [3].

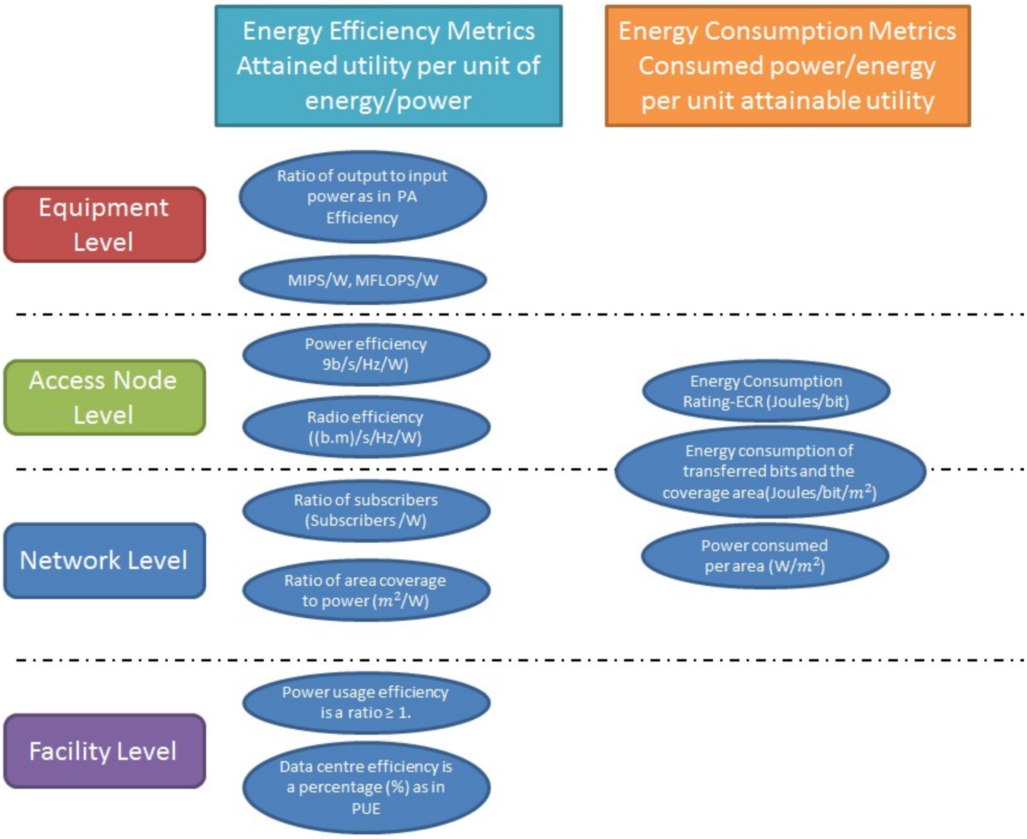


Figure. 2.1 Classification of metrics used in energy efficiency for wireless networks.

Existing research on energy efficiency for wireless sensor networks has focused on the design of energy efficient MAC protocols [33, 34], or routing protocols [35]. A few energy efficiency metrics proposed for wireless sensor networks consider physical layer properties, but with inadequacies since these are built at the component level. However, energy efficiency at the physical layer is more important for wireless sensor networks. In this section, we investigate the existing green radio energy efficiency metrics proposed generally for wireless systems, which highlight the proposed metrics for wireless sensor networks.

Several energy efficiency metrics have been used in wireless systems [4]. For example, the energy consumption rating (ECR) which quantifies the energy used to transmit a piece of information (Joules/bit), such as the ratio of the energy consumption to the effective system capacity [30]. Other metrics quantify the utility of various resources, such as the spectral efficiency (b/s/Hz) and the power efficiency (b/s/Hz/W) [32].

In [3], the access node level provides the basis for designing comprehensive energy efficiency metrics. The proposed metrics take into account the major factors that impact energy efficiency, such as the transmission distance and transmission power. The following efficiency aspects are considered in the proposed metrics in Eq 2.7, which include the bandwidth efficiency (b/S/Hz), the (b/TENU) power efficiency and the efficiency that relates to the spectral (b/s/Hz/m^2). These considered efficiency aspects were used to produce comprehensive metrics called green energy efficiency metrics ((b·m)/S/Hz/W). Since these metrics include the bandwidth, Shannon-Hartley theorems are used to describe the Gaussian channel capacity as in Eq.(2.3).

$$C = B\log_2(1+\gamma_s) \qquad (b/s) \tag{2.3}$$

Subsequently, the b/s/Hz bandwidth efficiency of a communication system is defined as

$$\eta_b = \frac{C}{B} = \log_2(1+\gamma_s) \qquad (b/s/Hz) \tag{2.4}$$

In addition to bandwidth efficiency, the power efficiency has been considered in this metric as well, which is represented by b/TENU power efficiency as (2.5).

$$\eta_{TENU} = \frac{\eta_b}{\gamma_s} = \frac{\log_2(1+\gamma_s)}{\gamma_s} \qquad (b/TENU) \tag{2.5}$$

The TNEU measures the value of the signal energy identical to the samples of AWGN which are recorded at the receiver. As a result, the (b/s/Hz/W) power efficiency is defined as in Eq (2.6)

$$\eta_w = \frac{\eta_b}{P_t} = \frac{\log_2(1+\gamma_s)}{P_t} \qquad (b/s/Hz/W) \tag{2.6}$$

Here, the propagation model is needed to find out the data transmission rate and the transmission distance that is attainable for a given bandwidth and level of power supplied as in Eq (2.7) [3].

$$\eta_m = \frac{d.\log_2\left(1+\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 N_0 d^2 L}\right)}{P_t} \qquad ((b.m)/s/Hz/W) \tag{2.7}$$

The combination of these factors is referred to as radio efficiency ((b.m)/s/Hz/W), which is intended to cover more aspects in a more general way. The advantage of this metric is that it takes account of the relationship between the bandwidth efficiency and the spectral efficiency by treating power as a category of resources. In order to improve these efficiencies, the author has proposed (AMC) as a solution. This solution shows any improvements in the efficiencies with increased transmission distance. However, for wireless networks where the nodes are stationary, this does not seem to be an effective solution. In addition, the above-mentioned energy efficiency metric is based on the Free Space Path Loss (FSPL) radio propagation model. In some practical scenarios such as propagation at ground level or low-power wireless sensors, the energy efficiency metric needs to be redefined. Otherwise, this metric will not be implementable, since some effective factors have not been condensed.

To introduce new energy efficiency for wireless sensor networks, there are also some energy efficiency optimization metrics. These have been built based on modulation schemes, to improve the efficiency per transmitted bit for wireless sensor networks, such as [1]. The authors of [1] proposed a cross-layer design which combines (AMC) and automatic repeat request (ARQ) in order to minimize the bit energy consumption under particular constraints, such as packet loss rate and retransmission delays as shown in Figure 2.2. The main aim of this combination is to achieve a considerable gain in spectral efficiency or reduce the packet loss rate. Originally, this energy efficiency metric was introduced by [36], and the contribution here is a new combination (ARQ and AMC) which tries to improve the energy efficiency by optimizing the cross layer and the consumed joule per transmitted bit.

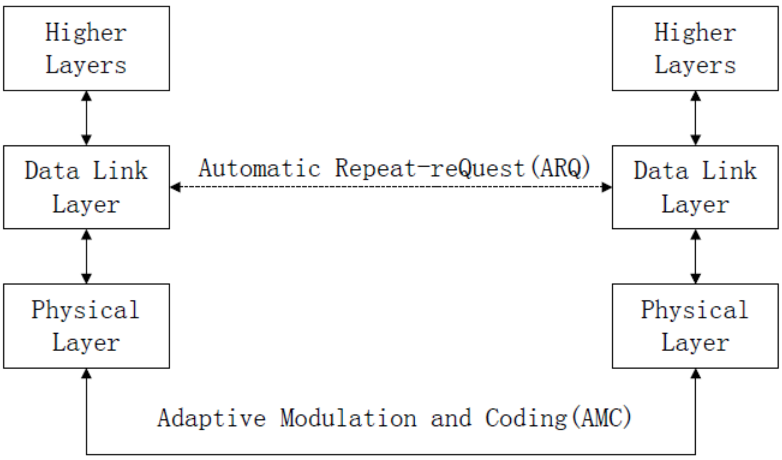


Figure. 2.2 Cross-layer structure [1]

A cross-layer communication model proposed here between two wireless nodes, as shown in Figure 2.2. A packets of data bits come from higher layers and then it will be stored in a buffer at the transmitter. After modulation, data bits in the packets are mapped into constellation symbols and transmitted from the transmitter to the receiver. At data link layer, ARQ protocol is employed. When an error occurs in a packet, the ARQ generator at the receiver sends a retransmission request to the ARQ controller via a feedback channel. The packet stored in the buffer will be retransmitted. At physical layer, M-ary square quadrature amplitude modulation (MQAM) are supported. The modulation mode is chosen by the receiver based on the channel state information (CSI), which is sent back to the transmitter via a feedback channel. Here the energy consumption model has been used . Since there are no complicated blocks such as iterative decoding in the single antenna system, the power consumed in baseband circuit is much smaller than that in RF circuits, and for simplifying the model it can be neglected [1].

The proposed metric in [1] has been specifically designed for wireless sensor networks and the metrics have been designed at access node level. The relationship between the energy consumption and the node spacing was explored under some constraints such as delays and retransmission. However, the important aspects of the efficiency were not considered such as the spectral, power and bandwidth, where this aspect reflects the channel capability. Although the technique used was not solidly cop with the main aspect of energy efficiency at access node level, this design is still acceptable and implementable to achieve best results in the presence of node mobility.

The role of power levels in wired and wireless devices are examined in [37] as a means of minimizing the overall energy consumption per unit of data that is effectively transmitted, in the presence of noise and interference. In order to reduce the transmission errors which are caused by the reduced transmission power, the author proposes an appropriate way to select the transmission power which should be used to transmit data over a common channel. Thus, the process energy cost and the energy consumed by retransmissions are considered. However, the proposed metric is specifically designed to measure efficiency at the component level only.

At network level, a new metric has been introduced in [38]. This metric relates to the network capacity referred to as 'bits-per-joule', which is defined as the maximum total number of deliverable bits over the networks per joule of energy deployed into the network. In a network, increases in the number of nodes lead to increases in the capacity of the bits-per-joule. This means large-scale wireless sensor networks with limited energy may only be suitable for data applications that apply delay-tolerant techniques. Thus, for energy saving in wireless networks, the bits-per-joule metric has been widely used as the utility function in game-theoretic approaches [39, 40].

.

In the aforementioned research, only the transmission power can impact the rate of transmitted data, and this is the only factor which can affect the energy efficiency models at least on access node level. However, transmission power does not reflect the overall energy efficiency on other level such as network or equipment level. Therefore, there are several factors affecting the energy efficiency such as (e.g. circuit power consumption of the transceiver) have been considered in other energy efficiency models [41, 42], these factors might not be appropriate to be used on access node level.

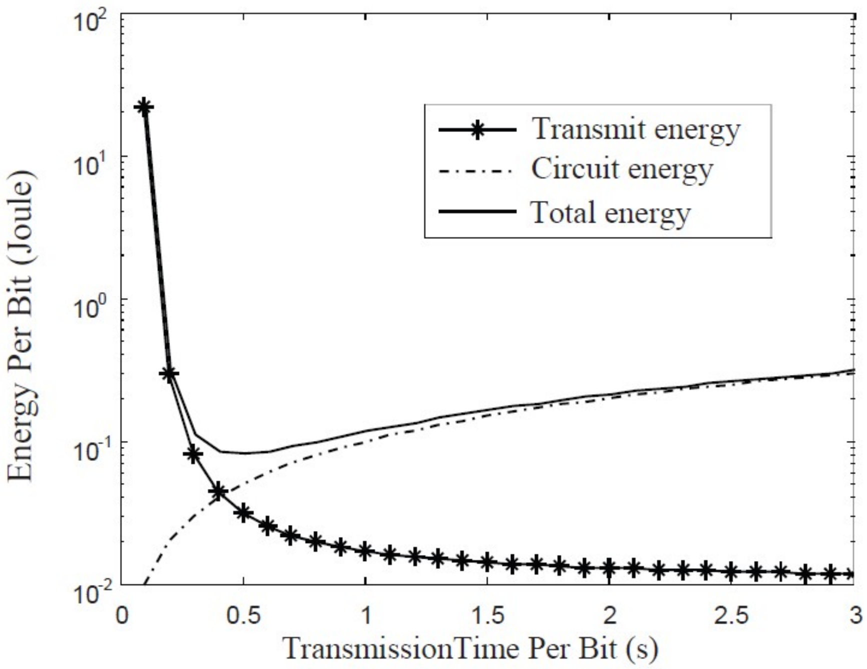


Figure. 2.3 Circuit energy and transmit energy trade-off for overall energy efficiency [2]

For example, the mathematical analysis in [2] shows that energy-efficient transmission by transmitting with the longest duration, is no longer the optimal approach. As an illustration, Figure.2.3 from [2] shows the trade-off between circuit energy and transmit energy for the overall energyefficient.

Although [37, 43] consider transmission power to measure the energy efficiency and appropriate methods to improve the efficiency, this is from an equipment-level perspective, whereas our work concentrates on the energy efficiency from an access-node perspective. Research has been carried out into different ways of improving the energy efficiency of wireless sensor networks through routing strategies [35, 44, 45], MAC layer protocols [33, 34, 46] and physical layer design [31, 3, 32, 30, 1]. However, to the author's best knowledge, there is no energy efficiency analysis work based on near ground level radio propagation which can be found in the literature.

2.3 Literature Review of MAC Protocols for WSNs

Numerous MAC protocols have been proposed to manage the access and share the medium for WSNs. The MAC protocol mechanism is defined as part of the data link layer, where it plays an important role in describing the packet flow to the shared medium. This mechanism guarantees that the channel can be shared with no or low probability of collision. WSN MAC protocols are mainly classified into two types which are: contention-based which assigns a duty cycle for the transmitter when the medium is available, and schedule-based that determines a time slot for the sensor who intends to transmit and receive [47]. On the other hand, there are some examples of WSN protocols that build on the schedule-based concept such as TRAMA [48], [49], EMACS [50] and LMAC [51]. Basically, these protocols have been introduced to be implementable on WSNs. However, this research mainly investigates the schedule-based MAC protocols that have been particularly designed for a chain topology and to support multi-hop communication. Thus, this literature will focus on this type of protocol instead of the common basic WSN protocols.

2.3.1 Contention-Based

S-MAC

S-MAC or Sensor-MAC is a contention-based protocol which relies on CSMA or ALOHA. It does not require synchronisation or full knowledge of the topology because nodes in this protocol race equally to access the channel and there is only one winner who will access it for a certain time. It aims to increase life time and reduce energy consumption. The basic concept of S-MAC relates to periodic sleep-listen schedules which are handled locally by the sensor network. Any two nodes from different clusters and close enough, they will share a common schedule. So they will be wake up at listen schedule for thier schedule [52].In addition, this results in the nodes waking up twice for different schedules and that leads to greater power consumption. The SYNC packet will be used to communicate the schedules of different nodes in the cluster, and this process is called the synchronization period. CS helps in collision avoidance. CS stands for the carrier sensing process, which is a technique used in this protocol as a collision avoidance method. In addition to this, Request To Send (RTS) and/or Clear To Send (CTS) procedures are used to send unicast data packets as in Figure 2.4.

The advantages of using this type of protocol are that it works well on a large scale and it is scalable. On the other hand, it has disadvantages such as the fact that the performance will drop in high load traffic, the size of the data packet is usually very small and the RTS and CTS procedures are more energy consuming. These RTS and CTS procedures are only useful for unicast communication. One of S-MAC's disadvantages is that it is designed for a peer-to-peer topology, where the coordination process is not required to be performed by cluster heads [53].

A new feature of S-MAC has been introduced, which is called message passing, where long messages are divided into small messages and then sent in bursts. This feature helps energy saving by using a common overhead. However, this concept may lead to high delays, known as 'latency'. The delay might be significant in the case of multi-hop routing algorithms, where every node between the sender and receiver will have their own sleep schedules. This phenomenon is known as "sleep delay". As a result, it is not suitable to be implemented in a chain topology due to there being a high possibility of collision in multi-hop topology.

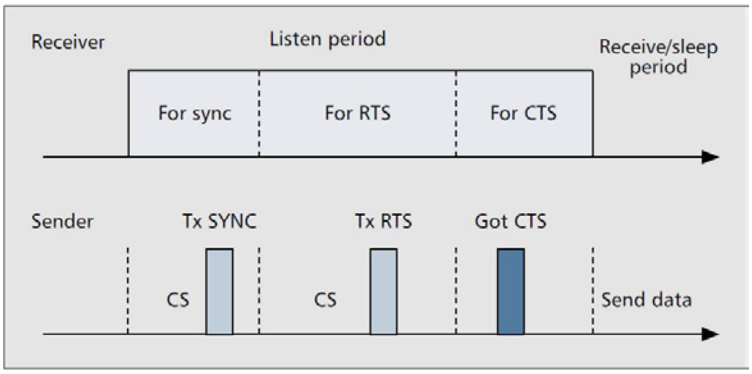


Figure. 2.4 S-MAC operation

T-MAC

This protocol's name is derived from Timeout-MAC, and it aims to minimize the energy consumption of variable traffic. The assumed topology for this protocol is peer to peer [54]. The proposed mechanism of this protocol aims to solve the static sleep–listen periods of the S-MAC which results in high latency and lower throughput, as indicated above. Timeout-MAC (T-MAC) [55] proposes to improve the performance of the S-MAC protocol under variable traffic loads. The 'listen' period in the T-MAC protocol ends when no activities have been detected for a certain time period called the time threshold *TA*. Generally, the main purpose of using *TA* is to provide a solutions for the early sleep problem.

Since the traffic load in wireless sensor networks is variable, so this result in the closest node to the sink forwards more traffic than other nodes. This traffic may change over the time shown in Figure 2.5. Despite the fact that T-MAC gives better results than S-MAC under

unexpected traffic loads, the synchronization of the listen periods within the virtual clusters is broken. This is the main source for the early sleep problem [55].
As a result, this protocol is not suitable for the chain topology, since it has weaknesses related to the early sleep problem. In addition, the nearest node to the sink will lose the connection [54].

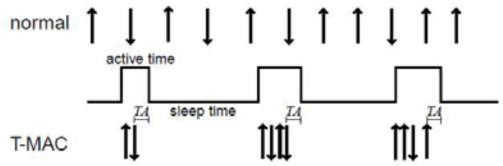


Figure. 2.5 the mechanism of T-MAC

WiseMAC

This is also known as Wireless Sensor MAC. It is specifically designed to treat the problems which result from idle listening periods, so it mainly aims to decrease idle listening periods. The WiseMAC protocol uses non persistent CSMA (np-CSMA) with preamble sampling to decrease idle listening [52].

In the WiseMAC protocol, the preamble sampling technique is used. The main concept of this technique is the preamble arrives before each data packet informs the receiving node that there is a data packet arriving. The medium is sampled by all nodes in the network with a common period, but the nodes schedule offsets are still independent. For example, if the node wakes up and samples the it found the medium busy, it will continuously listen to the medium until it receives a data packet or until the medium becomes idle again. Initially, the size of the preamble corresponds to the sampling period. The size of the preamble is initially set to be equal to the sampling period. However, sometimes, by the end of the preamble, the receiver is still not ready to receive the data packet because of some interference which leads to over-emitting and wasted energy. In addition, increasing the length of the preamble and the data packet will proportionally increase the over-emitting, due to that handshake not applied with the targeted receiver. Thus, the WiseMAC protocol provides a solution to identify the preamble length dynamically. This solution is offered to reduce the power consumption caused by the fixed-length preamble. The method applied in this solution relies on knowing the sleep schedules of the sender node's neighbours. The information on the sleep schedule of the sender node's neighbours can be learned and updated through every data exchange as part of the acknowledgement message. In this way, every node is able to collect and own information about the sleep schedules of its neighbours. As a result, WiseMAC is able to schedule transmissions based on the tables of the sleeping schedules of the neighbour's nodes and then the destination node's sampling time will correspond to the middle of the sender's preamble. A random wake-up preamble is the technique advised to reduce the chance of collisions caused by sharing the start time of a wake-up preamble. Figure 2.6 below presents the operational concept of the WiseMAC protocol [56].

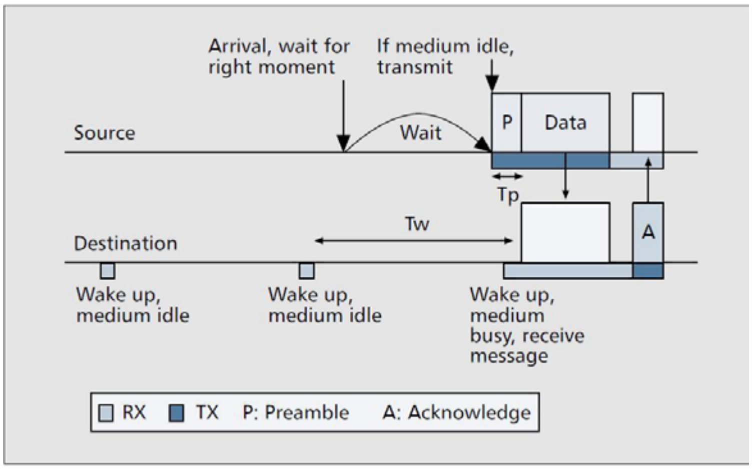


Figure. 2.6 WiseMAC operation

The main reasons why WiseMAC is not a suitable protocol to be implemented for a chain topology are: the decentralization of the scheduling and the non-persistent 'CSMA can cause collisions and hidden terminals.

SIFT

Sift is a contention-based MAC protocol which has been proposed for event-driven sensor networks. The main objective of the Sift design is to minimise energy consumption by reducing the latency which is caused by redundancy. The motivation behind Sift is that when an event is sensed, the first sent message R of N potential reports are the most crucial part of messaging and have to be relayed with low latency.

The non-uniform probability distribution function is used in SIFT to select a certain slot from the slotted contention window. If the node does not need to send its packet in the first slot of the window, then the transmission probability will be increased for each node to be prepared for the next slot as it assumes that the number of competing nodes is very small. According to [57], the latency in SIFT can be decreased considerably when there are many reports to be sent by nodes. As the SIFT protocol is a contention-based protocol which relies on an algorithm for slot assignment, it has been designed to coexist with other MAC protocols such as S-MAC. Based on the same idea, CSMA/p* [57] is proposed where p* is a nonuniform probability distribution that optimally minimizes latency. However, Tay et al [58], claim that SIFT uses the probability distribution function to pick a slot which is convergent to CSMA/p*. From a technical aspect, Sift is a non-persistent CSMA wireless

Table 2.1 A Comparison of Contention-Based Protocols

Protocol	Advantages	Disadvantages
S-MAC	• Sleep schedules are used to reduce idle listening periods . • Its implementation is simple.	• RTS/CTS are not used in BC, so the probability of collision is high. • Sleep / listen periods are predefined and constant, which decreases the efficiency of the algorithm under variable traffic loads.
T-MAC	• Achieves gives better results under these variable loads	• The synchronization of the listen periods within virtual clusters can be easily broken.
WiseMAC	• WiseMAC performs better when considering variable traffic load. • Clock drifts are handled well which mitigates the external time synchronization.	• Sleep–listen scheduling is decentralized • The hidden terminal problem accompanies the WiseMAC because it is based on non-persistent CSMA
SIFT	• Very low latency is achieved for many traffic sources.	• Increased idle listening is caused by listening to all slots before sending • Increased overhearing. • The implementation complexity of Sift would be larger than protocols not utilizing time synchronization

MAC protocol. In some protocols, after any transmission the time is immediately divided into CW slots, but the time used to send data packet is much longer than these divided CW slots called $r \in [1, CW]$. This procedure will be performed by the base station after any transmission, or collision process. Each station carrier will need to sense the medium, particularly during the contention slots preceding r. Once another transmission heard on the medium, the station carrier is required to stop or delay its pending transmission. This collision resulted from the absence or lack of a link level acknowledgement. If a collision is detected, most contention-based protocols duplicate the value of CW for the colliding nodes. This process is called binary exponential back-off (BEB). (BEB) has been applied in several protocols such as MACAW, 802.11, S-MAC and B-MAC [57]. Table 2.1 shows a comparison of contention-based protocols.

Analysis

The most common contention- based WSN protocols were reviewed in the previous section. The operation mechanisms and the features of each protocol demonstrated that each protocol has some inadequacies when implemented on a chain topology. These inadequacies exist mainly in the operation mechanism of these protocols, because they do not meet the application requirements where the nodes are required to sense periodically and sleep if there are no data to be gathered. Moreover, the presented "contention- based" protocols rely on random access to the channel. This method of sharing the medium is not suitable for applications which contain hundreds of nodes and the probability of collisions occurring is very high.

Due to the high probability of collisions occurring for the crowded networks, this type of protocol is not sufficiently reliable for organising channel access or to use to send sensitive sensed data. On the other hand, contention-based protocols use idle listening as a method to avoid collisions. However, the main source of wasted power is idle listening, so these protocols then become non-implementable for applications which involve power constraints.

2.3.2 Schedule-Based

This is the second type of WSN MAC protocols which are built based on a schedule-based technique. Here, several MAC protocols have been reviewed such as LEACH, OP-LEACH, TRAMA, LMAC, EMACS [59]. Schedule-based protocols rely on assigning a certain time for each node to use its duty to deliver its data [52, 59, 60]. The advantages of using this technique are no collisions, predictable delays, an increase in the overall throughput and fairness. However, these schedule-based protocols have some weaknesses that will be discussed in detail in the analysis section for this protocol type.

OP-LEACH

OP-LEACH or Optimised LEACH protocol [60] is a new version of LEACH protocol which aims to reduce energy consumption within the wireless sensor network. Where LEACH [52] is clustering based protocol that utilizes randomized rotation of local cluster-heads to evenly distribute the energy load among the sensors in the network. LEACH uses localized coordination to enable scalability and robustness for dynamic networks, and incorporates data fusion into the routing protocol to reduce the amount of information that must be transferred to the base station as shown in Figure 2.7. But LEACH is based on the assumption that each sensor nodes contain equal amount of energy which is not valid in real scenarios. LEACH uses a TDMA based MAC protocol, in order to maintain balanced energy consumption. A number of these TDMA slots are wasted when the nodes have random data distribution. Hence, OP-LEACH protocol has been introduced to be more realistic and overcome these weakness in LEACH protocol.

The mechanism of OP-LEACH rely on improves the performance of LEACH algorithm in terms of energy and time delay in real time networks. Every sensor node does not have data all the time. The data is available in random fashion. The sensors may be event driven, so data may be available only when they sense the event. The proposed method is utilizing the slots belonging to the node having no data to send. This method turns free slots into useful slots without making any changes in the TDMA schedule. This will reduce the waiting time for sensor nodes because now sensor nodes can get more than one slot per frame. It will reduce the data transmission delay and increase throughput of the network. Proposed method works in rounds. The operation of proposed algorithm is managed over consecutive cycles where each cycle consists of a fixed number of rounds. Each round consists of following two phases: cluster set-up phase and steady state transmission phase. Cluster set-up phase includes grouping of clusters and cluster head selection. Steady state phase includes transmission of data [60]. Initially, this could be implementable for a chain topology, but it needs some modifications to meet the design requirements such as multi-hop communication pattern.

