ENERGY EFFICIENT ROUTING WITH DIRECTIONAL ANTENNAS IN

WIRELESS SENSOR NETWORKS

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Approval of the Board of Graduate Programs

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ABSTRACT

ENERGY EFFICIENT ROUTING WITH DIRECTIONAL ANTENNAS IN WIRELESS SENSOR NETWORKS

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Without measurements, sustainable development effort can not progress in the right direction. Wireless sensor networks are vital for monitoring in real time and making accurate measurements for such an endeavor. However small energy storage in the sensors can become a bottleneck if the wireless sensor network is not optimized at the hardware and software level. Directional antennas are such optimization technologies at the hardware level. They have advantages over the omnidirectional antennas, such as high gain, less interference, longer transmission range, and less power consumption. In wireless sensor networks, most of the energy is consumed for communication. Considering the limited energy in small scale batteries of the sensors, energy efficient (aware) routing, is one of the most important software optimization techniques. The main goal of the technique is to improve the lifetime of the wireless sensor networks. In the light of these observations, it is desirable to do a coupled design of directional antennas with network software, for fully exploiting the advantages offered by directional antenna technology. In this thesis, the possibilities of doing such integrated design are surveyed and improvements are suggested. The design of the proposed microstrip patch antenna array is discussed and the performance characteristics are assessed through simulations. In the benchmarks, the proposed routing method showed improvements in energy usage compared to the existing approaches.

Keywords: Wireless Sensor Networks, Routing, Directional Antennas, Sustainable Development

ÖZ

KABLOSUZ SENSÖR AĞLARINDA YÖNLÜ ANTENLERLE ENERJİ VERİMLİ YÖNLENDİRME

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Ölçümler olmadan sürdürülebilir kalkınma çabaları doğru yönde ilerleyemez. Bu tür çabalar için, kablosuz sensör ağları, gerçek zamanlı olarak izleme ve kesin ölçümler yapmak için vazgeçilemez unsurdur. Ancak, sensör ağı, donanım ve yazılım düzeylerinde optimize edilmemişse, sensörlerde enerji yetersizliği görülebilinir. Yönlü antenler, donanım düzeyinde uygulanan optimizasyon teknolojilerinden biri olmakla birlikte, çok yönlü antenlerden farklı olarak, yüksek kazanç, daha az parazit, daha uzun iletim mesafesi ve daha az güç tüketimi sağlarlar. Kablosuz sensör ağlarında enerjinin çoğu iletişim için tüketilir. Sensörlerdeki limitli enerjili küçük ölçekli piller göz önüne alındığında, yazılım düzeyindeki önemli metodlardan biri olan enerji verimli (duyarlı) yönlendirme protokolü, kablosuz sensör ağının genel enerji kullanımını optimize etmek ve ömrünü uzatmak için gereklidir. Bu gözlemlerin ışığında, yönlü anten teknolojisinin sunduğu potansiyel avantajlardan tam olarak yararlanmak için, yönlü antenlerin ağ yazılımıyla birlikte entegre tasarımını yapmak arzu edilir. Bu tezde, böyle bir entegre tasarımın yapılma olasılıkları araştırılmış ve iyileştirmeler önerilmiştir. Tezde, küçük şeritli yamalı anten dizisinin tasarımı tartışılmış ve performans karakteristikleri simulasyonlarla ölçülmüştür. Önerilen yönlendirme algoritması, diğer yönlendirme algoritmaları ile karşılaştırıldığında, enerji kullanımında iyileştirmeler göstermiştir.

Anahtar Kelimeler: Kablosuz Sensör Ağları, Yönlendirme, Yönlü Antenler, Sürdürülebilir Kalkınma

To God Almighty for giving me mind to understand His creations

ACKNOWLEDGMENTS

Firstly I would like to thank to God for His generous graces, which I do not deserve but miraculously have received them. Many thanks to Dr. Tayfun Nesimoğlu and Dr. Fadi Al-Turjman for their time and patience. I feel very lucky to have such advisor. Thanks to Dr. Soydan Redif for his support from the European University of Lefke. Many thanks to Dr. Murat Fahrioğlu for his great support during my studies. Without his directions I would not be here. I should not forget Dr. Ali Cevat Taşıran and Dr. Enver Ever for their mentoring. Many thanks to my family and my wife Yücel for their support and for their patience. Thanks to Huriye for her assistance in Microwave lab. I also thank to METU for giving me opportunity for producing antenna prototypes in the Radio Frequency and Telecommunications Laboratory (RFTL). I should mentioned my cats for entertaining me. Last but not the least, thanks for the real ”GOONs”, Spike Milligan, Harry Secombe, and Peter Sellers, for making me laugh and inspiring me the cool name of the routing protocol I proposed, ”LaGOON”.

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LIST OF ABBREVIATIONS

A	Ampere
ACK	Acknowledgment
ANOVA	Analysis of Variance
AODV	Ad hoc On Demand Distance Vector
AODVM	Ad hoc On Demand Distance Vector Multi-path
AOMDV	Ad hoc On Demand Multi-path Distance Vector
Bps	Bytes per second
bps	bit per second
BW	Band Width
CDS	Connected Dominating Set
CH	Cluster Head
CST	Computer Simulation Technology
CPU	Central Processing Unit
DOA	Direction of Arrival
DS	Dominating Set
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing
DVCS	Directional Virtual Carrier Sensing
EEPROM	Electrically Erasable Programmable Read Only Memory
ESD	Electronically Switchable Directional
FCC	Federal Communications Commission
FIFO	First In First Out
FR4	Flame Retardant 4
GHz	Giga Hertz
HOLB	Head Of Line Blocking
HW	Hardware
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol
ISO	International Organization for Standardization
LEACH	Low Energy Adaptive Clustering Hierarchy
LQI	Link Quality Indicator

MAC	Medium Access Control
mAh	milli Ampere hour
MANET	Mobile Ad hoc Network
Mbit	Mega bit
MHz	Mega Hertz
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
NACK	Negative Acknowledgment
NS-3	Network Simulator-3
OS	Operating System
OSI	Open System Interconnected
PID	Proportional Integral Derivative
PRMSA	Planar Rectangular Microstrip Antenna
QoS	Quality of Service
RAM	Random Access Memory
RF	Radio Frequency
RFID	Radio Frequency Identification
RSD	Relative Standard Deviation
RSSI	Received Signal Strength Indicator
SICS	Swedish Institute of Computer Science
SIMO	Single Input Multiple Output
SISO	Single Input Single Output
SMA	Sub Miniature version A
SMR	Split Multi-path Routing
SPIDA	SICS Parasitic Interference Directional Antenna
SW	Software
TCP	Transmission Control Protocol
TTL	Time To Live
USB	Universal Serial Bus
V	Volt
VSWR	Voltage Standing Wave Ratio
W	Watt
WiFi	Wireless Fidelity
WNSN	Wireless Nano Sensor Network
WSN	Wireless Sensor Network

CHAPTER 1

INTRODUCTION

Every system is in need of sensing devices, like human senses, for autonomous, adaptive and efficient operation. The feedback loops are crucial in determining "correct direction" in any system. Our planet is an autonomous system by itself. But we human beings are progressing toward changing this autonomy according to our needs. However, we need to do that without harming the autonomy, and the delicate balance of the planet Earth. Otherwise, the future generations may suffer. Any political, economic, environmental, or social decision can have unforeseen effects for the future. Assessments, measurements, statistical analyses are scientific activities that are crucial in receiving feedback for the better decision making process.

For this thesis the whole situation of the Earth can be regarded analogous to "human body" and "Wireless Sensor Networks" can be regarded as analogous to "human nervous system". Then the process of "Sustainable Development" can be regarded as the "proper and efficient working" of the whole Earth. Efficient working of the "nervous system" then becomes the topic of this thesis. With these analogies, it is not difficult to see the importance of the "efficient nervous system" for the "proper and efficient" working of the whole body. In this context, the main goal for this thesis is to discuss and propose energy usage optimization methods in Wireless Sensor Networks, by presenting associated problems. In doing so sensor nodes are chosen as the main subject of the thesis, as they are deemed vital parts of the "Sustainable Development". In fact, sensor networks can be well associated with the "three pillars of sustainability". Namely economical, environmental, and social pillars. In the thesis numerical data presented to show the relationship between Wireless Sensor Networks and the economic effects of using them. Environmental applications of sensor networks, such as air/water quality monitoring, are vital for maintaining a healthy status of the environment. Applications in the social dimension are various. Even utilization of the sensors in mobile phones, like GPS, can be used in many applications serving the social well being. Child monitoring/tracking, health monitoring are such applications, functioning, in the social dimension. VigilNet [60] is one of those efforts, aiming to provide surveillance through the use of WSNs.

At this point, the reader should be warned about the difference between “power” and “energy”. In some parts of this thesis, the terms “power unit” and “energy unit” are used interchangeably. Since these terms are, mostly, borrowed from diverse publications, it is normal that they differ in words and for keeping the cited arguments coherent, the terms are not changed. Although there are differences, for this thesis, they both, designate “generic battery unit”. Energy is the ability of the system to do work and has the unit as “Joule” ($1\text{J} = 1\text{kgm}^2/\text{s}^2$, named after James Prescott Joule, 1818–1889). Power can be regarded as the rate that energy is transferred and has unit as “Watt” (1W = 1J/s, named after James Watt, 1739–1819). In relation to battery units, it can be said that batteries store energy and provide power [142].

In the rest of this chapter, a general overview of the historical and practical issues related to the sensor networks is given in Section 1.1. This section is followed by some technical details about sensor nodes in Section 1.2. After that, a little discussion is presented on current challenges about the issues related to sensors and sensor networks in Section 1.3. Finally, in Section 1.4, a little survey on the various energy optimization techniques related to WSNs is given.

In this thesis, two methods are studied for the energy usage optimization. While the main goal is to maximize the network lifetime, the two solutions offered for the energy problem can be associated with the optimizations at different levels. At the SW level thesis presented an energy aware routing protocol and discussed enhancements for using the routing method with directional antennas. At the HW level, simple patch-array antenna design is presented and energy savings that come from the directional nature of the antenna, along with the issues that are related to the directionality is explained in the thesis.

For the rest of the thesis the breakdown of the chapters is as follows: In Chapter 2, the energy aware routing protocol topic is discussed. The survey of the studies related to the routing algorithms for WNSNs are presented in Section 2.1 and for WSNs in Section 2.2.

After that, in Chapter 3 design and implementation (Section 3.1), visual examples on omnidirectional and directional versions (Section 3.2 and Section 3.3), and performance evaluation (Section 3.4) are given about the proposed LaGOON protocol. In Section 3.5, which is the final section of the Chapter 3, contributions of the thesis to routing are discussed.

In Chapter 4, an overview on the basics of the antennas is presented in Section 4.1 and the stature of the directional antenna research related to WSNs is discussed in Section 4.2.

In Chapter 5, design and implementation of the proposed directional antenna is presented in Section 5.1. Following that, in Section 5.2, a performance assessment on the proposed directional antenna is given. Section 5.3 is about the discussion on the size reduction technique for the proposed antenna. Finally, in Section 5.4 the contributions of the thesis to the directional antenna research is explained.

In the final chapter of the thesis, in Chapter 6, qualitative assessment and comments are provided for the proposed methods and suggestions on improvements for the future work are listed.

Additionally, appendices are provided for the antenna design sketches and parameters in Appendix A and for the statistical analyses related to the antenna benchmark results in Appendix B.

1.1 General Overview

The origins of the WSNs (Wireless Sensor Networks) goes back to 80's, to the Distributed Sensor Networks (DSN) program of the Defense Advanced Research Projects Agency (DARPA) [73]. The IoT concept can be traced back to the "Ubiquitous Computing" [156] idea of Mark Weiss [140]. IoT is the next revolution after the Internet. With this technology, smart devices/things can communicate with each other. In Figure 1.1 the evolution of the IoT, Smart Things, WSNs and the RFID technologies can be seen. By using sensor devices connected through networks, our awareness about

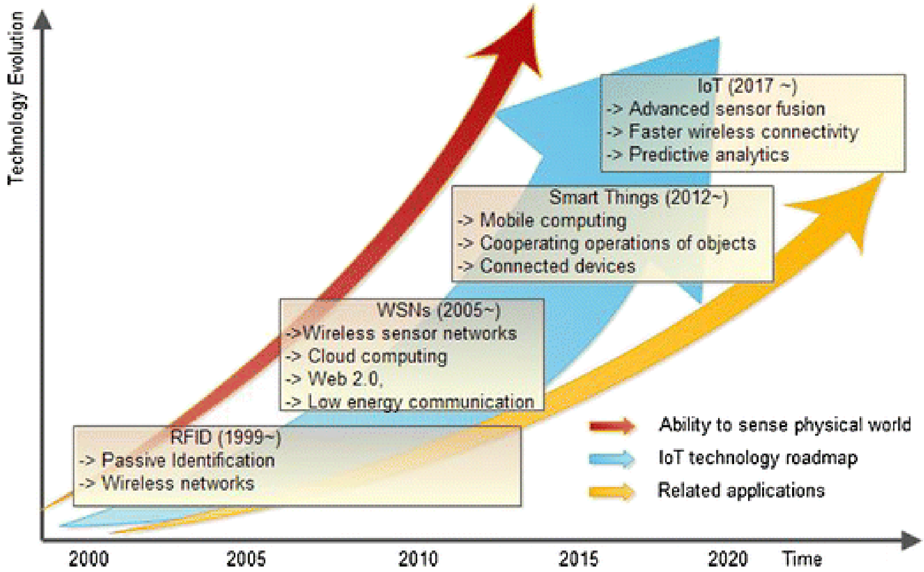


Figure 1.1: Evolution of the IoT and related technologies. (Source: [90])

the environmental conditions increased significantly. Furthermore, sensor networks have opened new horizons to make an assessment of the conditions of the world at different levels, with the help of communication at the micro (even nano) and macro scales. Without measurements, sustainable development effort can not progress in the right direction. Especially precise measurements from sensors are vital for the sustainable development of green systems. Wireless sensor networks are vital for monitoring in real time and making accurate measurements for such endeavor. With the IoT (and especially with sensor networks) not only energy statistics can be collected but also numerical data that provide information about the totality of the condition of the earth can be acquired. Applications such as air pollution control and measuring biodegradation can utilize sensors for making accurate measurements, for smarter and greener world. Great financial savings can be made by utilizing sensor networks. The paper [120] presents a striking example of the financial savings that can be made from the utilization of the WSNs:

> "First-order estimations indicate that such technology could reduce source energy consumption by two-quadrillion BTUs (British Thermal Units) in the US alone. This translates to $55 billion per year, and 35 million metric tons of reduced carbon emissions."

Just to give an idea about the diversity of application areas of WSN, the following short list can be given:

- **Environmental:** Flood Detection, Forest Fire Detection, Air Pollution Monitoring
- **Household:** Water/Energy Metering/Monitoring, Remote Control, Security
- **Health:** Patient Monitoring
- **Industrial:** Monitoring Hazardous Gases, Quality Control
- **Agriculture-Farming:** Green House Control, Animal Tracking

1.2 Sensor Nodes and Networks

Sensor nodes are basically small computers specialized on a certain task, namely sensing. Sometimes they can also “actuate” certain devices through “wired medium” or through “wireless medium”. The CPU part, generally, consists of very lightweight computing circuitry. Sensor node, which is generally called “mote”, consists of processing unit, communication unit, power unit, and sensing unit. Optionally, motes may have a harvesting unit, mobilizer unit (for movement), and a location finding subsystem. These units can be seen in Figure 1.2 below in which important functional and structural elements of a generic mote are depicted. A real life example can be seen in Figure 1.3. Mostly the modular structure enables motes to have various sensors and various communication units.

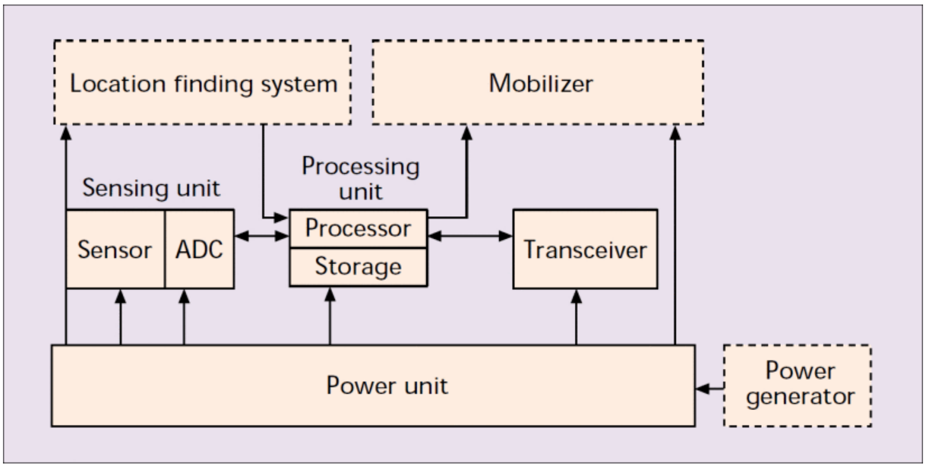


Figure 1.2: Components of a generic Sensor Node. Dotted lines is for optional elements. (Source: [9])

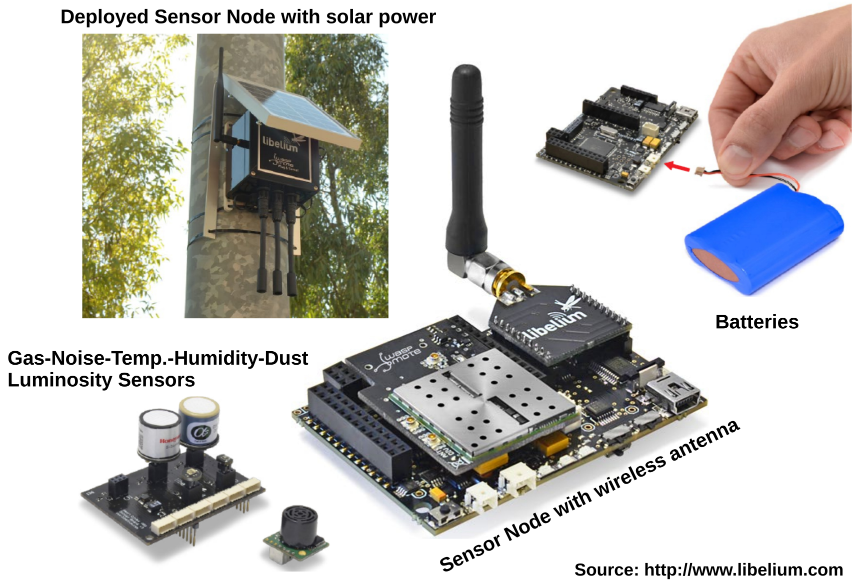


Figure 1.3: Typical Wireless Sensor Node. (Source: https://www.libelium.com/downloads/documentation/waspmote_datasheet.pdf)

In Table 1.1 specifications of several motes that are widely used are given. Motes generally have very lightweight CPUs with several kilobytes of memory. The communication system supports very low bitrates for transmission, which is generally (as of 2018) around 250 kilobits per second. They also have lightweight OSs, like TinyOS (http://www.tinyos.net/) and Contiki (http://www.contiki-os.org/). Communication software stack is also lightweight and sometimes requiring "cross-layer"([128]) optimizations. Cross-layer design is a new paradigm that is introduced for eliminating overheads that come from the standard design of the layered network. Taxonomy of the sensor nodes according to various criteria can be found in [141, pp. 81-84].

Table 1.1: Specifications of some widely used motes. (Source: Appendix A of [166])

Platform	CPU	Clock (MHz)	RAM/Flash/EEPROM	Radio Transceiver	BW (bps)	Freq. (MHz)
Telos	TI MSP430F149	8	2K/60K/512K	TI (Chipcon) CC2420	250k	2400
MicaZ	Atmel Atmega 128L	8	4K/128K	TI (Chipcon) CC2420	250k	2400
Mica2	Atmel Atmega 128L	8	4K/128K/512K	TI (Chipcon) CC1000	38.4k	900
Libelium Wasp mote	Atmel ATMega1281	8	8K/128K/2GB	XBee®module[1]	250/230/230k	2400/900/848

[1] XBee® is an IEEE 802.15.4 RF Module by Digi International: https://www.digi.com/

For the networking of motes, important design choices and parameters come into play. Network subsystem including the radio module determines the way the communication proceeds. Designers should consider factors like the mobility of the nodes, antenna types and specifications, modulation techniques, routing protocols, transmission medium (air, water, human body), transmission frequency (which depends on the antenna, power requirements, range requirements, and transmission medium). The physical network structure of the deployed nodes is called topology or topological structure. The topological structure of a WSN is also another important design element affecting performance and energy efficiency [79, 99]. Generally, there are two basic types of nodes in most of the WSNs. Sensor nodes (motes) that are responsible for actual sensing and "sink" (base station) nodes that are collecting the sensory data from sensor nodes. Sink nodes generally have different architecture. They should basically have better power units. In choosing topological structure designers can choose between hierarchical or non-hierarchical topologies. In the WSNs where nodes have mobility, the topology is not fixed. In this sense, these topologies are regarded as "static" type of topologies. MANETs are instances of mobile networks, in which devices can move.

In the case of static WSNs, following classification can be given for the widely used topologies:

- Hierarchical: Tree like topologies formed with multiple sink nodes.
- Non-Hierarchical: Topologies with, generally, single sink node.
  - Star
  - Mesh
  - Grid
  - Ring

Multiple sink nodes can be arranged in a "hierarchical" structures. In Figure 1.4 such topology example can be seen. In these type of topologies, multiple star, grid, or mesh topologies are connected in a recursive way. Consequently, multiple sink nodes are connected to a sink node at the higher level in the hierarchy.