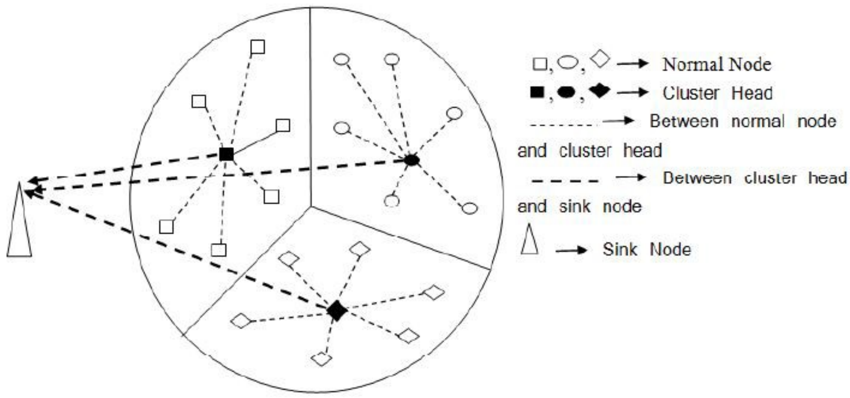


Figure. 2.7 LEACH protocol

TRAMA

Traffic-Adaptive Medium Access (TRAMA) aims to provide an energy-efficient method and collision-free channel access. This protocol allows every node to create its own schedule on demand.

The nodes are assumed to be time synchronized and the time is divided into cycles. Each cycle contains random access periods followed by a scheduled access period. There are three main components which represent the TRAMA protocol: the Adaptive Election Algorithm (AEA), the Neighbour Protocol (NP) and the Schedule Exchange Protocol (SEP). During the random access phase, the Neighbour Protocol (NP) allows nodes operating on TRAMA to exchange neighbour information over two hops by using randomly selected small timeslots

[61]. In addition, every node is able to transmit its current schedule to a neighbour by using the Schedule Exchange Protocol (SEP). Based on these neighbours' schedule information, nodes will be able to determine which slots of the scheduled access phase can be used. Thus, every node will calculate the priority *p* for its node identifier *x* for each timeslot *t* by using a global hash function *h*.

$p(x,t) = h(x \oplus t)$

Where $(x \oplus t)$ is the concatenation of node identifier *x* with current time *t*. The priority will be calculated by each node, so each one computes its own priority. Between two hop neighbours, the slots for which *x* has the highest priority value will be used by *x* to transmit its packets. The last winning slots are always used for broadcasting $x's$ next schedule and $x's$ neighbours should wakeup at this slot to receive $x's$ next schedule. Possible conflicts arise when node *D* has the highest priority in *B*'s two-hop neighbourhood, and *B* knows it, but on the other hand, node *A* has the highest priority in its two-hop neighbourhood so *A* thinks it can send its packet as long as it has the highest priority over two-hops. Figure 2.8 shows this case. The above problem is solved by Adaptive Election Algorithm (AEA) which allows

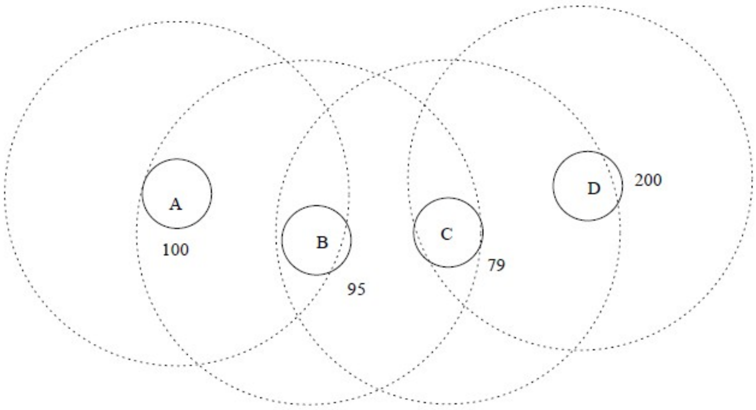


Figure. 2.8 Inconsistency issue in TRAMA protocol

nodes to reuse their neighbour's unused winning slots [61].

LMAC

This protocol is the Lightweight Medium Access Control (LMAC) protocol, which has been designed to solve the issue of static sleep intervals. This protocol proposes a solution by making the sleep interval adaptive to the amount of data traffic [51]. To achieve the flexibility in this protocol, the LMAC has introduced a self-organizing feature. The mechanism of this feature (self-organizing) is applied to timeslot assignment and synchronization. Thus, the number of transceiver switches can be minimised and therefore, it is possible to adapt the sleep intervals according to the amount of traffic [62]. Therefore, the LMAC protocol is designed to include two main components in each timeslot. These components are the Control Message (CM) and Data Message (DM) periods.

At the beginning of the network set-up phase, the gateway nodes take the step of controlling a timeslot to be synchronized. So the gateway nodes send a CM message using that timeslot. The CM message consists of the Distance to Gateway, the Sender ID, the Destination ID, Occupied Slots, Data size, Current Slot Number and so on. The gateway nodes send a CM message which includes this information to a one-hop neighbour. Then the neighbour node will synchronise its clock with the gateway clock. After this, the node will select a random timeslot to control(this node will only use this slot for sending, the other slots which are selected by its neighbours will be used for receiving only). By applying this localized scheduling algorithm, the algorithm guarantees that the same timeslot will not be used between two hop neighbours which avoid the hidden terminal issue.
The CM message will be continuously sent by nodes to their neighbours until all the nodes of the network become synchronised and all the timeslots are occupied. As a result, the data collection process to collect data from the source to the gateway will be conducted efficiently, that is referred to as the information provided (Distance to Gateway field) by the CM [4].

EMACS

The EYES MAC (EMAC protocol) proposed in [50], is a schedule-based MAC protocol where the energy efficiency is improved in exchange for some increases in latency. The concept of EMAC relies on dividing the time into timeslots and every node has the capability to use a slot to transmit its data without having any competitors on the medium. Every node in the network has its own table which is called a schedule table; the node cell's schedule will be stored in its schedule table. In addition, the neighbours' schedules will be stored in the node schedule table.

In terms of the timeslot structure, the timeslot itself is further divided into three sub-slots: communication request (CR), traffic control (TC) and data section. During the CR section, other nodes can request data or to notify the availability of data to the node controlling the timeslot. The nodes which have not received a request during their own time slots will keep their transceivers on during the entire duration of the CR section. The node owning a certain slot will be able to transmit its schedule during its data section and the schedule table will be populated in a broadcast by the TC section. When a slot is not owned by any node, all nodes will return to a sleep state during that slot. Once the node has not been addressed in the TC section, and its request has not been approved, it will go back to its standby state during the entire duration of the data section. After the TC section, the transmission of the data packet follows either an uplink or a downlink.

Table 2.2 A Comparison of Schedule-Based Protocols

Protocol	Advantages	Disadvantages
OP-LEACH	• Localized coordination and control for cluster set-up and operation enable scalability • Robustness for dynamic network changes. • Local compression to reduce global communication. • Randomized rotation of the high-energy cluster-head among the various sensors leads to a prolonged network lifetime.	• It assumes all the nodes in the network are homogeneous and energy constrained. • LEACH may encounter problems over large geographic areas, because a cluster-head may not have sufficient energy to reach the sink.
TRAMA	• Automatically adapt scheduling to the traffic load. • If a slot is not used by any node, it can be used by another node. • Nodes wake up only when they have data to send or receive. It offers high channel utilization.	• Computational complexity is high. • Assumes adequate synchronization among nodes. • It fails to address the issue of fairness
LMAC	• Self-organization of timeslot assignment and synchronization even when nodes are mobile reduces the protocol overhead. • Reduces the number of transceiver state switches to decrease the energy consumption and hence to increase the network lifetime	• It suffers from a higher source to sink delay. • Lower bandwidth utilization. Low throughput
EMACS	• This protocol allows nodes to determine their own schedule based on the requirements imposed by the service.	• The protocol is not designed to provide high bandwidth utilization. • Nodes consume energy due to idle

Analysis

Although schedule-based protocols have introduced some solutions to the issues identified within contention-based protocols, schedule-based protocols also come with some weak points. The greatest weaknesses that have been identified among schedule-based protocols are that they are not good for large networks, there are some scalability difficulties, so they only work perfectly with a stable topology. In addition, there are some challenges related to the synchronization because these protocols need precise synchronization and previous knowledge of network topology which requires expensive hardware and large overheads. Mostly, these protocols are not particularly designed to be implemented for a chain topology which has some special requirements. These requirements are represented by the topology and physical layer properties. In the best cases, the previously mentioned protocols that consider the topology and physical layer properties assume FSPL. However, a few schedule-based protocols have been designed for a chain topology and they have tried to meet the chain topology requirements and overcome the challenges. In order to assess these protocols, the next section will review schedule-based protocols for chain and linear topologies.

2.3.3 Schedule-Based Protocol for Chain or Linear Topology

A few schedule-based protocols have been proposed for chain or linear topology. These protocols use different techniques to generate a feasible transmission schedule with no interference.

As in [63], DiS-MAC is a protocol designed specifically for a chain topology, where the directional antenna was used to enhance the performance. The directional antenna introduced an advantage by concentrating the antenna beam in a certain direction and that increased the space between the deployed nodes. As well as using a directional antenna, a chain topology could help to reduce the space between any two nodes transmitting simultaneously. An advantage is gained since the back lobe of the directional antenna has a much smaller range effect of interference than the omnidirectional antenna.

The mechanism of channel access in the DiS-MAC is divided into two phases: Phase I and Phase II. Each phase has duration of *T1* and *T2*. (Optionally *T1* = *T2* = *T*). When the system is in Phase I, only the nodes in positions $2n - 1$ on the chain are allowed to transmit for a time interval T1 where n corresponds to each node's position on the chain as shown in Figure 2.9 Similarly, during Phase II, the remaining nodes (i.e. the ones located at $2n$ points) on the chain can access the channel and transmit their packets. During a scheduling cycle that lasts for *2T*, all nodes have been in two possible states, transmitting or receiving and packet transmission occur simultaneously.

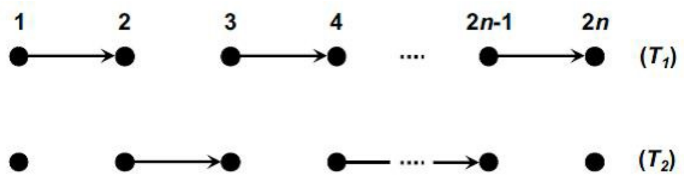


Figure. 2.9 DiS-MAC topology and operation

The graph-based approach was used to build the schedule of the simultaneous transmission, along with the performance demonstrated by the simulation which was conducted. However, the configuration of the simulation considers an ideal channel and path loss attenuation caused by the free space path loss model. This assumption does not reflect the practical scenario. In addition, the graph-based method has been used to determine the interference range, but this method does not estimate the interference range precisely, particularly when the directional antenna is used. However, the main focus of the paper is throughput rather than delays.

Simulations have been conducted using three main scenarios: firstly, with only the first node acting as the source; secondly, with all nodes generating packets and thirdly, with all nodes generating packets and these packets being forwarded to a final destination defined by the probability q. Results show that the protocol provides stable and reliable links between nodes. However, larger payloads result in more errors and in degradation of the system performance. The authors suggest that, in cases where the transmission of large packets is required, the incorporation of channel coding and data fragmentation techniques should be considered with Dis-MAC.

In [64], the author proposed a MAC protocol for wireless communication for a linear topology. The spatial reuse of time slots was considered a major concept of this protocol. The communication between WiWi nodes is synchronised, based on fixed size packets. The concurrent transmission schedule presented has been based on a graphical approach. The main scope of this protocol is likely to be fault tolerance and energy consumption [64]. WiWi [64] is a contention-free MAC protocol based on synchronous multi-hop transmission along a chain of independent nodes. Devices are displaced in order to build a linear (or curvilinear) strip. WiWi reuses a few features which were developed in the DiS-MAC. In particular, both protocols avoid interference between simultaneous transmissions by alternating transmissions between adjacent nodes. However, WiWi does not require directional antennas; it provides bidirectional communication over a single RF channel. The communication between WiWi nodes is synchronous, based on fixed size packets and follows a staggered pattern. The downstream data flow proceeds downwards from the head of the chain to the tail. Every node resynchronizes its clock upon the start of the incoming downstream packets. Once a node is synchronized with the downstream flow, its activity pattern is receive transmit idle transmit receive idle (R-T-I-T-R-I) regardless of its position in the chain. The upstream flow follows the same principle of passing messages along the chain, but between the reception of packet and its forwarding, the node waits for four time slots in order not to collide with the downstream one and this is shown in Figure 2.10.

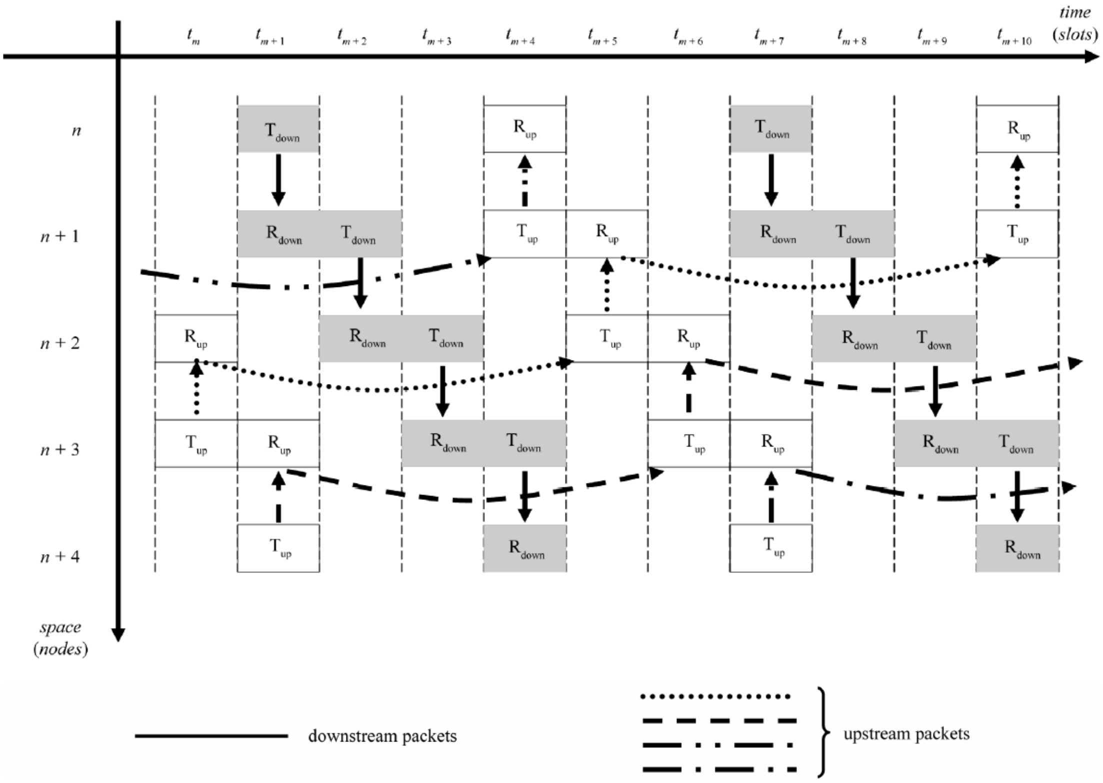


Figure. 2.10 Bidirectional staggered transmission

Moreover, WiWi nodes require no explicit addressing because within the range of transmission, there is only one receiving node (i.e the next hop for the packet). The authors argue that WiWi provides deterministic and predictable latency and throughput in both directions. However, a straightforward schedule for concurrent transmission has been briefly investigated. In this protocol, power consumption and the interference model have not been considered. Therefore, most of the parameters that affect the concurrent transmission schedule have been skipped such as the interference model and the propagation model.

In [65], an analytical framework is presented to investigate co-channel spatial reuse in dense wireless ad-hoc networks based on RF propagation models for some common network topologies. Physical layer properties are considered in this calculation to identify *k* value by calculating the SIR (Signal Interference Ratio). One of the physical layer properties that have been considered here is a link-budget-inspired SINR model used to characterise the wireless link. In addition, two propagation environments are considered here with different path loss exponents: the LOS and NLOS. To study the interfering transmitter, a *k* value is defined that represents the minimum separation distance between any concurrent transmissions in a chain topology with no interference. Thus, the axial interference model is used here to calculate the accumulated interference in one direction as interference model. This model is used to find the best achievable spatial reuse.

Two types of chain topology for wireless communications have been considered in this study and the minimum distance between two simultaneous transmissions has been calculated. The first type is a 1D chain network, and the second type is a 2D chain network. The separation distance has been validated, but without a transmission schedule. In addition, the propagation model used in this study is FSPL which does not reflect most practical scenarios. Moreover, the interference model only considers only the interference factors without noise, but it is important for the SINR to include the noise factor, since this affects the *k* value. In addition, the noise produced by the nearby nodes definitely exists especially on the chain topology. Therefore, this framework can be considered for node scheduling (where all the nodes broadcast and share the distension) but it is not appropriate for link scheduling, or for multi-hop communication patterns. This study concludes with an obvious fact that increasing the transmission power will lead to increasing the SINR where the spatial reuse can be improved. Moreover, this study used the SIR to approximate the SINR value and this increases the probable weakness of this study due to the lack of accuracy.

Analysis

As has been observed, most of the reported protocols rely on a graph-based approach to build schedules of transmission to enable spatial reuse TDMA and maintain interference. This approach is used to avoid complexity, but it sacrifices accuracy by avoiding interference. The required level of accuracy is likely to be provided by the SINR model that considers the physical layer properties and Signal Noise Ratio (SNR). Even though these protocols used the SINR model to estimate interference, they were not sufficiently accurate to build an interference-free spatial TDMA protocol for ground level communication. This referred to that; the existing protocols assume a free space path loss model to calculate SINR. However, these proposed protocols [63–67] are not suitable to be implemented in a road-based wireless sensor chain topology, where the propagation model used is designed specifically for ground level communication .Therefore, these reported protocols do not take into account the system topology and the properties of the physical layer.

2.4 Chapter Summary

Although the communication aspects are important for propagation models or MAC protocols for ITS systems, particularly those which are road stud-based, these aspects have not yet been investigated in an ITS context. This literature review investigated proposed near ground propagation models and energy efficiency metrics applied in wireless systems in-depth. None of the previously mentioned propagation models were formally designed for ground level communication, so they are not implementable in ground level scenarios such as those using road studs. As a result, there is a need to design a propagation model for ground level communication that is able to predict path loss and signal attenuation. In addition, the effect of the antenna height on ground level communication needs to be observed and considered in order to present an accurate propagation model.

On the other hand, the energy efficiency metrics presented were particularly designed for cellular systems to improve their energy efficiency, and this is not compatible with wireless sensor networks. However, the energy efficiency metrics which have been designed for wireless sensor networks are not based on the access level. The majority of proposed energy efficiency metrics for WSNs have been based on the concept of equipment-level or network-level efficiency. In addition, the physical layer resources in wireless sensors need an effective energy efficiency metric that has the capability to estimate the consumption of these resources.

A number of MAC protocols have been reviewed, classified under contention-based or schedule-based chain topology. The first two classes of protocol (contention-based and schedule-based) claim that their protocol is generalised and implementable for most WSNs' topologies. However, this claim is largely not true because every topology has constraints and every application has its own requirements. Therefore, one of the subsections in this literature review has highlighted a schedule-based protocol designed specifically for a chain topology. These protocols have been studied in-depth in order to find their advantages and disadvantages once applied to a ground level-fixed chain topology. Given that, in the system presented in this dissertation, the road studs are placed on the road and deployed as a chain topology, these proposed protocols are not compatible with a chain topology. Thus, the inadequacies in MAC protocol systems give rise to the need to design a new MAC protocol to suit wireless nodes deployed in a chain topology and to consider the topology constraints and the interference.

Since our proposed system will use as a solar powered sensor and rechargeable battery and the sensor will be deployed on motorways which will be difficult to access for maintenance purposes, it is very important to propose a new MAC protocol which reduces power consumption as much as possible, while, at the same time, providing an intelligent scheduling algorithm to avoid any collisions that would lead to power wastage.

Several technical issues were not addressed in these reported works. These issues are significant and it need to be addressed in this research are:

• The ground level radio propagation: this area has not been studied yet, so there is need to introduce a propagation model designed particularly for ground level communication. While the effect of antenna height will be investigated in order to determine the transmission range for ground level communication.

• Most of the existing energy efficiency metric for WSNs are built based on equipment level, where the propagation properties and the access node level were neglected. Hence, a new energy efficiency metric for WSNs need to be addressed based on access node level and the propagation properties should be considered on the this metric.

• A new MAC protocol for chain topology: thousands of MAC protocols has been proposed previously, most the existing MAC protocol were not consider the topology and propagation properties. Thus, in this research a new MAC protocol will be introduced that designed specifically for chin topology and consider the propagation properties. This protocol support multi hop communication, spatial reuse time slot efficiently and reduce the delay in chain topology.

Chapter 3

Ground Level Radio Propagation Model

3.1 Overview of Propagation Phenomena and Signal Behaviour

Before studying propagation phenomena and signal behaviour, it is important to identify what a radio wave is. A radio wave is an electromagnetic wave produced by a transmitter; it can travel for long distances to reach the receiver. During the travel period, whether through an indoor or outdoor environment, the transmitted signal is exposed to a variety of external, technical and environmental factors that affect signal behaviour and lead to the loss of part or the entire signal. The factors that could influence signal behaviour during radio wave's journey are countless, but the most important ones relate to the antenna's height environment (mountains, ground, underwater, etc.). These effects result in various appearance of propagation phenomena, which explain the resulting signal behaviour. Some of these phenomena are reflection, diffraction and scattering. Thus, research on radio wave propagation must consider the signal behaviour and propagation phenomena caused by these factors [68]. Several radio propagation models have been proposed to study signal behaviour and calculate the power received on the receiver side, to measure path loss and also to measure the signal attenuation caused by the environment or materials. These models include the two-ray model, Hata model and knife-edge model[69].

Before studying radio propagation phenomena, we need to review some basic phrases that are commonly used in the communication field, such as path loss and (FSPL). Alejandro in [69] defines path loss as the ratio of the transmitted power to the received power, usually expressed in decibels [69]. It includes all of the possible elements of loss associated with interactions between the propagating wave and any objects between the transmitter and the receiver antennas [69]. The main goal of radio propagation modelling is to predict L path loss as accurately as possible, allowing the range of a radio system to be determined before installation by Eq 3.1 as illustrated in Figure 3.1.

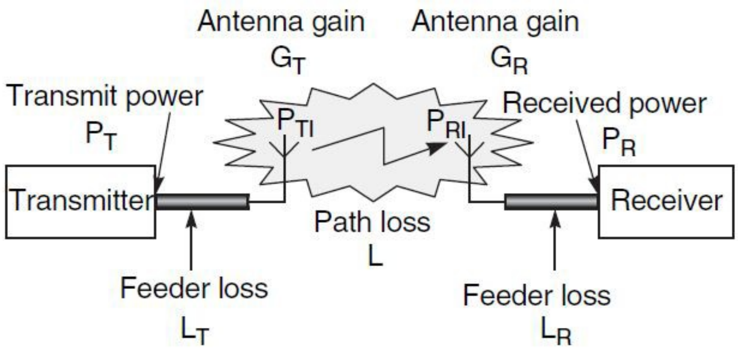


Figure. 3.1 Path Loss

$$L = \frac{P_{TI}}{P_{RI}} = \frac{P_T G_T G_R}{P_R L_T L_R} \tag{3.1}$$

Here, P_{TI} and P_{RI} are the effective isotropic transmitted power and received power respectively.

Regarding the free-space propagation or FSPL model, this radio propagation model is used to calculate the strength of the received signal when the distance between the transmitter and the receiver is a clear or unobstructed (line-of-sight) path. In the free-space propagation model, the power received by a receiver antenna from a radiating transmitter antenna at a distance d is given by Friis free space equation 3.2

$$P_r(d) = \frac{P_T G_T G_R \lambda_2}{(4\pi)^2 d^2 L} \tag{3.2}$$

where P_T is the transmitted power; $P_r(d)$ is the received power, which is a function of the T-R transmitter and receiver separation; and G_T and G_R represent the transmitter and receiver antenna gain, respectively. The distance between the transmitter and the receiver is represented by d, L is the system loss that is not related to propagation and λ is the wavelength in meters.

3.2 The Common Behaviour Of Signal

In wireless communication, the transmitted signal is exposed to many effects while it is travelling from the transmitter to the receiver. Except in a free space atmosphere, the signal is affected by physical or environmental factors which result in the signal strength and path loss. The physical factors include but are not limited to the transmission distance, antenna height, walls or metal etc., while the environmental factors could be trees, the ground or any object existing between the transmitter and receiver which are related to the environment. Once the signal is exposed to these factors, the signal behaviour will change and these changes are called phenomena. The most common types of behaviour or signal phenomena are reflection, diffraction and scattering. Each of these phenomenons describes the signal behaviour when it is exposed to the influencing factor and it identifies the effective and considerable factors to predict the path loss and the signal attenuation accurately. Next, the most relevant phenomena are highlighted below, to help identify to what extent they can be reused in our research.

Reflection

Reflection is a phenomenon which occurs when the signal propagated in one medium impinges upon another medium with different electrical properties, such as metal, water, wood, or concrete; in this case, the wave is partially reflected and partially transmitted. If the plane wave is incident on a perfect dielectric, part of the energy is transmitted to the second medium, while the other part is reflected back to the first medium. Meanwhile, if the second medium is a perfect conductor, then all incident energy is reflected back to the first medium without loss of energy [68]. Thus, wave reflection is classified into the following two types: reflection from a perfect conductor and reflection from dielectrics. As a result, the amount of received energy is affected by the type of the second medium. Therefore, many radio propagation models, such as the two-ray model, have been developed to predict the amount of received energy and the transmission distance after considering the coefficient of the permittivity and conductivity of the second medium's material.

Diffraction

Diffraction is a phenomenon that appears when the radio path between the transmitter and the receiver is obstructed by a surface that has sharp irregularities. The secondary waves resulting from the obstructing surface are present throughout the space and even behind the obstacles, giving rise to a bending of the waves around the obstacle, even when a line-of-sight path does not exist between the transmitter and the receiver. Fresnel zone geometry is a propagation model that has been proposed to calculate the minimum antenna height to avoid diffraction. In contrast, the knife-edge diffraction model has been proposed to calculate the signal attenuation caused by the diffraction of radio waves over hills and buildings [68].

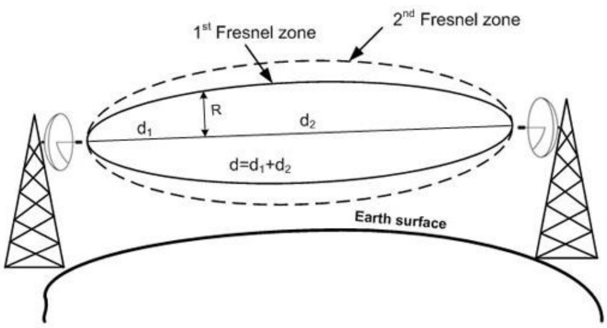


Figure. 3.2 Fresnel Zone

There are several factors that can affect diffraction, including the frequency. At high frequencies diffraction can be converted to reflection depending on the geometry of the object. Other factors include the amplitude, phase and polarisation of the incident wave at the point of diffraction.

Scattering

Scattering occurs when the medium through which the wave travels consists of objects with dimensions that are small compared to the wavelength, where the number of obstacles per unit volume is significant. A scattered wave is produced by a rough surface, small objects or terrain in mobile communication systems. The transmitted signal will impinge on a rough surface and the reflected energy is spread out in a random direction due to scattering. If the dimension of the obstacle is larger than the wavelength, however, it would be more accurate to model it as a reflective surface than to use scattering [70].

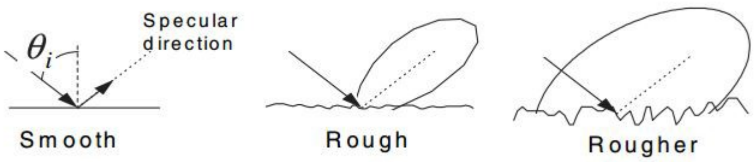


Figure. 3.3 Scattering

Surface roughness is calculated using the Rayleigh criterion, which defines a critical height h_c of surface protuberances for a given angle of incidence ϑ_i; this is given by the following:

$$h_c = \frac{\lambda^2}{8 \sin \vartheta_i} \tag{3.3}$$

To predict the strength of the scattered signal accurately, the Radar Cross-Section model (RCS) has been proposed and developed; this considers the important factors related to the objects, such as object-induced scattering and the physical location of the object [68].
Numerous radio propagation models have been introduced for different contexts. These models attempt to consider the main characteristics of the signal to provide an accurate propagation model that is able to predict signal behaviour and estimate the path loss and attenuation. Some of these propagation models suit particular environments and provide an accurate estimation for them. These radio propagation models are investigated and assessed in the next section.

3.3 Ground-Level Radio Propagation Models

Monitoring the traffic state and condition using road studs requires the installation of wireless sensor nodes at ground level. These installed nodes are responsible for sensing the traffic state and condition and sending the sensed data to the nearest node, from which it is then passed to the sink node. It is necessary to study ground-level communication to establish reliable communication amongst the nodes and measure the maximum transmission distance between them. Moreover, this helps to predict the signal behaviour, path loss and the effects of the environment before the installation stage.
The ground-level radio propagation model for low-powered wireless sensors involves the study of signal behaviour when the transmitter and receiver are installed on a wireless sensor and located at ground level. Although numerous radio propagation models have been proposed for different environments and scenarios, not all of these proposed models are implementable for ground-level communication; this is particularly the case if a low-powered wireless sensor is employed. Given these considerations, it is important to carry out a realistic measurement to study the signal behaviour for ground-level communication of a wireless sensor, since this type of communication has not been investigated sufficiently. So far, no radio propagation model has been designed specifically for ground-level communication. This chapter presents a proposed mathematical model for ground-level communication for

low-powered wireless sensors. This model is derived from a realistic experiment conducted at a tennis court layered with tarmac, which is similar to a motorway environment.

3.3.1 Signal Behaviour at Ground Level

Since the transmitter and receiver were located at the same height at ground level, the separation distance between them is clear and not blocked by any object; thus, the communication is considered to be line-of-sight. Although the transmitter and receiver were located directly on the ground on a rough surface (tarmac), which contains small stones, we did not consider the scattering phenomenon. Instead, the tarmac was considered a smooth surface because the dimension of these stones was much smaller than the wavelength [68].
The experiment was performed at different heights of 0–12 cm over different distances between transmitter and receiver. This experiment aimed to study the signal behaviour for an extremely low antenna height and to measure the maximum transmission distance. The findings from this measurement showed that the signal behaviour was significantly affected by antenna height. They also showed that when the antenna is placed at ground level, we can achieve 8 m of transmission distance between the transmitter and receiver. The chosen frequency was 2.4 GHz because this application required the antenna to be small enough to fit into a road stud. We faced several technical and environmental challenges during the measurement stages, and the next section discusses how we solved them.

3.3.2 The Challenges Involved in Ground Level Communication

All experimental work definitely entails some challenges, whether technical or environmental. In the present work, challenges arose even before the measurements were carried out. Some of these challenges related to the technical equipment, while others related to the environment.

The Technical Challenges

One of the technical challenges was selecting a type of antenna that would be suitable for this environment while being able to fit into a road stud. There are numerous types of antenna on the market with different specifications, but we found a suitable antenna for this experiment customised by Kent Britain manufacturer in USA [71]. Thus, the antenna used in this experiment was a Printed Yagi Directional Antenna. This antenna was selected for several technical reasons. First, this antenna is from a family of directional antennas that is able to concentrate the beam in a certain direction and achieve the maximum transmission distance. Secondly, the dimensions of the Printed Yagi make it small enough to fit into a road stud.

Difficulty was encountered in avoiding any damage while removing the previous antenna from the XBee module (where XBee modules are defined as embedded solutions providing wireless end-point connectivity to devices. These modules use the IEEE 802.15.4 networking protocol for fast point-to-multipoint or peer-to-peer configuration) [72],and soldering the antenna to the XBee module.

Several factors were considered in choosing the appropriate frequency, including the cost, wavelength and interference. For this experiment, we found that 2.4 GHz was the most appropriate frequency because it is a free frequency that is suitable for experimental purposes; moreover, it allowed us to avoid any legal obligations. Moreover, the wavelength of this frequency is 12.5 cm, which is much larger than the dimensions of any obstacles on the road. Thus, in choosing this frequency, we were able to avoid signal scattering caused by stones. Moreover, the frequency consists of 16 channels that can be used to prevent any interference.

The Environmental Challenges

Selecting the site of the experiment was a challenge because we needed an open space layered by tarmac to simulate the motorway environment. Most spaces layered by tarmac, such as car parks and small roads, are occupied by cars, and it would have been difficult to block traffic to perform our experiments. Thus, we determined that the tennis court at the Brookes Wheatley Campus at Oxford University would be a suitable location for conducting the measurements. It had the advantage of being an open area that was layered with tarmac where we would not be distracted by traffic. The other environmental challenge was the ground itself because the antenna needed to be placed directly on the ground; thus, a part of the propagated signal would be absorbed by the ground. Therefore, a directional antenna was used in this measurement to extend the transmission distance and overcome the ground effect.

It is known that weather conditions, such as wind and rain, affect any communication system, so it was difficult to predict the weather conditions and whether these would be ideal for performing the measurements or not. As a result, the experiments were delayed multiple times due to wind and rain, which could affect the results. In addition, to record an accurate result, we removed any metal in the measurement location and avoided any absorption of the propagated signal.

3.3.3 Plan of Measurement

The Required Equipment

This section describes the equipment required to perform measurements of nodes placed on the ground level. The main goal of the measurements that were carried out was to examine the propagation at ground level to determine the maximum distance between the road-based nodes as a function of the antenna height. The main part of this equipment was an Arduino microcontroller, which carried the XBee module. This was responsible for carrying the XBee module and passing on the command to allow XBee to communicate with other device in its range(see Figure 3.4).
The Arduino microcontroller was specifically selected because it has a variety of functions, and it provides interfaces to insert the commands or C++ code, Arduino microcontroller shown in Figure 3.5. The C++ interface coding provides the flexibility to fully control the module behaviour. As a wireless transceiver, the second generation of the XBee module was used because it provides better options than the first generation, especially regarding the available transmitting power. Thus, the effective isotropic radiated power (EIRP) of the transmitter used in this measurement was 2 mW. A lithium battery was used as the power source to operate the Arduino board and the attached components.

Figure. 3.4 XBee Module S2

Figure. 3.5 Arduino microcontroller

A laptop was used to send packets and record the signal strength by reading the received signal strength indicator (RSSI) value. Also, we needed to use open X-CTU software, which allows modification of the XBee parameters and testing of the connection. The directional Yagi antenna uses a frequency of 2.4 GHz; this frequency was preferred for this experiment because the antenna needed to be small enough to fit into a road stud. In addition, 2.4 GHz is a free frequency, so legal issues could be avoided.
Due to the difficulty of changing the height manually and achieving a high level of measurement accuracy, we used an adjustable stand to accurately modify the antenna height. The designed adjustable stand included a stable board to determine the height precisely and a wood base to avoid any absorption caused by metal.

The Scenarios

An experimental plan was designed to determine the targeted scenarios and expected results scientifically. This explained the background and goals of the experiment, as well as the required equipment and the measurement location. Furthermore, several scenarios were considered in this plan in order to understand the signal behaviour from different perspectives and study the factors that are the main sources of signal attenuation. In addition, the experiment aimed to test the maximum range for two transceivers placed at ground level and at different heights. Thus, we examined the signal attenuation and the maximum achievable transmission range between two nodes in an outdoor environment. These two nodes were placed at various heights and in different conditions; for example, two nodes communicated at 1 m height to measure the transmission range of the directional antenna in free-space condition. To increase the antenna gain in the direction of the receiver, a printed directional

Yagi circuit board with a gain of 8.5 dBi was used (see Figure 3.6).

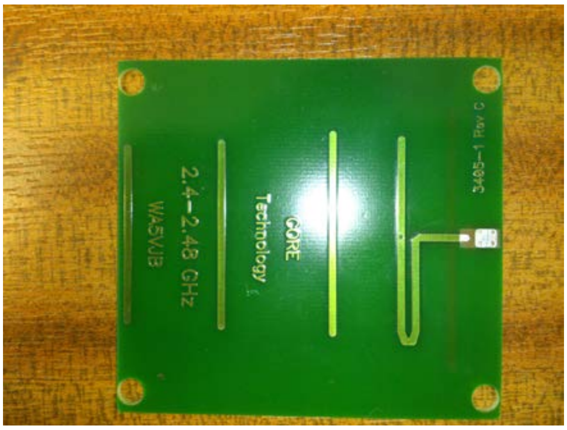


Figure. 3.6 Directional Antenna Yagi

Free Space Scenario In this experiment, we sought to test the maximum range for two nodes located at 1 m above ground level. Our aims were as follows:

- To specify the maximum transmission range of two modules at 1 m above ground level
- To identify the effects of the directed beam of the directional Yagi antenna
- To specify the minimum antenna height at which two nodes are able to communicate in free space (in the absence of obstacles).

Two nodes were placed on 1 m height, the separation distance was not contain any obstacles. Several packet sent over each distance in order to measure the received power values and how it can be effected by transmission distance. At every meter the received power value recorded and the the separation distance gradually increased till the the received signal missed at 38 meter. As a result, in this scenario the directional antenna studied, as well the relationship between antenna height and transmission distance was proved.

Ground Level Scenarios These scenarios were performed for two nodes with a directional antenna; the nodes were placed at the same height, from ground level to a height of 12.5 cm, so the antenna heights tested were 0 cm, 1 cm, 2.5 cm, 5 cm, 7.5 cm, 10 cm and 12.5 cm. The goals of these measurements were as follows:

- To measure the maximum transmission range between two nodes, where both were placed at the same height, but this height was changed to measure the effect of the antenna height on the transmission range.
- To investigate the effect of antenna height and the ground surface on the signal behaviour.

In general, the main aim of these measurements was to measure the path loss between wireless sensor nodes with antenna heights in the range 0∼12.5 cm using a frequency of 2.4 GHz. In first scenario of ground level communication, two nodes placed on ground level. This scenario was the hardest scenario since the nodes and its antenna placed on ground directly and the antenna height was approximately 0 cm. The received power value recorded over every meter, and then the separation distance was increased gradually every meter. This process followed to investigate the maximum transmission distance for antenna placed on ground level. This experiment repeated five times, but over different antenna height 2.5, 5, 7.5, 10, 12.5 cm. With these scenarios we collected a results which show the relationship transmission distance. As well as, it show the significant effect of antenna on the signal attenuation.

Figure. 3.7 Ground level communication

Figure. 3.8 Near Ground level communication

Location

The measurements were carried out on a tennis court at the Oxford University Brookes Wheatley Campus. This has a tarmac surface similar to that of a road. Different antenna heights were tested to study the effect of antenna height on path loss and signal behaviour. This site was preferred for this measurement because it was remote, and this guaranteed that it would be free from frequency interference, which could be caused by other devices operating on the same frequency. Moreover, this location did not contain any metal, which allowed the propagated signal to be observed effectively. The site shown in Figure 3.9.

Figure. 3.9 Measurement Location in the Tennis court at Wheatley campus

3.3.4 The Proposed Radio Propagation model

Multiple radio propagation models have been proposed and demonstrated to understand and predict signal attenuation [21, 22, 24]. Usually, these radio propagation models have been proposed for specific scenarios, such as urban models, or for particular environment, such as terrain or forest environment models [27, 73, 74]. A few studies have focussed on propagation near the ground and have studied the ground effect on path loss. However, ground level radio propagation has not yet been determined; there is no radio propagation model which can predict the signal attenuation and path loss of two nodes transmitting at ground level. Therefore, this research represents an opportunity to study signal behaviour when it is transmitted at ground level and then investigate the effect of antenna height on path loss and signal attenuation. Thus, we studied the ground-level propagation of wireless communication to determine the effect of antenna height and predict the maximum transmitting distance. This proposed model will be very useful for estimating the maximum transmission range of two road studs installed to monitor traffic conditions. The proposed radio propagation model aims to analyse the variation in received power as a function of height. The overall propagation model is the Friis equation multiplied by the blocking factor in Eq 3.6, as shown in Eq 3.4.

$$P_r = P_t \frac{G_t G_r \lambda^2}{(4\pi d)^2} \cdot \left(\frac{h}{d}\right)^n \tag{3.4}$$

3.3.5 The Mathematical Model

With the same equipment and configuration as described in the previous section, a measurement was carried out at a height of 1 m. This measurement aimed to determine the minimum antenna height at which free space could be achieved. In addition, free space was used as a reference radio propagation model from which to derive the ground-level radio propagation model, with consideration of the antenna height. Following this, the antenna height was gradually reduced from the free space level until the nodes were placed at ground level. This was helpful for studying the effect of antenna height on transmission distance and signal attenuation.

The proposed empirical radio propagation model was derived from the FSPL model [68] with an adjustment factor to take the antenna height and the blocking effect of the ground into account. The FSPL model, modified to include the gain of the transmitter and the receiver antennas, is given by Eq 3.5.

$$P_r = P_t \frac{G_t G_r \lambda^2}{(4\pi d)^2} \tag{3.5}$$

where P_r and P_t are the power at the receiver and the transmitter respectively; G_t and G_r are the corresponding antenna gains; λ is the radiation wavelength; and d is the distance between

the transmitter and the receiver.
For antennas placed very close to the ground, the FSPL model given in the equation is modified by a blocking factor F as shown in Eq 3.6.

$$P_r = P_t \frac{G_t G_r \lambda^2}{(4\pi d)^2} .F \tag{3.6}$$

Assuming the transmitter and receiver heights are equal, the blocking effect of the ground F increases as a function of the ratio of the height of the antenna h and the distance d between the transmitter and the receiver. The blocking factor is modelled by F as shown in Eq 3.7.

$$F = \frac{h}{d}^n \tag{3.7}$$

where the exponent, n, determines the magnitude of the blocking. It depend on the antenna height, n can be calculated by Eq 3.9. The overall radio propagation model is the Friis equation multiplied by the blocking factor in Eq 3.6, as shown in Eq 3.8.

$$P_r = P_t \frac{G_t G_r \lambda^2}{(4\pi d)^2} . \frac{h}{d}^n \tag{3.8}$$

3.3.6 The methodology

The methodology which has been used here to derive this model was the reverse engineering. The reverse engineering method relay mainly on the realistic data. Therefore, Eq 3.5 has been used at the beginning to estimate the received power over each distance. And we compared FSPL calculation result with the measurements results, we noticed that our result was highly effected by antenna height and transmission distance. Then, the same calculation repeated, but with considering the effects of antenna height divided over the transmission distance which represented lately by Blocking Factor as in Eq 3.7. The calculation results compared with measurements results which was conducted on the field. A highly matching was figured out between the measurements results and the calculation results which considered antenna height and transmission distance. In order to improve the accuracy of the proposed equation, the path loss component has been added to the blocking factor F. This path loss exponent represented by n. The next step ws studying the optimum value for n in order to calculate the received power value accurately.
The calculation results with existing the blocking factor compared with the measured results over each distance. This process performed to determine the slight difference between the

proposed equation and measurement results. This difference will be helpful for us to predict the n value and understand the effect of the path loss exponent. The comparison produced a new value which represent the difference between the calculation results and measurement results. This value is n, so the proposed equation in Eq 3.6 which consider blocking factor 3.7 and the new value n as exponent will able accurately estimate the received power as in the measurement results. The n has been added to blocking factor F to matching the measured results. As last step curve fitting technique has been used to modelling the value of n for each antenna height. Therefore, for each antenna height we collected the optimum value of n as exponent for F which produce an accurate result that matching the measured results. The n values has been plotted and the third order of polynomial regression type was used to generate an equation as in Eq 3.9. This equation able to estimate the suitable value for n based on antenna height, and with additional constant values represented by A, B, C and D. It can be seen if Figure 3.13 that the value of n is a function of height. As a result, a new mathematical model has been introduced here for ground level communication, it was validated by use the proposed model to generate a results to compare it with measurement results.

$$n = A.h^3 + B.h^2 + C.h + D \tag{3.9}$$

where h = height of the antenna and A, B, C and D are constants. Using curve fitting, the optimum values for constants A–D were found to be the following:

$$A = -0.0096, B = -0.1485, C = 1.1904, D = 12.591 \tag{3.10}$$

3.3.7 The Results

The results of the measurements of received power as a function of node separation and antenna height are shown in Figure 3.10. The minimum height was achieved with the printed antenna placed on the ground (0 cm).

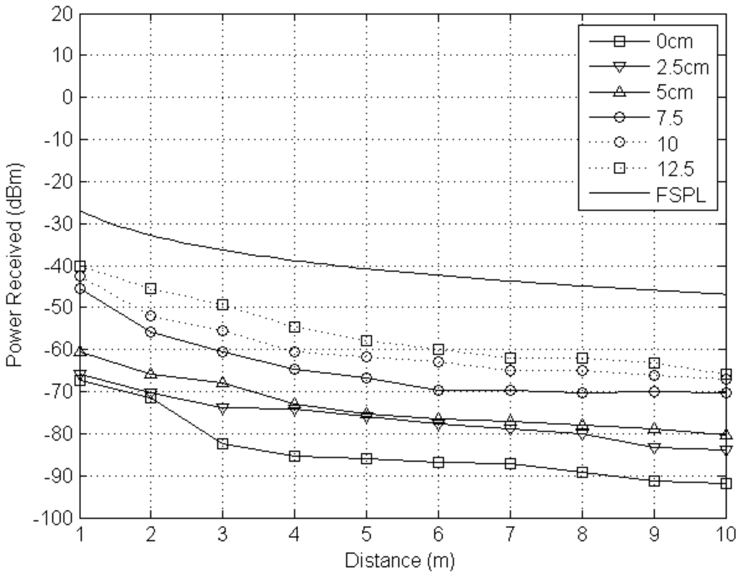


Figure. 3.10 Measurement Results for Different Heights

The results show that the received power decreases with distance and increases proportionally with antenna height. The minimum received power for the Xbee receiver was –92 dBm, so the maximum range for the antenna at ground level was about 9 m. The calculation result

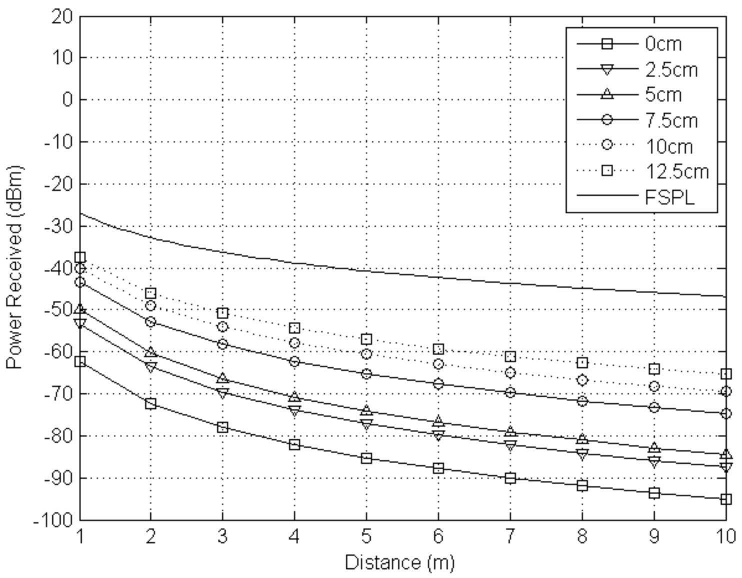


Figure. 3.11 Results of the Proposed Model

of the proposed radio propagation model is in accordance the results collected from real experiments. So by using the proposed radio propagation model, it will be easy to predict accurately the value of the power received on the receiver side. This will be helpful to numerically identify the maximum transmission distance, signal attenuation and path loss for different antenna heights as shown in Figure 3.11.

To analyse the variation of received power as a function of height, the results have been re-drawn as shown in Figure 3.12. This graph illustrates the received power recorded as a function of the antenna height for distances of 3m, 5m and 8m; it clearly shows how the received signal strength increases with antenna height.

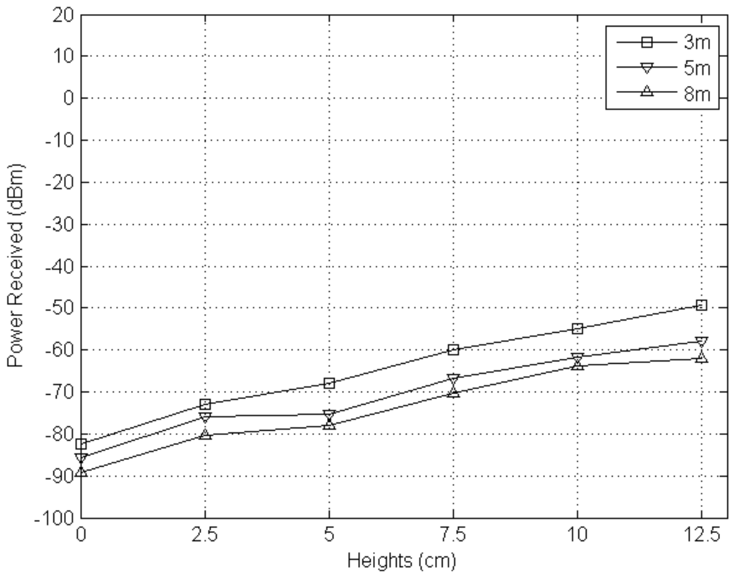


Figure. 3.12 The Effect of Antenna Height

This model has been matched to the measured results using curve fitting and the values predicted by the model are shown in Figure 3.14. The antenna gain is assumed to be $G_t = G_r = 4.5$ db. The value of n for each height is given in Figure 3.13. It can be seen that the value of n is a function of height. The parameter n has therefore been modelled as shown in Eq 3.9.

3.3.8 Validation

Comparing the values predicted by the proposed model with the measurement results

Validation was an important step in evaluating the proposed radio propagation model. This was done by comparing the measured results and the calculated results. A calculation was carried out to estimate the received power on the receiver side, and then the outcomes were

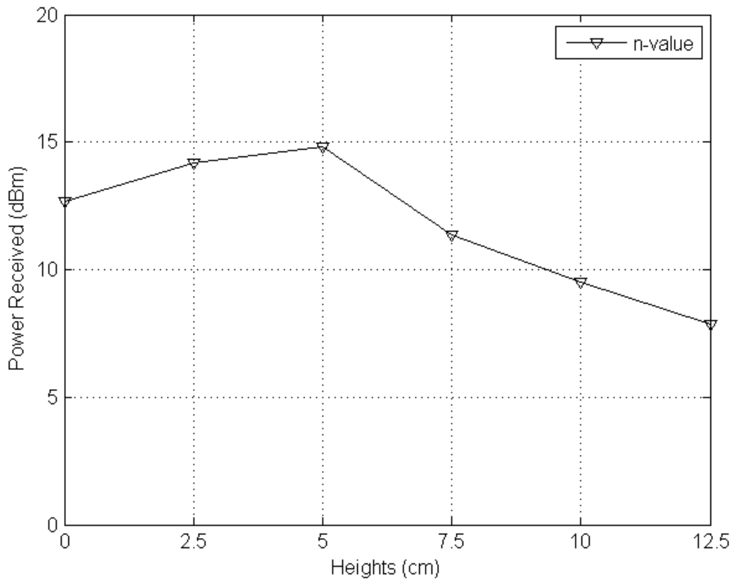
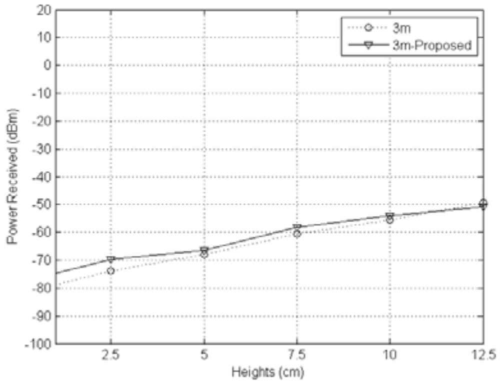
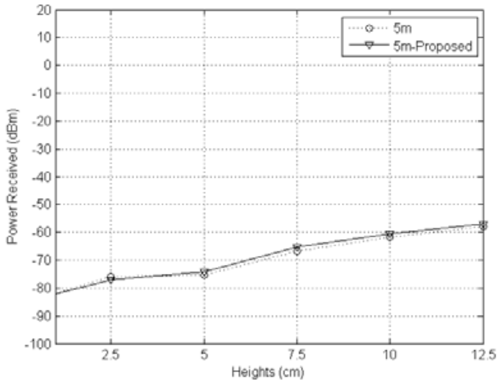


Figure. 3.13 The n Values for Different Heights

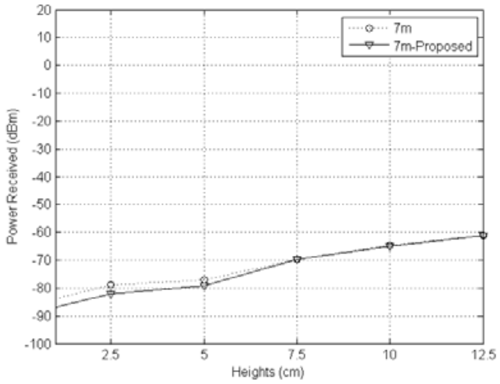
compared with the measured results. In Figure 3.14, the values of the received power for distances of 3, 5, 7 and 9 m calculated using the proposed formula are compared with the collected results from the field measurements. It can be seen that there is a close match between the values predicted by the model and the measured values, which demonstrates that the proposed model can accurately predict the path loss for heights of 0~12.5 cm, which represents the range of interest for road-based wireless sensors.



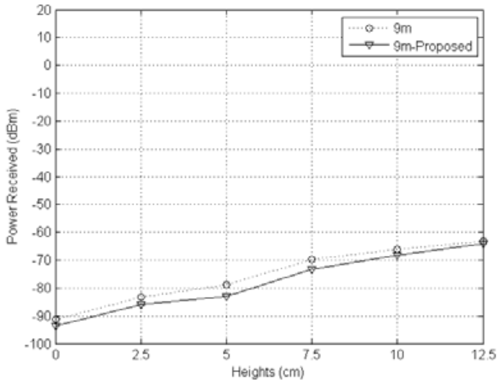
(a) 3 meter distance



(b) 5 meter distance



(c) 7 meter distance



(d) 9 meter distance

Figure. 3.14 validation of different heights at different distance

Comparing the proposed model with previously reported models

In previous work [21, 26, 25], the researchers proposed radio propagation model for near ground level communication. The lowest antenna height for which results have been presented is 8.25 cm [26]. Figure 3.15 compares the received power predicted by the Environmental Prediction Model (EPM) in [26] with the measured results and the model proposed in this work for an antenna height of 7.5 cm. The results show that the model proposed in this chapter provides a more accurate fit to the measured results than the EPM model in [26]]. The EPM model in [26] uses an environmental factor which is based on soil as the ground surface whereas the results in this experiment are based on a tarmac surface. This may explain the difference between the results.