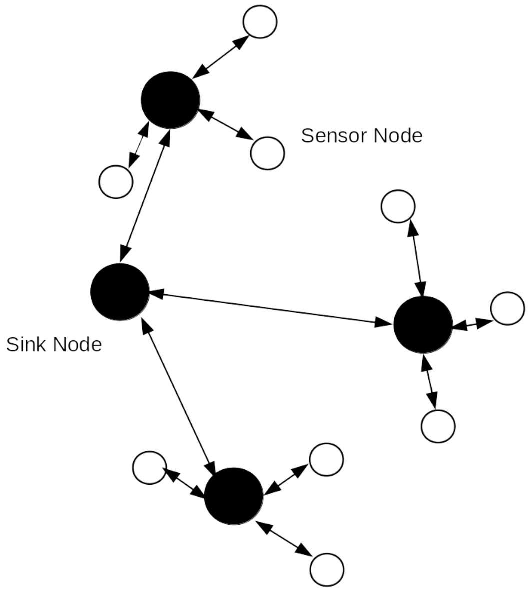
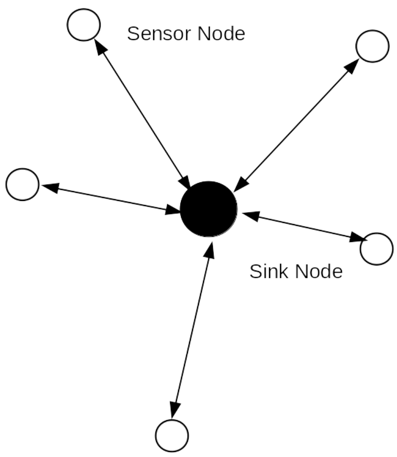
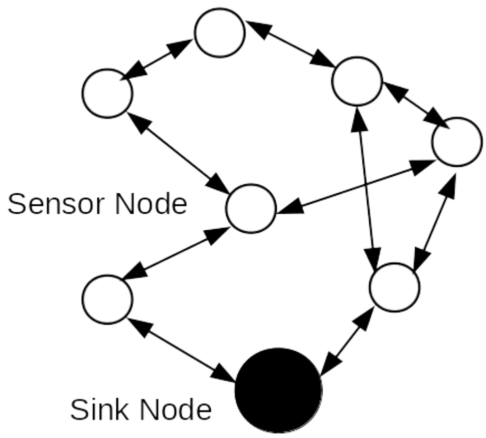


Figure 1.4: Hierarchical Topology used in WSNs.

Star (Figure 1.5a), mesh (Figure 1.5b), grid (Figure 1.6a), and ring (Figure 1.6b) are examples of non-hierarchical topologies, in which there is a single sink node. In Figure 1.4, and figures 1.5a-1.6b arrows are depicting routing information. They are not representing wired connection.

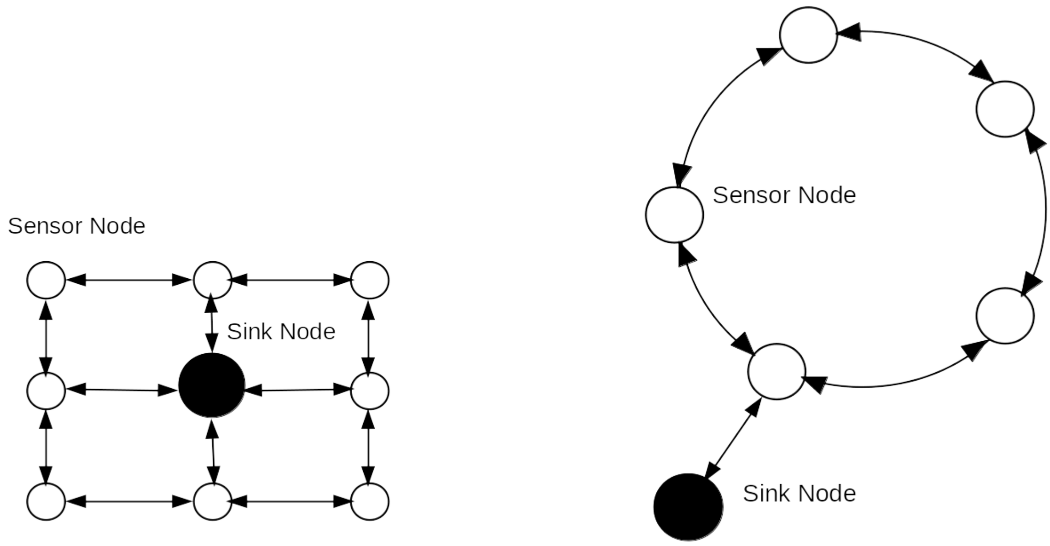


(a) Star Topology.



(b) Mesh Topology.

Figure 1.5: Non-Hierarchical Topologies used in WSNs.



(a) Grid Topology. **(b)** Ring Topology.

Figure 1.6: Non-Hierarchical Topologies used in WSNs.

In today's technology, nanosensors are utilized in various applications like biomedical, industrial, environmental, and military. With the networking technology, nanosensors, in general nanomachines, become more potent, since they can cooperate and communicate for achieving more challenging tasks. Figure 1.7, shows the general network architecture to be assumed in this thesis for the targeted nanonetworks.

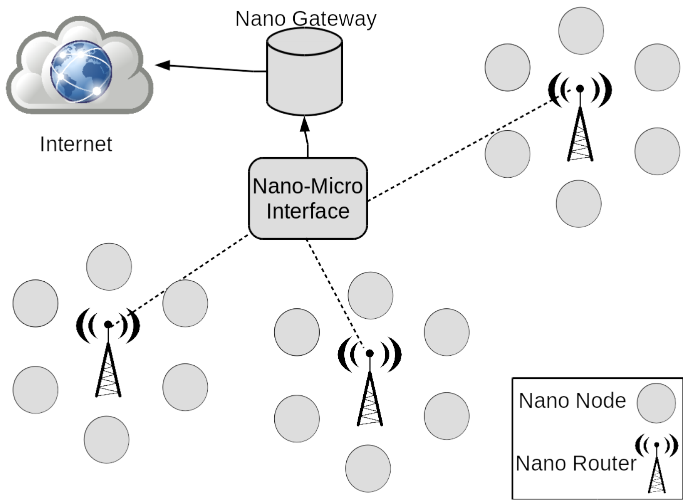


Figure 1.7: Network architecture and components for nanonetworks

WNSNs are not very much different than the WSNs when we consider the architecture of the system. In Figure 1.8, a typical multi-path WSN structure can be seen. Important elements of the nanonetworks are nanonodes, nanorouters, and nanomicro interfaces. Through gateways, these type of networks can be connected to the traditional Internet.

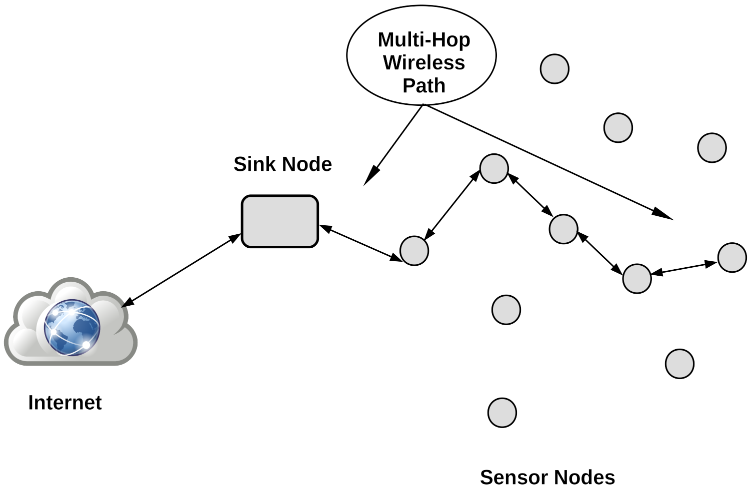


Figure 1.8: Typical Wireless Sensor Network - WSN

The communication in nanonetworks can utilize one of the following technologies; nanomechanical, acoustic, electromagnetic and chemical or molecular communication [11]. A comparison for the existing communication technologies can be summarized as shown in Table 1.2.

Table 1.2: Comparison of communication technologies used in nanonetworks

Comm. Type	Internet	Nano-Molecular	Nano-Wireless
Signal Type	Electro-Magnetic	Chemical	Electro-Magnetic
Signal Speed	High	Low	High
Power Consumption	High	Low	Low

Mainly due to their tiny sizes, nanonetworks introduce difficulties in both hardware and software design. Detailed explanations on the hardware design of the electromagnetic wireless nanosensors can be found in [13]. Especially for the software part, the communication layer stack needs fine tuning as the hardware imposes many restrictions. The physical signaling is at the THz levels, due to antenna size, requiring special modulation techniques [75]. On the other hand, promising research is being done by using graphene based plasmonic materials for antennas to overcome signaling difficulties [75, 77]. Nano scale batteries can not store much energy for the long duration of the nonstopping operations in the nanonodes.

The limitations that are listed in this section impose restrictions on the design of network communication layers. For the nanosensor nodes instead of regular TCP/IP protocol suite customized network stack has to be used, although there is no standard protocol stack for nanocommunication. In [114], authors proposed a prototype protocol (layer) stack that is customized for nanosensor nodes. The proposed layer stack consists of four layers. These layers and their functions can be listed as follows:

- Message Process Unit: Generation and processing of messages.
- Network layer: Routing of the packets.
- Media access control entity: MAC layer without acknowledgments and retransmissions.
- PHY (physical) interface: Modulation of the signals in THz band and bit transmission.

One of the best examples of the difficulties in software is the routing protocols for nanocommunication (overview on routing can be found in [103]). Considering the communication as being the most energy consuming operation for nanonodes, it is not difficult to see the importance of the "energy efficient" methods in communications. The energy cost of a routing protocol is high for a nanodevice and nanobatteries are very limited. In fact, the effectiveness of routing plays important role in energy efficient use of nanonetworks. Different from the traditional network routing protocols, nanorouting protocols have to be "energy-aware" optimization methods. Unlike the regular TCP/IP communication where devices can emit thousands of packets in seconds and the buffer memory is not a problem, in nano communication, only a few packets in a minute can be sent and the memory is limited.

Mostly because of the limitations in the current technology, any design on the nanotechnology has to follow a bottom-up approach. Structure of the system and the system element in nanoscales determine the design of the higher level elements. This is shown in Figure 1.9 ([14]) below. Alternatively, innovative and nature-inspired ideas related to topology and fault tolerance in nanonetwork design can be found in [7], [131], and in [68].

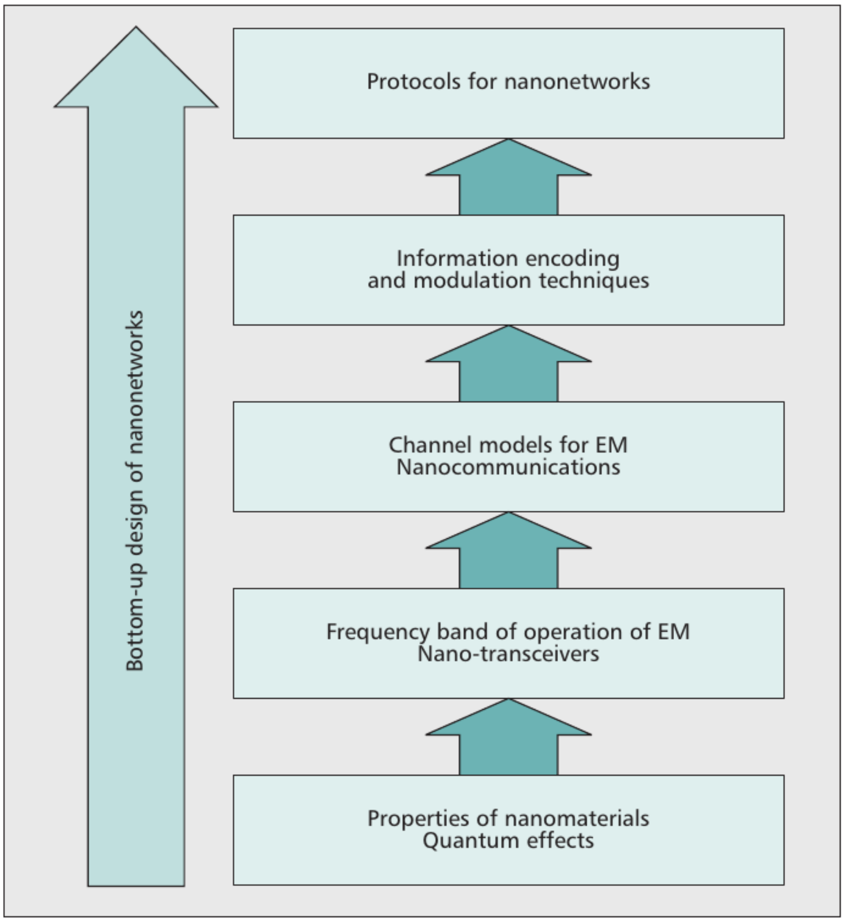


Figure 1.9: Bottom-up Approach to the Design of Nano-networks. (Source: I. F. Akyildiz and J. M. Jornet, The Internet of nano-things [14])

1.3 Current Challenges

As the new application areas are emerging for the use of sensors, the number of sensors is growing rapidly. Considering the industrial uses of sensors, a forecast can be seen from Figure 1.10, about the number of the industrial wireless sensors for the beginning of the 2020s. It is estimated that the number will reach 33 million by 2021.

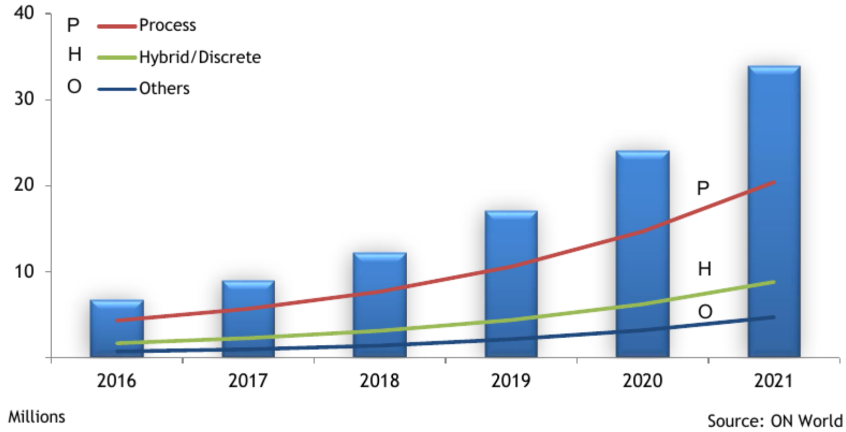


Figure 1.10: Global installed industrial WSN devices by market segment for 2016-2021. (Source: Industrial Wireless Sensor Networks [107])

The number of devices or "things" connected to the Internet is also increasing rapidly. According to [125] the number of "things" (including all networked devices) will reach close to 30 billion by 2020s, as it can be seen in Figure 1.11 below. For practical

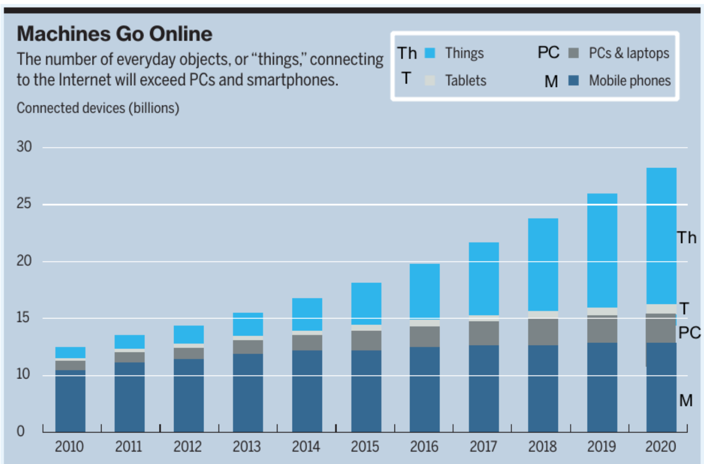


Figure 1.11: Breakdown of the devices connected to the Internet. (Source: [125])

uses of the sensors, the density of the sensor or other embedded networking devices, in a given unit space (m^3), can reach to a very high number. The cabling for such configurations may not be possible to realize. For this reason, such devices are mostly battery powered wireless devices that are designed to have maximized lifetime. In this sense, wireless communication is one of the peculiarities of the sensors.

Another peculiarity is the use of small batteries. Sensors, being very small devices present ease of use. But their small scale footprint implies small scale energy unit. For this reason, small energy storage in the sensors can be a bottleneck if the sensor networks and sensor nodes are not optimized at the hardware level and at the software level. Generally, battery replacement is difficult due to the number of sensors nodes, and the cost of the labor for replacing batteries can be a major issue [34]. Maximizing lifetime of the sensor nodes is essential in order to reduce the maintenance of this devices [134, p. 13]. Even some times due to the difficulties in reaching the sensor node, battery replacement is not an option. For example, in leakage detection sensor systems, sensors can be placed several meters under the ground, making it difficult to do any wireless recharging or perform battery replacement. Energy harvesting is another technology that can be utilized for overcoming limited energy on the sensor nodes. A comprehensive review on the harvesting technologies for the sustainable use of the WSNs can be found in [6, 109, 132, 149]. On the other hand, according to [152] not only the battery capacity is growing slowly, but also harvesting technologies are limited because of the available low energy density. In [45], a similar argument on the power demand of the consumers and slow pace of the development of the battery technology to keep up with this demand is presented. Table 1.3 presents a comparison of some harvesting sources.

Table 1.3: Comparison of energy harvesting sources. (Source: [6])

Energy Source	Conditions	Performance	Surface or volume providing energy of an AA
Solar	Outdoors	7500µW$/cm^2$	23x23$/cm^2$
Solar	Indoors	100µW$/cm^2$	198x198$/cm^2$
Vibration	$1m/s^2$	100µW$/cm^3$	34x34x34$/cm^3$
RF	WiFi	0.001µW$/cm^2$	625x625$/m^2$
RF	GSM	0.1µW$/cm^2$	62x62$/m^2$

According to [47, 83], AA type alkaline batteries (E91 - 1.5V) can provide $2850\mathrm{mA}$ from $8.3\mathrm{cm}^3$ volume, which is $3.90\mathrm{Wh}$ maximum energy at nominal voltage and for $50\mathrm{mA}$ drain [160]. Taking this as a reference, the last column of Table 1.3 is elaborated by estimating surface or volume required to provide the same amount of power that an AA type alkaline battery can provide.

As of the year 2018, the AA type batteries are widely used in sensor nodes. This type of batteries are low cost, and widely available. They are suitable for low current drawing applications at room temperature. But there are two disadvantages in using this type of batteries. The first is that, they do not perform well in the cold. So in cold and under high current draw, their capacity decreases sharply as it can be seen from the curves in Figure 1.12.

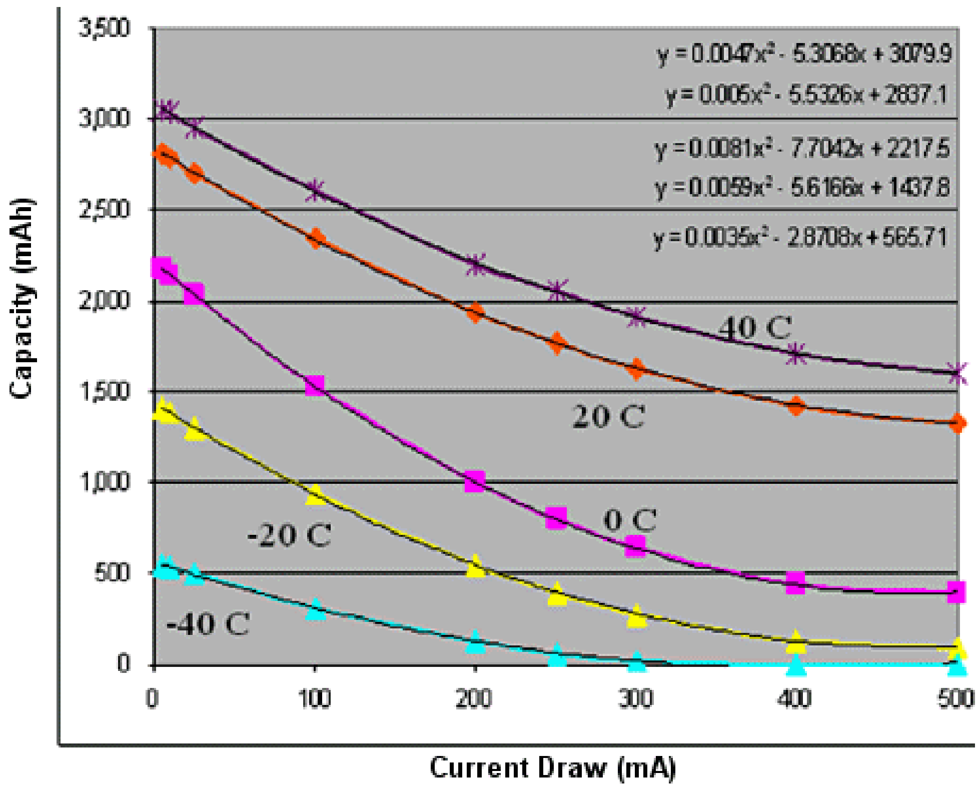


Figure 1.12: Temperature current model of an alkaline AA (E91 - 1.5V) battery. (Source: [169])

The second drawback is that, under high current draw they do not perform well. Figure 1.13 depicts the comparison of the performances of various types of batteries in two modes. Namely, they are labeled as “Rated” and “Actual”. “Rated” mode is related to the specific energy while the battery is discharging at a very low current. “Actual” mode specifies discharges at 1 Coulomb, which is the general way that batteries are rated. In the case of “Actual” mode, the performance of alkaline batteries drops as it is shown.