Figure 3.16 compares the received power predicted by the Free-Space Outdoor Model (FOM) presented in [25] with the measured results and the model proposed in this chapter for an antenna height of 12.5 cms. The transmitter power used in [25] is 0 dBm, so the

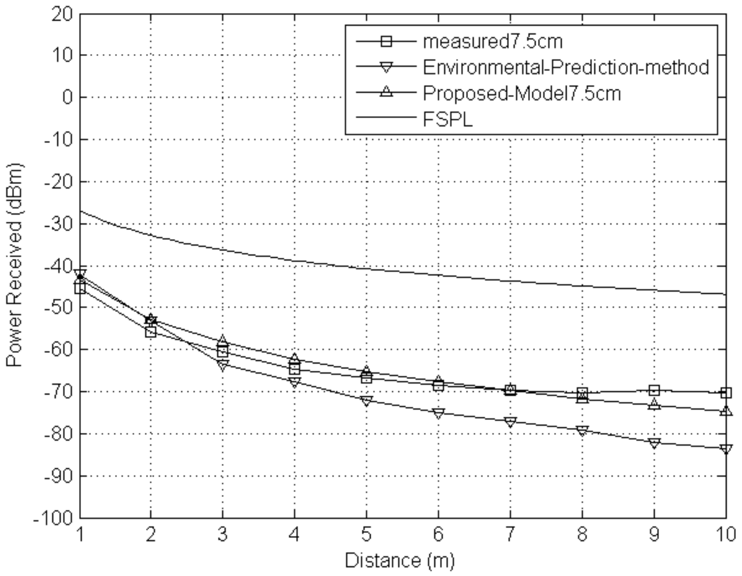


Figure. 3.15 Comparison of the measured and modelled results in this work with the values predicted by the EPM model in [5] at a height of 7.5 cm

received power has been increased by 3 dB to make it comparable with the results in our measurements which used a transmitter power of 3 dBm. The frequency is 2.4 GHz. The results show that the model proposed in this chapter provides a more accurate fit to the measured results than the FOM model in [25].

Our proposed model therefore provides a more accurate prediction of the path loss for antennas placed close to a tarmac ground surface than previously reported results. The proposed radio propagation model will be the main key to estimating the separation distance between sensor nodes deployed on ground level which will then the topology of the monitoring system will be predicted accurately. This will simplify the next step which focuses on designing a suitable MAC protocol.

3.4 Chapter Summary

The aim of this work was to determine the viability of a wireless sensor network where wireless transceivers are embedded in road studs located on the ground. Previously, propagation measurements at a frequency of 2.4 GHz have been reported for antenna heights down to 12 cm above the ground, but for the proposed application, the antennas need to be lower than this. To determine the maximum separation of these nodes, measurements of propagation

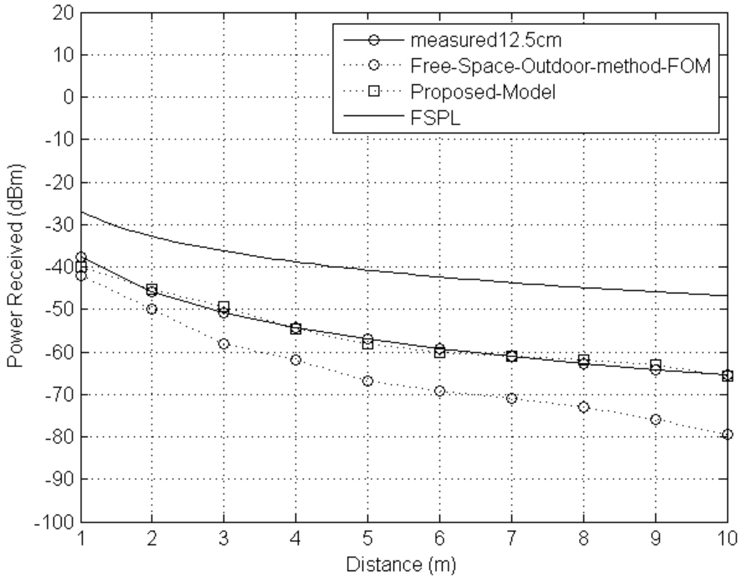


Figure. 3.16 Comparison of the measured and modelled results in this chapter with the values predicted by the FOM model in [6] at a height of 12.5 cm

loss were carried out for antenna heights of 0～12.5 cm and a node separation of 0～10 m. The measurements were carried out at a frequency of 2.4 GHz, as this is an unlicensed band, and the antenna could be smaller than required at lower frequencies. A directional antenna was used to improve the range. The measurements showed that a range of up to 9 m is possible for an antenna at ground level. This determines the maximum separation of the nodes in a road-based wireless sensor network operating at a frequency of 2.4 GHz. An empirical model was developed based on the measurement results and this model is able to predict the path loss as a function of distance for antenna heights in the range 0～12.5 cm. Since the proposed radio propagation model is to be implemented on low powered road studs that monitor traffic, it is important to consider the energy efficiency factor. Recently, the energy efficiency issue has been intensively studied, especially at the MAC layer. However, there is an opportunity to improve the energy efficiency by considering the properties of the physical layer and the available resources. The next chapter introduces a new energy efficiency metric designed specifically for a ground level radio propagation model. This energy efficiency metric is a new feature that can improve the energy efficiency by customising the physical layer properties and the available resources to achieve the highest level of energy efficiency.

Chapter 4

Energy Efficiency Metrics for Low-Power Near Ground Level Wireless Sensors

4.1 Introduction to Energy Efficiency Metrics

With the explosive growth of high-data rate applications in wireless networks, energy efficiency in wireless communications has recently drawn increasing attention from the research community. It is important to emphasize the role of energy efficient metrics in energy efficient communications. The concept of energy efficiency becomes meaningful only when it can be measured. Thus, metrics provide quantified information to evaluate efficiency. Energy efficiency metrics are normally used for three purposes: to compare the energy consumption performance of different components and systems in the same class; to set explicit long term research and development targets for energy efficiency; and to reflect the energy efficiency of certain configurations in a system/network and enable their adaptation to more energy efficient configurations. Since energy efficiency can be achieved in different parts of a system/network, a range of metrics has been developed. Learning these metrics will help to build a better understanding of energy consumption problems [28].

Existing research into the energy efficiency of wireless sensor networks has focused on the design of energy efficient MAC protocols [33, 34], or routing protocols [35]. A few energy efficiency metrics have been proposed for wireless sensor networks considering the physical layer properties, but with inadequacies since these have been built at the component level [42, 41, 38, 75, 76]. However, energy efficiency at the physical layer is more important for wireless sensor networks. In this section, we investigate the existing green radio energy efficiency metrics proposed generally for wireless systems, with highlight the proposed metrics for wireless sensor networks.

This section investigates green communication in wireless sensor networks and proposes energy efficiency metrics that suit wireless sensors running at ground level. The proposed metrics introduce useful guidance that shows the relationship between energy efficiency, the spacing between nodes and antenna height for near ground level wireless communication. These metrics are derived from our previous work [3] on green radio energy efficiency applied to cellular networks and a near ground level radio propagation model.

4.2 The Current Project in Energy Efficiency for Wireless Communication

Several international research projects dedicated to energy-efficient wireless communications are being carried out. Table 4.1 outlines the main solutions to dealing with energy efficient from Green Radio, EARTH [77], OPERANet [78], and eWIN [79]. From Table 4.1, it is clear that Green Radio has come up with several solutions related to energy metrics and models, energy efficient hardware covers, efficient architecture and energy-efficient resource management, while the EARTH project studies energy-efficient analysis at the system level, optimization of cell size and heterogeneous network deployment provided under the Energy-Efficient Architectures solution. In addition, EARTH provides energy efficient solutions related to radio technologies and components such as MIMO Multiple-Input and Multiple-Output and OFDM Orthogonal Frequency-Division Multiplexing, it also focuses on energy efficient solutions related to resource management such as cooperative scheduling and interference coordination, such as Multi-RAT. The OPERA-Net project has highlighted energy efficiency solutions that focus on the network level such as optimization techniques for link-level , the Energy-Efficient Mobile Radio Access Network and the network test bed which includes integration of devices. Most likely, the eWin project will provide energy efficiency solutions that consider the architecture and resource management such as dynamic spectrum and auto-configuration of networking resources.

However, since energy-efficient hardware techniques, resource management and the radio access network are outside the scope of this thesis, they are not included in this work.

Under the subject of Green Radio, energy efficiency metrics provide information that can be used to assess and compare the energy consumption of various components of a wireless network and of the network as a whole. These metrics also help us to set long-term research goals for reducing energy consumption [30].

4.2 The Current Project in Energy Efficiency for Wireless Communication

Table 4.1 Current Projects related to Energy Efficiency Wireless Communications [4]

Project Name	Solutions
Green Radio [30]	1.Energy Metrics and Models (Energy metrics , energy consumption models) 2.Energy Efficient Hardware cover (Hardware Integration and amplifier techniques, DSP Techniques and Max equipment reuse) 3.Energy Efficient Architecture focus on (cell deployment, cooperative networking, Bounding energy requirements) 4.Energy-Efficient Resource Management concerns (Differentiated QoS,SISO vs. MIMO with packet scheduling, energy-efficient cooperative physical layer architecture, Applying (DSA) to minimize energy consumption, Solar-powered relaying allocating resources)
EARTH [77]	1.Energy-Efficient Analysis, Metrics and Targets include (Life cycle analysis of energy consumption, Energy efficient metrics at the system level) 2.Energy-Efficient Architectures cover (Optimization of cell size, Heterogeneous network deployment, Relay and cooperative communications) 3.Energy-Efficient Resource Management include (Dynamic load adaptation , Cooperative scheduling and interference coordination, Multi-RAT (radio access technology) coordination) 4.Radio Technologies and Components concerns (MIMO, OFDM, adaptive antennas , Power scalable transceiver and power control on component)
OPERA-Net [78]	1.Energy-Efficient Mobile Radio Access Network include (Defining the key performance indicators of EE, Energy saving in base stations, Efficiency from the management of MAC, DC power, cooling system) 2.Link Level cover (Optimization techniques for link-level , Heterogeneous network deployment, Energy-aware device) 3.Technology Enablers include (Develop efficiency amplifier , Innovative energyrecovering) 4.Network Test Bed concerns (Integration of devices , Mobile radio access network's end-to-end efficiency)
eWin [79]	1.Energy-Efficient Architectures include (Architectural designs for low-energy wireless access, Infrastructure) 2.Energy-Efficient Resource Management focus on (Auto(re)-configuration of networking resources, Dynamic and flexible spectrum management, Radio resource management,Policy-driven management)

For more clarification, it is important to explain the difference between two common terms related to energy efficiency and consumption that could lead to confusion; these are: "energy efficiency metrics" and "energy consumption metrics". Energy efficiency metrics refer to the ratio of attained utility to the consumed power/energy used (for example, the transmission distance reached, the area covered, the output power, the bits transmitted), while the energy consumption metrics refer to the energy/power consumed per unit of attainable utility [80].

4.3 The Levels of Energy Efficiency Metrics

Several energy efficiency metrics have been investigated by researchers in order to find the most appropriate metric to measure energy efficiency. Zhao et al [30, 4] have classified energy efficiency metrics on different levels as in Figure 2.1 Facility level, Equipment level, Access node level and Network level and, on each level, the energy efficiency metric considers a range of energy related parameters to determine the overall efficiency.

4.3.1 Equipment Level

Facility-level metrics assess initial power usage but do not reflect the energy efficiency of individual pieces of equipment. Thus, equipment-level metrics, such as the power amplifier efficiency metric, which quantifies the performance of individual pieces of equipment, are required. The ATIS introduced the telecommunications energy efficiency ratio (TEER), which is the ratio of useful work to power consumption and is measured in units of Gbps/Watt. Another equipment-level metric, the telecommunications equipment energy efficiency rating (TEEER), introduced by Verizon Networks and Building Systems [81], quantifies the total energy consumption as the weighted sum of the amounts of energy consumed by the equipment under different load conditions.
Another equipment-level metric is the energy consumption rating (ECR), which is the ratio of the energy consumption to the effective system capacity, measured in units of Watt/Gbps [82]. However, even the busiest networks do not always operate under full load conditions. Therefore, it would be useful to complement metrics such as the ECR to incorporate dynamic network conditions such as energy consumption under full load, half load, and idle conditions. Other metrics suitable for these purposes include the ECRW (weighted ECR), ECR-VL (energy efficiency over a variable-load cycle), and ECR-EX (energy efficiency over an extended-idle load cycle). Hence, ECR provides manufacturers with insight into the performance of hardware components. However, these metrics (ECR,

TEER, and TEEER) are unable to capture all the properties of a system. Due to that this level concern the components themselves and the power consumption per unit, with skipping other effective parameters that affect the energy efficiency level such as subscribers, coverage area, radio efficiency and spectral efficiency. While the definitions of energy efficiency metrics at the component and equipment levels are fairly straightforward, it is more challenging to define energy efficiency metrics at the system or network level.

4.3.2 Access Node Level

In general, access node level metrics mainly quantify the energy used to transmit a piece of information. As an example, the energy consumption rating (ECR) [82], gives the energy used to transmitting a piece of information (Joules/bit). Some other metrics aim to observe the attained utility of the different resources regarding any trade-offs which exist, such as the spectral efficiency (b/S/Hz) and the power efficiency (b/S/Hz/W). One metric targeted to cover all the aspects in a more general way is the radio efficiency ((b·m)/S/Hz/W) [3], which measures the data rate transmitted and the transmission distance attainable given the respective figures of bandwidth and supplied power resources.

4.3.3 Network Level

Network level metrics assess energy efficiency at the network level by considering the features and properties of the capacity and coverage of the network. The ETSI has defined two network-level energy efficiency metrics. The first metric is the ratio of the total coverage area to the power consumed at the site and this is measured in units of km2/Watt. The second metric is the ratio of the number of subscribers to the power consumed at the site and this is measured in units of users/Watt [28]. Some specific metrics have been used to measure the performance of computing processing associated with energy consumption, such as the number of instructions per second per unit of power and the number of floating-point operations per second per unit of power [28]. Reference [77] highlighted a metric with units of energy per bit per unit area (J/bit/m^2). This metric relates energy consumption to the number of transferred bits and the area of coverage. This is equivalent to analysing the average power usage with respect to the average rate and the area of coverage (W/bps/m^2).

4.3.4 Facility Level

This level defines the ratio of total facility power consumption to total equipment power consumption. Total Facility Power is defined as the power measured at the utility meterthe power dedicated solely to the data center (this is important in mixed-use buildings that house data centres as one of a number of consumers of power). The IT equipment power is defined as the equipment that is used to manage, process, store, or route data within the data center. It is important to understand the components of the loads in the metrics.

The facility-level metric refers to high-level systems (such as data centres). The Green Grid (TGG) association of IT professionals [83] proposed the metrics of power usage efficiency (PUE) and data centre efficiency (DCE) to evaluate energy efficiency in data centres. Despite being a good metric for quickly assessing the performance of data centres at a macro level, PUE, which is defined as the ratio of total facility power consumption to total equipment power consumption, does not account for the energy efficiency of individual pieces of equipment. Therefore, to quantify efficiency at the equipment level, a measure of the ratio of the energy consumption to the performance of a communication system would be more appropriate.

4.4 Proposed Energy Efficiency Metric

4.4.1 The Main Contribution of The Proposed Energy Efficiency Metric

We propose specific energy efficiency metrics for wireless sensors located near ground level. We have reshaped the metric used for cellular systems [3] to be suitable for shorter distance wireless sensor communications. In particular, we use a near ground level radio propagation model, one piece of our early work, to replace the FSPL model. This reflects real implementation and gives more accurate guidance for deployment in practice.

The proposed metric will be based on the access node level that was introduced by [3]. The access node level is preferred as the basis of our energy efficiency metric since it is a comprehensive metric that covers most of the communication aspects. Furthermore, the main source of power consumption in wireless communication is the transmitting power, and this factor is considered at the access node level. Thus, the transmitting power needs to be optimised over the entire transmission distance and available resources to improve the energy efficiency.

The objective of this chapter is to design energy efficiency metric for ground level communication for wireless sensors deployed in a chain topology. This metric will optimise the energy per transmitted bit as an attained utility. The target metric aims to optimise the transmitting rate per available resources such as transmitting power. However, optimisation is required to fit the energy efficiency of the transmitting power for each distance, node spacing and chain length. Thus, a new concept of efficiency is introduced here that concerns optimising the available resources to the minimum level required to improve the efficiency level. Hence, new energy efficiency metric has been developed to calculate the optimal sensor deployment, antenna height and energy efficiency level for the near ground wireless sensor.

4.4.2 Components and Effective Factors

This section describes some essential components of the proposed green energy efficiency metrics based on our previous work on energy efficiency for cellular systems and a near ground level radio propagation model.

Green Energy Efficiency Metrics for Cellular Systems

Green energy efficiency metrics are related to the efficiency of the whole system, not just the energy consumption. It includes the bandwidth efficiency (BE) in (b/s/Hz), power efficiency (PE) in (b/S/Hz/W) and the green energy efficiency in ((b.m)/S/Hz/W) [42]. In [3], the green energy efficiency for cellular network has been defined as shown in Figure 4.1. It is based on a FSPL propagation model for the radio path that presented by Eq 4.4. Energy efficiency can be defined as the ratio of the attained utility (e.g. transmission distance reached, area covered, output power, bits transmitted, etc.) to the consumed power or energy used [80].

In wireless communications, the objective is to transmit information (data bits) successfully with the required quality-of-service (QoS) and within the available resource constraints over a certain distance to the receiver [28, 42]. Hence, the utility metrics should include the number of bits, QoS metrics (such as bandwidth in b/s, delay and jitter in seconds, and packet loss rate), and the transmission distance in meters. To measure bandwidth efficiency that reflects the maximum possible transmission rate or system capacity, the Shannon-Hartley theorem will be used to calculate it as given by Eq (4.1).

$$C = B.\log_2(1 + \gamma_s) \qquad \text{(b/s)} \tag{4.1}$$

where B is the channel bandwidth in Hz. $\gamma_s = S/N_0$ is the average signal-to-noise ratio (SNR) in dB recorded at the receiver, where S denotes the signal power, and N_0 denotes the noise power.

Hence, the definition of green efficiency can be expressed as the product of the number of data bits and the transmission distance per-second- per-Hertz-per-Watt [3]:

$$\eta_m = \frac{d.\log_2(1+\gamma_s)}{P_t} \qquad ((\text{b.m})/\text{S/Hz/W}) \tag{4.2}$$

Where $\gamma_s = S/N_o$ is the average signal-to-noise ratio (SNR) recorded at the receiver. S denotes the signal power, and N_o denotes the noise power. Using the FSPL propagation model, the free-space power (S) received by an antenna at a distance d from the transmitter is given by [3]:

$$S = P_t . PL = P_t * \frac{G_t G_r \lambda^2}{4\pi^2 d^2 L} \tag{4.3}$$

where P_L is the path loss and L the system loss. Substituting Eq 4.3 into Eq 4.2, we can derive a formula for the green efficiency η_m versus the transmission power $P_t$and the transmission distance d:

$$\eta_m = \frac{d.\log_2\left(1 + \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 N_0 d^2 L}\right)}{P_t} \qquad ((\text{b.m})/\text{S/Hz/W}) \tag{4.4}$$

where d is the transmission distance between the transmitter and the receiver, P_t is the transmitting power, G_t and G_r are the transmitter and receiver antenna gains respectively, λ is the wavelength, L is the system loss L and N_o denotes the noise power.

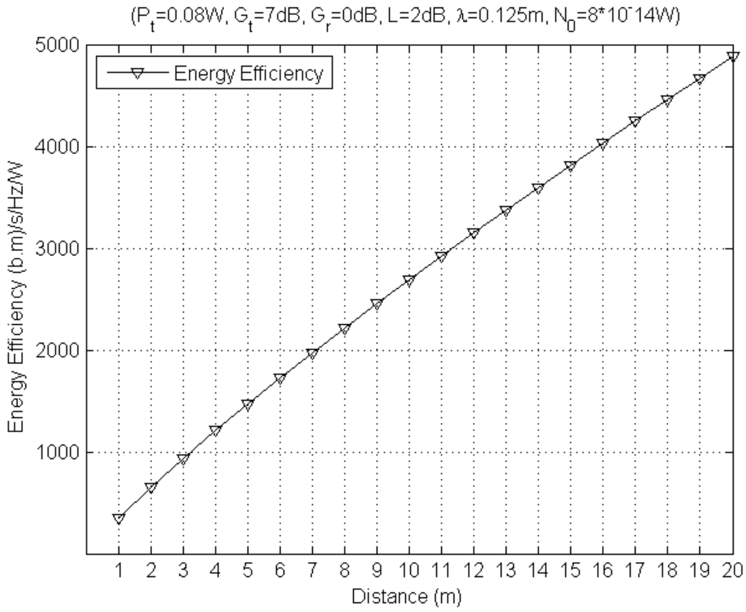


Figure. 4.1 The (b.m)/s/Hz/W green efficiency as a function of the transmission distance [3]

Ground Level Radio Propagation Model

In the previous section, the metric is based on the FSPL propagation model. In order to apply the green energy efficiency metric to near ground level wireless sensors, a near ground level radio propagation model is required. We have derived an empirical propagation model for near ground level wireless communications IN chapter three. It is derived from numerous field measurements and is based on the FSPL model by adding an adjustment factor to take account of the antenna height and the blocking effect of the ground as in Eq 3.4. where *n* in Eq 3.4 is the path loss exponent for the adjustment factor and it is calculated by 3.9
The *h* in Eq 3.4 represent the height of the antenna. A, B, C and D are constants can be used to calculate the appropriate value of *n* based on antenna height *h*:
A = -0.0096, B = -0.1485, C = 1.1904, and D = 12.591.
As an example of using the near ground level propagation model, Figure 3.11 shows the results of various received power at different antenna heights compared with the FSPL model, for wireless sensors working at 2.4GHz and where the transmitter EIRP is 3 dBm.

4.4.3 Mathematical Model

In this sub-section we adapt the energy efficiency metrics to allow for variable transmitter power. As mentioned in the previous sections, the energy efficiency metrics used in [3] have

been particularly designed for cellular system. They considered FSPL model in order to calculate the amount of transmitted data per the available resource as in Eq 4.4. However, our propagation model, introduced in chapter three designed specifically for wireless sensor communicate on ground level. Here, the proposed concept is to introduce new energy efficiency metrics able to measure the energy efficiency on WSNs which communicate at ground level. Thus, the radio propagation model used in Eq 4.4 needs to be replaced by the ground level radio propagation model given by Eq 3.4. By this concept, we will try to achieve as many attainable utilities as possible such as (increase transmitted data, and improve the transmission distance) that will be within the boundaries of the available resources.
By substituting the near ground level propagation model in Eq 3.4, into Eq 4.4 which is the expression for green energy efficiency, we can derive an explicit formula for the new energy efficiency measure the transmission power and transmission distance. As a result, Eq 4.4 becomes:

$$\eta_m = \frac{d.\log_2\left[1+\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 N_0 d^2 L}.F.J\right]}{P_t} \qquad ((\mathrm{b.m})/\mathrm{S}/\mathrm{Hz}/\mathrm{W}) \tag{4.5}$$

Where F is the blocking factor in the near ground level propagation model introduced in chapter three, and J is the energy efficiency adjuster which is defined as:

$$J = \left(\frac{d}{h}\right)^y \tag{4.6}$$

Where $y = n - L$ which is the exponent for the energy efficiency adjuster J.
Since energy efficiency can be influenced significantly by distance and antenna height as shown in Figure 4.2, an adjuster factor, J, is included to take account of these factors.
The exponent n is defined in Eq 3.8 as path loss exponent calculated by Eq3.9 for the blocking factor F and L is the system loss which is assumed to be 1 in this scenario. The path loss has been considered in the free space propagation model, where this propagation model used to calculate the energy efficiency. However, since the proposed approach rely on replace the free space propagation model to be GLPM, it is important to consider the path loss as well. Due to the relationship between the system loss and the propagation path loss exponents as in y and n, these two adjusters F and J haven multiplied in order to isolate the effect of system loss on the propagation model. As a result the J adjuster has been introduced in Eq 4.6 which is responsible to perform this process and then protecting the propagation blocking factor as in Eq 4.7.

By multiplying F and J in Eq 4.6, then

$$J = \left(\frac{h}{d}\right)^{n} \cdot \left(\frac{d}{h}\right)^{n-L} \tag{4.7}$$

As result, the η_m energy efficiency is given by Eq 4.8 .

$$\eta_m = \frac{d.\log_2\left[1 + \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 N_0 d^2 L} \cdot \frac{h}{d}\right]}{P_t} \quad ((\text{b.m})/\text{S/Hz/W}) \tag{4.8}$$

.

4.4.4 Numerical Results

Comparison of Different Radio Propagation Models

As mentioned above, most of the existing energy efficiency metrics are based on the free space path loss model. Our proposed metrics are based on our near ground level propagation model. A comparison of the metrics using different radio propagation models is plotted in Figure 4.2. It shows green efficiency ((b.m)/S/Hz/W) as a function of the transmission distance and for the heights of 2.5cm, 1cm and 0 cm.
To validate the proposed metrics, Figure 4.2 compares green efficiency when it considers the FSPL propagation model and energy efficiency metrics that considers near ground level propagation model. This figure shows a superiority of energy efficiency with FSPL over the proposed metric, and this results were expected due to that the proposed metrics in [3] consider free space where the obstacles does not exist and not considered. Thus the transmission range will definitely be longer than any other propagation model. On the other hand, our proposed metric, despite it being worse than metrics which consider FSPL, our metric still reflects actual results in the real conditions by considering the blocking factor which represented by transmission distance and antenna height. The results of Figure 4.2 also show that the energy efficiency of near ground level communication is lower than that reported for cellular networks modelled using FSPL as in [3].

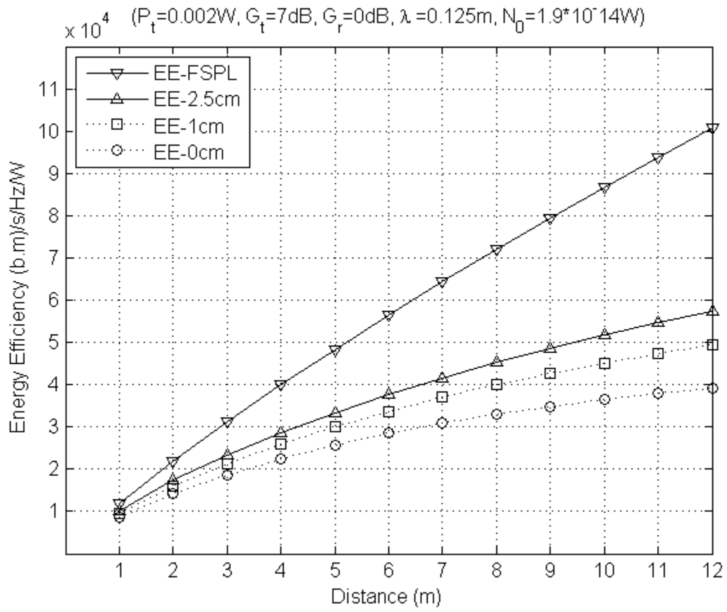


Figure. 4.2 The ((b.m)/S/Hz/W) green efficiency as a function of the transmission distance

For fixed transmission power, the energy efficiency increases proportionally with distance. Because of that the utility metrics should include the number of bits, and the transmission distance as (b.m) which is presented as axis in Figure 4.2. Here in Figure 4.2 the horizontal axis the distance means the separated distance between nodes in the chain. Another fact that has been given by Figure 4.2 is that the antenna height can play an important role into improving the energy efficiency. It is noticeable that the nearest antenna to ground level (as in 0cm) has the lowest level of energy efficiency value. This figure reflects the relationship, not only between the energy efficiency and transmission distance, but also between the energy efficiency and the antenna height.

Energy Efficiency vs Transmission Power

The energy efficiency metrics described above assume that the transmitter power is fixed, but it may be possible to reduce the energy consumption in a wireless sensor network by minimising the transmitter power for a given transmission distance. We now look at the relationship between the overall energy efficiency and the transmission power.

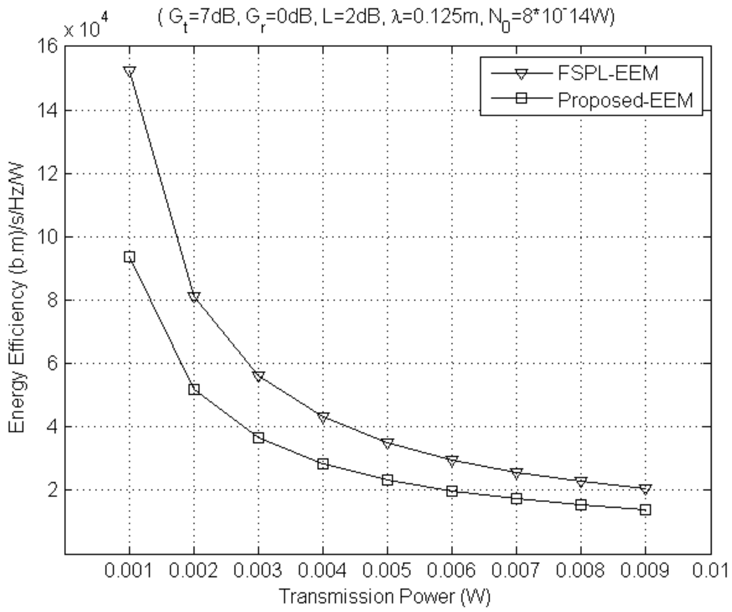


Figure. 4.3 The (b.m)/s/Hz/W green efficiency as a function of the transmission power

Figure 4.3 clearly shows that, for given distance 10 m, it is low efficient for wireless sensors which are running at near ground level, due to the fact that a large part of the signal is blocked by the ground surface. As a result, the transmission range will decrease, unless the transmission power increases and which will then bring down the overall energy efficiency. Therefore, Figure 4.3 also indicates the significance of how the transmitting power impacts on the energy efficiencymetrics.

Varying Transmission Power for Fixed Distance

In some systems, the location of the wireless sensor nodes is fixed, for example road studs topology. In this case, energy efficiency analysis to find the minimum transmission power is useful so that the sensor node energy consumption can be reduced by using the minimum transmission power to only cover the required transmission distance. Equation 4.9 is used to calculate the minimum amount of Pt for each distance.

$$r_p = \frac{4\pi^2.d^2.P}{P_t.G_t.G_r.\lambda^2} * \frac{d}{h}^{n} \tag{4.9}$$

Figure 4.4 shows the minimum transmission power as a function of transmission distance. It can be seen that the required transmitting power increases as the transmission distance increases. It also shows that when the antenna height decreases, the transmission power has to go up in order to cover the required distance. The energy efficiency will increase when the antenna is placed at a higher height over the ground. The dotted curve represents the results of using the FSPL model which assumes the antenna is high enough and there is no signal blockage near the ground.

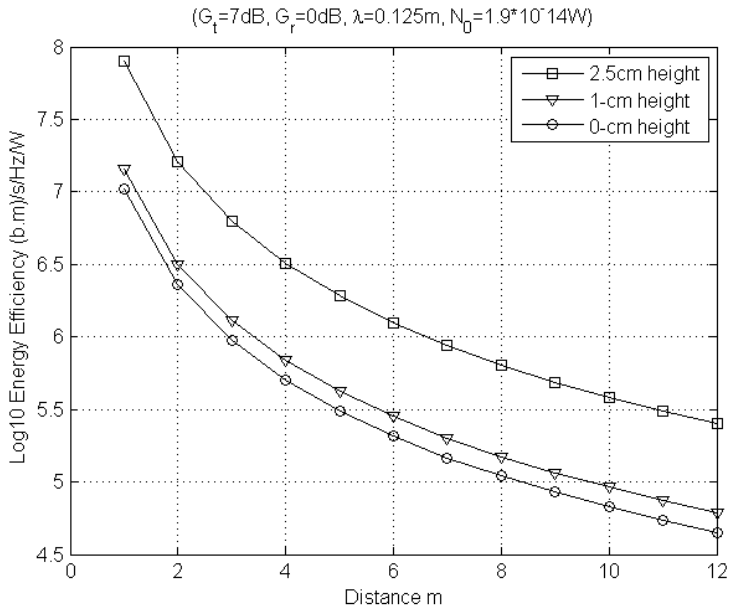


Figure. 4.4 Minimum transmitting power as function of transmission distance

In contrast to Figure 4.2 which shows that energy efficiency increases proportionally with increased transmitting distance, Figure 4.4 shows that the energy efficiency decreases when the transmitting distances increases, if the minimum transmitting power is used at the sensor nodes. The results shown in Figure 4.2 are based on fixed transmitting power at all distances. Moreover, Figure 4.4 clearly shows the effect of environmental factors on the energy efficiency. When the antenna height increases, it will clear the signal blockage from ground obstacles and thus the required transmitting power can be reduced.

For each transmission distance the minimum value of transmitting power was considered based on the ground level propagation model GLPM. Then, this mini transmitting power considered to calculate the energy efficiency by the proposed metric which considers the GLPM. The vertical axis value reflects the achievable level of energy efficiency when the minimum transmitting power is considered for each distance. Figure 4.4 prove that the energy efficiency metric can also be affected by the transmitting power, and this is reflected in the plotted values. Therefore, the transmitting power should not be a fixed value, and it need to be minimised to the lowest value for each distance to improve the efficiency level.

It can be argued that the value of the energy efficiency metric decreases over the distance and that is not sensible. However, the explanation for this is that here the transmitting power is not a fixed value over the entire transmitting distance. In order to achieve a better energy efficiency level, the transmitting power needs to be optimised for each distance and each antenna height. Thus, the transmitting power increases gradually as the distance requires and these increases in transmitting power affect the value of the energy efficiency level and then reduce it. Hence, to achieve a good level of energy efficiency, the transmitting power is a very influential factor that should be optimised and considered for each distance.

4.4.5 Application

One of the applications of the proposed energy efficiency metrics is to give a more accurate guidance for wireless sensor deployment.

Wireless sensors are widely used for traffic monitoring, where sensors are embedded in road studs that are installed in the road. The sensors detect the presence of vehicles passing along the road and send the sensed data over a wireless link to a roadside unit. The road studs are battery powered and can be re-charged using a solar cell. As the energy available is limited, energy efficiency is a key factor in the design of this system. Figure 4.5 shows a typical linear chain configuration of these nodes. The road studs which contain the sensors will be deployed in a fixed chained structure along a highway. These studs will normally be organized in clusters and managed by roadside units which have the capability to collect the sensed data and send back it to traffic management centres via a back-haul link.

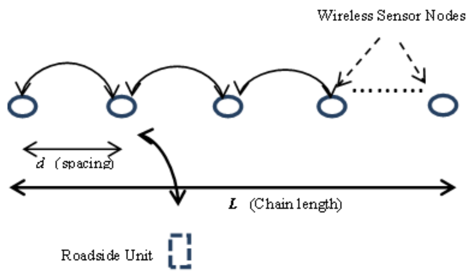


Figure. 4.5 Road-based wireless sensor network deployment scenario

From Figure 4.5, the energy efficiency increases when the node spacing reduces. However, in a real chain deployment scenario, reducing the space between nodes will increase the total number of nodes required to cover a given length of road, and thus it will increase the cost of the overall system. The trade-off between deployment cost and energy efficiency should be taken into account in the design of a wireless sensor network.

According to the results shown in Figures 3.11, 4.2 and 4.4, a system designer is able to identify the acceptable signal attenuation limit in order to increase the node spacing and reduce the deployment cost. At the same time, the energy efficiency can be optimized.

Hence, it is most cost effective to maximize the spacing between the nodes within the signal attenuation limitations given in Figure 3.11. While concurrently minimising the transmitting power as suggested in Figure 4.4.
The total energy consumption for a chain of length L and node spacing d is:

$$P_{total} = \frac{L}{d} * Pt_{min} \qquad (4.10)$$

Where Pt_{min} is the minimum power consumption for each node.
Since our priority is to measure the energy efficiency metrics that refer to the ratio of attained utility, this Eq 4.10 will firstly be used to optimise the node deployment. The energy used for receiving and for signal processing are not considered in Eq 4.10, this equation does not aim to calculate the power consumption for the whole system. This equation aims to define the boundaries of consumed power/energy used, and then use it to estimate the ratio of attained utility (e.g the transmission distance reached, the area covered, the bit transmitted). However, the relationship between the chain length, L, the node spacing, d, and the total power consumption is shown in Figure 4.6.

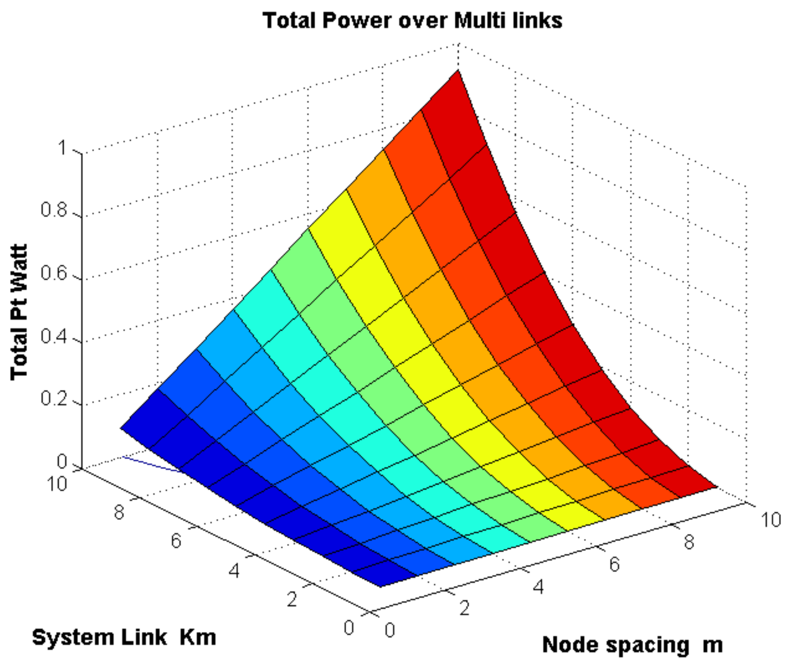


Figure. 4.6 The relationship between the node spacing, transmitting power and the chain length

For a given length of chain and node spacing, we can find the total power consumption, as shown in Figure 4.6. For example, for a chain length of 1 km and a node spacing of 5 m, the total power consumption is 0.0034 W.

Figure 4.7 shows the relationship between energy efficiency and node spacing and the corresponding required transmitting power for each node, at a given distance. As can be seen, the energy efficiency decreases as the node spacing increases. This reflects the fact that increasing the node spacing requires more transmitting power. Figure 4.6 also shows that as the transmitting power increases, the energy efficiency decreases.
Another important observation is that minimising the node spacing improves the energy efficiency, but increases the total number of nodes required and therefore the overall cost of the system. Hence, the recommended design is to use the maximum node spacing that can be supported by the ground level propagation, which is approximately 9 m as indicated in our field measurement. In that case, the energy efficiency is approximately 105 ((b.m)/S/Hz/W).

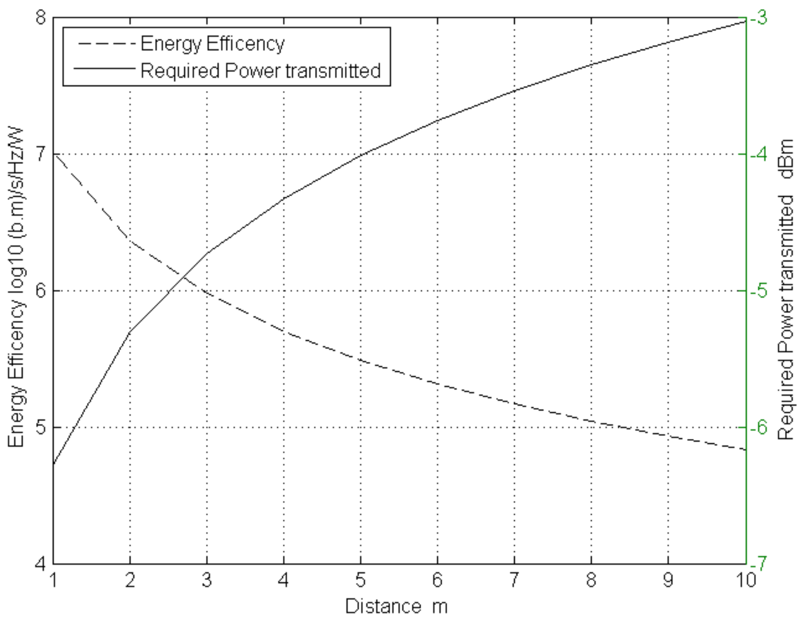


Figure. 4.7 The relationship between energy efficiency and transmitting power as a function of node spacing

4.5 Chapter Summary

In this chapter, we have studied the green energy efficiency of near ground level wireless sensor networks. Based on our previous work on green energy efficiency metrics for cellular radio systems and our near ground level radio propagation model, we have proposed new energy efficiency metrics for wireless sensors running at near ground level. These metrics have been analysed numerically and the relationship between the energy efficiency, transmitting power and antenna height has been investigated.

As a result, the proposed metrics contribute a useful tool to choose the optimum antenna height and energy efficiency level for near ground wireless sensor networks. As an application, the proposed metrics have been used to analyse a traffic monitoring system with wireless sensors deployed in a fixed chain structure along a highway. The proposed metrics have revealed the relationship between energy efficiency, transmitting power, node spacing, and antenna height. The results provide guidance on the most energy efficient and cost-effective deployment of the wireless sensors in this system. Future work will include an investigation of the energy efficiency taking into account the MAC layer design.

Chapter 5

MAC Protocol for Wireless Sensors in a Fixed Chain Topology

5.1 Overview of Schedule-Based MAC Protocols

Several Medium Access Control (MAC) protocols have been proposed for wireless sensor networks which aim to provide an efficient way of sharing the transmission medium.. The primary constraint of sensor nodes in WSNs is their low battery capacity. Furthermore, sensor nodes are often left unattended after deployment, and this makes the replacement or recharging of their batteries difficult; MAC protocols running on WSNs must consume energy efficiently to achieve a long network lifetime [84].

The sources of energy wastage have been addressed in several studies. These sources include idle listening, collision overhearing and protocol overhead [85]. Most MAC protocols are designed based on schedule-based or contention-based concepts. Schedule- based or TDMA (Time Division Multiple Access) protocols reduce the duty cycle of sensor nodes because the transmission and sleep periods are defined and scheduled in advance. As a result, all the aforementioned wasted energy sources are avoided or diminished because the nodes transmit or receive in their own allocated slots.

Any protocol, whether built on the basis of schedule or contention, should consider the physical layer properties and implementation topology involved. One of the most challenging topologies is the long chain topology. The chain topology is commonly used for monitoring and surveillance applications, where the sensor is deployed linearly. However, the few MAC protocols proposed particularly for this type of topology are contention-based MAC protocols as in [86].

One application for a chain topology is a wireless sensor network where the sensor nodes are embedded in a road and are used to monitor traffic [64]. This type of network can provide a source of data for intelligent transport systems (ITS). This application requires the MAC protocol to consider energy-efficiency as the nodes may be battery powered. In addition, the physical layer properties should be considered including the choice of wireless technology, the radio frequency, the transmitter power and the propagation loss.

5.1.1 TDMA Schedule-Based MAC Protocol

TDMA is a method of sharing the medium which may be either wired or wireless. TDMA is used in digital 2G cellular systems such as the Global System for Mobile Communications (GSM) [64]. The TDMA method is used to design MAC protocols to allows several users or devices to share the same frequency channel by dividing the access frame into time slots. MAC protocols based on the TDMA concept are responsible for scheduling the given time slots based on certain criteria such as topology, mobility or the number of nodes. Then, these time slots are allocated to users who need to transmit their packet on the same frequency. In this way, one frequency is used efficiently across multiple users and, at the same time, interference can be avoided.

5.1.2 Spatial-TDMA Schedule-Based MAC Protocol

In this research we refer to Spatial-Reuse Time Division Multiple Access (STDMA). This concept allows simultaneous transmission by several nodes in one time slot. This transmission is conditional, in that this simultaneous transmission does not lead to interference or a collision. A number of the recently proposed TDMA protocols [85, 65, 63], have been built based on this concept of “slot reuse”. The concept helps to increase the throughput of the channel and reduce the end-to-end delay.

5.1.3 1.4 Challenges

Topology

A wireless sensor network based on a chain topology is a collection of wireless nodes that are deployed linearly and are connected through multi-hop communication [87]. A chain topology is not widely used to implement wireless applications, but it is the best topology to cover a long linear system. This topology introduces some design challenges, notably delay, throughput, relays and power consumption. All these issues need to be considered and treated. Thus in a long chain topology for wireless monitoring we have the same challenges which need to be taken into account during the design stage of a MAC protocol.
Due to the nature of a fixed chain topology, the data packets are relayed hop-by-hop. As a

result, traffic load increases for the relay nodes closer to the sink. This also leads to increased packet collisions, congestion and loss and results in significant end-to-end delay.

One of the major challenges in chain topology is to ensure the end-to-end packet delivery relaying on a more limited number of relay nodes then other WSNs. Clearly, nodes closer to the sink end up forwarding or relaying more packets than nodes further away. Over time, this uneven load distribution, known as the "relay burden problem", results in a disproportionate share of energy consumption and leaves the "close-in" nodes with considerably less energy. Therefore the risk of prematurely terminating the network's lifetime is greatly increased. At the same time, these nodes cannot afford long sleep times because they must be alert, in idle listening mode, to carry out their relaying function [88]. That is why more intelligent methods for traffic load distribution must be applied in order ensure and prolong the network lifetime. Due to the linear topology of the network data delivery is more exposed to failure in the chain than in classic WSNs. A single node failure can totally disturb the communication process in the network which is an obvious weakness of chain wireless network. Nodes can fail due to battery exhaustion, hardware failures, and natural or intentional damage.

These kinds of failures may cause drastic problems so innovative recovery solutions need to be considered at the MAC layer since there are no alternative routing possibilities to the sink. Furthermore, consecutive faulty nodes form holes which may cause the chain to be divided into multiple disconnected segments and failure of overloaded nodes closer to the sink may shorten the network's lifetime [87]. In fixed chain topology, it is also difficult to deal with the accumulation of the traffic produced by each node.

Nodes closer to the sink tend to be more congested than others; channel access becomes more difficult which leads to buffer overflow and packet drop. As a result, both packet loss and end-to-end latency is additionally increased [89]. One possible solution can be assign larger buffers to the nodes closer to the sink. However, this simple approach is not always the right solution since most WSN nowadays use off-the-shelf components with standard characteristics. Such a solution would require bringing heterogeneity in the network which would increase the implementation cost.

Another important issue in chain topology is energy consumption. Due to the linearity of the network and the traffic congestion created in the nodes close to the sink, there is an unbalanced energy consumption profile in the network. Also, the nodes in the network can experience exposed and hidden terminal problems which induce high latency and frame collisions. Thus, techniques for balancing the energy consumption should be considered while ensuring data traffic is being delivered within an accepted delay margin. An interesting approach to dealing with the exposed and hidden terminal problem is presented in [63].

However, there are potential benefits to using chain topology. These benefits are that the deployed nodes know their neighbour's position and can schedule packet transmission beforehand and regulate the duty cycle accordingly. In most cases nodes are deployed at equal distances which creates advantages in terms of positioning and synchronization [90]. In addition, since the topology information is already defined, so any additional control overhead caused by network discovery can be minimised. Thus, well known techniques such as flooding are not required in a fixed chain topology [91].

Interference

Many proposed protocols aim to improve the throughput and reduce delay by providing concurrent transmission and avoiding interference [66, 48, 64]. Under normal operating conditions, any two nodes using the same media and attempting to transmit their packets simultaneously, will cause interference for a receiver which is located in the transmission range of both transmitters. Thus, in order to design a MAC protocol that allows a simultaneous transmission among multiple transmitters, the interference model should be considered in the design stage. The interference model is able to identify the minimum separation distance between two transmitters that will allows concurrent transmission. The minimum separation distance between two transmitters is calculated based on the physical layer properties that include the transmitting power for both transmitters, the separation distance between the transmitters and the receiver and the expected Signal Noise Ratio SNR. Once the system design is able to detect the minimum distance required for concurrent transmissions, the protocol will be able to produce a feasible transmission schedule. This schedule will allow multiple nodes to transmit at the same time. As a result, the MAC protocol performance will be improved with reduced delay, as well as increased throughput.

Delay

Delay is an important design and performance characteristic of any network. The delay specifies how long it takes for a bit of data to travel across the network from one node or endpoint to another. It is typically measured in multiples or fractions of seconds. This is a very important measure of the protocol performance. Both the maximum and average delay can be specified, and the delay is divided into several parts:

- Processing delay which means the time routers take to process the packet header
- Queuing delay which reflects the length of time the packet spends in routing queues

- Transmission delay which means the time it takes to push the packet's bits onto the link
- Propagation delay which refers to the time for a signal to reach its destination

There is a certain minimum level of delay that will be experienced due to the time it takes to transmit a packet serially through a link. If the protocol is designed for a long chain topology, which relies on multi hop communication, this introduces some delay due to the long distance between the source node and the sink, the large number of relay nodes and the congested MAC queue. It is an important factor to be considered in our work, because we aim to design this protocol to serve in traffic monitoring, and that require a real time data delivery.

Throughput

Throughput measures the rate of successful message delivery over a communication channel. Throughput is usually measured in bits per second (bit/s or bps), and sometimes in data packets per second (p/s or pps) or data packets per time slot. For fixed-chain WSNs where the traffic condition is sensed periodically, the protocol needs to be designed to optimise the throughput.

Power Control

Several studies focused on the power control as a method of reducing the interference [92, 93]. These studies investigate the appropriate value of the transmission power needed to reduce the probability of interference. Usually, these studies rely on general propagation models such as the FSPL model. However, using FSPL propagation models will not enable us to predict the most suitable value for the transmission power for the topology as a whole, so interference become unavoidable. However, in this research, power control is not our main concern, especially in the MAC protocol design, because our own propagation model GLPM (introduced in chapter 3) identified the correct value of the transmission power at ground level. Thus, the transmission power in our scenario is considered a constant value, where it is selected to achieve the maximum transmission distance at ground level. As a result, the appropriate value of the transmission power that fits the transmission distance without interference caused to other nodes has already been defined.

5.2 Proposed MAC protocol for Ground level Wireless Sensors in a Fixed Chain Topology

The aim of this work is to design a new MAC protocol that is optimised for WSNs deployed in fixed chain topology where the transmission is at near ground level. The proposed protocol considers a topology that consists of a set of stationary nodes deployed in a linear chain. The deployed nodes communicate with road side units (RSUs) over a multihop path. A spatial reuse technique is utilised which allows one-time slot to be used by several spatially separated transmitters. This reduces the frame size, as well as the delay and improves the throughput. The amount of spatial separation required is determined by the SINR and this is calculated using Ground level Propagation Model which was introduced in chapter three.

5.2.1 System Model of The MAC Protocol

Fixed-chain WSNs in a chain topology have applications in road-based network monitoring smart cities and intelligent transportation systems, mining and in bridges. The use of an appropriate MAC protocol responsible for the allocation of wireless channels among sensor nodes is critical to meet the application requirements of chain-type WSNs. WSN sensor nodes which are battery powered need to minimise energy consumption. This means the transmitter power should be minimised and so the transmission range is limited. They also have limited processing power and storage capacity. Therefore, these factors should be taken into account in the design of a suitable MAC protocol.

Physical layer Properties

For road-based sensor applications, the sensors will be installed on the road and will sense when vehicles move over the nodes. A chain topology allows continuous monitoring over a section of the road. One of the issues in a multihop chain network is the delay taken to transfer data from the sensor nodes to the access point. In this design, the topology is divided into a sub-chain containing many road studs (RSs) and RSU nodes. The topology consists of two types of nodes, RSU and RS. These nodes have different functions. The RSU is responsible for collecting the sensed data by the RS nodes and the channel allocation process. The RS node role is to sense traffic conditions and measure the average speed prior to sending the collected data to the RSU.

RSU and RS nodes have some technical differences. RSU nodes have more storage, memory and access to a mains power source. By contrast, RS nodes are battery powered which can be augmented by a small solar cell. These differences and limitations need to be considered during uplink and downlink planning and the topology design. The maximum distance between road studs is a key factor in the system design, because increasing the chain length will reduce the number of RSUs and the total system cost. The Friis equation in Eq 5.1 is used to calculate the maximum distance for the downlink from the RSU to the RS nodes as this is a LOS link [94]:

$$F_r = \frac{P_t\, G_t\, G_r \lambda^2}{(4\pi R)^2} \tag{5.1}$$

The range equation can be derived from the Friis equation for a given receiver sensitivity P_{sens} [94], as in Eq5.2.

$$d_{max} = \sqrt{\frac{P_t G_t\, G_r \lambda^2}{(4\pi)^2 P_{sens}}} \tag{5.2}$$

where P_t is the transmitting power, and G_r and G_t are the antenna gain for the receiver and transmitter, respectively.
The chain length d_{max} will be affected mainly by the transmitting power of the RSU and the receiver sensitivity. It is important to consider these limitations in the topology design stage. The relationship between transmission range and antenna height has been investigated and is described in chapter three. This shows that the maximum transmission distance between RS nodes is 8 m. As a result, the maximum number of nodes in each chain is represented by L in Eq 5.3.

$$L = \frac{d_{max}}{8} \tag{5.3}$$

The uplink can be divided into two categories; the first category has the capability to communicate with the RSU node over one hop on the basis of Eq 5.2. The second category will rely on a multi-hop path to send its packet to the RSU. The relationship between transmitter power and received power between two ground based nodes is given by the Eq 3.4. This equation was presented in Chapter 3 on the propagation model for ground-level wireless communication. It will be used as a basis to define the node spacing.

Interference Model

In order to support simultaneous transmission for several nodes on the same time slot, it is necessary to consider SINR. The SINR is a criterion for successful communication (with high probability) if and only if the average SINR at the receiver is above the threshold ϑ that assumed = 1, as in Eq 5.4.

$$SINR = \frac{P_i . G_{ii}}{\eta_i + \Sigma_{j=1, j\neq i}^{Q} P_j . G_{ij}} \geq \vartheta \tag{5.4}$$

where P_i denotes the transmission power of link $i's$ transmitter is; η_i is the receiver noise at link $i's$ receiver ir; G_{ii} and G_{ij} are the link gain from is to i_r and that from link $j's$ transmitter j_s to i_r , respectively; Q denotes the number of simultaneous transmissions with link i; and ϑ is the $SINR$ threshold, which is greater than or equal to 1.

Here, the numerator is G_{ii}. P_i is the received power at i_r. In the denominator, G_{ij} P_j means the attenuated power of P_j at i_r, and it is regarded as the interference power for link i; thus, $\Sigma_{j=1, j\neq i}^{Q}$ means the accumulated interferences caused by all other simultaneous transmissions. Assuming no fading over the short distance involved, the link gain can be represented by an inverse power law model of the link length, i.e. $G_{ii}=1/d^n$ (i_s , i_r) and $G_{ij}=1/d^n$ (j_s, j_r). Here, d is the Euclidean distance function, and n is the path loss exponent that is equal to 12 for an antenna height of 1 cm on the basis of (GLPM) studied in chapter 3.