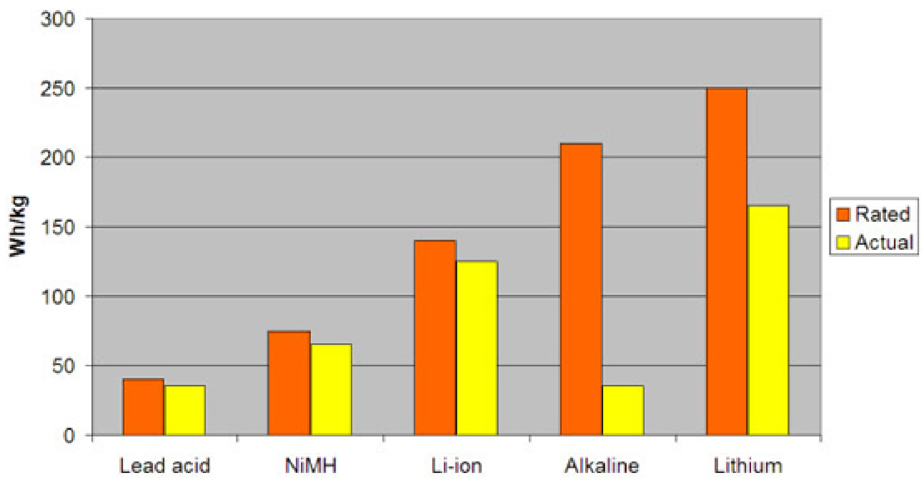


Figure 1.13: Battery comparison. Because of the high internal resistance, alkaline battery performance degrades under high current draw. (Source: https://batteryuniversity.com/learn/article/primary_batteries)

Considering the use of Mica2 sensor node for measuring temperature every minute with 128 bytes data packets (Zigbee protocol[2] allows max packet size of 133 bytes), at 38.4Kbps (1 kilobit = 1024 bits) rough estimate for each transmission can be given with the equation 1.1 below:

$$(128 \times 8)/(38.4 \times 1024) \ = \ 0.02604\text{s} \ = \ 26.04\text{ms} \tag{1.1}$$

For a rough estimate, the inclusion of the control signals like positive and negative acknowledgments (ACK and NACK) as extra packets and wake up time of 0.18ms [118], will make transmission time about 50ms (overestimation). The rest of the time it is assumed that the sensor node is in “sleeping state”. In this sense, “awake time” and

[2] Zigbee is an IEEE 802.15.4 based specification for high-level communication protocols developed by Zigbee Alliance http://www.zigbee.org/

“sleep time” is given in equations 1.2 and in 1.3 below:

$$\text{Awake Time per day} = 24 \times 60 \times 0.05\mathrm{s} = 72\mathrm{s} = 0.02\mathrm{h} \tag{1.2}$$

$$\text{Sleep Time per day} = 24 \times 60 \times 6072\mathrm{s} = 86\,328\mathrm{s} = 23.98\mathrm{h} \tag{1.3}$$

According to Mica2 datasheet[3] sleep current is about $15\mu\mathrm{A}$ and the wake-up, transmission, and CPU currents, for an overestimation, can be summed up as $50\mathrm{mA}$. According to [23], Mica2 node consumes maximum $27\mathrm{mA}$ on transmission and $10\mathrm{mA}$ in average for receiving. With some additional sensor board, the overestimation offered can be regarded rather realistic. Then energy requirement for $24\mathrm{h}$ in $\mathrm{mA\,h}$ can be given in equation 1.4 and the average daily current draw is given in equation 1.5:

$$\text{Energy for } 24\mathrm{h} = (15\mu\mathrm{A}) \times (23.98\mathrm{h}) + (50\mathrm{mA}) \times (0.02\mathrm{h}) = 1.36\mathrm{mA\,h} \tag{1.4}$$

$$\text{Average Current} = 1.36\mathrm{mA\,h}/24\mathrm{h} = 56.67\mu\mathrm{A} = 0.056\,67\mathrm{mA} \tag{1.5}$$

Taking the rough estimates in the previous paragraphs as a reference, in Table 1.4, the capacity of an AA size alkaline battery is listed under current draw of $0.056\,67\mathrm{mA}$ for sensing temperature every minute with the Mica2 sensor node in various temperature conditions.

Table 1.4: Calculating capacity under $0.056\,67\mathrm{mA}$ current draw of an Alkaline Model (E91 - AA) at different temperatures. i represents current draw in mA. (Source: [169])

Temperature (°C)	Capacity (mAh)	Output measured in $\mathrm{mA\,h}$	Number of days Mica2 can be sustained
40°C	3080	$0.0047\, i^2 - 5.3068\, i + 3079.9$	2265
20°C	2837	$0.005\, i^2 - 5.5326\, i + 2837.1$	2086
0°C	2218	$0.0081\, i^2 - 7.7042\, i + 2217.5$	1631
−20°C	1438	$0.0059\, i^2 - 5.6166\, i + 1437.8$	1057
−40°C	566	$0.0035\, i^2 - 2.8708\, i + 565.71$	416

By using the data in Table 1.4 number of days that the Mica2 sensor node can be sustained at $20°\mathrm{C}$ is calculated as in the equation 1.6 below:

$$2837\mathrm{mA\,h}/\ 1.36\mathrm{mA\,h} = 2086\text{day} = 5.7\text{year} \tag{1.6}$$

[3] http://www.investigacion.frc.utn.edu.ar/sensores/Equipamiento/Wireless/MICA2_Datasheet.pdf

The same calculations can be repeated for sensing temperature every second (almost real-time). The daily energy requirement can be found as $60.34\mathrm{mA\,h}$ and the average current draw for each day can be found as $2.51\mathrm{mA}$. With these values, equation 1.7 can be used to find the number of days that the Mica2 sensor node can be sustained at $20°\mathrm{C}$ as:

$$2823\mathrm{mA\,h}/\,60.342\mathrm{mA\,h} \;=\; 47\mathrm{day} \tag{1.7}$$

The estimates and the tables that are presented above are rough estimates and they are subjected to change over time with new and better technologies. On the other hand, they are presented to depict the situation of the energy management issues related to the WSNs numerically. Although harvesting technologies are vital for sensor nodes, currently they can not provide enough sustainability. However, in the long run, they should be improved to provide sustainable operation for WSNs. This does not mean to eliminate research in the energy optimization. Currently, because of these power related issues, there is a growing research effort in the optimization of the energy consumption related methods. Studies are focusing on the hardware and software optimization techniques. In [19], a comprehensive and systematic taxonomy of the energy conservation schemes for the WSNs is presented. Limitations in the power supply units are not the only reasons that fuels the research in energy optimization techniques. Analysis had shown that most of the energy is consumed by the communication module of the motes. Example breakdown of the power consumption can be seen in Figure 1.14.

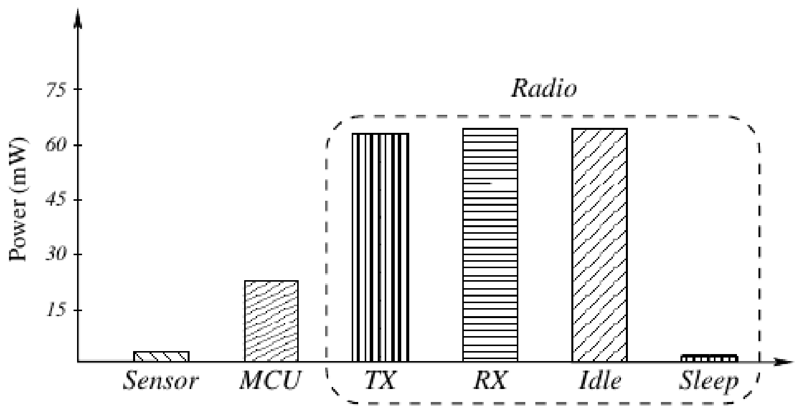


Figure 1.14: A breakdown of the power consumption of a MicaZ sensor node. (Source: p. 44 of [15])

A similar comparison can be expressed in a quantitative way by quoting from [170]:

> "For the Sensoria sensors and Berkeley motes, the ratio of energy consumption for communication and computation is in the range of 1000–10000."

The Mica2®[4] mote can be seen in Figure 1.15. Compared to MicaZ®, which transmits at 2.4GHz, Mica2 transmits at 900 MHz. Similar to Figure 1.14, in which MicaZ

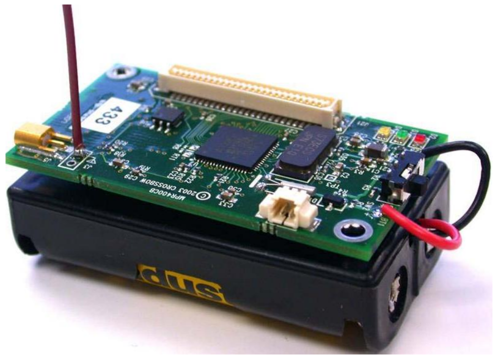


Figure 1.15: Picture of Mica2 sensor node. (Source: http://www.snm.ethz.ch/snmwiki/pub/uploads/Projects/mica2.jpg)

power consumption comparison is given, in Figure 1.16, the comparison of various power consuming events can be seen. In the figure, measured current draw for transmission is compared to other events.

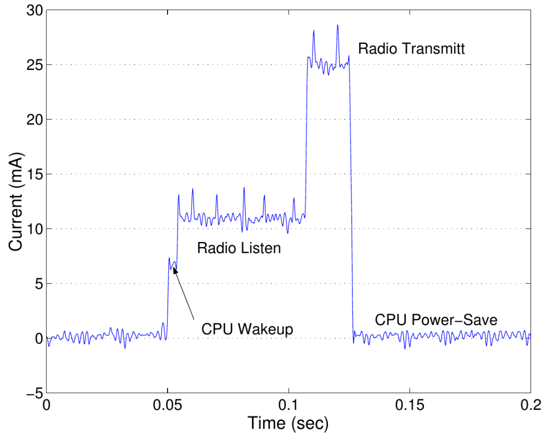


Figure 1.16: Power consumption graph of Mica2 sensor node. (Source: [136][5])

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[4] Mica2® http://www.investigacion.frc.utn.edu.ar/sensores/Equipamiento/Wireless/MICA2_Datasheet.pdf and MicaZ® http://www.cmt-gmbh.de/MICAz.pdf are sensor nodes produced by CrossBow http://xbow.com/

[5] https://www.eecs.harvard.edu/~shnayder/ptossim/mica2bench/img/radio_scope.pdf

Table 1.5 summarizes power model of the Mica2 mote by considering CPU and Radio current draw.

Table 1.5: Power model for Mica2 mote, with micasb sensor board and 3V power supply. (Source: [136])

CPU Modes	Current
Active	8.0mA
Idle	3.2mA
ADC Noise Reduce	1.0mA
Power-down	103µA
Power-save	110µA
Standby	216µA
Extended Standby	223µA
Internal Oscillator	0.93mA
LEDs	2.2mA
Sensor board	0.7mA

EEPROM access	Current
Read	6.2mA
Read Time	565µs
Write	18.4mA
Write Time	12.9ms

Radio Modes	Current
Rx	7.0mA
Tx (-20dBm)	3.7mA
Tx (-19dBm)	5.2mA
Tx (-15dBm)	5.4mA
Tx (-8dBm)	6.5mA
Tx (-5dBm)	7.1mA
Tx (0dBm)	8.5mA
Tx (+4dBm)	11.6mA
Tx (+6dBm)	13.8mA
Tx (+8dBm)	17.4mA
Tx (+10dBm)	21.5mA

Considering the current limitations of the harvesting technologies and the current battery performances along with the high power consumption of the communication subsystem of the sensor nodes, it is necessary to do research for finding energy optimization methods related to the communication subsystem. Saving from the energy can always be used in other ways to increase the effectiveness, robustness, and longevity of the WSN. In this sense, the HW and SW optimization techniques are very much focused on the communication substructure of the motes, compared to the research on energy harvesting and on efficient power unit design [31].

1.4 Energy Optimization Techniques in WSNs

While many research studies agree upon the energy problem in WSNs, designing a sustainable WSN requires interdisciplinary collaboration, as it involves expertise in SW, HW, electric circuitry, electromagnetics, electronics, and statistics. This does not mean that an expert in one of those fields listed can not offer a sustainable solution for the energy usage in WSNs. While the trade-offs are in play as in every optimization problem, very specialized optimization can not be very effective if any possible synergy is ignored. The basic idea is to prolong the network lifetime. Sometimes this goal may conflict with the QoS requirements. The extending lifetime may bring the cost of longer delay in transmissions. On the other hand, different lifetime criteria and definitions exist. In some specific application areas of WSNs, the network may die when the first node is out of batteries (dies), and in some when all the nodes die. With these caveats in mind, energy optimization techniques in the literature should be carefully analyzed. In fact, authors in [123] has mentioned one of the similar issues related to trade-offs, in which they argued that optimization techniques proposed so far are not "universally applicable". The main idea in the paper [123] is to optimize according to the application requirements of the WSNs. Authors listed five different application areas and seven different requirements specific to these application areas of the WSNs which can be seen in Table 1.6. The paper proposes these requirements as conditions that the energy optimization techniques should satisfy.

Table 1.6: Applications and their requirements for WSNs. VL=Very Low, L=Low, H=High, VH=Very High. (Source: [123])

Application	Example	Scalability	Coverage	RT Delay	QoS	Security	Mobility	Robustness
Healthcare	Vital status monitoring	VL	VL	VH	H	VH	VH	H
	Remote surveillance	VL	VL	H	H	VH	VH	L
Agriculture and environment	Precision agriculture	VH	VH	VL	VL	VL	VL	H
	Cattle monitoring	VH	L	L	VL	VL	H	L
	Environment monitoring	VL	VL	H	H	VH	VH	L
Public safety and military systems	Active intervention	VL	VL	VH	H	VH	VH	VH
	Passive supervision	VL	H	VH	H	VH	VL	L
Transportation systems	Traffic control	VL	L	VH	VH	VH	VH	L
	Safety system	VL	L	VH	VH	VH	H	H
	Services	VL	VL	L	H	H	H	L
Industry	SCADA systems	VL	L	VH	H	VH	VL	VH
	Smart grids	H	L	VH	H	VH	VL	VH

The paper presents an extensive classification of the energy efficient mechanisms specific to battery operated WSNs, which can be seen in Figure 1.17.

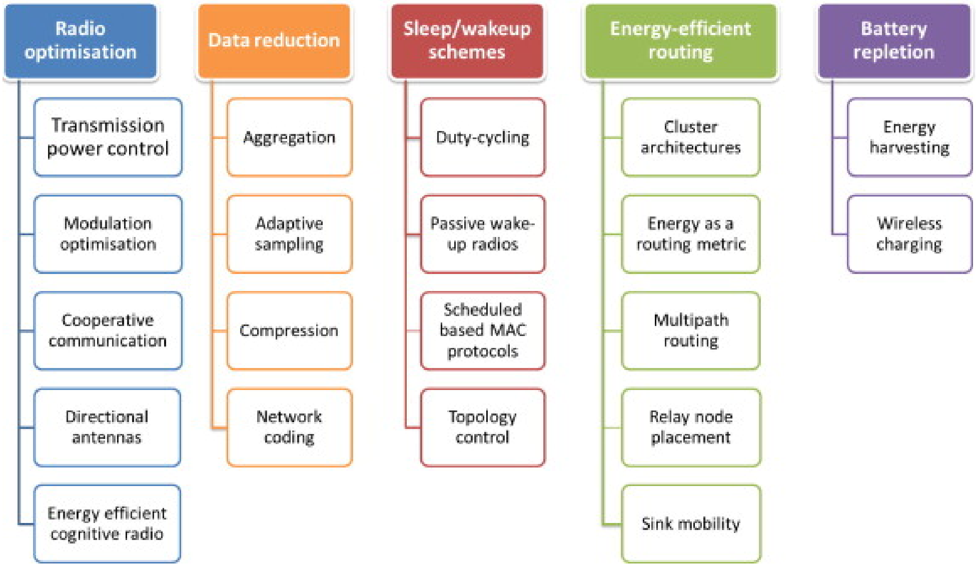


Figure 1.17: The classification of the energy efficient mechanism used in WSNs. (Source: [123])

Authors in [123] also provide discussions and give a comprehensive analysis of the effects of these techniques on the performance of the applications. Case studies are included to show how trade-offs between multiple requirements can be handled for designing efficient and sustainable WSNs.

In [19], authors focused mostly on sensor node architecture and gave a taxonomy of energy conservation schemes. Their classification basically involves three classes of energy conservation schemes, namely duty cycling, data-driven, and mobility based schemes. Duty cycling is an effective OS and HW level optimization technique, in which the components can cycle between various levels of "SLEEP" and "WAKEUP" states. The idea is to put the components into "SLEEP" state when they are not needed and change the state to "WAKEUP" when they are needed. The data-driven schemes build a statistical model of the sensed data for reducing the actual "sensing" activities with the "prediction". The idea in mobility based schemes is to equip some or all nodes with mobility when the energy cost of mobility can be used to further reduce the communication energy cost.

Clustering is one of the optimization techniques that is offered for efficient energy usage (both network level and sensor level) and for “data aggregation” (prevents data duplication). While the topology of the WSN is “clustered logically” introducing hierarchy, the transmission flow is also controlled by elected “Cluster Heads” (CH). Various algorithms are proposed for the “election process” of the CHs, which is a crucial process for energy optimization. The main idea is “balancing” the energy usage of the clusters and increasing the lifetime of the network [33]. The next phase is the cluster formation, in which nodes based on some heuristics decide to join to a certain CH for forming a cluster. Clustering is very extensively researched for the past twenty years. The clustering literature goes back to papers, like the one from 1997 by Lin and Gerla [93]. In [127, 165] excellent surveys are given on various clustering techniques. Diverse algorithms are proposed by utilizing Neural networks [145], Genetic algorithms [101], fractals [18], and PID controller theory [63].

The paper [82], analyzed energy consumption schemes, harvesting, and wireless energy transferring methods for battery-operated WSNs. Authors basically focused on the “sources” and the “sinks” of the energy in the WSNs. The taxonomy for the energy management methods they presented can be seen in Figure 1.18. While authors

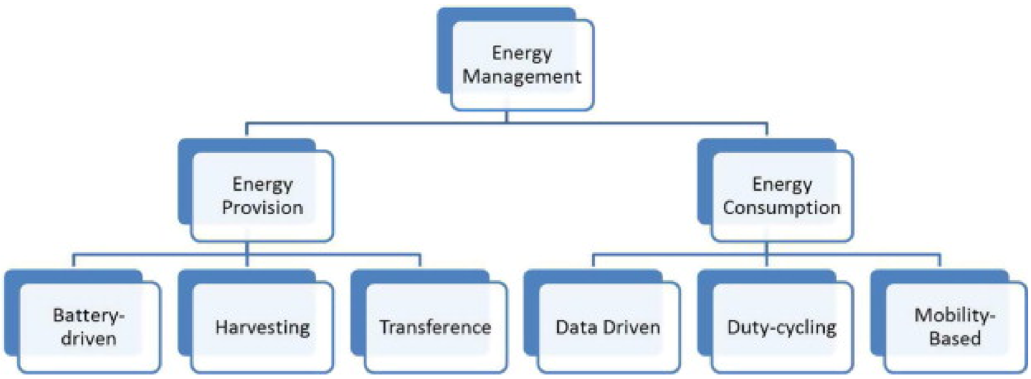


Figure 1.18: The taxonomy of energy management schemes based on the source and the sink of the energy. (Source: [82])

provided a classification of the energy management schemes in the paper, they also provided some statistical data related to these schemes. The survey that is given in the paper related to the energy transfer schemes is very unique and valuable information. Table 1.7 summarizes these energy transfer schemes and their properties.

Table 1.7: Current (as of 2018) energy transfer modes that can be used for WSNs. (Source: [82])

Technology	Efficiency (%)	Range	Coverage	Remarks
Wired	90–95	As desired	Limited to wires deployment	Static deployment, cost
Microwave beam	30–80	>2 km	Narrow beam	Potential hazards, line of sight required
Magnetic Resonance	45–90	1–2 m	Omnidirectional	Limited range
Reflected Solar Energy	>90	>1 km	Narrow or wide beam	Daytime only, line of sight required
RF Energy	70	12–14 m	Omnidirectional	Limited range
LASER beam	10–18	1 km	Narrow beam	Potential hazards, line of sight required

The paper [132] provides a comprehensive survey of the energy harvesting technologies specific to WSNs. Classification of the harvesting technologies is provided in the paper and also recent developments are discussed related to these technologies. Figure 1.19 shows the taxonomy of the harvesting technologies that is given in the paper. Different from others, this paper considers two different harvesting sources. Namely ambient environment and external sources are listed as two possible harvesting source classes. Authors also provided tabular data related to various popular sensor nodes and presented statistical data related to the properties and capacities of those energy harvesting sources.

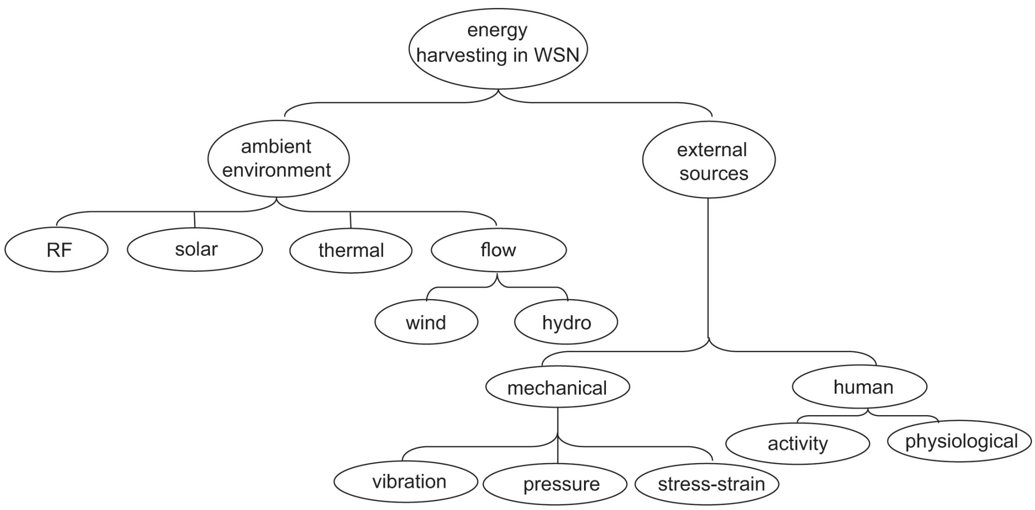


Figure 1.19: Classification of the energy harvesting technologies that can be used in WSNs. (Source: [132])

In [8], the topic was energy replenishment from renewable and traditional energy resources. Authors presented a survey on the renewable energy sources and their characteristics. They also discussed applications of such technologies in WSNs. For the traditional energy resources, the paper describes recharging technologies for battery-operated WSNs. The paper presents a taxonomy for the various energy resources that can be used in WSNs. Figure 1.20 gives the taxonomy authors provided. The paper looks the issue of energy problem in WSNs, from the point of sustainability and provides taxonomy of energy resources that can be used in WSNs. Authors also provided discussion on the characteristics of each technology and commented on future research directions.