Integration of the GLPM with the interference introduces a new interference model that calculates the $SINR$ for ground-level communication. The $SINR$ contains a blocking factor to to account for the losses associated with ground-level communication to consider the path loss exponent on each antenna height, as in Eq 5.5.

$$SINR = \frac{P_i . \left(\frac{1}{d_{ii}}\right)^n}{\eta_i + \Sigma_{j=1, j\neq i}^{Q} P_j . \left(\frac{1}{d_{ij}}\right)^n} \geq \vartheta \tag{5.5}$$

where the value of n can be calculated by Eq 3.9 on the basis of antenna height, as stated in chapter 3.

Where h is the height of the antenna, and A, B, C and D are the curve fitting constants, which have been studied in chapter three.

Spatial reuse in a fixed chain topology

This process involves assigning one-time slot for multiple transmitters to send their packets at the same time. Node assignment and link assignment are the most common methods to allocate the time slots for multiple-nodes. For multihop communication, link assignment will be used, where the directed link is assigned a slot. Thus, a node can only use this slot for transmission to a particular neighbour [95].

In the following, we describe the criteria for a set of links to be able to transmit simultaneously with a sufficiently low interference level at the receiving nodes, as shown in Figure 5.1. We say that a link (j, j) is adjacent to any other link $(i, i) \in L$ if $i, i \cap j, j = \varphi$, $(i, i) \neq (j, j)$. Furthermore, we define $\Psi(L)$ as the union of all adjacent links to the links in L. We assume that a node cannot transmit more than one packet in a time slot and that a node cannot receive and transmit simultaneously in a time slot. Alternatively, we say that a set of links L and the set of its adjacent links $\Psi(L)$ must be disjoint. We also require that the SINR value be sufficiently higher than the SINR threshold value, for reliable communication If the above two conditions, hold for a set of links $L \in L$, we say that the links in L can transmit simultaneously as shown in Figure 5.1.

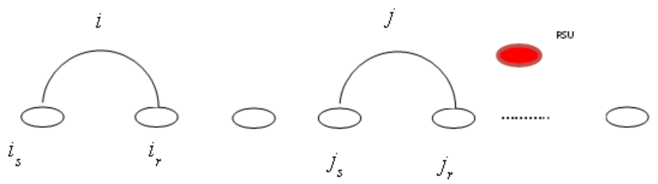


Figure. 5.1 Link Assignment for the simultaneous transmission

Figure 5.1 represent the targeted topology, and it describe how the simultaneous transmission can be achieved. The nodes deployed as chain topology, where the nodes need to transmitting simultaneously to reach the RSU over multi hop communication. If the above conditions achievable, then the links *i* and *j* can be used for a concurrent transmission without any interference.

One of the essential tools for building a feasible schedule is the ranking function. This function indicates the preferred order of transmissions and then produces a feasible schedule [66].

$$R_i^H = R_i \mod H \tag{5.6}$$

where H is a constant usually larger than or equal to three, where this value reflects the minimum number of hops between any concurrent transmission that is defined by the interference model [66, 96]. In our ground level fixed chain topology, the constant value of H can be two and the frame length will be shorter and the interference model prove that this value does not result in any interference, if the directional antenna is used. However we have assumed the *H* value as three because of it is difficult to approve it and the simulator does not support the directional antenna. Thus, the value of H which is the minimum hop required

between simultaneous transmission is three in order to consider bidirectional antenna.
The rank function is used to calculate the transmission order in every slot. Suppose this is used in slot 1, every node will be represented by R_i^H, as in Eq 5.6. In calculating the node transmission order, the first node that has a packet to send will be considered in rank value $R_i = 1$. Once the node has finished its transmission in slot 1, in the next hop, node 1 will be terminated from the rank assessment, so node 2 will obtain rank number 1. This process will be repeated in every slot as in algorithm 1. Finally, the output of rank function in Eq 5.6, will be on of the slot state which is represented by Eq 5.7 either 1 for transmission, 2 for receiving or 0 for sleep.

$$R_i^H = \begin{cases} 1, & Slot\,for transmission \\ 2, & Slot\,for receiving \\ 0, & Slot\,for sleep \end{cases} \tag{5.7}$$

Algorithm 1 Algorithm of Rank Function

Input : q, N, H
Output : A appropriate Slot state
for node $\in$ N **do**
    while $q \geq 1$ **do**
        Compute Rank List by $R = N$ mode H **Rank Function**;
        if R= 1 **then**
            slot for transmission;
        else if R=2 **then**
            slot for receiving;
        else if R=0 **then**
            slot for sleep;
        else
            Isolate *node* with no queued packet;
RETURN Rank List **R** which contains slot state for each *node*

The ranking function in Eq 5.6 is performed in every slot. Suppose link j follows link i on the path, such that $R_i < R_j$. Then, in the proposed transmission ordering, i will transmit before j. The identified bound of the *SINR* in Eq 5.5 and the transmission order by the rank function in Eq 5.6 are important keys to scheduling the links to be collision-free.
The shown algorithm in 1 explain the process and the conditions that are applied on the rank function. By executing the rank function algorithm 1, the transmission order for every nodes on a certain slot will be identified accurately. For instance, if there are several nodes attempt to transmitting on the same slot, the rank function algorithm will guarantee that the transmission will be performed simultaneously without interference. Thus, this mechanism

performed by allocate an appropriate state for each node during one slot as shown in the algorithm output in Figure 5.2. By implementing these aforementioned equations in a small chain topology, then we can derive an equation that determines the minimum number of required slots, as in Eq 5.8.

$$S_f = (n * H) - H \tag{5.8}$$

Where n is the number of nodes in the chain, and H is the constant value representing the number of hops between two transmitters that are using the same slot. When the chain topology contains some nodes that have the capability to reach the RSU node over one hop, the minimum number of required slots is calculated by Eq 5.9.

$$S_{total} = (n_f * H) + n_c \tag{5.9}$$

where n_f is the number of nodes using multi-hop to reach the RSU, and n_c represents the number of nodes that have the capability to arrive at the RSU by one hop. Another important parameter that should be calculated is the slot length. The slot length is the time allocated to transmit a certain amount of data or packets. The appropriate slot length can be determined on the basis of the number of nodes calculated by Eq 5.3 and the defined frame length, as in Eq 5.10.

$$S_l = f/S_{total} \tag{5.10}$$

where f is the frame length, S_l is the suitable slot length and S_{total} is the minimum number of required slots defined by Eq 5.9. Once the transmission order is determined, the number of slots and slot length are defined, some assumptions are made. One of these assumptions is data rate. The assumed data rate α is 250 kbps; this rate has been selected because it is sufficient to transfer the data generated in the road-based wireless sensor network scenario. The data rate and slot length are required to calculate the packet size. As a result, the maximum packet size is calculated by Eq 5.11.

$$P_{siz} = S_l * \alpha \qquad kbit \tag{5.11}$$

Therefore, the delay in the chain topology, given by Eq 5.12

$$D = \frac{S_f}{C_h} * S_l \qquad (5.12)$$

where S_f is the number of required time slots to deliver a packet from the transmitter to the sink, and S_l is the slot length of each slot ms. C_h represents the number of chains following the sink.

5.2.2 Proposed MAC Protocol

The proposed protocol is specifically designed to be compatible with a fixed chain topology and support simultaneous transmission. The interference approach considered to calculate the interference range which is helpful to estimate the minimum hops required for successful concurrent transmission. The GLPM has been used as propagation model used for the interference model. The physical layer properties have been taken into account to maintain the interference range accurately. Each node transmits data only during this dedicated time slot allocated to it even with presence another concurrent transmission. Since the main concentration of this protocol is avoiding the interference which could be caused by the simultaneous transmission, the proposed MAC protocol assumed that the clocks in each of the nodes are perfectly synchronised.

Time Slot Allocation Scheme

The allocation scheme describes the technique used to allocate a time slot for each of the nodes. This scheme is the key to building the schedule of allocated slots. It mainly relies on the rank function in Eq 5.6 to assign a one-time slot for several nodes. The spatial separation is determined by the spacing required to maintain the SINR above the required threshold. The number of nodes and the frame length should be considered to determine the time slot allocation. These variables comprise the input allocation process to calculate the slot length by Eq 5.10. After the slot length is determined, each time slot will be assigned to several nodes on the basis of the rank function, which considers the value of H to be larger than or equal to three bases on the interference model. The output of the allocation scheme is shown in Figure 5.2; the time slot is allocated to several nodes to allow simultaneous transmission. The schedule identifies the node state in each slot.

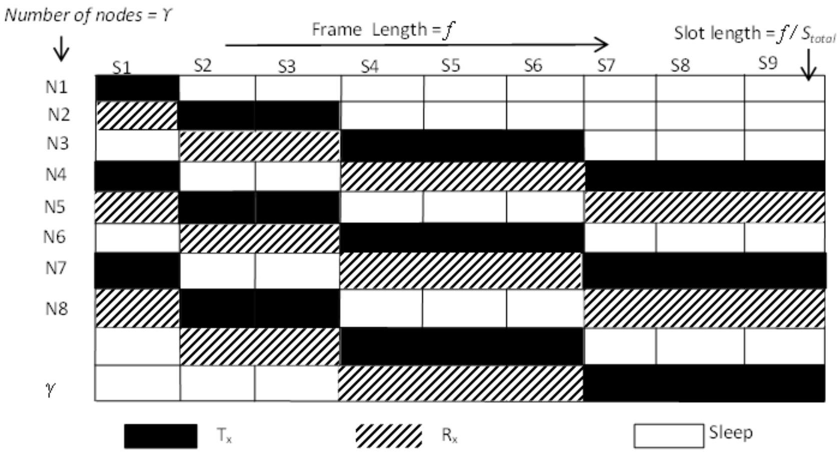


Figure. 5.2 Time slot allocation scheme

The first slot is assigned to nodes number one, four, seven and ten, to use for transmission T_x. The same slot will be allocated to other nodes to receive the transmitted packet by their neighbours. The rest of the time slots will be allocated to a sleep mode to minimise the energy consumption. This scheme will guarantee efficiency in slot usage and reduce the frame length.

Protocol Specification and algorithm

The proposed protocols rely on the network topology and information on the physical layer. The protocol operation is divided into two phases.

Phase one: The protocol requires the following physical information: the number of nodes, the node spacing and the antenna height. This information is needed to calculate the value of the *SINR* on the basis of GLPM. Therefore, the new *SINR* metric will consider the path loss exponent of the ground-level propagation model. Then, to avoid any interference, it is essential to ensure that the *SINR* value is larger than the *SINR* threshold. This will guarantee that the required criteria of simultaneous transmission in one slot are met as described in the proposed algorithm 2.

Phase two: Once the *SINR* value and H value are defined, the protocol starts to request some initial information, such as the frame length f and the number of nodes. Then, the appropriate slot length will be calculated with the use of this information, as in Eq 5.10. In each slot, the rank function will then be used to derive the transmission order for each node. The outcome of this function will indicate the node state in each slot, as shown in Figure 5.2 The final step in this phase is releasing the transmission schedule to all the nodes in the topology. As a result, simultaneous transmission will be possible without any degradation.

Algorithm 2 Time Slot Allocation Algorithm

Input : $\vartheta, H, d, q, h, n, f$
Output : A feasible schedule under Physical interference.
Initialize : calculate SINR by h, n, d
if SINR $\geq \vartheta$ **then**
    compute $S_l = \frac{f}{S_{total}}$;
    compute Transmission order by **Rank Function**;
    Build Schedule and release it to Nodes;
else
    increase d;
RETURN A feasible schedule for **N**

MAC Protocol Design

The protocol determines the operation of the MAC protocol in each node and how it manages the time slot assignment. The MAC protocol consists of three main parts, which work integrally to deal with the scheduling of transmission without any conflict [97].

Central MAC: All the data packets ready for transmission by the node are sent down from the IP to the Central MAC. Upon receiving the packets, the Central MAC queues them and waits for the turn of these nodes to transmit. As soon as these nodes have their turn to transmit, the Central MAC looks up the MAC queue for any queued packets. It then iteratively de-queues packets, attaches the MAC header and trailers and then sends them to the simple-wireless-channel. Before sending them, the Central MAC calculates the transmission time required on the basis of packet size and data rate. It adds up the transmission times of all the packets sent and compares these with the slot time provided by the TDMA Controller. If the Central MAC could not transmit any more packets in a particular slot, the loop terminates, and further transmissions stop. The simple-wireless-channel forwards the packets to the node address defined in the header.

MAC Controller: The TDMA controller handles all the scheduling aspects of the protocol. It initiates spatial time division multiple access (STDMA) sessions and authorises the nodes to transmit in the slots it specifies. The number of slots allocated for transmission, along with the slot durations, is provided to it by the allocation scheme and rank function. Then, the MAC Controller maintains a list of MAC pointers associated with all the nodes. Based on the slot assignment provided by the allocation scheme, this list is populated by the TdmaHelper class before the simulation starts. After the simulation starts, the MAC Controller initiates the scheduling of STDMA sessions on the basis of node IDs. It calls the Central MAC from its list of MAC pointers and instructs the nodes that they can transmit for a particular slot time on the basis of the rank function. As soon as the transmission slot for such nodes is complete, the MAC Controller waits for GuardTime, and then the MAC controller calls the nodes again to perform the rank function to determine the transmission order. Once all the nodes from the list are assigned a transmission slot, the controller waits for the InterFrameTime before starting with the same procedure again as in Figure 5.3.

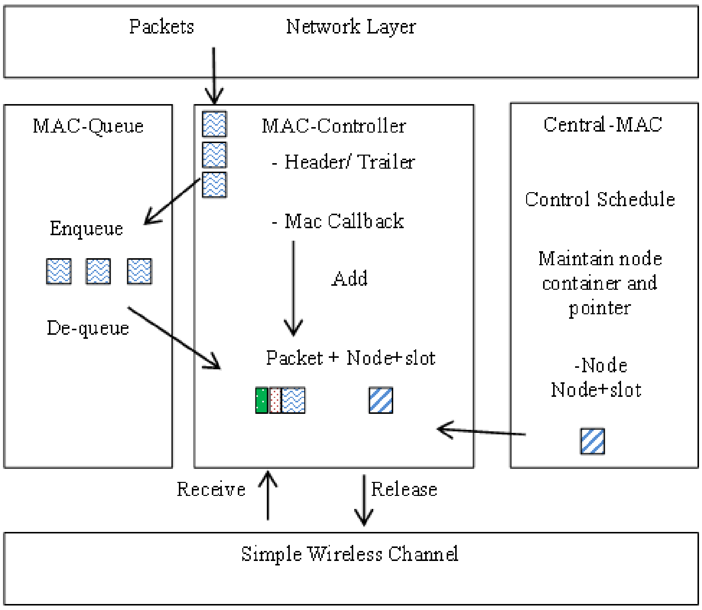


Figure. 5.3 Protocol component

MAC Queue: The TDMA maintains a drop-tail queue to store the packets received from the network layer until it gets its transmission slot. The attributes that can be modified for this class are the MAC queue length and MAC queue time. Thus, all the packets trying to be enqueued after the queue size reaches the MAC queue length are dropped; the packets stored in the queue for a time interval longer than the MAC queue time are also dropped.

5.3 Simulation and Performance Analysis

5.3.1 NS-3 Simulator

It is open source discrete-event network simulator, targeted primarily for research and educational use. Ns-3 is free software, licensed under the GNU GPLv2 license, and is

publicly available for research, development, and use [98].
The goal of the ns-3 project is to develop a preferred, open simulation environment for networking research: it should be aligned with the simulation needs of modern networking research and should encourage community contribution, peer review, and validation of the software.
It is flexible, since the ns-3 simulator is open source and relies on C++ and python, this allows the researcher to modify and customize the module to meet the system requirements. Thus, it is possible to make changes even to the core part of the simulation. In addition, the NS-3 simulator provides a feature which gives the developer space to design his own module. In addition to flexibility, the ns-3 simulator is scalable which means it is designed to simulate large number of nodes. So it is the right choice to simulate different scenarios that require varied node density. Also, the ns-3 is a powerful tool for analysis and improvement of networking technologies, and many simulation packages are available [99].

5.3.2 Requirements for Simulation

The NS-3 Simulator was selected to perform the simulation tests for this research due to the reasons mentioned above. The NS-3 simulator is designed to work on a range of platforms, but it is strongly recommended by the NS-3 developers to use an open source operating system in order to achieve the best performance. Thus Ubuntu 14 was selected. The TDMA module has been installed on NS-3 to be a starting point of our protocol. The available TDMA module is not officially developed by NS-3 simulation, but it was designed by a member of NS-3 community. This TDMA module only supports a classic TDMA operational concept that allocates one time slot for each node. Also, this TDMA module does not consider the any physical layer properties that may affect the performance of the MAC protocol. Therefore, the module has been modified and rebuilt again to meet our system requirements which includes concurrent transmission, the interference model and considers the properties of the physical layer. The last requirement was to create a chain topology and configure the channel to communicate with the allocated sink.

5.3.3 Scenarios

The main scenario considered in this work was at chain topology. This was considered since it will be used to deploy the sensor nodes in a linear topology suitable for deployment among a motorway, with dimensions as shown in Figure 5.4.

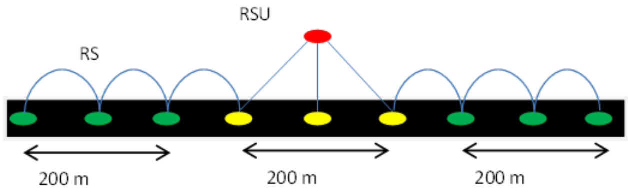


Figure. 5.4 Simulation-scenario

Upstream communication

Regarding the uplink, the deployed RSs will be divided into two group based on capability. The first group comprises the nearest 25 nodes to the RSU that can communicate with the RSU over one hop on the basis of Eq 5.2 and the technical capability in Table 5.1. The second group comprises the remainder of the RS nodes in the chain that rely on multiple-hops to reach the RSU node.

Downstream communication

In the downlink, the RSU node can reach all the RS nodes in the chain because all the RS nodes are located in its coverage range. We have assumed that the RSU has the technical capability to reach the farthest node on the chain. The RSU has access to mains power so there are no limitations in terms of the transmitting power. This assumption is due to the fact that the RSU will be required to communicate commands directly to all RSs, to send some commands that flash the LED lights installed in RSs. Therefore, the transmitting power for the downlink or for the RSU will be 100 mW which gives the RSU a transmission range of 700m.

5.3.4 Parameters

The parameter values in Table 1 have been evaluated with the use of the simulator to validate the proposed protocol. In this scenario, one chain is considered; this chain is controlled by one RSU node, and its transmitting power is 100 mW, so we use Eq 5.3 to calculate the number of nodes. The node spacing is 8 m based on the GLPM used in Eq 3.8 which is given in chapter three. Thus, the number of nodes is 75 nodes, and the frame length is assumed to be 1 s. Based on Eq 5.1, Eq 5.2 and the node capability, the topology will be divided, as shown in Figure 5.4.

In the downlink, the RSU node can reach all the RS nodes in the chain because all the RS nodes are located in its coverage range. As mentioned earlier, in relation to the uplink, the

Table 5.1 Simulation variable values

Parameters	Value
Slot length	10 ms
Frame length	1 s
Number of Nodes	75
Number of Slot	100 slot
Packet size	312 bytes
Data Rate	250 kbps
Ptx for RSUs	100 mW
Ptx for RSs	2 mW

nearest 25 nodes to the RSU can communicate with the RSU one hop on the basis of Eq 5.2 and the technical capability in Table 5.1. The remainder of the RS node will reach the RSU node over multi-hops.

Equation 5.10 is used to calculate the slot length for each node, which is 1/100 s, and Eq 5.11 determines the maximum packet size for each transmission for each node, which is 312 bytes. Based on the packet size, the magnetic sensor can collect 100 samples/car, and the sample size is 8 bit=800 bits/car; if the packet size is 2,500 bits or 312 bytes, then each packet can carry the information of 3 sensed cars because 2500/800=3.12 cars/sec. The simulation ran several times and considered two MAC techniques: classic TDMA and the proposed spatial TDMA.

5.3.5 Results

Delay

The efficiency of a protocol depends on several factors, including delay and the dropped packets ratio. Here, two types of protocols are assessed: classic TDMA and developed Spatial TDMA have been implemented in the chain topology. We used the same input value for both to measure the delay and the dropped packet ratio.

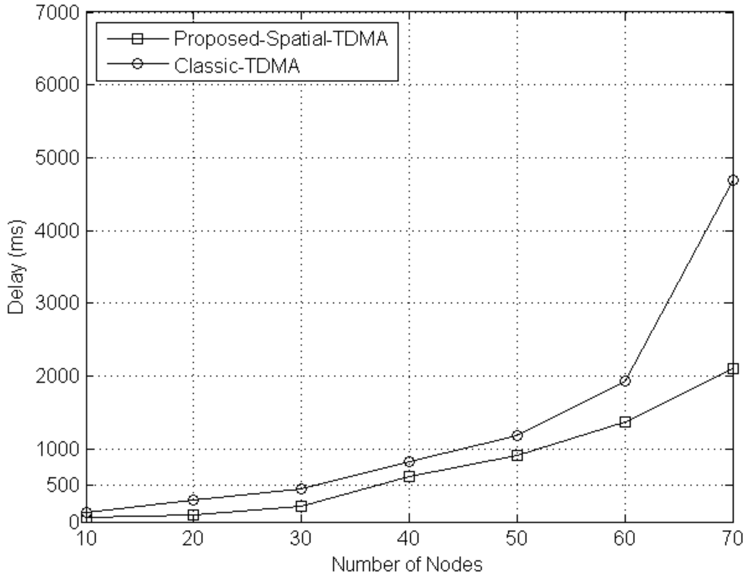


Figure. 5.5 Compared Delay of Classic TDMA and Proposed Spatial TDMA in the chain topology

As shown in the above Figure 5.5, the delay has been measured in a chain topology based on Eq 5.12. It compares the delay between scheduled concurrent transmission TDMA and classic TDMA: The experiment was conducted with different node number, with one transmitted packet. The result in Figure 5.5 shows that in the chain topology, the delay of the classic TDMA increases rapidly when the number of nodes increases. By contrast, the delay of the proposed spatial TDMA is still at an acceptable level. This phenomenon refers to that the classic TDMA is designed to assign one time slot for each node. Thus, when classic TDMA is applied to a chain topology where the nodes are required to transmit their packets and the forwarded packets in a multi-hop communication pattern, then the number of required slots for each node will increase cumulatively as in Eq 5.13. As a result, the frame size will be expanded dramatically as shown in Figure 5.6, this leads to an increase in the delay as shown in Figure 5.5.

$$N_i = \frac{n(n-1)}{2} \tag{5.13}$$

where N_i is the number of required slots, and n is the number of nodes [100]. This increase of allocated slots will lead to an increase in the frame length which can cause significant delay. Therefore, the proposed protocol reduces the end-to-end delay by take the advantage of spatial technique to reuse time slots for simultaneous transmission for nodes that are outside the radio interference range, and reduce the delay.

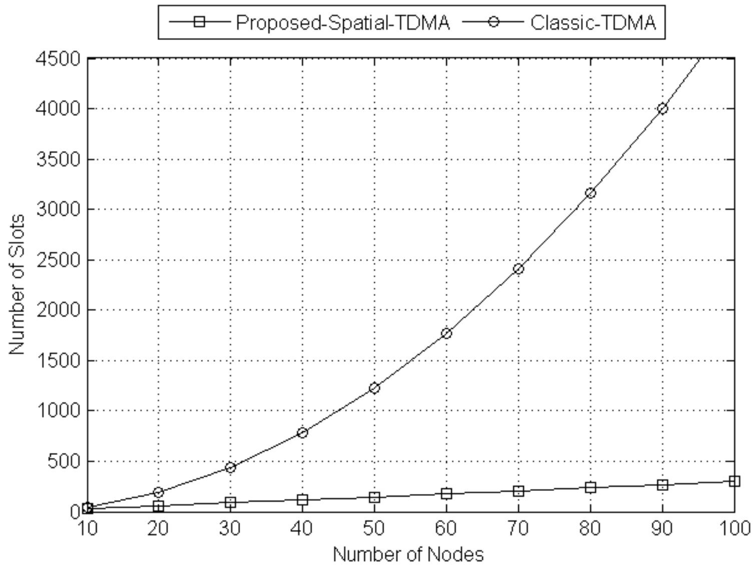


Figure. 5.6 Compared allocated slots of Classic TDMA and Proposed Spatial TDMA in the chain topology

Packet Received Ratio

In terms of Packet Received Ratio, Figure 5.7 clearly shows the ratio of received packets in classic TDMA is lower than in the proposed spatial TDMA. To simplify the scenario, different numbers of nodes are considered and one packet is transmitted through a fixed data rate. Typically, the number of scheduled packets is in proportion to the number of nodes in the chain, so increasing the number of nodes leads to an increase in the number of scheduled packets. In classic TDMA, this requires at least one slot to be assigned for each node to send its packet and it will ask another slot to send the forwarded packets. However, the rapid drop in the packet received ratio in classic TDMA relates to the fact that increasing the number of nodes leads to an increase in the number of assigned slots. Therefore, the frame length will expand and then some of the scheduled nodes will exceed the accepted level of delay which is predefined on the queuing delay specification. As a result, some scheduled packets will be dropped due to their having exceeded the acceptable queuing delay. By contrast, the proposed spatial TDMA delivered most of the sent packets despite a large number of transmitters. This success in the deceived packets is due to the slot allocation process used which relies on the spatial reuse technique. The spatial reuse technique allows multiple users to transmit packets simultaneously, which minimises the frame length. In addition, the proposed protocol considers the nature of the topology where multi-hop communication is required. Moreover, the physical layer properties are included in the SINR model based on

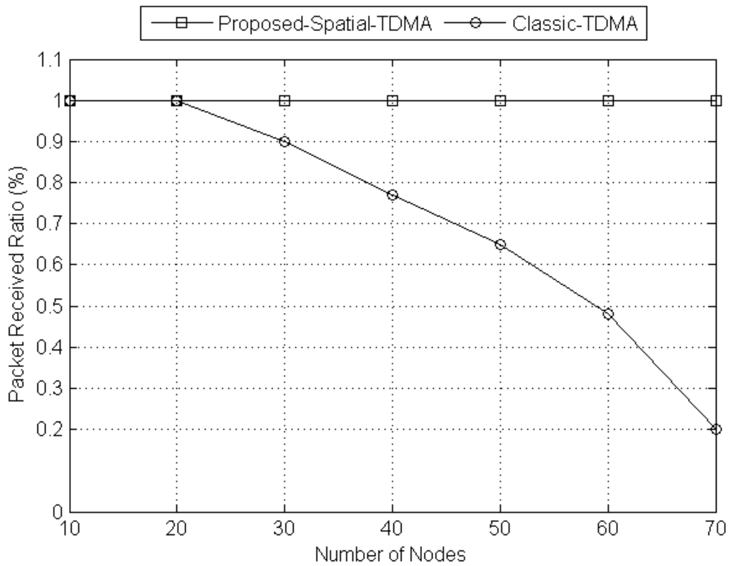


Figure. 5.7 Compared Packet Received Ratio of Classic TDMA and Proposed Spatial TDMA in the chain topology

the ground level propagation model. Hence, although the multi-hop communication pattern is used at ground level, interference is avoidable. All these significant factors have been considered in the proposed spatial TDMA protocol, and this improvement is reflected in the PRR and reduced delay.