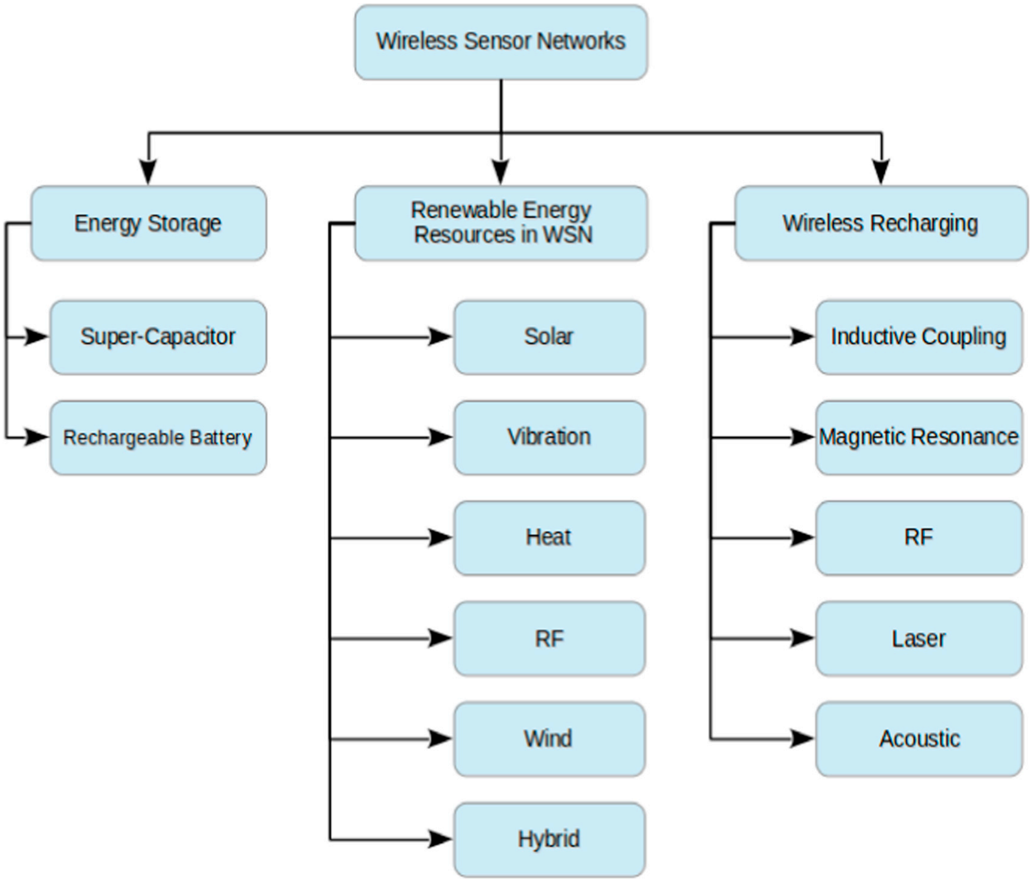
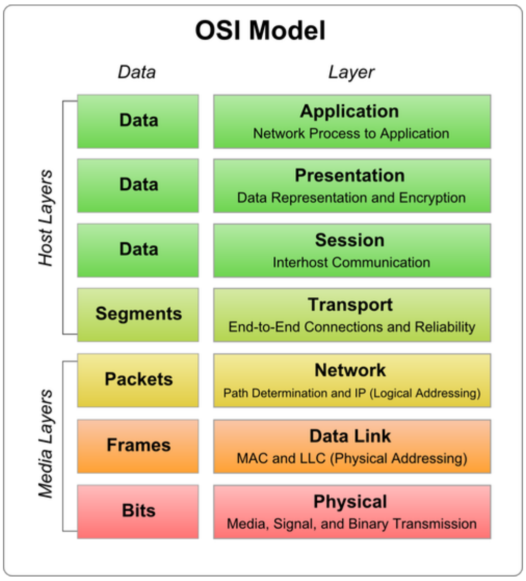
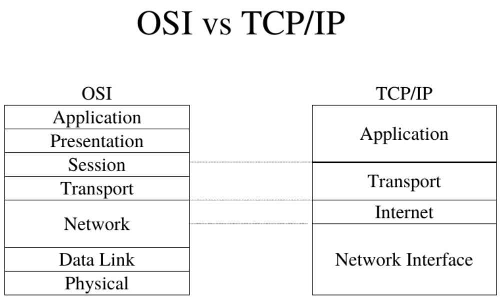


Figure 1.20: Types of energy resources that can be used in WSNs. (Source: [8])



(a) The ISO-OSI model and the layers of the Network Software. (Source: [151])



(b) OSI vs TCP models. (Source: [22])

Figure 1.21: OSI and TCP layers.

The optimization techniques proposed in this thesis fall into two classes according to Figure 1.17. The first one is directional antenna design which is in the class of "radio optimization". The second optimization technique, namely energy-aware routing protocol, falls into "energy-efficient routing" class. An alternative classification of these energy optimization techniques can be given by considering the layers of the Network Software that are used almost in every device that communicates. The network software is designed according to the ISO-OSI model consisting of 7 layers, which can be seen in Figure 1.21a. While the OSI model remained as theoretical reference model, in practice today TCP/IP model is used in communication. The relationship between OSI and TCP/IP model is shown in Figure 1.21b. According to OSI layers, routing (path finding) is a function of the Network Layer (Layer 3), while the antennas are devices used in the Physical Layer (Layer 1).

CHAPTER 2

ENERGY AWARE ROUTING

Routing is one of the most important functions that can be applied to the SW part of the system. The goal in routing is basically finding a path for packets from source to destination, which generally known as “forwarding” or “routing”. Routing is called “path finding” in some sources. Many design factors and constraints should be considered together for the design and implementation of the routing protocol. For example, the effect of the topology of the nodes, which is mainly a HW property of the system, can be effective on routing too. The energy efficiency is one of the most important factors a routing should handle while trying to “route” packets. In multi-hop networks, the delivery of the message should take the least “costly” path from source to destination. The “cost” can be associated with many of the QoS requirements. “Least energy usage” is one of the most important QoS attributes. In any network where energy is very much limited, like WSNs, “minimum energy usage” for the routing is vital, as the communication consumes the most power. In this sense, “energy-aware” or “energy-effective” routing tries to minimize the overall energy usage of the transmissions. The goal is to prolong the network lifetime while forwarding packets to their destinations so that the maintenance cost will decrease and the autonomy of the WSN will increase. The first solution proposed in this thesis is a simple energy aware routing protocol, which can be regarded as SW optimization method. This method is studied for WNSNs (Wireless Nano Sensor Networks) and for WSNs. The methodology that is applied for the research on the routing involved, firstly, a literature survey both in breadth and depth for getting an overview of the research activities and discovering the gaps in the field respectively. After that the idea of the simple energy aware routing is implemented by using a suitable simulator for performance assessment. In the following sections short literature review is presented related to the topic and then the general overview of the proposed routing algorithm is given. Finally, simulations and results are discussed in detail for each solution.

2.1 Routing Research in WNSN

Routing has a special stature in the WNSNs. Not only WNSNs are new technologies, but also they are fundamentally different technologies. Although there is no standard routing protocol for WNSNs yet, several promising studies are published. Unfortunately, current network protocols can not be applied to nano communication. They are too complex for nano sensors and the energy constraints of nanosensors can not sustain such protocols. Due to the nanoscale dimensions of the sensor nodes and the size of their antennas, THz frequency is the only band that the communication can be done. As a result new protocols, new modulation techniques, and new signal encoding methods are necessary for THz frequency communications. The only work toward practical standardization is the framework IEEE 1906.1 [65], which contains recommendations.

However, there are several studies focused on different aspects of the nano communication, like physical layer, THz antenna technology, routing, and energy harvesting. Several aspects can be considered in the design of a routing protocol such as the nano-network topology, multi phase settings, mobility, 2D-3D. But, according to current nanotechnology studies such as [13, 113], the most important and most limiting factor is the energy. In that sense, the special case of routing protocol design for the WNSNs can be seen as energy optimization problem with various constraints. Routing protocols in nanonetworks can be classified into two main groups. Mainly, unicast protocols like simple flooding and multicast protocols like random point-to-point protocol. While in the flooding simply every node forwards the received message, in point-to-point group protocols, forwarding is done to a specific node based on certain criteria.

Studies like in the following paragraphs, tried to develop routing frameworks focusing on different layers of the network. However, it can be seen that comprehensive routing framework not only requires cross-layer design, but also collaborative involvement of various engineering departments. The ideal optimized routing requires synergy among various parts of the sensor node architecture such as, antenna, signal encoding method, duty-cycling mechanism, routing software, customized packet format, addressing scheme, and power unit controller. On the other hand, such efforts are the first steps towards standardization. In this sense, the performance comparison among these methods not only can be difficult, but also can not fully explain the isolated algorithm performance. However, several promising works can be listed, like the ones in [3, 59, 92, 153, 171]. The studies in [1, 148], provide survey and overview on the routing research related to the nanonetworks.

Authors in [171], focused on the physical layer part for their routing protocol. They proposed Physical Network Coding based “pair-to-pair” routing framework by extending the geographical greedy routing algorithm. The packets are divided into two parts and transmitted in pairs along the pipelined multi-hop route, with the idea of gathering weak nodes into groups where integrated routing can be achieved for energy efficiency. The paper extends the idea of GPSR (Greedy Perimeter Stateless Routing) in [78]. While the GPSR is point-to-point routing algorithm, authors extend it to be a pair-to-pair routing in their work, calling it “Buddy Unicast” routing. Although the Buddy routing is not energy efficient, its performance in throughput is very high.

In [59], a channel-aware routing protocol is proposed. Authors considered the special attributes of the THz band communication. The forwarding is optimized by considering two cost factors, namely avoiding long-distance region in which the signal may suffer the path loss and avoiding the short-distance region in which the number of hops may be increased unnecessarily. For the simulations 1D “string” network topology is considered. The paper considered metrics like end-to-end performance, end-to-end capacity and end-to-end delay. For the parametric simulations, authors used different node densities and different water percentages representing various human body tissue characteristics, as the targeted application was in-body health monitoring system. The proposed routing algorithm achieved high channel capacity and exhibited low hop count reducing transmission delays.

In [153], coordinate-based addressing scheme, CORONA, is proposed for nanonodes placed uniformly in a rectangular 2D topology. The proposed routing protocol tries to minimize the hop count of the packet transmission by placing anchor nodes at the vertices of the grid and using the coordinate based addressing scheme as it can be seen in Figure 2.1. Through simulations, the routing protocol is assessed by considering the packet retransmission rate, successful packet reception rate, and packet loss rate. According to the simulations done in the paper, CORONA showed low packet retransmissions and low energy consumption compared to the flood routing. However, the paper stated that global packet reception rate is very low for CORONA. Although the paper does not present an energy efficiency measure, the energy efficiency is associated with the metrics that are used in the simulations, such as global packet send (packets per nano second), receive and interference rate .

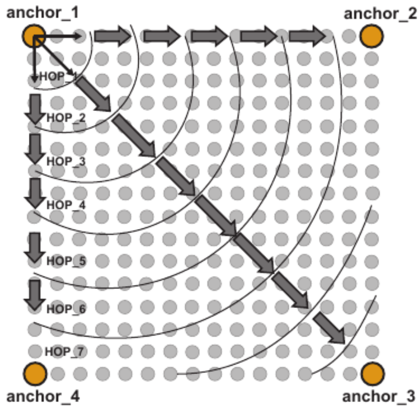


Figure 2.1: The anchor nodes based coordinate system. (Source: [153])

In [92], authors proposed peer-to-peer type routing protocol. For the simulations, 2D uniform grid and 2D uniform random topologies are assumed, in which identical nanonodes are deployed. The assumption for the nano communication was 100GHz frequency with standard atmospheric conditions. This condition is assumed for providing the minimum effect for the path loss due to molecular absorption and high data rate. Packet collisions and redundant retransmissions, being the two metrics that are considered in the paper, are optimized in the proposed protocol. During the setup phase, nodes are classified based on the packet reception statistics they have logged. The routing scheme exploits this classification.

The paper [3] proposes an energy conserving protocol based on the hybrid clustering of the nanonodes and centralized scheduling. The proposed method, Nano Cluster Composition Algorithm (NCCA), offers a model which designed for channel behavior, by considering aggregated impact of molecular absorption, spreading loss, and shadowing. The energy model of NCCA considers harvesting in addition to the consumption.

In [148], authors pointed out the lack of research related to the protocols in higher network layers for the WNSNs. They also added that most research is focused on the lower network layers, especially on the MAC layer and Physical layer. After benchmarking classical WSN protocols like AODV (Adhoc On-demand Distance Vector) [62, 72, 111], DSDV (Destination Sequenced Distance Vector) [112], and DSR (Dynamic Source Routing) [74], on WNSN, authors find out that AODV performs better in WNSNs. Their performance metrics criteria include packet delivery ratio, throughput (Kbps), average delay, packet drop rate, and energy consumption. As a parameter, the paper proposes a varying number of nanonodes (50, 100, 150, 200) for simulating networks with varying densities, from sparse to dense. The paper based on this benchmarks, proposed a modified version of AODV as "Hierarchical AODV" routing protocol. The protocol which is customized for WNSNs performed better than all the others.

The paper [1], provides benchmarks for the current nano communication routing protocols. In the benchmarks, three routing protocols were considered. Namely, controlled flooding, coordinate routing (CORONA [153]), and Hierarchical AODV ([148]). The performance metrics were focused on the number of successfully delivered packets, delay, and energy consumption. Authors used parameters as number of nanonodes (50-250 nodes, sparse to dense network spectrum) and their transmission range (1mm, 10mm, 15mm, 20mm). CORONA and controlled flooding are found to be worst in delay and energy consumption for increasing number of nodes and transmission ranges. While the Hierarchical AODV protocol is found to have the best energy consumption, it presented higher complexity and lower throughput.

2.2 Routing Research in WSN

Compared to the WNSNs, in the field of WSNs, routing is studied in much more depth and breadth. Nanosensor nodes are very new technology compared to the classical sensor nodes. Routing by itself studied since the beginning of the computer networks. It is interesting to take a look at one of the early papers on routing in mobile networks like the paper from 1996 by Ramanathan [122]. Several papers can be regarded as some of the first efforts to consider energy as metric in routing like [126, 138, 143], and [144]. With the LEACH (Low Energy Adaptive Clustering Hierarchy) paper ([61]) energy based routing and clustering gained momentum and LEACH protocol became standard benchmarking algorithm for most of the energy based protocols. The comprehensive survey on the historical development of the LEACH-based protocols can be found in [139]. There are many ways to classify existing routing protocols. Especially the case had been studied extensively for the wireless sensor networks in [16, 23, 110, 129]. In the following paragraphs, different works are presented related to the classification of the routing protocols and related to the issues in designing routing protocols.

The paper [16] presents a comprehensive survey on the routing techniques in WSNs. Authors provided a framework for their classification by describing the architecture of the sensors and listing challenges in routing along with the design issues related to the WSNs. In Figure 2.2 the proposed classification of the routing protocols can be seen. The paper bases the classification presented, on the network structure (external) of the WSN and on the behavior of the routing protocol (internal) in the nodes.

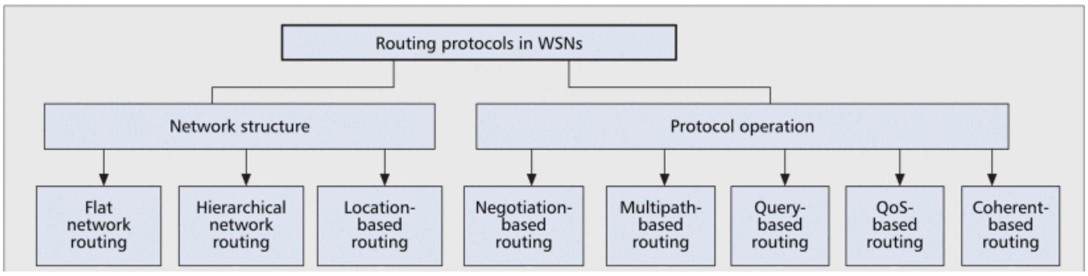


Figure 2.2: Taxonomy of routing protocols in WSNs. (Source: [16])

The paper [49] presents a survey on the operating systems for WSNs and lists several characteristics of the WSNs (nodes), like size, scarce resources being important factors in the design of software and hardware of the WSNs. Authors also present optimizing sensors' lifetime as a fundamental objective and they comment on the necessity of the new design paradigm. The paper is valuable in the sense of analyzing the sensor node system in holistic way by considering both SW and HW. In doing so, the paper provides the reader a broader panorama for viewing the place and the interaction of the routing in the sensor node system architecture.

In [102], authors focused on the constraint based routing protocols. They basically considered routing algorithms considering limited power, low computing power, low storage, and short-range radio communication. The paper claimed that while there are efforts in designing constraint based routing protocols for WSNs, still there are no formal and standard solutions offered in this direction. Authors proposed configuration management based routing protocol for WSNs.

According to [110] the study [10] introduced the framework for the design issues related to the issues related to network layer stack, while leaving out the classification of the routing protocols. In this work authors presented a framework for routing protocols by considering energy consumption models for nodes and traffic patterns for their communication. Figure 2.3 shows the traffic patterns in [110] considered.

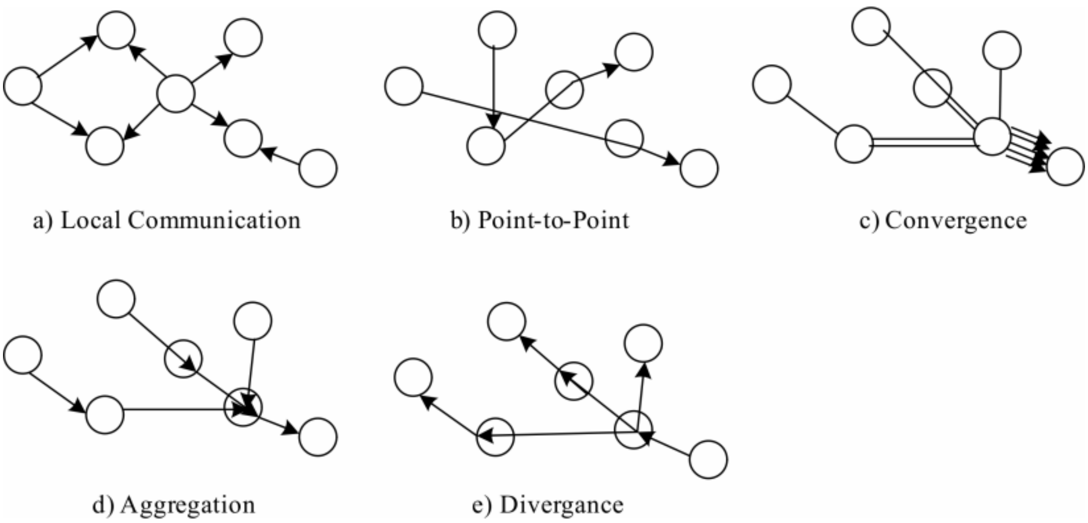


Figure 2.3: Traffic patterns specific to WSNs. (Source: [110])

In the energy consumption model, they consider energy cost for sensor state changes, processing, and communication. The paper lists asymmetric, WSN specific traffic patterns due to the way the data are collected in WSNs. This is due to the fact that, generally sensor nodes send data to sink nodes and the sink node very sporadically sends control messages to sensor nodes. The classification paper proposes for the routing protocols can be seen in Figure 2.4.

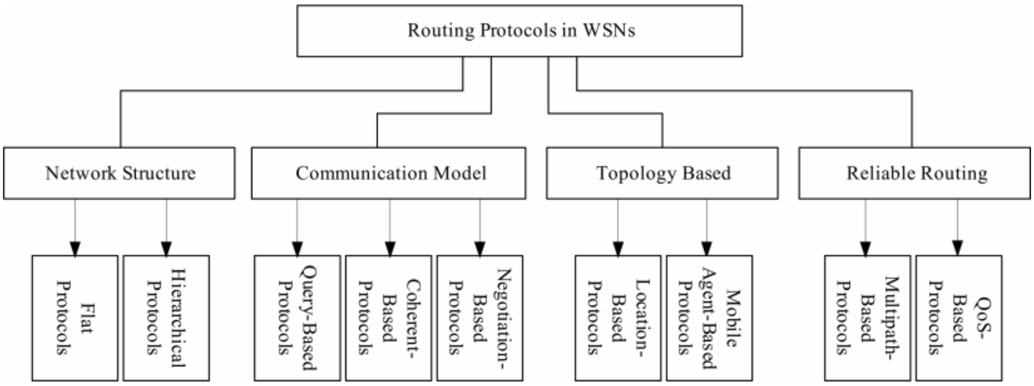


Figure 2.4: Classification of the routing protocols for WSNs. (Source: [110])

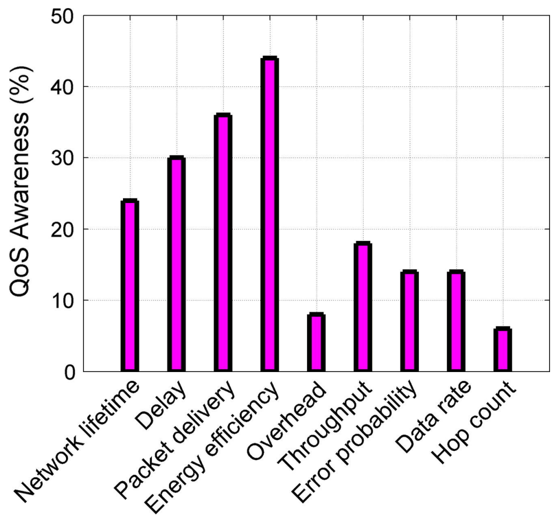


Figure 2.5: The distribution of the research on QoS parameters. (Source: [129])

The topic of the paper [129] was "the research in routing" itself. The paper, not only provides a valuable survey and classification of the routing algorithms for WSNs, but also provides statistical data on the research situation of the routing algorithms. In Figure 2.5, one such statistical data is given related to the percentages of the papers published for each QoS parameter. The top group is the "energy efficiency", consisting 44% of the publications.

In thesis [116] the author proposed three energy efficient routing. In the first method, Game Theory used in clustering based routing protocol for energy savings in WSNs. The second energy efficient method that was proposed involved Graph Theoretic Connected Dominating Set (CDS) concept. Domination is an active research area of Graph Theory where various optimization problems are tackled. The roots of the concept go to N-Queens problem ([24]). In computer networks Dominating Set is used for maintaining the hierarchical structure where nodes in the Dominating Set (DS) can communicate better. A Connected Dominating Set (CDS [159]) is a dominating set in a computer network, which nodes are connected (reachable) to each other. Based on these four attributes a network can be called CDS:

- Connected, so that routing is possible.
- Reasonably small for cost effectiveness.
- Contains shortest paths for effective routing.
- Consists of nodes with enough energy.

In Figure 2.6 sample WSN is shown along with the DS and CDS. Better routing can be achieved with smaller DS. So constructing Minimum Connected Dominating Set (MCDS) in WSN is desirable.

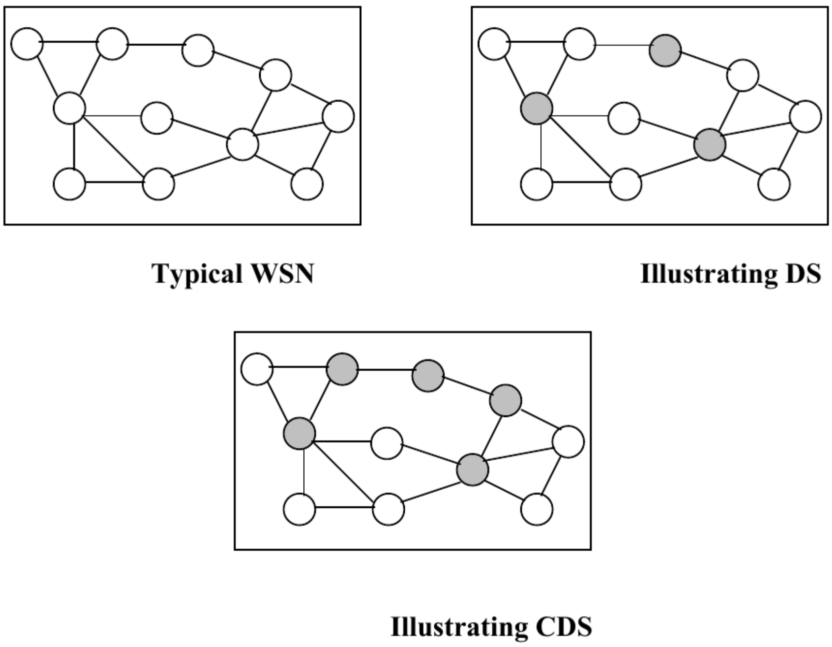


Figure 2.6: Example WSN and its DS and CDS. (Source: [116])

The third routing scheme proposed in the thesis was based on the bio-inspired swarm optimization. The energy aware clustering based routing protocol inspired by honey bee colony is proposed as optimal routing with the minimum number of hops in communication.

The routing protocols mentioned in previous discussions like AODV and DSR are all "single path" routing algorithms. That means the algorithms propose single path information for forwarding packets. However, there are "multi-path" routing algorithms that can offer more than one routing paths. In [64] authors proposed such multi-path routing algorithms as an optimization to energy constraint. The paper claimed that multiple routes are useful because of the dynamic and unpredictable nature of the ad hoc networks. Further authors stated that for WSNs multi-path routing focuses on load-balancing or fault tolerance. The paper listed the benefits of the multi path routing as:

- **Load Balancing:** Congestion avoidance and improved performance.
- **Fault Tolerance:** Redundant information routed to the destination node in multi paths increase fault-tolerance.
- **Bandwidth Aggregation:** Data to the destination node, can be split into multiple streams and each stream can be routed in multi paths simultaneously.
- **Reduced Delay:** In WSNs in case of node failure alternative routes should be found. This causes delays in transmission. However multi-path routing can reduce these delays since there can always be alternative routings.

Firstly the paper describes several multi-path routing algorithms like Ad hoc On Demand Distance Vector Multi-path routing protocol (AODVM) [167], Ad hoc On Demand Multi-path Distance Vector protocol (AOMDV) [97] (extension of AODV for discovering paths that are node-disjoint or link-disjoint), and Split Multi-path Routing (SMR) [89]. Then the paper describes the proposed energy-efficient multi-path routing based on AOMDV. The design of the proposed routing algorithm involved the integration of the MAC protocol with periodic wake-up and multi-path routing protocol. While the sleep/wake-ups cycling increases the network lifetime, it also provides load-balancing. The paper reports 10-15% performance increase in lifetime and end-to-end communication delay.

In [23], authors considered the routing from the designer's point of view, listing 17 factors that they deemed important in the design of a routing algorithm. In Table 2.1 below, these factors and the situations that they are effective are summarized.

Table 2.1: Factors and the situations that should be considered in designing routing algorithm for WSNs. (Source: [23])

Factor	Situation
Energy Consumption	The life of a node depends on its battery which is limited and small considering the node's size.
Scalability	The Routing protocol used must be able to handle large number of nodes.
Connectivity	Nodes must stay in connection even after some node failure.
Network costs	The cost of a node affects the cost of the whole network.
Data aggregation	Multiple nodes may generate redundant data causing an unnecessary traffic. Similar data can be aggregated, combined, to reduce the transmission.
Quality of service	The routing protocol must deal with the demands needed for an application.
Fault tolerance	The routing protocol must be able to reroute a packet if any node fails, in order to reach the sink.
Mobility	The routing protocol should handle topology changes and should consider the energy a node uses for relocation.
Node deployment	The routing protocol should consider the deployment of nodes which can be random.
Environmental conditions	Sensor nodes must be able to overcome any environmental condition.
Hardware constrains	Sensor nodes can vary in size, in architecture, in types of power units they have.
Transmission media	Wireless links can be formed by infrared, radio, or even optical media.
Network topology	For high number of nodes a good topology maintenance plan must be followed.
Deployment phase	Sensors can be manually deployed, one by one, or randomly deployed, by a plane or missile.
Post-deployment	Topology can change due to relocating nodes in case of environmental changes, malfunction of a node, or even death of a node (no energy).
Redeployment	To keep this sensor network functioning, additional nodes may be added to replace the lost nodes.
Security	Data transmitted must be secured from any external attacks or unauthorized access.

In [25], authors pointed out the lack of consideration of the energy optimization in the design of a reliable multi-path routing algorithms. In their approach to the reliable multi-path routing, they proposed a conceptual model in which constraints like distance and energy consumption are included. The algorithm proposed in the paper consists of two phases. The first one is the “construction” phase in which special packets called “weight setup packets” are utilized. In the second part, which is called “data transmission” phase, the actual transmission begins. For this conceptual framework, authors are planning to carry out simulations as a future work.

CHAPTER 3

PROPOSED LAGOON ROUTING PROTOCOL

Considering the limitations of the WNSNs and WSNs along with the high energy cost of communication, a simple energy-efficient routing protocol, "LaGOON" (Last GOOd Neighbor), is proposed and benchmarked in this thesis. The proposed routing algorithm is called "LaGOON" (Last GOOd Neighbor) as it applies "backward learning" and remembers the "last good neighbor" in making routing decisions. As the nanodevices have a simple hardware, rather restricted software is needed. The layered structure for the TCP protocol stack was proposed to overcome complexities of big software systems. However, for the nanodevices, software should be rather simple and efficient. The routing protocol should not introduce unnecessary communication overhead and has to be energy efficient. In this context two main principles have guided the design of the LaGOON, were to keep the least communication overhead and to use the simplest data structures that are necessary for the routing functionality. The basic idea was to make use of the information in the arriving packets as much as possible, with the assumption of symmetric communication. The adaptive "Backward-Learning" paradigm utilizes the "path length" (from TTL) information and the "source" of the path for future transmissions. Moreover, the proposed method does not assume any specific topology. Since it involves an evolving distributed scheme, the proposed method can handle both mobile and static configurations in communication systems. Here the method offers optimization at the global level (covering all the network). Energy efficient or aware routing protocol is essential for optimizing the overall energy usage of the sensor network and increasing the lifetime of sensors. Mostly, the implementation of the proposed energy-aware routing protocol involves static topologies. On the other hand, mobility can be handled by the proposed method with some delays and overheads in the communication.

In the case of WNSNs, it offers less energy consumption compared to flooding and random routing protocols. It is simulated by using "ns-3[1]", which is a discrete-event network simulator for Internet systems, and "Nano-Sim[2]" library of the ns-3, which is developed for nanonetworks [114, 115]. In conducting this study, WNSNs have been chosen on the basis of their very limited energy sources. In this respect, WNSNs represent the most energy critical networks. Although the algorithm is proposed for the WNSNs, it is also applicable to WSNs.

1 https://www.nsnam.org
2 https://telematics.poliba.it/index.php?option=com_content&view=article&id=30&Itemid=204&lang=en

3.1 The Protocol

The proposed method integrated “setup phase” into the actual communication. In fact, there is no “phase” solely dedicated to the setup, in which nodes discover their neighbors and they figure out how “far” (in number of hops) the others are. However, the addition of the dedicated setup phase can speed up “path learning”. The topological information and the optimum routing evolves with time as the nodes communicate with each other. The proposed method exploits the duplex nature of the wireless transmissions. The idea is to remember the best path that packets arrive, and use it in reverse direction for future transmissions. Nodes update information on every packet arrival and they also update the path cost from their immediate neighbor to the originator of the arrived packet. This information comes almost “freely” with every packet. No additional bytes or attribute is necessary to be allocated for this extra information, as “layer 3” (end-to-end addresses) and “MAC” (link-based) addresses along with the TTL values are already written in the packets. Here TTL value is deducted on each forwarding. In other words, if the “max value” is kind of “hard-coded” in the protocol (every node knows it), then the “path-length” or “hop count” can be found by simply subtracting the current TTL value that comes with a packet, from the “max value”. This value is important for the energy efficient routing as it gives information about the number of transmissions necessary for the packet. Initial transmission can be based on flooding routing or to random point-to-point routing with some improvements (not the brute-force). Specific assumptions for the implementation are given below in the explanations of the algorithm. For the workings of the method, each node will have a small routing table called “reachability-cost-table”. For routers, it can be full (for every node) and for the nanosensor node partial (fixed number of entries).

The routing tables consist of triplets (src, cost, dst-neighbor):

- **src** is the originator (source) of the packet.
- **cost** is the total energy cost, each node between src and dst add to it, the amount of energy (predetermined) required to send the packet.
- **dst-neighbor** (dn) is the last node on the path before the dst, the immediate neighbor of the destination node. This will be determined by the destination node.

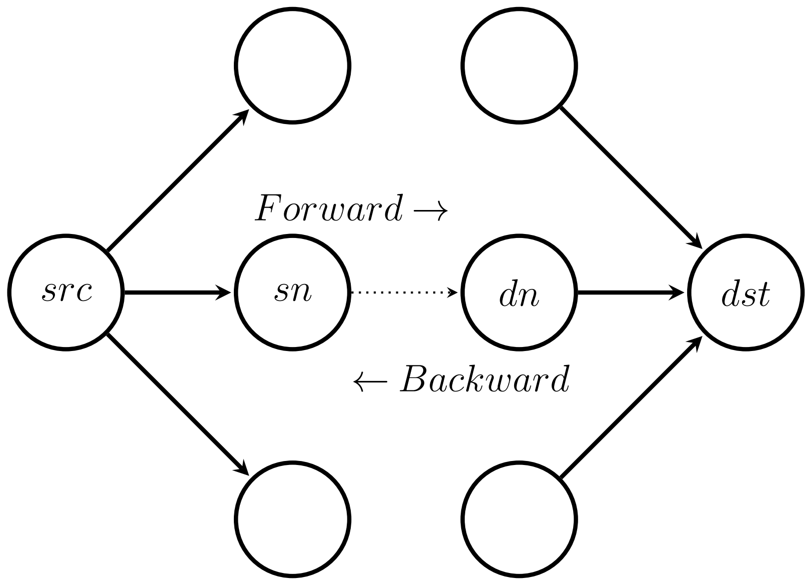


Figure 3.1: sn, dn are src-neighbor and dst-neighbor respectively.

Figure 3.1 illustrates the nodes that are mentioned in the discussion above. Assuming duplex transmission then the “dst” node can mark in its table the cost to reach to “src” via “dst-neighbor” as “cost”. This is the information extracted for the “Backward” path shown in Figure 3.1. Any value less than that updates the table of the node. In that way table entries will tell the nodes the best neighbor or “the last good neighbor” (LaGOON, “dn” in Figure 3.1) to pick for transmitting back to the source node in the future. The assumption that each node knows its neighbor must be considered along with the algorithm, in order to fully understand the operation of the routing protocol. Also for the simulation, when the packet is created randomly by the node, the node chooses random destination and random neighbor to initiate the transmission. In our implementation “unreliable” (without ACK) transmission scheme is used. “Reliable” transmission scheme can be implemented by adding “ACK” mechanism and the information that comes from the ACK packet can be helpful to update the “Forward” (Figure 3.1) path information as it is proposed in [108]. Although dynamic topology is assumed in the implementation, the nodes are confined into rectangular regions so that neighbors will not be outside of the range. Gauss-Markov mobility model that is used in the example “healthcare” [114, 115] application of the Nano-Sim package is assumed in our simulations.

The pseudo-code of the proposed method is given in the algorithm 1. The algorithm is used by every node to decide on forwarding. Each node is either in “FULL” state or in “CHARGING” state, depending on the battery level.

Algorithm 1 LaGOON Routing mechanism for each nanodevice

Input: Packet Arrival

Output: Drop, Forward, or Process Packet

```
Initialization :
Setup routing table:
Mark all other nodes as NOT-REACHABLE
On Packet Arrival :
UPDATE routing table according to the information in the packet
if (STATE == CHARGING) then
    DROP Packet
else
    if (TTL == 0) then
        DROP Packet
    else if (LAYER3_{DST-ADDR} == ID_{NODE}) then
        PROCESS Packet
    else if (MAC_{DST-ADDR} == ID_{NODE}) then
        FORWARD Packet to LAYER3_{DST-ADDR}
        via “LaGOON”. Flood/Random forward if no “LaGOON” in the table
    else
        This is “RUMOR PACKET”, do nothing
```

- For the step 1, every node initializes its routing table by marking all the distances to other nodes as NOT-REACHABLE. With the arrival of the first packet, nodes start to utilize the information that comes with the packet. As they receive packets that come from the other nodes, the TTL field gives idea about the path length (hop-count) for the backward path. If shorter path is found then the node updates in its routing table entries associated to the destination node, namely the last good neighbor and the path length, which is a simple cost metric.

- The nodes that are in "CHARGING" state basically "DROP" the packet since there is not enough power to "FORWARD", but use the information ("UPDATE" the routing table) that comes with the packet. It is assumed that nodes put themselves into "CHARGING" state when there is "low" (predetermined value) level of energy left. This process is summarized in step 2-4 of the algorithm 1.

- The steps from 5-15 are related to the activities of the nodes which are in "FULL" state.

  – The nodes that have enough battery for forwarding, firstly check the TTL value of the packet. Packets with expired TTL are "DROP"ed (step 6-7).

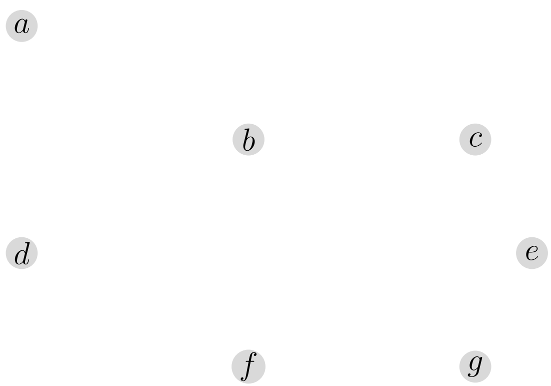
  – Packets that are destined to the node (node is "dst" node as it is shown in Figure 3.1) are "PROCESS"ed (step 8-9).

  – For the packets that are forwarded to the intermediate nodes on the "src-dst" path (please see Figure 3.1), the "FORWARD"ing is applied according to the most recent state of the routing table that the intermediate node has. As it is the case for every packet, addresses and TTL values in the packet are valuable information and before forwarding takes place, they are used to "UPDATE" the routing tables of the intermediate nodes, which is summarized in step 10-11 of the algorithm 1.

  – Because of the wireless nature of the transmissions, nodes can also "listen" other packets that are not destined to them. These packets are labeled as "RUMOR" packets in step 13 of the algorithm 1. These packets are also valuable to "UPDATE" the routing tables of the "hearing" nodes.

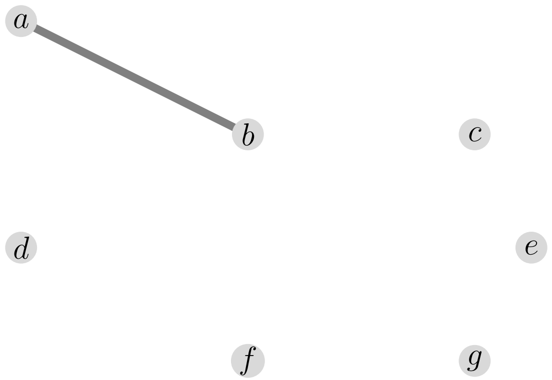
3.2 Visual Example for Omnidirectional Version

For visualizing the operation of the algorithm and the use of the associated data structures, figures from 3.2 to 3.10 are given below. Figures from 3.2 to 3.7 are showing sample transmission from node “a”. In the scenario, it is shown when the transmission (flooding) from “a” to “g” via “d” is later than the transmission from “b”, how “g” can update the “reverse path” to “a”. In the case the flooding reaches earlier to “g” via “d”, the less costly path is not affected by the arrival of the packet via “b”, since its cost is higher than the one registered in the routing table. The “global routing table” (for this example) is shown next to the network graph to show the individual updates to the routing tables that nodes keep track for themselves. In the actual implementation, each node, as time passes and as they receive packets (from transmissions and from floods), updates its individual routing table. Figures from 3.8 to 3.10 are showing how the algorithm updates data structures when a better alternative route is found between source and destination. In routing tables “Ns” represent the “last good neighbor”. The “Dists” column is the cost of the path measured as the path length given as a hop count. If a node has an “empty” routing table, which is the case at the startup, it can be programmed to do flooding or to send to a randomly picked neighbor (if neighborhood discovery is possible to do beforehand). Flooding can be customized to be a “directional”, in which nodes that “flood” do not repeat the “echoes” of their transmissions.



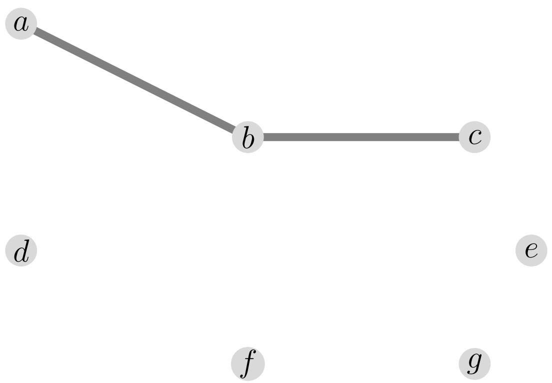
Node	Ns	Dists
a	-	-
b	-	-
c	-	-
d	-	-
e	-	-
f	-	-
g	-	-

Figure 3.2: Initial collection of entries from “routing tables” of nodes.



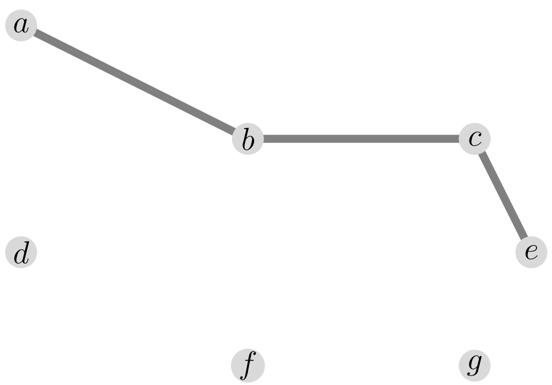
Node	Ns	Dists
a	-	-
b	a	a-1
c	-	-
d	-	-
e	-	-
f	-	-
g	-	-

Figure 3.3: “a”, having an empty routing table starts to flood. When a packet arrives to “b”, it updates for reaching “a” via “a” with cost 1, marks “a” as neighbor.



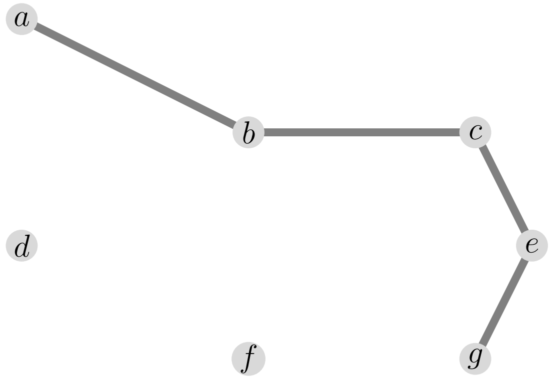
Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	-	-
e	-	-
f	-	-
g	-	-

Figure 3.4: “c” updates for reaching “a” via “b” with cost 2, marks “b” as neighbor.