Throughput

Throughput is defined as the largest admissible traffic load that yields a finite network delay. One of the parameters which has been used to test the proposed protocol is the average measured throughput as a function of node number. We have assumed that all data packets are of equal length and that one packet can be sent in each time slot. As shown in 5.8, the throughput of the classic approach TDMA and the proposed spatial TDMA was measured when these approaches were applied to a chain topology. Clearly, the decrease in the throughput of the classic TDMA began at node number 30. This decrease of throughput relates to the fact that the TDMA's allocation scheme only assigns one time slot during which each node must send its packet, so when this protocol is applied to a chain topology or a multi-hop communication environment, the number of required slots increases dramatically. The number of required slots then exceeds the frame length and the accepted level of delay. Therefore, many packets will queue for a long time to await their slot, but this waiting time makes them vulnerable to being dropped. Thus, the number of dropped packets will affect the throughput since the throughput criteria is used to measure the rate of successful message delivery over a communication channel.

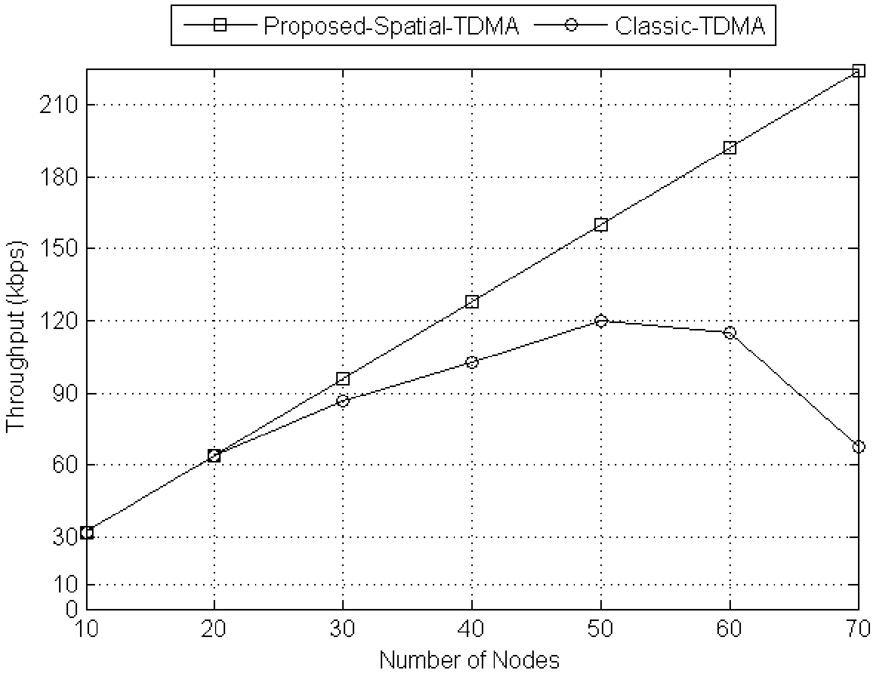


Figure. 5.8 A comparison of throughput in classic-TDMA and Proposed Spatial-reuse TDMA

On the other hand, the throughput of the proposed spatial TDMA increases stably and proportionally with the number of nodes. The increase in the throughput of the proposed spatial TDMA relates to the fact that this protocol is designed to support simultaneous transmission where any slot can be occupied by several nodes without any interference. This transmission strategy helps to reduce the number of queued packets and sends the packet through in the next available slot. Thus, the dropped packet ratio will be small, and that means the rate of successful message delivery over a communication channel (throughput) is high.

5.3.6 Validation

Proposed TDMA vs. WiWi and Dis-MAC

In this section, a numerical analysis and simulation are conducted to predict the delay of the proposed protocol and compare it with those of the other spatial TDMA protocols in Figure 5.9.

The spatial reuse technique has been considered in several TDMA protocols in order to reduce end-to-end delays. However, the spatial reuse concept has been implemented and redesigned for these protocols based on different approaches such as the graph-model and SINR model [64, 65, 63]. These protocols have been specifically designed for chain topology, but the ground level communication was not considered in these protocols. The results in Figure 5.9 reflect that a better delay can be achieved with the proposed spatial TDMA protocol compared with the transmission schedule for spatial TDMA protocols in [64,66].

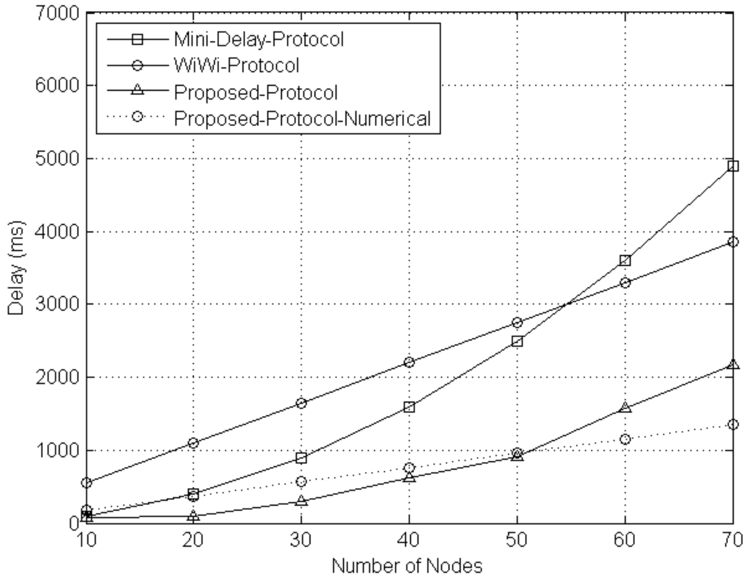


Figure. 5.9 End-to-end delay of a different TDMA approach implemented in the chain topology

This difference in Figure 5.9 relates to the fact that the transmission schedules used in [64, 66] have been designed according to a graph-based model where physical layer properties have not been considered. Graph-based approaches do not reflect the accuracy of the estimated spacing between any concurrent transmissions. In addition, proposed transmission schedules that are based on the SINR approach or the physical model come with longer delays. The recorded high delay referred to that the considered propagation model is FSPL. FSPL estimates a longer transmission range which leads to larger spacing between any simultaneous transmissions to avoid interference. At the end, the effect of using FSPL is reflected in the transmission schedule. Thus, the proposed spatial TDMA achieves a lower level of delay due to the fact that it is SINR-based which is more accurate than the graph-based approach. The SINR model considers the properties of the physical layer in order to estimate the interference range. In addition, the proposed spatial TDMA protocol relies on GLPM instead of using FSPL. Using GLPM to calculate the SINR is essential to define the physical boundaries and the interference range precisely for ground level communication. As a result, interference can be avoided with a shorter separation distance between simultaneous transmissions and the combination of GLPM and SINR will produce a much smaller frame length that reduces the delay.

5.4 Chapter Summary

In this chapter, we have proposed our MAC protocol for ground level wireless sensors in a fixed chain topology. The SINR model is combined with the GLPM to build an efficient concurrent transmission schedule. This combination takes into account physical properties and achieves the highest level of slot reuse. This efficiency is achieved with the use of the rank function to determine the transmission order, which serves as the key to building a feasible transmission schedule. Numerical analysis has been conducted to optimise the topology, which includes the chain length and the simultaneous transmission range.

Additionally, we have proposed equations to calculate the minimum number of required slots for each chain. To evaluate the proposed protocol, numerical analysis has been carried out and the performance of the proposed protocol has been compared with those of the other TDMA protocols. Moreover, a simulation scenario was designed to assess the performance of the proposed protocol compared with the classic TDMA. The results show the ratio of dropped packets in the proposed TDMA is stable compared with classic TDMA where the ratio of dropped packet increases dramatically. In addition, the proposed delay metric shows that the proposed protocol has a lower delay than the classic TDMA and STDM.

Chapter 6

Conclusion

6.1 Summary of The Work

In this thesis, a technical solution has been proposed for a fixed chain topology of wireless sensor networks deployed on the ground for traffic sensing. An empirical ground level propagation model has been proposed that is able to predict the path loss and signal attenuation between road studs or nodes that are located on the ground. This has been followed by an energy efficiency metric designed specifically for WSNs, which is able to optimise the physical layer parameters to achieve the maximum level of efficiency. Furthermore, a new MAC protocol has been introduced which is designed particularly for chain topology WSNs to communicate at ground level.

In chapter two, existing ITS systems were reviewed, then the investigation was narrowed down to highlight the existing technical solution that could be implemented to solve the technical issues in ITS systems such as near ground propagation models, power constraints and MAC layer protocols. Thus, several propagation models, energy efficiency metrics and MAC protocols have been reviewed and analysed in the literature review chapter.
Then the investigation has been narrowed down to highlight the existing technical solution that could be implemented to solve these technical issues in ITS systems such as near ground propagation models, the power constraint and MAC layer protocols. Thus, several propagation models, energy efficiency metrics and MAC protocols have been reviewed and analysed in the literature review chapter.
The review of the propagation models aimed to find the most appropriate propagation model for ground communication. This would be a model which can predict the transmission range between road studs. Following this, several energy efficiency metrics were studied to find out to what extent they could be implemented in a WSN system. The latter part of chapter two highlights the MAC protocols of WSNs in different classes, namely contention

or schedule-based. For each class of MAC protocol, reported WSN MAC protocols were studied, analysed and compared to identify the strengths and weaknesses of each protocol. In the last part of the literature review, schedule-based protocols designed for chain and linear topologies were investigated. The concept of schedule-based protocols is based on scheduling accessibility to the channel to guarantee a clear channel for each node.

After studying the existing propagation models and the signal behaviour, we determined that the lowest propagation model reported measured the signal attenuation at a height of 8cm. Thus, this propagation model was not sufficiently accurate to measure the maximum transmission range and signal attenuation for nodes placed at ground level. As a result, it was important to conduct realistic measurements to investigate the signal behaviour for this height of antenna. Real life measurements were carried out to measure the signal attenuation and transmission range when the antenna height is close to ground level. The measurements were performed at different heights between 0 ~ 12.5cm and the RSSI value was recorded at each distance between 1m ~ 10m. Then, the reverse engineering method was used to derive the propagation model based on the measurement results. Our results show that the maximum range of transmission at ground level is 8m when the antenna height is 0cm. These measurements prove that communication with low powered nodes at ground level is possible within a maximum transmission range of 8m. In addition, the experimental results show that the directional PCB Yagi antenna can extend the transmission range at ground level by concentrating the main lobe onto the targeted direction. To validate the results, the proposed empirical model derived from the results was used to predict the signal attenuation and the path loss. The result of this validation process showed that the predictions of the proposed empirical model accurately matched the real measurements. The next step was to validate the proposed model against similar propagation models. The output values reflected the fact that the other propagation models were not able to predict the signal attenuation precisely compared with the proposed model which predicted results matching the measured results. This investigation aims to find a way to specify an energy efficiency metric similar to that developed for mobile cellular systems. New energy efficiency metric has been proposed here to be applied to WSNs. The proposed metric is suitable for wireless sensor networks that operate at or near ground level. It shows the relationship between energy efficiency, the spacing between nodes and the antenna height. The proposed energy efficiency metric is based on an access node level model. The access node level considers most of the utility aspects such as the transmission distance reached, the area covered, the output power and the bit transmitted in order to estimate the energy efficiency precisely. When the ground level propagation model is used as the propagation model in the energy efficiency metrics, the numerical results indicate that the energy efficiency metrics are implementable in a ground level communication scenario. The results show that the energy efficiency can be optimized not only as a function of transmission distance and transmitting power, but also that the antenna height influences energyefficiency.

In terms of the MAC layer, a new schedule-based MAC protocol has been proposed that considers the properties of a chain topology and ground level propagation. Since the MAC protocol is affected by the topology and propagation properties, it was important to design a new MAC protocol that is based on ground level propagation. This protocol relies on a time division multiplexing concept that allocates a time slot where the channel is free for transmission. To improve the throughput and reduce the delay in a long chain topology, a spatial reuse technique has been applied in this protocol to allow concurrent transmission in one slot in spatially separated sections of the chain. The interference avoidance method is based on the SINR which was reported previously. However, in this case, the ground level propagation model introduced in chapter 3 was used so that the protocol can be implemented for transmission near ground level. The proposed protocol was modelled mathematically and the results demonstrate the possibility of providing concurrent transmission for multiple nodes communicating at ground level in a chain topology.
As a result, a new algorithm has been proposed which will consider the spatial reuse technique for a chain topology. The spatial reuse technique allocates a time slot for multiple nodes without interference based on the proposed interference model. Here, a new interference model is proposed for ground level communication in chain topologies; this model contains a rank function which is responsible for giving a transmission order to the senders.

After this, the proposed protocol was evaluated using the NS-3 simulator with a chain topology. The simulation results showed that the packet received ratio in the proposed spatial TDMA protocol is stable compared with classic TDMA protocols because the queued packets in classic TDMA wait for their slot until this slot is not being used by anyone else on the medium. This technique makes the packets queue for longer especially in large networks, so the packets will be highly vulnerable to exceeding the queuing delay which may mean that they will be dropped. In contrast, the proposed spatial TDMA supports concurrent transmission, so the slot can be used by multiple nodes which will help to reduce the packet queuing time and so decrease the possibility of packets being dropped as a result of excessive queueing delays. Therefore, the packet received ratio in classic TDMA decreases rapidly when the number of nodes increases. Delays are another parameter that has been assessed to compare the proposed TDMA and classic TDMA. The delay results show that significant delays appear in classic TDMA, but the proposed spatial TDMA achieved lower delays. The better level of delay achieved in the proposed TDMA relates to the fact that the required number of slots in classic TDMA is large compared with the proposed protocol which employs a spatial reuse technique to reduce the number of slots required. Thus, the frame length in classic TDMA is much longer than in the proposed protocol because the former does not apply the spatial reuse technique, while this technique is used in the proposed TDMA protocol to allow simultaneous transmissions. As a result, it achieves better performance than classic TDMA when implemented in a chain topology.

On the other hand, the proposed protocol has been compared with similar spatial TDMA protocols designed for linear or chain topologies. The results show that the level of delay in similar protocols such as WiWi and other linear TDMA protocols is much higher than the delay level achieved in the proposed protocol. This reflects the fact that these protocols are designed for a chain topology and they support the spatial reuse technique, but they consider the FSPL model when estimating the interference range. Using the FSPL model to calculate the transmission range will result in a longer interference range, due to the absence of obstacles. This increase in the interference range will affect the transmission schedule and so increase the required hops between any simultaneous transmissions. Increasing the number of required hops between simultaneous transmissions will lead to an increase in the frame length which will directly affect the network delay.

The proposed spatial TDMA protocol is more realistic, since it uses the ground level propagation model to calculate the interference range for concurrent transmissions. Thus, the frame length in the proposed protocol is smaller than previously reported protocols and this leads to a reduction in the network delay.

6.2 Main Contributions

This research aimed to study the WSNs that communicate on ground level. Several issues have been addressed, these issues related to the propagation, the power constraint and the appropriate MAC protocol. As the result of this research, several technical solutions has been proposed on physical and MAC layer. On physical layer, a new propagation model has been contributed which study the relationship between antenna height and the achievable transmission mission range. The proposed model able to predict the signal attenuation, path loss and estimate transmission range accurately.

For the power constraint, a new energy efficiency metric has been proposed as second contribution. The proposed metric built based on access node level which has not been done before especially for wireless sensor networks. It will be a powerful tool for the designer to study the relationship between the power consumption and the attainable utility. Thus, by using this metric for wireless sensor networks the deployment can be optimised base on the

available resources.
The third contribution of this work represented by a new MAC protocol designed for fixed chain topology. The novelty of this protocol that the simultaneous transmission is supported without any interference. This protocol designed specifically to support the concurrent transmission for nodes communicate on ground level. Thus, the physical layer and the topology properties has been considered to introduced the new interference model for ground level communication. This interference model will be used to estimate the minimum separation distance or minimum hops that are required between any two nodes transmitting simultaneously on ground level.

6.3 Critical Analysis

Every work contain some shortcomings, and this work as others works come with some limitations. The limitations differing from chapter to chapter. For instance, chapter three introduce ground level propagation model, this propagation model designed specificity to study the ground level communication. The model capability limited by antenna height between 0 ~ 12.50 cm. Because of this model built based on real measurements, it is difficult to generalise it for any antenna height. Thus, this model designed accurately for ground level communication only.
In chapter four, a new energy efficiency metric has bee introduced. This metric relay mainly on the propagation model to optimise the attainable utility to the available resources. The proposed energy efficiency metric in chapter four confined to the wireless sensor that communicate on ground level. Thus, the used propagation model in this metric designed fro ground level communication only which has been introduced in chapter three. Therefore, we can state that the limitation on our energy efficiency metric related to the used propagation model which only consider the ground level communication.
The proposed MAC protocol in chapter five designed specifically for fix chain topology. Since the simultaneous transmission was required to reduce the delay, a new interference model introduce here. The interference mode require some physical layer properties that related to the propagation mode in order to establish concurrent transmission with free interference. The limitation of this protocol is the used interference model, this model designed specifically for ground level communication based on the proposed propagation model in chapter three. As the results, the protocol can work perfectly for fixed chain topology that contain wireless sensor communicate near ground level.

6.4 Future Works

The following are possible areas for further work. The ground level propagation model could be developed for use in the NS-3 simulator. The parameters of the propagation model can then be included in the NS-3 Library as a supported propagation model. This would allow the propagation model to be exposed to more validations and testing by NS-3 developers and communication researchers.

The propagation model requires further work to determine performance when the nodes are located underground. This scenario would aim to measure the coefficient value of the conductivity and the permittivity for different materials. This would make the model usable for different environments and different ground materials. The directional PCB Yagi antenna was proposed in this work and has been used in the propagation measurement. During the design stage of the MAC protocol, it was noted that this type of "directional" antenna was not officially supported on NS-3. Thus, one of the areas that is need for further work is to redesign the MAC protocol to consider directional antenna. This will be helpful for improving the transmission schedule which is produced by the allocation scheme algorithm. The directional antenna will also improve the interference range.

Another area of further work relates to the upper layer (the network layer). We need to design a routing protocol that is implementable in a chain topology, where the properties of the MAC protocol (interference model) are specifically considered. This will be helpful in contributing a new routing protocol which does not place a high computation load on low powered wireless sensors.

Following this, real life measurements can be taken to test the whole system performance, including deploying road studs to communicate at ground level and exchange sensed traffic data. While the proposed energy efficiency metrics will be used in the early stages by the designer to optimise the deployment and the available resources to achieve a higher efficiency level, the proposed protocol will be applied to the nodes to manage the process of data gathering.

References

[1] Y. Fei, P. Zhang, and Y. Zhao, "Energy-efficient cross-layer optimization for wireless sensor networks," *Communications and Network*, vol. 5, p. 493, 2013.

[2] G. Miao, N. Himayat, Y. G. Li, and A. Swami, "Cross-layer optimization for energy-efficient wireless communications: a survey," *Wireless Communications and Mobile Computing*, vol. 9, no. 4, pp. 529–542, 2009.

[3] L. Zhao, J. Cai, and H. Zhang, "Radio-efficient adaptive modulation and coding: green communication perspective," in *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*. IEEE, Conference Proceedings, pp. 1–5.

[4] D. Feng, C. Jiang, G. Lim, L. J. Cimini Jr, G. Feng, and G. Y. Li, "A survey of energy-efficient wireless communications," *Communications Surveys & Tutorials, IEEE*, vol. 15, no. 1, pp. 167–178, 2013.

[5] K. Sohraby, D. Minoli, and T. Znati, *Wireless sensor networks: technology, protocols, and applications*. Wiley-Interscience, 2007.

[6] B. Alipour, L. M. Khanli, and F. Mahan, "Kgic-its, a new system in intelligent transport system with corporation knowledge grid & cloud technology," in *Vehicular Electronics and Safety (ICVES), 2012 IEEE International Conference on*, Conference Proceedings, pp. 296–301.

[7] A. Sharma, R. Chaki, and U. Bhattacharya, "Applications of wireless sensor network in intelligent traffic system: A review," in *Electronics Computer Technology (ICECT), 2011 3rd International Conference on*, vol. 5. IEEE, Conference Proceedings, pp. 53–57.

[8] Z. Huang, T. Yamazato, and M. Katayama, "Optimal cluster partitioning for wireless sensor networks with cooperative miso scheme," in *Telecommunications (AICT), 2010 Sixth Advanced International Conference on*. IEEE, Conference Proceedings, pp. 323–328.

[9] P. Papadimitratos, A. La Fortelle, K. Evenssen, R. Brignolo, and S. Cosenza, "Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation," *Communications Magazine, IEEE*, vol. 47, no. 11, pp. 84–95, 2009.

[10] A. Amanna, "Overview of intellidrive/vehicle infrastructure integration (vii)," *VriginiaTech Transportation Institute*, 2009.

[11] R. Baldessari, B. Bödekker, M. Deegener, A. Festag, W. Franz, C. C. Kellum, T. Kosch, A. Kovacs, M. Lenardi, C. Menig *et al.*, "Car-2-car communication consortium-manifesto," 2007.

[12] A. Festag, G. Noecker, M. Strassberger, A. Lübke, B. Bochow, M. Torrent-Moreno, S. Schnaufer, R. Eigner, C. Catrinescu, and J. Kunisch, "'now–network on wheels': Project objectives, technology and achievements," 2008.

[13] C. Campolo and A. Molinaro, "Vehicle-to-roadside multihop data delivery in 802.11 p/wave vehicular ad hoc networks," in *Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE.* IEEE, Conference Proceedings, pp. 1–5.

[14] Y. Zhang, X. Huang, L. Cui, and Z. Zhao, "Design and evaluation of a wireless sensor network for monitoring traffic," in *The 14th World Congress on Intelligent Transportation Systems (WCITS'07)*, Conference Proceedings.

[15] J. Micek and J. Kapitulík, "Wireless sensor node for traffic monitoring: Analysis and design," *European International Journal of Science and Technology*, vol. 2, no. 1, pp. 85–97, 2013.

[16] A. N. Knaian, "A wireless sensor network for smart roadbeds and intelligent transportation systems," Ph.D. dissertation, MIT Media Lab, 2000.

[17] S.-Y. Cheung and P. P. Varaiya, *Traffic surveillance by wireless sensor networks: Final report*. California PATH Program, Institute of Transportation Studies, University of California at Berkeley, 2007.

[18] K. Wu, J. W. Schuster, and R. J. Luebbers, "Full wave modeling of rf propagation between low-to-the-ground antennas," in *Antennas and Propagation Society International Symposium, 2005 IEEE*, vol. 2. IEEE, Conference Proceedings, pp. 711–714.

[19] W. Zhengjie, Z. Xiaoguang, and Q. Xu, "The application and issuse of linear wireless sensor networks," in *System Science, Engineering Design and Manufacturing Informatization (ICSEM), 2011 International Conference on*, vol. 2, Conference Proceedings, pp. 9–12.

[20] V. J. Alappat, N. Khanna, and A. K. Krishna, "Advanced sensor mac protocol to support applications having different priority levels in wireless sensor networks," in *Communications and Networking in China (CHINACOM), 2011 6th International ICST Conference on*, Conference Proceedings, pp. 340–343.

[21] D. Wang, L. Song, X. Kong, and Z. Zhang, "Near-ground path loss measurements and modeling for wireless sensor networks at 2.4 ghz," *International Journal of Distributed Sensor Networks*, vol. 2012, 2012.

[22] S. Sangodoyin, S. Niranjayan, and A. Molisch, "Ultrawideband near-ground outdoor propagation channel measurements and modeling," in *7th European Conference on Antennas and Propagation (EuCAP)*. IEEE, Conference Proceedings, pp. 3034–3038.

[23] K. G. Tan and T. A. Rahman, "Receiving antenna height dependence of radio propagation path loss in fixed wireless access environment," in *Microwave Conference, 1999 Asia Pacific*, vol. 3. IEEE, 1999, pp. 797–800.

[24] S. Majedi and F. Farzaneh, "A new empirical-physical method for calculation of path loss for fixed wireless access in suburban areas," in *Telecommunications, 2008. IST 2008. International Symposium on*. IEEE, 2008, pp. 92–96.

[25] T. Stoyanova, F. Kerasiotis, A. Prayati, and G. Papadopoulos, "A practical rf propagation model for wireless network sensors," in *Third International Conference on Sensor Technologies and Applications. SENSORCOMM'09*. IEEE, Conference Proceedings, pp. 194–199.

[26] J. F. Janek and J. J. Evans, "Predicting ground effects of omnidirectional antennas in wireless sensor networks," *Wireless Sensor Network*, vol. 2, no. 12, pp. 879–890, 2010.

[27] S. G. Vougioukas, H. T. Anastasiu, C. Regen, and M. Zude, "Comparison of radio path loss models for wireless sensor networks in orchard environments," in *CIGR-AgEng International Conference of Agricultural Engineering*, Conference Proceedings, pp. 79–83.

[28] T. Chen, H. Kim, and Y. Yang, "Energy efficiency metrics for green wireless communications," in *Wireless Communications and Signal Processing (WCSP), 2010 International Conference on*. IEEE, Conference Proceedings, pp. 1–6.

[29] L. Suarez, L. Nuaymi, and J.-M. Bonnin, "An overview and classification of research approaches in green wireless networks," *Eurasip journal on wireless communications and networking*, vol. 2012, no. 1, pp. 1–18, 2012.

[30] M. H. Alsharif, R. Nordin, and M. Ismail, "Survey of green radio communications networks: Techniques and recent advances," *Journal of Computer Networks and Communications*, vol. 2013, 2013.

[31] L. Zhao, G. Zhao, and T. O'Farrell, "Efficiency metrics for wireless communications," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on*. IEEE, Conference Proceedings, pp. 2825–2829.

[32] L. Zhao, L. Gao, X. Zhao, and S. Ou, "Power and bandwidth efficiency of wireless mesh networks," *IET Networks*, vol. 2, no. 3, 2013.

[33] S. Junfeng and M. Yongchang, "A dynamic sleep mac protocol for wireless sensor networks," in *Information and Automation (ICIA), 2010 IEEE International Conference on*, Conference Proceedings, pp. 1538–1543.

[34] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient mac protocol for wireless sensor networks," in *INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE*, vol. 3. IEEE, Conference Proceedings, pp. 1567–1576.

[35] L. Han, “Leach-hpr: An energy efficient routing algorithm for heterogeneous wsn,” in *Intelligent Computing and Intelligent Systems (ICIS), 2010 IEEE International Conference on*, vol. 2. IEEE, Conference Proceedings, pp. 507–511.

[36] S. Cui, A. J. Goldsmith, and A. Bahai, “Energy-constrained modulation optimization,” *IEEE transactions on wireless communications*, vol. 4, no. 5, pp. 2349–2360, 2005.

[37] E. Gelenbe and D. Gunduz, “Optimum power level for communications with interference,” in *Digital Communications-Green ICT (TIWDC), 2013 24th Tyrrhenian International Workshop on*. IEEE, Conference Proceedings, pp. 1–6.

[38] V. Rodoplu and T. H. Meng, “Bits-per-joule capacity of energy-limited wireless networks,” *Wireless Communications, IEEE Transactions on*, vol. 6, no. 3, pp. 857–865, 2007.

[39] F. Meshkati, H. V. Poor, S. C. Schwartz, and N. B. Mandayam, “An energy-efficient approach to power control and receiver design in wireless data networks,” *IEEE transactions on communications*, vol. 53, no. 11, pp. 1885–1894, 2005.