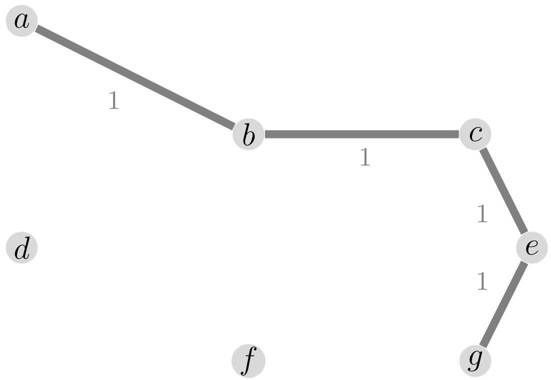
Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	-	-
e	c	a-c-3
f	-	-
g	-	-

Figure 3.5: “e” updates for reaching “a” via “c” with cost 3, marks “c” as neighbor.



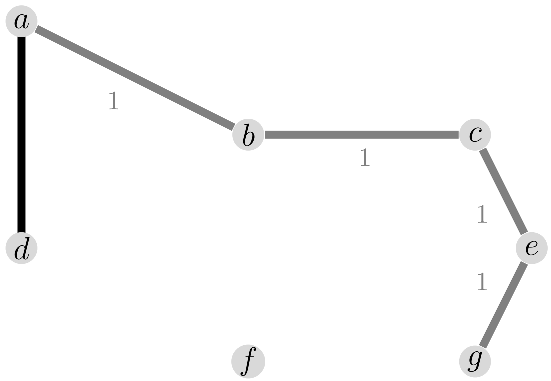
Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	-	-
e	c	a-c-3
f	-	-
g	e	a-e-4

Figure 3.6: "g" updates for reaching "a" via "e" with cost 4, marks "e" as neighbor.



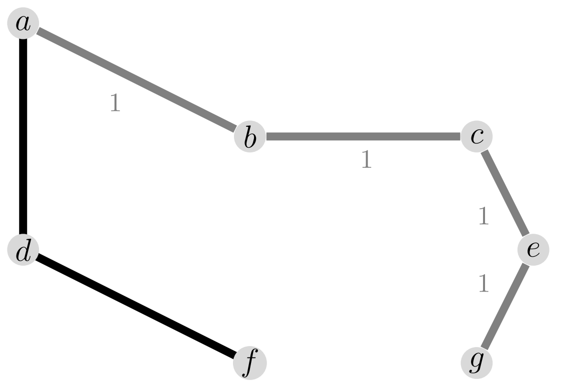
Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	-	-
e	c	a-c-3
f	-	-
g	e	a-e-4

Figure 3.7: "g" remembers that "a" can be reached via "e" with cost 4.



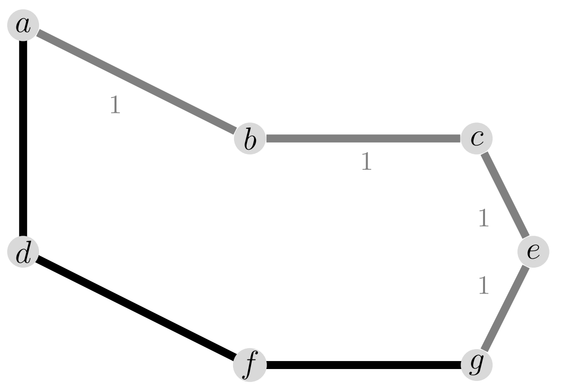
Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	a	a-1
e	c	a-c-3
f	-	-
g	e	a-e-4

Figure 3.8: "d" (having received the flood packet later than "b") updates for reaching "a" via "a" with cost 1, marks "a" as neighbor.



Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	a	a-1
e	c	a-c-3
f	d	a-d-2
g	e	a-e-4

Figure 3.9: "f" updates for reaching "a" via "d" with cost 2, marks "d" as neighbor.



Node	Ns	Dists
a	-	-
b	a	a-1
c	b	a-b-2
d	a	a-1
e	c	a-c-3
f	d	a-d-2
g	e, f	a-f-3

Figure 3.10: "g" updates for reaching "a" via "f" with cost 3, marks "f" as neighbor.

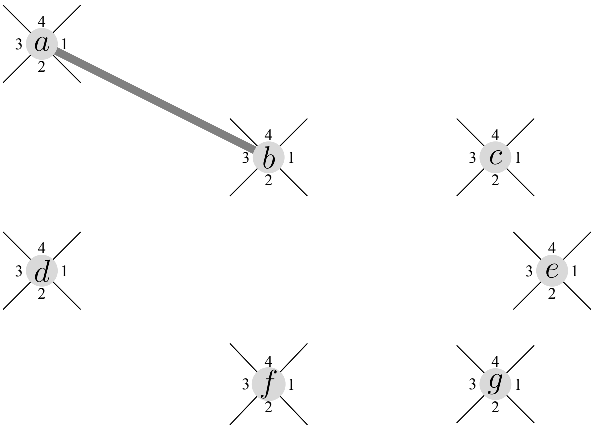
One may argue here about the first path being better than the second one in the example, since the packet arrival was quicker. Even if the assumption that the “reverse” (when the destination node uses last good neighbor) path is identical to the “forward” (actual packet arrival) path holds, the important metric is the number of hops for the proposed algorithm. LaGOON assumes that each transmission is consuming equal amount of energy for the simplicity. This assumption can be modified depending on the simulator’s abilities for modeling the physical medium. On the other hand, there is no guarantee that both forward and reverse paths they will introduce the same delay.

However, many improvements can be suggested to LaGOON, as its simplicity allows such flexibilities. As the “Backward” path discovery is explained above, it is also possible to do “Forward” path discovery (please see Figure 3.1) from the arriving packets. The immediate neighbor of the “src”, (“sn” in Figure 3.1) can be included in the message of the packet (piggy-backing) and the destination node (“dst” in Figure 3.1), depending on the energy level, can send back some kind of “ACK” packet to the originator (“src” in Figure 3.1), informing the cost of the transmission via “sn”. Which could help originator nodes to update their routing table for the cost of the “Forward” path. In this case, packet traffic can increase significantly. To alleviate this problem, some kind of “probability of sending” value can be integrated into the protocol, as it is in the case of “persistence policies” of the CSMA. The basic idea is to use the communication packets as the source of information to determine the best neighbor for a specific destination and also inform the originator node about the path cost. The “robustness” of the algorithm can be increased by considering “periodic controlled flooding” for node failures and special control packets in the case of long range (out of range of the neighbors’ antennas) mobility.

3.3 Visual Example for Directional Version

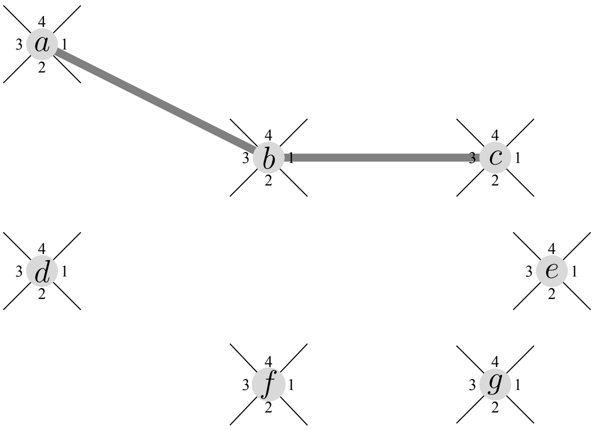
At the level of routing, proposed LaGOON algorithm does not need significant changes to be adapted for communication with directional antennas. However, MAC and physical layers should be customized for antenna switching or beam steering. The only enhancement required is the addition of the "direction" for the "last good neighbor". In the proposed directional version of the LaGOON algorithm. Sensor nodes remembers the "direction" of the incoming packets. The antenna system should tell the upper communication layer from which direction the packet is received. In the case of antenna switching simply the receiving antenna informs its "id number". However, for the beam steering system, antenna subsystem should have "direction of arrival" (DOA) capability.

Although the proposed directional algorithm is not implemented, for understanding the mechanisms involved, only the visual presentation will be given in the following figures, similar to the ones given for omnidirectional version. The same scenario that was explained for the omnidirectional version, will be repeated in figures from 3.11 to 3.18 below. Figures from 3.11 to 3.15 are showing sample transmission from node "a". The "global routing table" consisting of the related individual entries from the nodes is shown next to the network graph. Necessary individual updates are shown in the routing tables that nodes keep track for themselves. It should be noted that, different from the omnidirectional version example, nodes record the direction of the "last good neighbor" in the individual routing table entries. Figures from 3.16 to 3.18 are showing how the algorithm updates data structures, when a better alternative route is found between source and destination by recording the DOA of the packet transmission. In figures, antennas are labeled with numbers in the clockwise orientation. The example that is explained in figures, considers sensor nodes equipped with four switchable directional antennas, oriented to the south (antenna 2), to the north (antenna 4), to the east (antenna 1), and to the west (antenna 3).



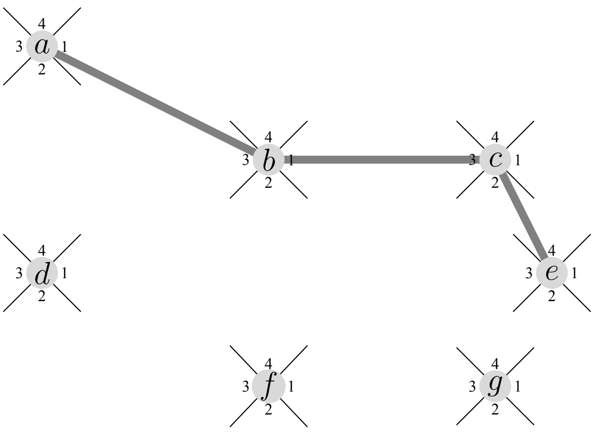
Node	Ns	Dists
a	-	-
b	a	3a-1
c	-	-
d	-	-
e	-	-
f	-	-
g	-	-

Figure 3.11: “a”, having an empty routing table starts to flood. When a packet arrives to “b”, it updates for reaching “a” via “3a” (a with antenna 3) with cost 1, marks “a” as neighbor.



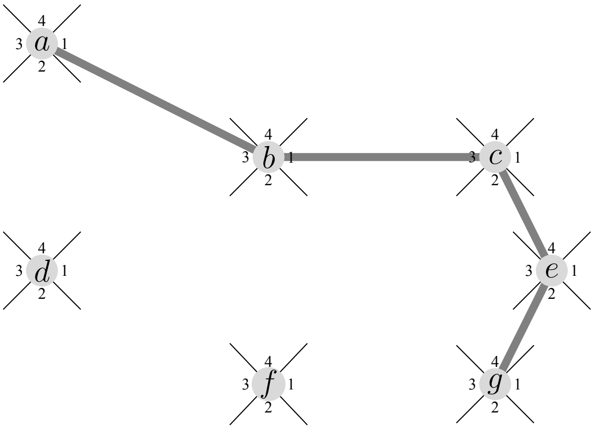
Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	-	-
e	-	-
f	-	-
g	-	-

Figure 3.12: “c” updates for reaching “a” via “3b” with cost 2, marks “b” as neighbor.



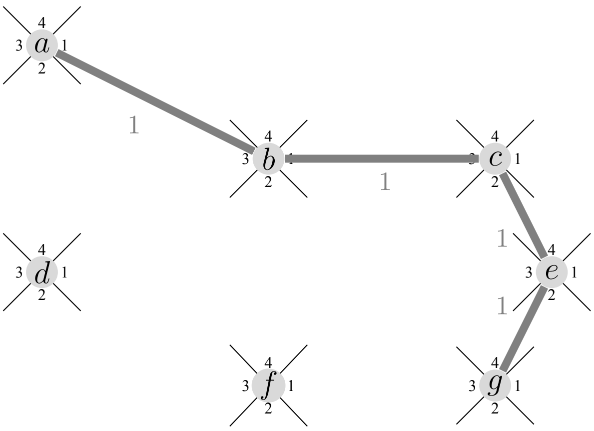
Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	-	-
e	c	a-4c-3
f	-	-
g	-	-

Figure 3.13: “e” updates for reaching “a” via “4c” with cost 3, marks “c” as neighbor.



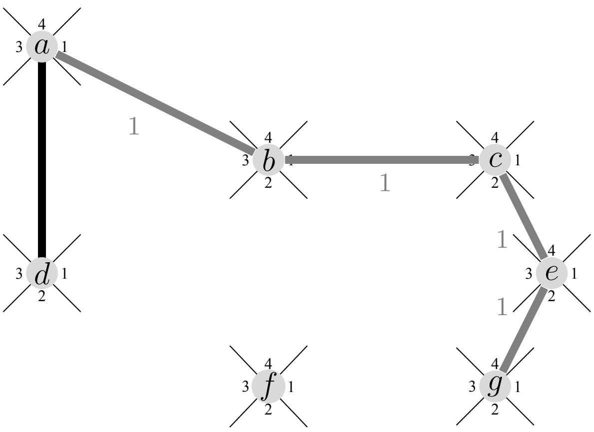
Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	-	-
e	c	a-4c-3
f	-	-
g	e	a-4e-4

Figure 3.14: “g” updates for reaching “a” via “4e” with cost 4, marks “e” as neighbor.



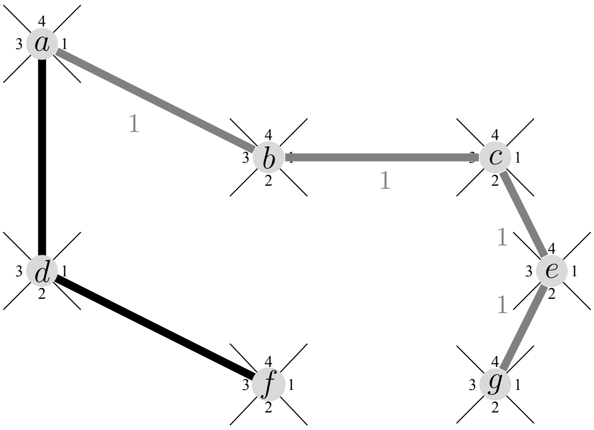
Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	-	-
e	c	a-4c-3
f	-	-
g	e	a-4e-4

Figure 3.15: “g” remembers that “a” can be reached via “4e” with cost 4.



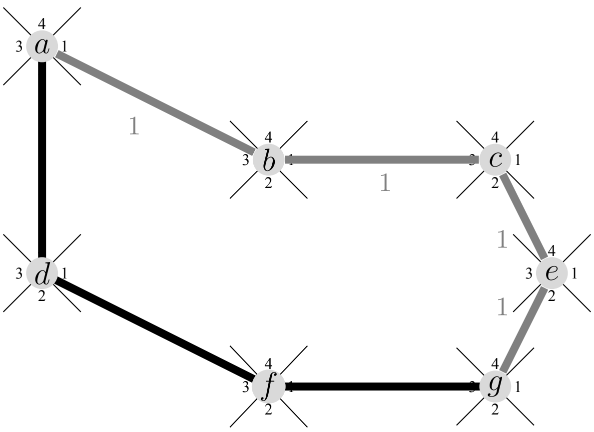
Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	a	4a-1
e	c	a-4c-3
f	-	-
g	e	a-4e-4

Figure 3.16: “d” updates for reaching “a” via “4a” with cost 1, marks “a” as neighbor.



Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	a	4a-1
e	c	a-4c-3
f	d	a-3d-2
g	e	a-4e-4

Figure 3.17: “f” updates for reaching “a” via “3d” with cost 2, marks “d” as neighbor.



Node	Ns	Dists
a	-	-
b	a	3a-1
c	b	a-3b-2
d	a	4a-1
e	c	a-4c-3
f	d	a-3d-2
g	e, f	a-3f-3

Figure 3.18: “g” updates for reaching “a” via “3f” with cost 3, marks “f” as neighbor.

3.4 Performance Evaluation

For the WNSNs, simulations are carried out by using "ns-3[3]", which is a discrete-event network simulator for Internet systems, and "Nano-Sim[4]" library of the ns-3, which is developed for nanonetworks [114, 115]. The Nano-Sim package is modified to include "Battery level" and two states, "FULL" and "CHARGING", are added to the nodes. The proposed method, LaGOON routing, is compared through simulations with the base case as "plain flooding" and the "random routing" (nodes are chosen randomly for forwarding) of the Nano-Sim package, to see if there is any improvement. The proposed method for WNSNs is benchmarked against flooding and random routing. Flooding and random routing are two simple and widely used protocols. Flooding is computationally simplest routing protocol in the sense of requiring no heuristics. But it is very costly when energy consumption is considered. The multiplication of packets is for increasing the chance of successful transmission. Periodic flooding is a technique that is used in exploratory purposes, like in [69]. Random routing is another computationally "light" routing method, in which nodes randomly choose neighbors to forward packets. This type of routing works well if the network is highly interconnected and does not lead to high energy consumption like flooding. Random forwards, in this case, can allow packets to reach the destination quickly. Also, random routing is proven to balance sensors' energy consumption in the wireless network (fair), as the next nodes are chosen randomly to transmit data [20, 104]. In this regard, the LaGOON protocol is benchmarked against flooding which is computationally lightweight and robust protocol and against random routing which is computationally lightweight and energy-wise "fair" protocol. For this thesis, results are presented from the simulations of the energy-aware routing protocols for the ad hoc WNSNs.

In the following sections, detailed discussions is presented for the simulation setup and results. In Section 3.4.1, overview of the simulation setup is given. After that in Section 3.4.2, the metrics used for assessing the performance of the routing algorithms and the parameters are explained. Finally, in Section 3.4.3 the results of the simulations are tabulated.

[3] https://www.nsnam.org
[4] https://telematics.poliba.it/files/tools/nano/nanonetworks.tar

3.4.1 Simulation Setup

For the simulations, “healthcare” ([114, 115]) example program of the Nano-Sim package is utilized by changing some parameters. The simulation time is fixed at 7 seconds in order to give routing algorithms enough time to do several rounds of forwarding to each node. More simulation time generates excessive amount of trace files. The system generated about 10 packets per second per node for the transmissions. Some of the packets are dropped prematurely if the sending node is in charging stage or simply does not have enough energy. Four different values for the transmission range of nanonodes are used as 0.005m, 0.01m, 0.015m, and 0.02m. “Transparent MAC”([114, 115]) scheme is utilized for simulations. The assumption that used in the Nano-Sim package for the nodes already knowing their neighbors (in the transmission range) is also used in simulations and in the implementation of the LaGOON routing protocol. The number of devices is fixed as, 1 nanogateway, 10 nanorouters, but for the nanonodes, four different values are used as 50, 100, 200, and 300 nanonodes. The summary of the important simulation parameters is given in Table 3.1.

Table 3.1: Summary of the simulation parameters.

Parameter	Value
Simulation time	7 secs
Packet rate	10 packet per sec
Transmission range	0.005m, 0.01m, 0.015m, 0.02m
Number of gateways	1
Number of routers	10
Number of nodes	50, 100, 200, 300

3.4.2 Performance Metrics and Parameters

The LaGOON routing is benchmarked against the baseline cases of "plain flooding" and "random routing". Four metrics are selected to assess the overall energy efficiency and the transmission efficiency. Namely the number of "CHARGED", "DROP", "SEND", and "FORWARD" events. In order to determine the the number of these events, 50 (for a better approximation) simulations are carried out and the average number from these simulations are rounded.

For measuring the overall energy efficiency, the number of times that nodes experienced "CHARGED" event is counted. This simple measure, shows indirectly the level of the energy the system has used in the simulation duration. The consumed energy level and the packet traffic are proportional to the number of the "CHARGED" event. Energy efficient routing should avoid redundant energy consumption unless this helps to optimize further transmissions. Unnecessary "FORWARD" events may cause packets to go around and consume energy of the devices. Packets that are forwarded many times may be dropped because of two reasons: Expired TTL and arrival to the node in "CHARGING" state.

The number of "DROP" packet events is a simple metric that can measure the performance of the overall transmission and reliability of the method.

The number of "SEND" events depend mainly on the battery capacity of the nanonodes. Most of the packets are dropped prematurely because when they are created to be sent, the associated nanonode selected by the simulation system was in "CHARGING" stage. Since this was valid for all routing algorithms, no adjustments were necessary, as only the comparison was required. The aim in measuring "SEND" events, was to see roughly the fraction of time that is spent for "CHARGING" stage by the nodes utilizing specific routing algorithm. Successful algorithm should yield higher number of "SEND" events. If the algorithm is spending much time in "forwarding" due to "bad" routing decisions, then nodes will be in "CHARGING" stage most of the time, and the algorithm will yield very low number of "SEND" events.

The number of "FORWARD" events basically tells how "parsimonious" is the specific routing algorithm in carrying out the "routing". Less number of "FORWARD" events is desired, as this means “less energy” is spent in carrying packets to their destinations. The simulation time is fixed at 7 seconds, for all routing algorithms as it is stated.

Four different transmission range values are used for the nodes, as shown in Tables 3.2, 3.3, 3.4 and 3.5 below. The idea here is to see the performance of the overall system under the increased transmission traffic. As the transmission range of the nodes increases, the number of receiving nodes also increases. Especially in the case of flooding, this causes many copies of the packets to be generated for forwarding.

3.4.3 Simulation Results

The results are summarized numerically in Tables 3.2 - 3.5 and visually in Figures 3.19 - 3.22 below. In the 3D bar charts (Figures 3.19 - 3.22), the number of nodes and the transmission ranges are listed on the right horizontal axis. Namely four different levels of transmission ranges (0.005m, 0.010m, 0.015m, 0.020m) are permuted with four different number of nodes (50, 100, 200, 300), producing total of 16 levels. Each metric listed in this section is representing average of 50 simulation results. For three different methods (flood, random, lagoon), four different levels of transmission range and four different number of nodes are used. In total, 2400 ($50 \times 3 \times 4 \times 4$) simulations are carried out.

Table 3.2: Comparison of "CHARGED" events

TX Range	Method	Number of Nano Nodes			
		50	**100**	**200**	**300**
0.005	**lagoon**	224	444	893	1336
	random	227	458	909	1340
	flood	266	569	1175	1770
0.01	**lagoon**	226	428	839	1252
	random	226	434	858	1283
	flood	286	593	1196	1796
0.015	**lagoon**	219	421	825	1226
	random	220	421	825	1226
	flood	295	601	1200	1799
0.02	**lagoon**	219	420	822	1222
	random	218	420	822	1222
	flood	302	603	1200	1803

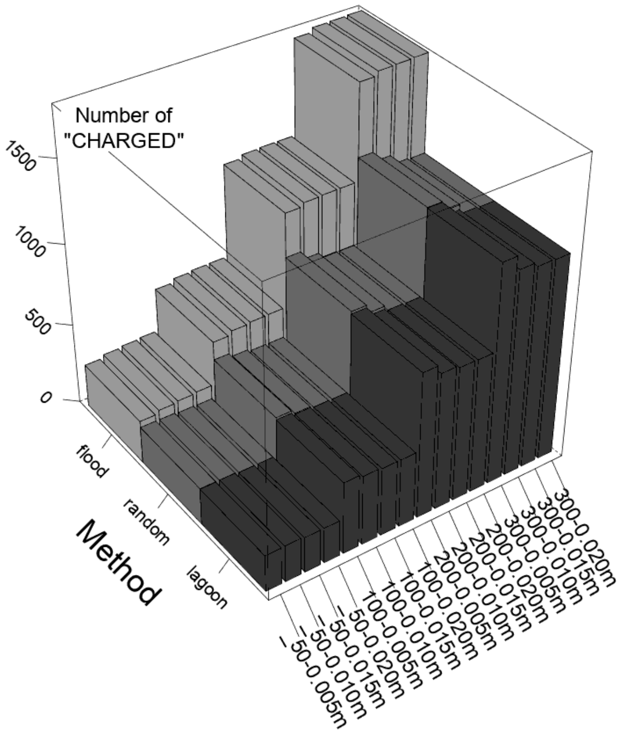


Figure 3.19: 3D bar chart for the "CHARGED" events.

The number of "CHARGED" events are lower in LaGOON, which can be seen from Table 3.2 and from Figure 3.19. The implication of the results is that the LaGOON has better energy efficiency and better transmission efficiency compared to the plain flooding protocol. Considering Algorithm 1, it can be seen that the space complexity is at the order of O(N) where N is the number of the nodes. Where as the time complexity to pick the best neighbor or "LaGOON", is just O(1), as fast table lookup mechanism can be used by utilizing node ids. Considering computational cost, this is not much different than picking a random node to forward. It can be said that the difference between LaGOON and random routing is insignificant. But when other factors are considered, like the number of “DROP” events, the LaGOON is better than random routing. In fact, LaGOON has the least “DROP” rate, and it is the “most reliable” protocol compared to flooding and random routing. This difference can be seen from Table 3.3 and from Figure 3.20 more clearly, where the number of the “DROP” is very low in LaGOON protocol compared to the plain flooding protocol and to the random routing. This is expected as the LaGOON is keeping the minimum number of “forwarding” events. From Table 3.3 and from Figure 3.20 it can be seen that for increasing range and number of nodes (denser traffic), the difference between LaGOON and random routing grows. Denser traffic may help random routing for finding routes to the destination. But also increases the chance of choosing “charging” nodes and “circulating” packets unnecessarily longer in the network. Notably, the number of “DROP” events for the flooding protocol is very high since many copies of the same packet are generated and forwarded.

Table 3.3: Comparison of “DROP” events

TX Range	Method	Number of Nano Nodes			
		50	100	200	300
0.005	lagoon	716	1668	3599	5498
	random	858	2013	4114	6156
	flood	2603	8512	28394	54689
0.01	lagoon	853	1608	3474	5325
	random	1002	2127	4316	6546
	flood	4220	14119	40593	79041
0.015	lagoon	883	1524	3113	4797
	random	1043	2317	4626	7013
	flood	5955	17708	51303	89375
0.02	lagoon	900	1206	2589	4105
	random	1167	2524	5138	7867
	flood	6462	20492	65714	154610

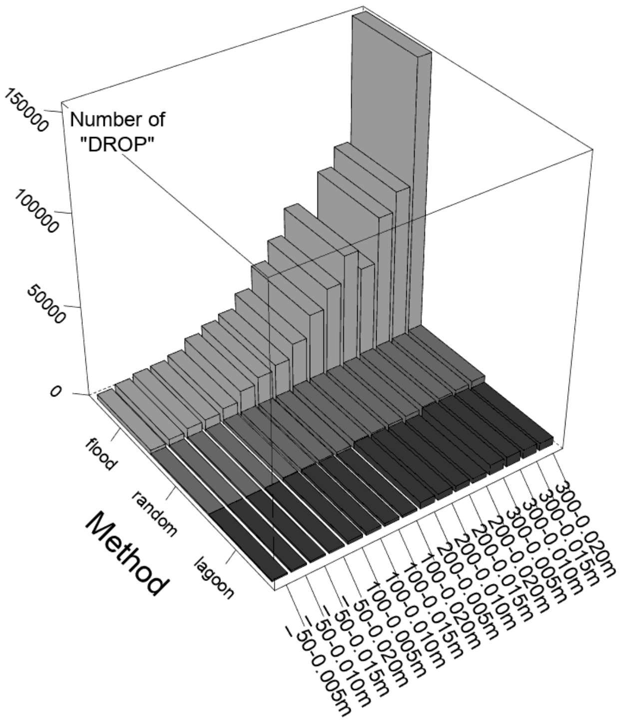


Figure 3.20: 3D bar chart for the “DROP” events.

Table 3.4 and Figure 3.21 show the statistics about the number of "SEND" events. This measure is related to the "overall energy utilization performance" of the protocol. It also shows the "throughput" of the overall system in terms of successful packet generation and delivery. If nodes are, most of the time, in "charging" state, the number of "SEND" events will be low. The only reason for this is the bad routing decision. As it can be seen from Table 3.4 and from Figure 3.21, LaGOON and random routing being almost similar in performance. But without looking at Table 3.5 and at Figure 3.22, it can not be understood the difference between LaGOON and random routing.

Table 3.4: Comparison of "SEND" events

TX Range	Method	Number of Nano Nodes			
		50	**100**	**200**	**300**
0.005	**lagoon**	1152	2360	4604	6871
	random	1102	2260	4488	6607
	flood	757	1183	1572	1911
0.01	**lagoon**	1215	2542	4946	7328
	random	1231	2415	4728	7070
	flood	643	831	1124	1419
0.015	**lagoon**	1343	2790	5496	8131
	random	1319	2646	5150	7689
	flood	536	678	998	1194
0.02	**lagoon**	1463	2951	5900	8840
	random	1439	2888	5763	8626
	flood	445	599	828	1192

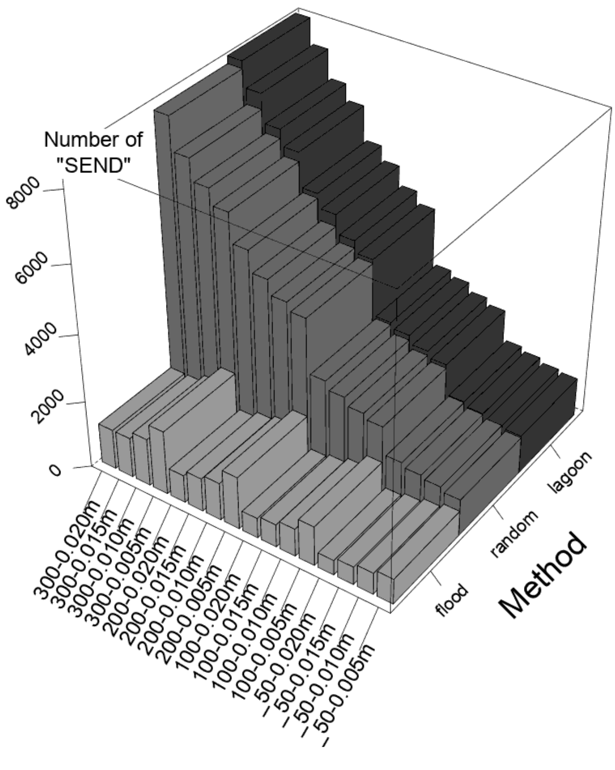


Figure 3.21: 3D bar chart for the "SEND" events.

Table 3.5 and Figure 3.22 show again increasing difference between LaGOON and random routing as the transmission range gets further and the number of nodes increases. Basically for increased traffic LaGOON becomes better than random routing. In other words, in the case of less number of nodes, choosing nodes for forwarding randomly may help, but when the traffic increases this way may be costly as it is explained in the previous paragraph. That is where LaGOON excels, by utilizing the minimalist way and adding little "heuristics" to routing decisions.

Table 3.5: Comparison of "FORWARD" events

TX Range	Method	Number of Nano Nodes			
		50	**100**	**200**	**300**
0.005	**lagoon**	749	1344	2771	4157
	random	793	1536	3002	4452
	flood	1472	3467	8026	12554
0.01	**lagoon**	713	1127	2231	3351
	random	688	1266	2478	3677
	flood	1702	4020	8648	13249
0.015	**lagoon**	550	820	1592	2442
	random	579	992	1981	2924
	flood	1892	4234	8811	13515
0.02	**lagoon**	402	511	938	1358
	random	425	701	1272	1859
	flood	2045	4331	8986	13536

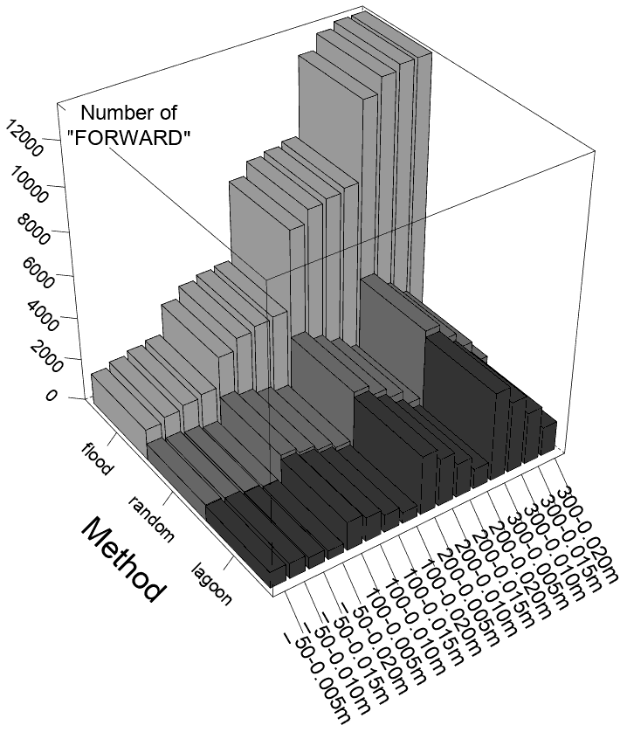


Figure 3.22: 3D bar chart for the "FORWARD" events.

In general, in all the benchmarks, proposed LaGOON protocol performed very well, without compromising among energy saving, reliability, and computational cost for routing decisions. The results are justified with the statistical analysis in which "ANOVA analysis" (whether means are different) and "Tukey Honest Significant Differences" (which mean differences are statistically significant) tests are applied to verify the differences in mean values. One of the highlights of the LaGOON protocol is the fact that having such a good level of efficiency with a little computational cost can give space to further optimizations.

Flexibility is another good feature of the protocol. Not only the protocol is topology independent, but also it can be customized for handling different mobility models. The "evolving learning" mechanism for route discovery is carried out in a distributive manner. In the implementation used in this thesis for the experiments, control packets are not included. However, for mobile networks, additional control packets can be added easily for broadcasting position changes. This can help LaGOON for faster route discovery. In the same manner, hierarchical position information can also be added to LaGOON by imposing restrictions in the routing.

3.5 Contributions of the Thesis to Routing

In this section, the contributions of the thesis to the routing research will be listed. As a theoretical contribution, the gaps in the energy aware routing research will be listed and discussed. The discussions on the proposed routing algorithm will be presented as a framework for a simple and energy aware routing.

While the routing is very extensively researched for WSNs, still for WNSNs there are open issues and challenges. In nanonetworks still, there is no standard routing protocol, as in the case of WSNs. In WSNs there are well known routing protocols like AODV, DSR. However, in the case of nanonetworks the routing protocols are in the preliminary stage. There are many reasons for that. One reason is the peculiarities of the THz frequency communication. In THz communication, not only MAC layer needs to be customized, but also antenna technologies should be customized too [12].

On the other hand, still, there are gaps and issues that can be further elaborated in the routing related research for WSNs. Statistical modeling of the packet arrival is one of them. In fact, the issue is rooted in considering the "user (sensor) behavior". The sensor nodes, depending on the application of the deployed WSN, can exhibit a peculiar way of transmission patterns. For example in the temperature sensing, the transmission may obey certain communication patterns, if the system reports temperature every 5 minutes or reports the temperature change during the day when there is one or two Celsius deviance. These type of "user behavior" can be modeled statistically in the simulators. One of the benefits that such study can provide is the customized MAC protocol in which duty cycling can be adjusted to the "user behavior" or can learn the "user behavior" patterns. Such enhancements can save energy in the WSNs. Certain assumptions regarding the existing statistical models for the system attributes should be validated before applying them to the simulations. The paper [46] is one of the good examples of the perils of accepting conventional models without verification. The study focused on the statistical modeling of the packet arrivals, specifically for the cluster heads in WSNs. While authors stated that the exponential packet inter-arrival distribution holds only under special conditions involving small scale WSNs (10-15 nodes) and sparse traffic, they also explained the trade-off between energy consumption and average end-to-end delay of the system. The study emphasized the importance of the statistical validation of the distribution types regarding the packet inter-arrivals.

Another important issue is the customized routing algorithm that combines “battery awareness” and “duty cycling”. Battery aware routing topic is proposed and studied in [96] and comprehensive taxonomy on the duty cycling is given in [35]. Batteries can “self-recover” if the current draw can be kept in the specific margins according to the type of the battery. Energy aware routing algorithm combined with the appropriate MAC layer can interleave duty cycling to allow battery self-recovery. Energy aware MAC layer can also decide on the splitting of the frame into smaller sizes for avoiding current over-draw. These two techniques can keep the battery in safe margins allowing it to self-recover. However, in the literature no such technique is proposed. One important factor in researching such a technique is the battery models that the WSN simulators offer. Mostly simulators assume simple “linear” battery model, in which every transmission and reception require the same amount of energy. However, this assumption is so limiting and simplistic.

Although the thesis is pointing out such issues listed above, they are not included in the implementations of this study. However, as a theoretical contribution, discussions on these issues are offered as conceptual frameworks. The practical contributions of the thesis are mainly focused on the routing, since the idea of transmissions being the most energy consuming activities is embraced as a main premise in the thesis. The proposed routing algorithm is itself a contribution for the routing research related to the WNSNs, when the number of existing implementations is considered. In Table 3.6 existing approaches related to the WNSNs are listed and compared.

Table 3.6: Comparison of existing routing algorithms for WNSNs (as of 2018).

Paper	Contribution Summary
zhou2012 [171]	PHY layer and pair-to-pair routing. Not very energy efficient.
yu2015 [59]	Channel-aware routing protocol. 1D topology. Energy not considered.
liaskos2015 [153]	CORONA. Minimize hop count. 2D Grid topology. Energy considered. “Anchor” nodes.
liaskos2016 [92]	Peer-to-peer routing. 2D Grid topology. Node classification based on past statistics.
tairin2017 [148]	Hierarchical AODV. Energy considered.
afsana2018 [3]	Channel aware energy conserving protocol. Hybrid clustering of the nanonodes and centralized scheduling.
lagoon	Lightweight energy aware protocol. Minimize hop count. Topology independent.

In the proposed routing algorithm, the setup was not necessary, although it can be applied to speed up the "route learning" process. The sensors nodes do not have to follow certain flooding period. However, any node that does not have any path information in its routing table, individually, can do flooding. This feature makes the algorithm very lightweight and flexible, both in computation and in transmission. In some protocols, this phase is important and specialized packets need to be transmitted. Even in some protocols time synchronization is essential as the network limits the setup time according to the time limit set by the network administer. Such protocols may have higher energy consumption due to the extra transmissions for set up packets. Especially in WNSNs energy is very limited and such protocols can not be used. Compared to other proactive algorithms (table driven, e.g. DSDV), in which route discovery is done before the request and global routing tables are distributed, LaGOON does not proceed in this way. In the proposed LaGOON protocol routing tables are local and evolve with the time as the new information is received. Also contrary to the reactive routing algorithms (on demand, e.g. AODV), LaGOON does not request route discovery on demand. However, nodes route packets according to the local routing they have so far. In the case of "empty routing" table, LaGOON can be customized to initiate routing with flooding or by choosing a random neighbor. Node failures and node mobility can be solved with periodic controlled flooding.

Another contribution of the thesis is the "directional" version of the LaGOON protocol, which is explained in Chapter 3. The flexibility of this protocol is based on the directional MAC and physical layers. It requires minor changes to be adapted to directional communication. The routing proceeds as in the case of omnidirectional case, with the addition of direction information recorded in the routing tables. The algorithm can accommodate an arbitrary number of directional antennas. The implementation of this version was not included in this thesis. One of the reasons was the capabilities of the available simulators did not cover directional antenna simulations.

CHAPTER 4

DIRECTIONAL ANTENNA

In the previous section, the proposed energy aware LaGOON protocol is discussed in detail by highlighting its energy aware properties. An energy aware routing algorithm can save energy in many ways. It can forward messages over shortest paths reducing the number of transmissions. The routing method in doing this, it can also try to keep the overhead associated to the mechanism low. Namely, control messages specific to the routing itself. Routing algorithm can also be "battery aware". The batteries can be depleted faster if the current draw is very high for transmission. The "battery aware" routing can use packet division and duty cycling in such ways that the continuous high current draw can be optimized to allow self-recharging of the battery. But still, with the use of omnidirectional antennas, the signal will be transmitted all around. With the exception of "flooding", this transmission pattern is not necessary. By "broadcasting" the signal all around, omnidirectional antennas consume higher levels of energy and introduce limits to the energy savings of the "routing" algorithm. On the other hand, directional antennas for the same transmission ranges, they consume less energy for communication and they contribute to the energy savings from the directional antennas. In this sense, it is desirable to establish synergy between the energy aware routing and the directional antenna.

This section will present the second method that is proposed related to the energy problem in WSNs, which involves the use of directional (directed, sectored, etc...) antennas. In the following subsections little overview of the important antenna characteristics, comments on the works related to the use of directional antennas in WSNs, and performance characteristics of the designed directional microstrip patch antenna array will be presented.

4.1 Antenna Basics

According to the IEEE Standard Definitions of Terms for Antennas document (IEEE Std 145–20133) [67], antenna defined as:

> "That part of a transmitting or receiving system that is designed to radiate or to receive electromagnetic waves."

Antennas come in various types and geometries. In [21] various types of antennas listed, mainly according to the geometry and architecture:

1. Wire
2. Aperture
3. Microstrip
4. Array
5. Reflector
6. Lens

Figure 4.1 below presents a classification of the antennas used in communication systems based on the radiation technology.

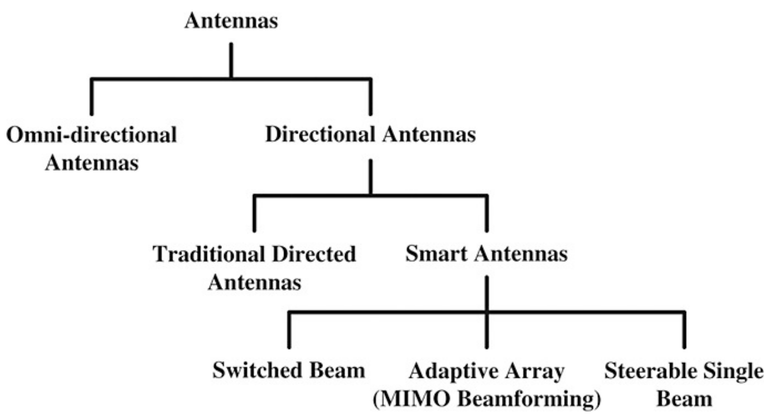


Figure 4.1: Classification of antennas based on the technology utilized for directing signals. (Source: [43])

In this thesis hybrid type is used, in which microstrip antennas are combined in 2 by 2 array to form directional antenna. Microstrip antennas basically consist a dielectric substrate sandwiched between a metallic patch and a ground layer. Various types of substrates are used, which should be selected according to the frequency and performance requirements. The article [81] presents discussions on the performance effects of the substrates that can be used for microstrip antennas. As it is stated in [21, pp. 25-105], there are many parameters that can “describe” the performance of an antenna. Detailed discussions on the various characteristics of antennas can be found in textbooks such as [21] and [119]. The thesis [158] presents substantial material on the theory and practice of the antenna design, specific to WSN applications.

For this thesis the focus of interest was on the “gain” and the “return loss” (S11: S-parameters [28]). “Efficiency” of an antenna is a multidimensional concept. Basically, it considers losses related to the input terminal of the antenna. These losses can be grouped as “reflections” and “conduction and dielectric” losses. Reflections are due to the mismatch between transmission circuitry (brings current to the antenna) and the antenna. Conduction and dielectric losses are due to resistance [21, p. 60].

Voltage Standing Wave Ratio (VSWR) is a performance measure that is related to losses due to the mismatch between antenna and the transmission line. It has a value that is either greater than 1 or equal to 1. VSWR value 1 means a perfect match between the antenna and the transmission line. Values that are greater than 1 signify greater losses due to mismatch [27]. VSWR is a function of the reflection coefficient known as S11 (return loss) which is represented by Γ in the formulas. Generally, S11 is given in dB. The formula for S11 represented in dB is given in equation 4.1 below:

$$\text{S11} = -20\log|\Gamma| \text{ (dB)} \tag{4.1}$$

Reflection coefficient quantifies the power reflected from the antenna. The relationship between VSWR and S11 can be given in equation 4.2 below [29]:

$$\text{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{4.2}$$

Table 4.1 shows the relationship among VSWR, S11, and reflected power numerically [29].