[40] F. Meshkati, H. V. Poor, S. C. Schwartz, and R. V. Balan, “Energy-efficient resource allocation in wireless networks with quality-of-service constraints,” *IEEE Transactions on Communications*, vol. 57, no. 11, pp. 3406–3414, 2009.

[41] H. M. Kwon and T. G. Birdsall, “Channel capacity in bits per joule,” *Oceanic Engineering, IEEE Journal of*, vol. 11, no. 1, pp. 97–99, 1986.

[42] F. Meshkati, H. V. Poor, S. C. Schwartz, and R. V. Balan, “Energy-efficient resource allocation in wireless networks with quality-of-service constraints,” *Communications, IEEE Transactions on*, vol. 57, no. 11, pp. 3406–3414, 2009.

[43] E. Gelenbe and B. Oklander, “Cognitive users with useful vacations,” in *2013 IEEE International Conference on Communications Workshops (ICC)*. IEEE, 2013, pp. 370–374.

[44] S. A. Nikolidakis, D. Kandris, D. D. Vergados, and C. Douligeris, “Energy efficient routing in wireless sensor networks through balanced clustering,” *Algorithms*, vol. 6, no. 1, pp. 29–42, 2013.

[45] N. Zaman, A. R. Khan, and M. Salih, “Designing of energy efficient routing protocol for wireless sensor network (wsn) using location aware (la) algorithm,” *J. Inform. Commun. Technol*, vol. 3, no. 2, pp. 56–70, 2009.

[46] Z. Chen and A. Khokhar, “Self organization and energy efficient tdma mac protocol by wake up for wireless sensor networks,” in *Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. 2004 First Annual IEEE Communications Society Conference on*. IEEE, Conference Proceedings, pp. 335–341.

[47] J. Kabara and M. Calle, “Mac protocols used by wireless sensor networks and a general method of performance evaluation,” *International Journal of Distributed Sensor Networks*, vol. 2012, 2012.

[48] A. El Masri, L. Khoukhi, and D. Gaiti, "A tdma-based mac protocol for wireless mesh networks using directional antennas," in *CTRQ 2011, The Fourth International Conference on Communication Theory, Reliability, and Quality of Service*, Conference Proceedings, pp. 95–98.

[49] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, "Energy-efficient communication protocol for wireless microsensor networks," in *System Sciences, 2000. Proceedings of the 33rd Annual Hawaii International Conference on*. IEEE, Conference Proceedings, p. 10 pp. vol. 2.

[50] T. Nieberg, S. Dulman, P. Havinga, L. van Hoesel, and J. Wu, "Collaborative algorithms for communication in wireless sensor networks," in *Ambient Intelligence: Impact on Embedded Sytem Design*. Springer, 2003, pp. 271–294.

[51] L. F. Van Hoesel and P. J. Havinga, "A lightweight medium access protocol (lmac) for wireless sensor networks: Reducing preamble transmissions and transceiver state switches," 2004.

[52] I. Demirkol, C. Ersoy, and F. Alagoz, "Mac protocols for wireless sensor networks: a survey," *Communications Magazine, IEEE*, vol. 44, no. 4, pp. 115–121, 2006.

[53] Y. Wei, J. Heidemann, and D. Estrin, "Medium access control with coordinated adaptive sleeping for wireless sensor networks," *Networking, IEEE/ACM Transactions on*, vol. 12, no. 3, pp. 493–506, 2004.

[54] S. Khatarkar and R. Kamble, "Wireless sensor network mac protocol: Smac & tmac," *Indian Journal of Computer Science and Engineering (IJCSE)*, vol. 4, no. 4, pp. 304–310, 2013.

[55] T. Van Dam and K. Langendoen, "An adaptive energy-efficient mac protocol for wireless sensor networks," in *Proceedings of the 1st international conference on Embedded networked sensor systems*. ACM, 2003, pp. 171–180.

[56] P. Hurni and T. Braun, "Evaluation of wisemac on sensor nodes," in *Wireless and Mobile Networking*. Springer, 2008, pp. 187–198.

[57] K. Jamieson, H. Balakrishnan, and Y. Tay, "Sift: A mac protocol for event-driven wireless sensor networks," in *European Workshop on Wireless Sensor Networks*. Springer, 2006, pp. 260–275.

[58] Y. C. Tay, K. Jamieson, and H. Balakrishnan, "Collision-minimizing csma and its applications to wireless sensor networks," *Selected Areas in Communications, IEEE Journal on*, vol. 22, no. 6, pp. 1048–1057, 2004.

[59] K. Kunert, "Tdma-based mac protocols for wireless sensor networks: State of the art and important research issues," *Halmstad Univeristy, Halmstad*.

[60] S. Gambhir and N. Fatima, "Op-leach: An optimized leach method for busty traffic in wsns," in *2014 Fourth International Conference on Advanced Computing Communication Technologies*, Feb 2014, pp. 222–229.

[61] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves, "Energy-efficient, collision-free medium access control for wireless sensor networks," *Wireless Networks*, vol. 12, no. 1, pp. 63–78, 2006.

[62] J. Mao, Z. Wu, and X. Wu, "A tdma scheduling scheme for many-to-one communications in wireless sensor networks," *Computer Communications*, vol. 30, no. 4, pp. 863–872, 2007.

[63] T. Karveli, K. Voulgaris, M. Ghavami, and A. H. Aghvami, "Dis-mac: A mac protocol for sensor networks used for roadside and highway monitoring," in *2009 International Conference on Ultra Modern Telecommunications & Workshops*. IEEE, Conference Proceedings, pp. 1–6.

[64] D. De Caneva and P. L. Montessoro, "A synchronous and deterministic mac protocol for wireless communications on linear topologies," *Int'l J. of Communications, Network and System Sciences*, vol. 3, no. 12, p. 925, 2010.

[65] X. Guo, S. Roy, and W. S. Conner, "Spatial reuse in wireless ad-hoc networks," in *Vehicular Technology Conference, 2003. VTC 2003-Fall. 2003 IEEE 58th*, vol. 3. IEEE, Conference Proceedings, pp. 1437–1442.

[66] P. Djukic and S. Valaee, "Link scheduling for minimum delay in spatial re-use tdma," in *INFOCOM 2007. 26th IEEE International Conference on Computer Communications. IEEE*. IEEE, Conference Proceedings, pp. 28–36.

[67] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks," *Communications magazine, IEEE*, vol. 40, no. 8, pp. 102–114, 2002.

[68] T. S. Rappaport, *Wireless communications: principles and practice*. Prentice Hall PTR New Jersey, 1996, vol. 2.

[69] A. Aragon-Zavala, *Antennas and propagation for wireless communication systems*. John Wiley & Sons, 2008.

[70] N. Blaunstein and C. Christodoulou, *Radio propagation and adaptive antennas for wireless communication links: terrestrial, atmospheric and ionospheric*. John Wiley & Sons, 2007, vol. 193.

[71] K. Britain. (2013, apr) Printed circuit board (pcb) antennas. [Online]. Available: http://www.wa5vjb.com/index.html

[72] Digidocs, "Xbee-pro® rf modules," Digi International, Tech. Rep., 2009.

[73] J. A. Azevedo and F. E. Santos, "An empirical propagation model for forest environments at tree trunk level," *Antennas and Propagation, IEEE Transactions on*, vol. 59, no. 6, pp. 2357–2367, 2011.

[74] J. T. Hviid, J. B. Andersen, J. Toftgard, and J. Bojer, "Terrain-based propagation model for rural area-an integral equation approach," *Antennas and Propagation, IEEE Transactions on*, vol. 43, no. 1, pp. 41–46, 1995.

[75] S. Verdú, "Spectral efficiency in the wideband regime," *Information Theory, IEEE Transactions on*, vol. 48, no. 6, pp. 1319–1343, 2002.

[76] F. Meshkati, H. V. Poor, S. C. Schwartz, and N. B. Mandayam, "An energy-efficient approach to power control and receiver design in wireless data networks," *Communications, IEEE Transactions on*, vol. 53, no. 11, pp. 1885–1894, 2005.

[77] M. Imran, J. Alonso-Rubio, G. Auer, M. Boldi, M. Braglia, P. Fazekas, D. Ferling, A. Fehske, P. Frenger, and R. Gupta, "Most suitable efficiency metrics and utility functions," *EARTH Project Report*, pp. 1–89, 2011.

[78] R. Esnault, "Optimising power efficiency in mobile radio networks (opera-net) project presentation," 2008.

[79] T. Edler and S. Lundberg, "Energy efficiency enhancements in radio access networks," *Ericsson review*, vol. 81, no. 1, pp. 42–51, 2004.

[80] K. Samdanis, P. Rost, A. Maeder, M. Meo, and C. Verikoukis, *Green Communications: Principles, Concepts and Practice*. John Wiley & Sons, 2015.

[81] V. N. Compliance, "Energy efficiency requirements for telecommunications equipment," *VZ. TPR*, vol. 9205, 2011.

[82] Y. Zhang, P. Chowdhury, M. Tornatore, and B. Mukherjee, "Energy efficiency in telecom optical networks," *IEEE Communications Surveys & Tutorials*, vol. 12, no. 4, pp. 441–458, 2010.

[83] C. Belady, A. Rawson, J. Pfleuger, and T. Cader, "Green grid data center power efficiency metrics: Pue and dcie," Technical report, Green Grid, Report, 2008.

[84] H. Gong, M. Liu, G. Chen, and X. Zhang, "A study on event-driven tdma protocol for wireless sensor networks," *EURASIP Journal on Wireless Communications and Networking*, vol. 2010, p. 9, 2010.

[85] S. Rahman, M. Ahmad, and S. A. Bazaz, "A new energy-efficient tdma-based mac protocol for periodic sensing applications in wireless sensor networks," *International Journal of Computer Science Issues*, vol. 9, no. 1, pp. 214–221, 2012.

[86] C. Fang, H. Liu, and L. Qian, "Lc-mac: An efficient mac protocol for the long-chain wireless sensor networks," in *Communications and Mobile Computing (CMC), 2011 Third International Conference on*. IEEE, Conference Proceedings, pp. 495–500.

[87] R. SOKULLU and E. DEMİR, "Mac layer protocols for linear wireless sensor networks: A survey," *Commun. Special Issue on Ad-hoc Netw*, vol. 38, no. 4, pp. 393–422, 2014.

[88] H. O. Sanli and R. Simha, "A joint design approach for communication schedule and layout of wireless sensor networks," *Proceedings of ICWN'05*, 2005.

[89] M. Noori and M. Ardakani, "Characterizing the traffic distribution in linear wireless sensor networks," *IEEE Communications Letters*, vol. 12, no. 8, pp. 554–556, 2008.

[90] W. Nan, M. Qingfeng, Z. Bin, L. Tong, and M. Qinghai, "Research on linear wireless sensor networks used for online monitoring of rolling bearing in freight train," in *Journal of Physics: Conference Series*, vol. 305, no. 1. IOP Publishing, 2011, p. 012024.

[91] G. Shafiullah, S. A. Azad, and A. S. Ali, "Energy-efficient wireless mac protocols for railway monitoring applications," *IEEE transactions on intelligent transportation systems*, vol. 14, no. 2, pp. 649–659, 2013.

[92] J.-C. Kuo, W. Liao, and T.-C. Hou, "Impact of node density on throughput and delay scaling in multi-hop wireless networks," *IEEE Transactions on Wireless Communications*, vol. 8, no. 10, pp. 5103–5111, 2009.

[93] O. Somarriba and T. Giles, "Transmission control for spatial tdma in wireless radio networks," in *Mobile and Wireless Communications Network, 2002. 4th International Workshop on*. IEEE, 2002, pp. 394–398.

[94] B. Black, *Introduction to Wireless Systems*. Prentice Hall Press, 2008.

[95] J. Grönkvist, "Interference-based scheduling in spatial reuse tdma," Ph.D. dissertation, KTH, 2005.

[96] P. Djukic and S. Valaee, "Delay aware link scheduling for multi-hop tdma wireless networks," *IEEE/ACM Transactions on Networking (TON)*, vol. 17, no. 3, pp. 870–883, 2009.

[97] H. Narra. (2011, jul) Simple-wireless-tdma. [Online]. Available: https://codereview.appspot.com/4747046/

[98] "what is ns-3." [Online]. Available: https://www.nsnam.org/overview/what-is-ns-3/

[99] C. Thomas, "Ns-3 simulation of wimax networks," Master's thesis, School of Engineering & Applied Science, 2011.

[100] S. Razak, V. Kolar, N. B. Abu-Ghazaleh, and K. A. Harras, "How do wireless chains behave?: the impact of mac interactions," in *Proceedings of the 12th ACM international conference on Modeling, analysis and simulation of wireless and mobile systems*. ACM, Conference Proceedings, pp. 212–220.

Appendix A

Realistic Measurements of Ground level propagation model

A.1 Components

A.1.1 XBee Module

1. Two xbee module S2
2. Arduino Shields to connect XBee module with Arduino Board
3. Two Arduino Board
4. Directional PCB Yagi antenna
5. Usb cable
6. Laptop
7. 1 meter height adjustable wood stand

A.1.2 X-CTU software of microcontroller

XCTU is a free, multi-platform application compatible with Windows, MacOS and Linux. It provide a Graphical Network View for simple wireless network configuration and architecture. http://www.digi.com/products/xbee-rf-solutions/xctu-software

A.1.3 Commands

Firstly, we need to configure one of XBee module as coordinator and the other module as end node. The coordinator will be continuously connected to the laptop, and send a packet to the end node that is located a way from the coordinator and powered by battery. The coordinator will be able to measure the received signal strength of the reflected signal from the end node.

Figure. A.1 Connected module to the laptop in the field

1. Conntect XBee module.
2. Open X-CTU sofware from the top tab select Modem configuration.
3. The device will be recognised, and then from Function Set select the operation mode whether (Coordinator) or (end node)
4. Place the (End node) on on a certain distance.
5. Keep the coordinator connected to the laptop.
6. From the top tab of X-CTU go to Terminal.

7. Type these command
   (a) +++ to test the connection, it should return OK
   (b) ATID will return XBee ID
   (c) ATND needed to discover other XBee module operated on the same band
   (d) ATIC it should return 11
   (e) ATIC 12 set the node into loopback mode
8. Now go to top tab of X-CTU and select Range Test
   (a) Create Data 32 Bytes
   (b) Check box RSSI
   (c) Press Advanced , then define the Data received Time-out "2000"
   (d) Start

You can use the Terminal to measure the RSSI value via command mode, and skip Range Test step. Only type ATDB after ATND, ATDB will return RSSI value in hexadecimal.

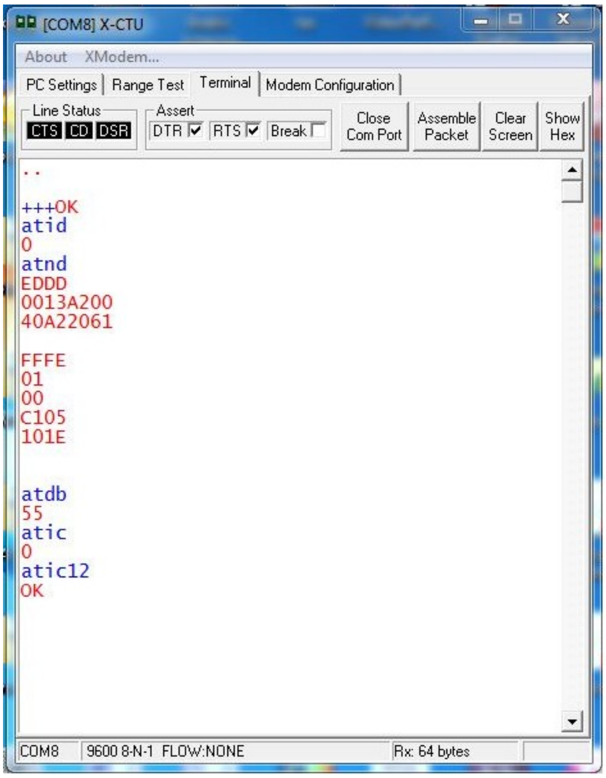


Figure. A.2 X-CTU Command to configure the XBee module for range test

A.2 Measurements Results

Table A.1 Measured Antenna Heights

h_t (m)	0.125	0.075	0.05	0.025	0.01	0.003
h_r (m)	0.125	0.075	0.05	0.025	0.01	0.003

Table A.2 Considered Parameters

Parameter	Value
$Gain_t$	6.5 dBi
$Gain_r$	6.5 dBi
P_t	2 mW
λ	0.125 m

Table A.3 Measured RSSI value in real field, as function of antenna height

distance	12.5	10	7.5	5	2.5	1	0
1	-40	-42.4	-45.4	-60	-65.8	-66.4	-67.2
2	-45	-52	-55	-65.8	-70.2	-70.8	-71.3
3	-49	-55.5	-60.6	-68	-73.8	-78	-82.4
4	-54.6	-60.6	-64.6	-73	-74.2	-81	-85.4
5	-58	-61.8	-66.8	-75.2	-76	-83	-85.8
6	-60	-62.8	-68.6	-76.7	-77.5	-84.2	-86.6
7	-61	-64.8	-69.9	-77	-79	-85.6	-87.1
8	-62	-63.8	-70.2	-78	-80	-88	-89.2
9	-63.3	-66.1	-69.8	-79	-83.2	-90.8	-91.4
10	-65.8	-67	-70.4	-80.3	-84	-92	-94.0

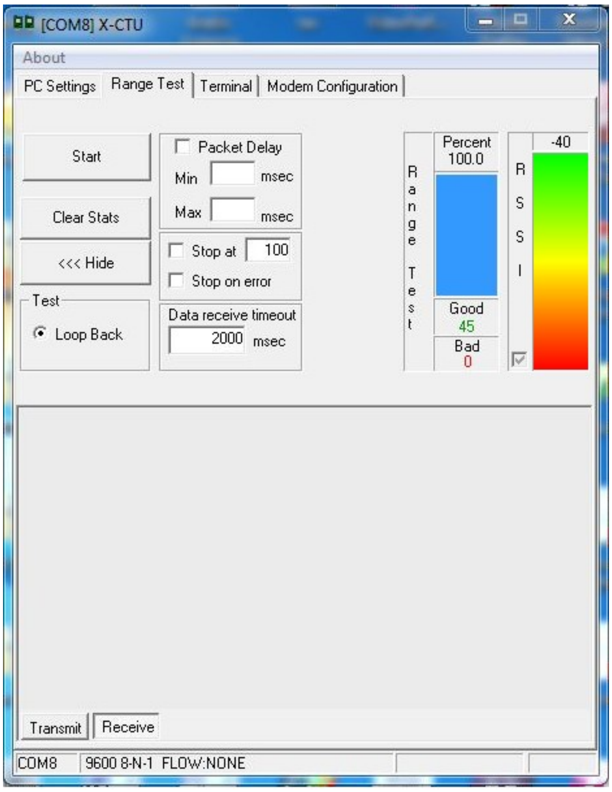


Figure. A.3 Range test Interface of X-CTU software

Appendix B

NS-3 Simulation configuration

B.1 Install TDMA module

1. Install the preferred Linux version

2. Download the TDMA file from

3. Select the module location in src folder on NS-3

4. Make some modification on TDMA module based on the TDMA configuration that provided in the below section.

5. Create a new simple-wireless-tdma-module.h file in build/ns3 folder, and it should contains these information:

```
✶✶ ✐♠♣❧¶✱✇✐ ¶❧¶ ✱ ”♠‘✱♠♦”✉❧¶✳♥
✶✶ ▼♦”✉❧¶ ♥¶‘”¶ ✿
★✐♥“❧✉”¶ ✧ ✐♠♣❧¶✱✇✐ ¶❧¶ ✱“♥‘♥♥¶❧✳♥✧
★✐♥“❧✉”¶ ✧ ”♠‘✱“¶♥ ‘❧✱♠““✳♥✧
★✐♥“❧✉”¶ ✧ ”♠‘✱“♦♥ ♦❧❧¶ ✱♥¶❧♣¶ ✳♥✧
★✐♥“❧✉”¶ ✧ ”♠‘✱“♦♥ ♦❧❧¶ ✳♥✧
```

```
★✐♥“♉☐”❡ ✧ ”♠‘✳♥❡♉♣❡ ✳♥✧
★✐♥“♉☐”❡ ✧ ”♠‘✳♠‘“✳♉♦✇✳♥✧
★✐♥“♉☐”❡ ✧ ”♠‘✳♠‘“✳♥❡ ✳”❡✈✐“❡✳♥✧
★✐♥“♉☐”❡ ✧ ”♠‘✳♠‘“✳ ☐❡☐❡✳♥✧
★✐♥“♉☐”❡ ✧ ”♠‘✳♠‘“✳♥✧
★✐♥“♉☐”❡ ✧ ”♠‘✳ ♉♦ ✳‘ ✐❢♥♠❡♥ ✳♣‘ ❡ ✳♥✧
★❡♥”✐❢
```

6. Reconfigure NS-3 again by

```
✳✴✇‘❢ “♦♥❢✐❢☐ ❡
```

7. Build NS-3 again

```
✳✴✇‘❢ ’☐✐♉”
```

B.2 Configure TDMA Module

The required modifications beore install TDMA module are done on wscript. Replace the wscript file in that simple-wireless-tdma folder with a file having following information

```
★ ✳✯✳ ▼♦”❡✿ ♣②♥♦♥❀ ♣② ✳✐♥❡❢❢❡✿ ✷❀ ✐♥”❡♥ ✳“ ✳♠♦”❡✿ ♥✐♉❀ “♦”✐♥❢✿ ☐❢✳✳❀ ✳✯✳

★ ”❡❢ ♦♣ ✐♦♥ ✯♦♣ ✯✿
★       ♣‘

★ ”❡❢ “♦♥❢✐❢☐ ❡✯“♦♥❢✯✿
★       “♦♥❢✳“♥❡“❡{♥♦♥❢‘ ‘♉✯♥❡‘”❡ {♥‘♠❡❂✯ ”✐♥ ✳♥✯✱ ”❡❢✐♥❡{♥‘♠❡❂✯❍❈⟩✳{▌❈■◆▌{❍✯✯

”❡❢ ’☐✐♉”✯’♉”✯✿
    ♠♦”☐♉❡ ❂ ’♉”✳“❡‘❡{♥ ✱{♠♦”☐♉❡✯✯ ✐♠♣♉❡✳✇✐ ❡♉❡ ✳ ”♠‘✯✱ ⟨✯♥❡✇♦ ❡✯✱ ✯♣ ♦♣‘❢‘ ✐♦♥
    ♠♦”☐♉❡✳ ♦☐ “❡ ❂ ⟨
        ✯♠♦”❡✳ ✐♠♣♉❡✳✇✐ ❡♉❡ ✳“♥‘♥❡♉✳““✯✱
        ✯♠♦”❡✳ ”♠‘✳♠‘“✳““✯✱
```

B.3 Modify The TDMA Module

TDMA module It is a module designed to allocate time slot for each node to transmit its packet. TDMA module contains three main parts:

- Controller
- Central-MAC
- MAC-Queue

The operational concept of TDMA is allocate time slot for each not to use it to transmit it packet. In chain topology where the multi hop communication is needed and the packets are forwarded over several hops to reach the sink, the nodes will need more than time slots. These slots will be used by nodes to send its packets and forward the received packets. Thus it was important to modify the TDMA module to allocate more than slots for each node to complete the delivery process. In the same time provide a mechanism to assign one time slot foe several nodes to support the simultaneous transmission. This mechanism is needed to reduce the frame size and then reduce the delay.

B.3.1 How to convert TDMA module to Spatial TDMA module

The most essential part in this MAC protocol that need a modification to provide this feature is tdma-helper. Tdma-help contains all the function which are responsible to manage the slot allocation and organise the transmission order. Thus, we have coded a new function to perform the proposed algorithm of time slot allocation scheme. As well as, we coded another function that play role of rank function. Rank function responsible to identify the transmission order for the concurrent transmission without interference. The interference range defined by *H* value which is considered as input for the rank function.

Algorithm of Slot Assignment

Time slot allocation algorithm operation rely on the proposed interference model. The interference model responsible to calculate the SINR that required for successful simultaneous transmission. To estimate the SINR transmission distance, antenna height and path loss exponent are required as inputs.

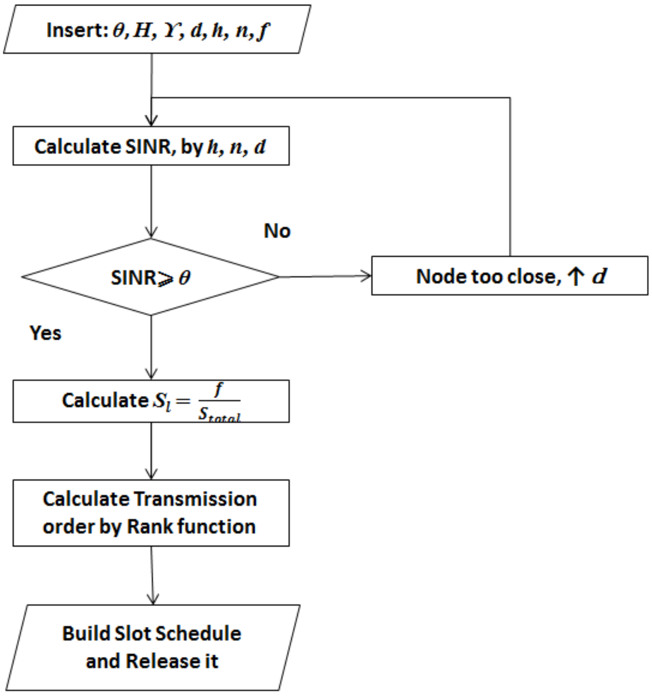


Figure. B.1 Time slot allocation algorithm

Rank Function

The operation of Rank function rely mainly on *H* value, where *H* represent the minimum hops required between any concurrent transmission. the value of *H* derived from the proposed interference model which is built based on on the proposed Radio Propagation on Ground level. The minimum hops guarantee the concurrent transmission without interference. Thus, minimum hops value considered to represent *H* value in Rank function.

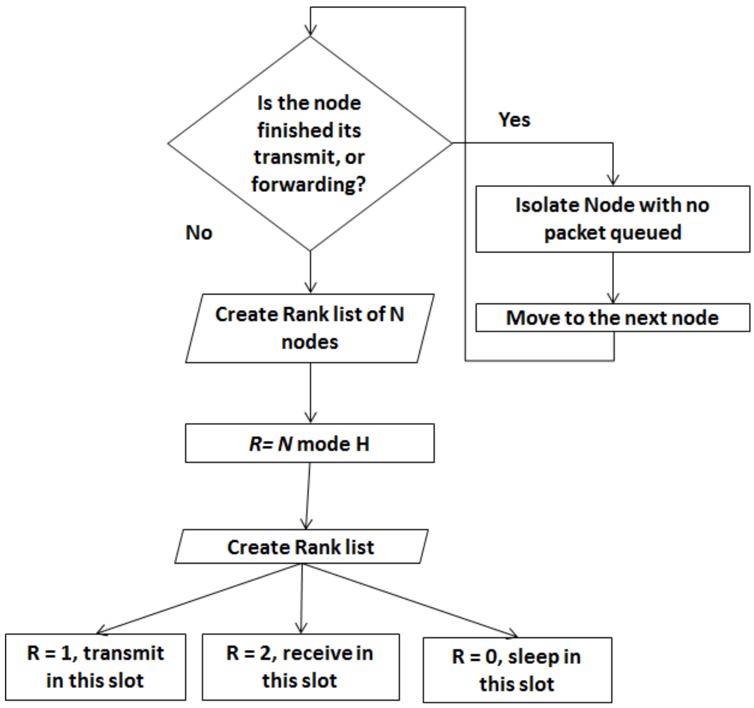


Figure. B.2 Rank-function