Table 4.1: Numerical relationship among VSWR, S11, reflected power percentage, and reflected power in dB. (Source: [29])

VSWR	Γ (S11)	Reflected Power(%)	Reflected Power(dB)
1.0	0.000	0.00	$-\infty$
2.0	0.333	11.1	-9.55
4.0	0.600	36.0	-4.44
8.0	0.778	60.5	-2.18
20.0	0.905	81.9	-0.87
50.0	0.961	92.3	-0.35

"Gain" (relative gain) is, mostly, stated in reference to isotropic antenna. Isotropic case represents ideal case of an antenna in which the radiation of signals are spherical (equal in all directions). More technical explanation can be given by quoting Balanis [21]:

> "Gain of an antenna (in a given direction) is defined as the ratio of the intensity, in a given direction, to the radiation intensity that would be obtained if the power accepted by the antenna were radiated isotropically. The radiation intensity corresponding to the isotropically radiated power is equal to the power accepted (input) by the antenna divided by 4π. "

Figure 4.2 depicts the antenna coordinate system that is helpful for explaining the concept of "gain". Directional antennas, when they radiate they form a "beam" like radiation pattern, instead of a "sphere" which isotropic antenna supposed to form. This beam, which is named as "main lobe" can be seen in Figure 4.2.

The equation 4.3 [21, p. 62] describes gain (relative to isotropic) in mathematical format, which is dimensionless. In the equation 4.3, $U(\theta, \phi)$ represents "intensity" in a given direction, which can be defined as "the power radiated from an antenna per unit solid angle" [21, p. 37].

$$\text{Gain} = \frac{4\pi U(\theta, \phi)}{\mathrm{P}_{in}(\text{lossless isotropic source})} \tag{4.3}$$

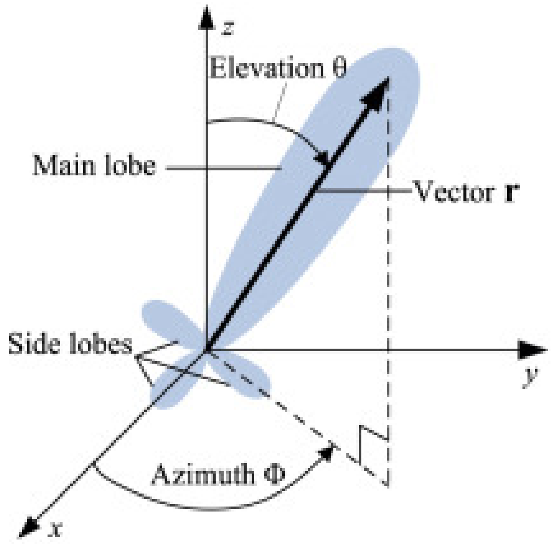


Figure 4.2: Antenna Coordinate system. (Source: [91])

In order to show the gain relationship among different types of antennas, in Figure 4.3, radiation patterns of isotropic, omnidirectional, and directional antennas are depicted. In the figure, typical gain values are given in dBi (unit of gain as deciBel relative to the isotropic radiator).

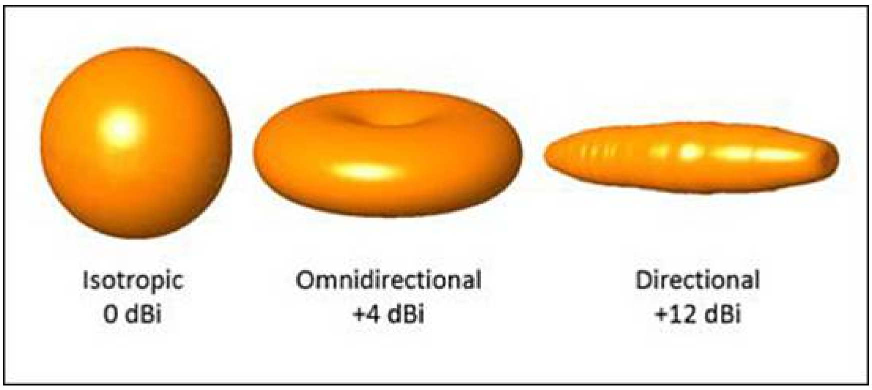


Figure 4.3: Radiation patterns of isotropic (theoretical), omnidirectional (typical), and directional (typical) antennas and typical gain values. (Source: http://apprize.info/network/ccna/ccna.files/image102.jpg)

4.2 Research in Directional Antenna

Research for utilization of directional antennas in sensor nodes is developed in to two branches. While several studies focus on the performance characteristics of the physical antenna design, others emphasize the development of specialized routing and/or specialized MAC protocols.

Since in sensor networks most of the energy is consumed for communication, optimization of the transmissions and receptions can improve sensor battery lifetime along with the overall network lifetime. In that sense, directional antennas offer optimization at the local level (involving only the sensor node) and also at the global level (overall network lifetime). Considering the architecture of a sensor node, it can also be said that directional antennas are one of the optimization technologies at the hardware level [71, 123, 163]. They have advantages over the omnidirectional antennas, such as higher gain, less interference, spatial reuse, longer transmission range, security, and less power consumption [39, 42, 43, 54]. However, the directional antennas are not widely used in WiFi communication today. Mostly omnidirectional antennas are utilized in personal computers. This is because, originally the IEEE 802.11 (physical and MAC level specifications for wireless communication) standard designed for omnidirectional antennas in 1997.

On the other hand, many studies tried to extend this standard and implemented experimental support for directional antennas like in [84] and in [172]. Consequently, the first MIMO (Multiple Input Multiple Output) support is included in the IEEE 802.11n standard, in which multiple antennas are utilized for achieving higher data rates through aggregation, compared to the SISO (Single Input Single Output), MISO (Multiple Input Single Output), SIMO (Single Input Multiple Output) systems.

In Figure 4.4, the possibility of increasing the data rate in MIMO systems is depicted compared to other types of systems.

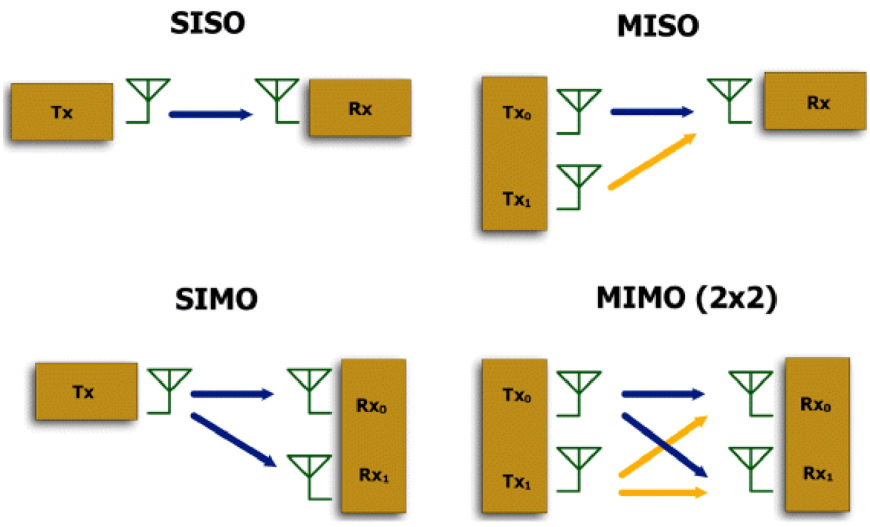


Figure 4.4: Data rate aggregation in a MIMO antenna system compared to other systems. (Source: [26])

Data can be divided and transferred through many lines simultaneously in the MIMO systems. Both transmission and reception can benefit from the multi-channel communication without requiring extra power.

After that, first support for directional antennas came with the IEEE 802.11ac standardization of the beamforming property in 2008. A brief comparison of various IEEE standards for WiFi communication can be seen in Table 4.2.

Table 4.2: IEEE WiFi standards. (Source: [51, 161])

IEEE Standard	Frequency (GHz)	Bandwidth (MHz)	Max Data Rate (Mbit/s)
802.11	2.4	20	2
802.11b	2.4	20	11
802.11a	5	20	54
802.11g	2.4	20	54
802.11n	2.4, 5	20,40	600
802.11ac	5	20, 40, 80, 160	6930
802.11ad	60000	2160	6760
802.11ah	0.9	1–16	347

In thesis [30], performance improvements in ad hoc networks with directional antennas topic was studied. The author pointed out the current weakness of the IEEE 802.11 Distributed Coordination Function and proposed solution based on the use of directional antennas. The idea was to use directional antennas in accordance with the carrier sensing threshold adjustments and power control for transmissions with a proposed MAC protocol for performance improvements. The thesis proposed novel way in achieving this idea by considering heterogeneity (nodes with omnidirectional and directional antennas) of the sensor nodes. The simulations in the thesis considered standard IEEE 802.11 Directional Virtual Carrier Sensing (DVCS) MAC protocol, the IEEE 802.11b (improved version of the IEEE 802.11 with 11 Mbit/s throughput), and the proposed version of the DVCS (PVDVCS, Power Controlled Directional Virtual Carrier Sensing). The thesis reported that PCDVCS achieved 99.3% increase in throughput compared to the IEEE 802.11b and 35% increase over DVCS. Also, PCDVCS achieved reduced power consumption of 83% over the IEEE 802.11b and 64% compared to DVCS.

In [88], the author presents interesting comparisons on the capacity of sensor networks (n identical nodes, each transmitting W bits per second) using directional and omnidirectional antennas. The paper [57] calculated the capacity of the network using omnidirectional antennas and gave the formula as it is shown in equation 4.4 below:

$$\sqrt{\frac{1}{2\pi}}W\sqrt{n}\text{ bits per second} \tag{4.4}$$

On the other hand, authors in [168] calculated the capacity of the network using directional antennas (with transmission beam of α and receiving beam width of β) and gave the formula as it is shown in equation 4.5 below:

$$\sqrt{\frac{2\pi}{\alpha\beta}}W\sqrt{n}\text{ bits per second} \tag{4.5}$$

As it can be seen from the equations 4.4 and 4.5, the capacity of a network with directional antennas, can be increased by using arbitrary values for the α and β. The author in the same talk ([88]) goes further in comparing the energy consumption of omnidirectional and directional antennas by introducing a parametric framework based on the range and the transmission beam angle of the antennas. The talk proposes that the energy consumption (E) of an antenna is related to its range (R) and to its transmission beam (α). This proportional relationship is shown with the equation 4.6 given below:

$$E \propto \frac{\alpha}{2} \cdot R^2 \text{ (For omnidirectional } \alpha = 2\pi) \tag{4.6}$$

Considering the same energy amount given to each type of antenna as E, the expression for the relationship among energy, range, and transmission beam angle can be given in equation 4.7 below:

$$R \propto \sqrt{\frac{2E}{\alpha}} \text{ (For omnidirectional } \alpha = 2\pi) \tag{4.7}$$

The implication of the equation 4.7 is that, for the same energy amount, directional antenna with narrower transmission beam can reach further distances. It can also be concluded that for the fixed range, the directional antenna spends less energy, since the transmission beam angle is less than 2π. Total energy saving can be calculated by summing up all the savings from each node in the WSNs. For large WSNs with hundreds of sensor nodes the energy saving can be huge if directional antennas are used. This concept is visualized in Figure 4.5 below, in which the communication range difference between omnidirectional and directional antennas is depicted.

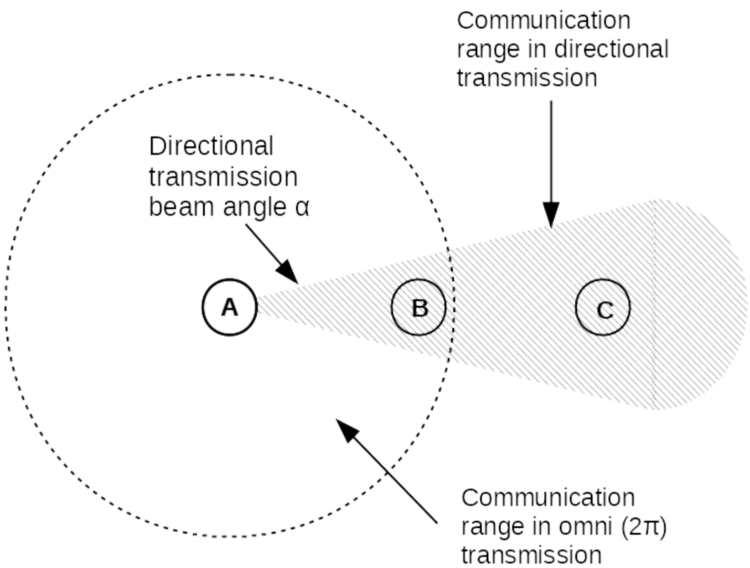


Figure 4.5: Comparison of the transmission coverage of the omnidirectional and the directional antennas. (Source: [40, p. 308])

In the figure, the transmission ranges are shown for equal energy consumption. Transmission from sensor node A to B can be achieved with lower energy consumption in the case of directional antenna. However for transmission from A to C, omnidirectional antenna should consume greater energy compared to the directional antenna. While directional antennas can have a more focused signal beam and greater ranges in signal transmission requiring the same amount of energy, omnidirectional antennas send the signal all around with smaller range. This way directional antennas can be more frugal in energy consumption for the required range.

Figure 4.6 depicts the visual comparison of the spatial reuse differences between omnidirectional and directional antennas. Spatial reuse is higher in the case of the directional antennas as more than one communication link can be formed at the same time. However in the case of omnidirectional antenna, when two nodes are in communication, all the nodes in the range has to be silenced.

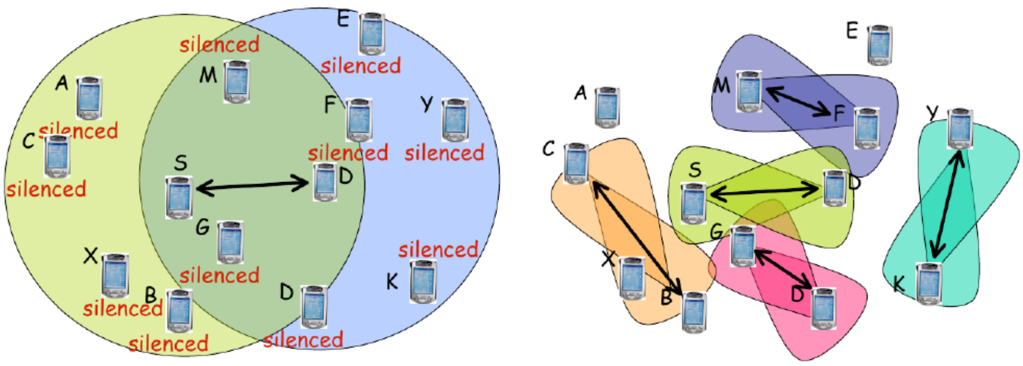


Figure 4.6: Comparison of the omnidirectional and directional antennas in communication. (Source: [37])

Table 4.3 below gives a comparison of omnidirectional and directional antennas according to various properties. These properties help designers and users of the communication system in choosing the appropriate technology.

Table 4.3: Comparison of omnidirectional and directional antennas according to various properties. (Source: [40, p. 307])

Characteristics	Omnidirectional	Directional
Spatial reuse	Low	High
Network connectivity	Low	High
Interference	Omni	Directional
Coverage range	Low	High
Cost and complexity	Low	High

However there are problems that should be taken care when directional antennas are used in communication. Majority of the problem cases are inherent in wireless communication. In some cases use of directional antennas can introduce more specific problems, because of their ability of focusing transmission to a specific region rather than "broadcasting" all around. In other cases this ability of focusing the transmission to a specific region can be the solution to some problems. The severity of these problems can be ranged from mild performance degradations (e.g. decrease in throughput) to deadlocks in communication. In [43, 85, 163] authors presented and discussed these problems related to wireless communication. Generally, these problems can be solved by designing directional antenna based MAC protocols [4, 5, 146, 147, 164]

- Deafness: When two nodes are communicating by using directional antennas, the transmitting node is said to be "deaf" to the third transmitting node.
- Hidden Terminal: When two nodes are communicating by using directional antennas, the third node that transmits to one of them is said to be "hidden" to the other two communicating nodes.
- Exposed Terminal: When two nodes are communicating by using directional antennas, other nodes in the range that hears the conversation is said to be "exposed" to that conversation, since they can not communicate to other nodes out of this range.
- HOLB (Head Of Line Blocking): This problem arises when FIFO packet queues are utilized along with the directional antennas. In Figure 4.7 node C has two consecutive packets to B via node A. But after the first packet to B via A, node A becomes "deaf" to the second packet to B from C. Since the queue is FIFO, the third packet to D is blocked.

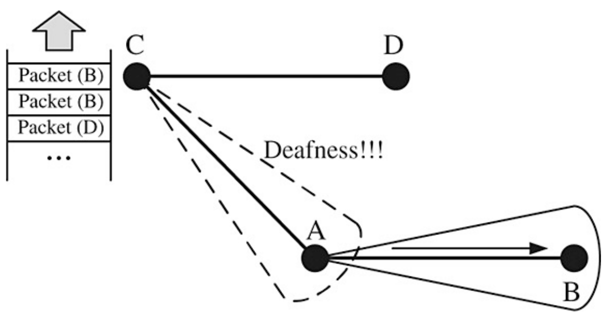


Figure 4.7: HOLB problem in directional antennas. (Source: [43])

The problem of "deafness" and solutions to this problem is discussed in [56]. Hidden and exposed terminal problems are discussed and solutions are proposed in [2, 124, 130]. The problem and the solutions related to HOLB is discussed in [86]. In [146, 147], authors discussed deafness and hidden terminal problems specific to directional antennas in wireless multi-hop networks and proposed a MAC protocol to solve the associated problems.

In [88], the author proposed another comparison of various characteristics of the omnidirectional and directional antennas. Table 4.4 shows the list of the characteristics discussed in the talk. The property called "Routing - Stretch Factor" is related to the memory efficiency of the algorithm, which is defined as the maximum ratio of the length of the routes (in hops) found by the routing algorithm and the distance between the source and the destination nodes [53]. Routing algorithm with lower "Stretch Factor" is favored.

Table 4.4: Comparison of omnidirectional and directional antennas according to various characteristics. (Source: [88, p. 14])

Characteristics	Omnidirectional	Directional
Energy	More	Less
Throughput	More	Less
Capacity	Less	More
Collisions	More	Less
Interference	More	Less
Connectivity	Stable	Intermittent
Discovery	Easy	Difficult
Coverage	Stable	Intermittent
Routing - Stretch Factor	Less	More
Security	Less	More

In [98, 105, 106, 173], authors presented a prototype of a directional antenna for WSNs called the SPIDA (SICS Parasitic Interference Directional Antenna). The directional antenna was cheap to build and it was operating at the 2.4GHz frequency, with a gain about 7 dB. Figure 4.8 shows the picture of the proposed directional antenna system. The antenna can transmit in six equally spaced directions. For assessing the performance of the antenna, author investigated 3 different metrics, namely number of packets received, RSSI and LQI, and average noise (noise level sampled every second), by changing the number of packets transmitted, inter-packet time, and noise measurement time interval.

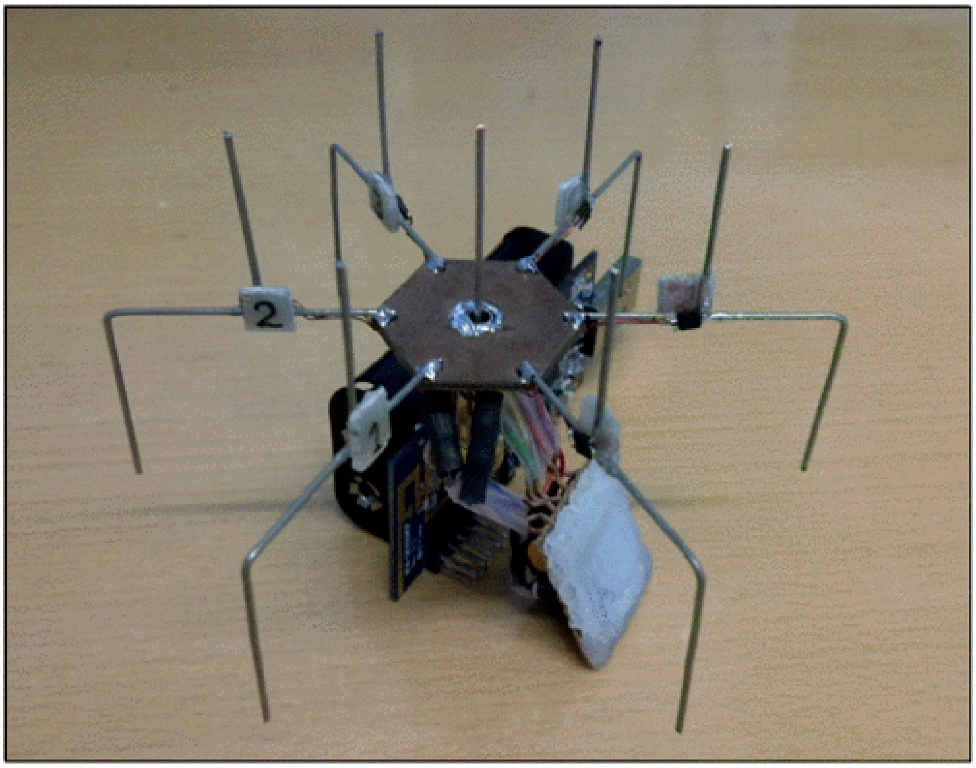


Figure 4.8: SPIDA antenna with TMote Sky mote. (Source: [98])

The paper [55] proposed directional 2.4GHz four-beam patch antenna (FBPA) for low-rate wireless personal area networks (IEEE 802.15.4). In the design, the authors used two layer FR4 substrate. The paper reported patch gain between 8.3dBi and 7.5dBi. The antenna is connected to the CC2420 radio module of the TelosB platform. Authors benchmarked the proposed antenna by considering omnidirectional-omnidirectional, FBPA-omnidirectional, and FBPA-FBPA communication combinations. Paper reported superior RSSI performance for the FBPA-FBPA communication. The connection of the four directional patches can be seen in Figure 4.9 below.

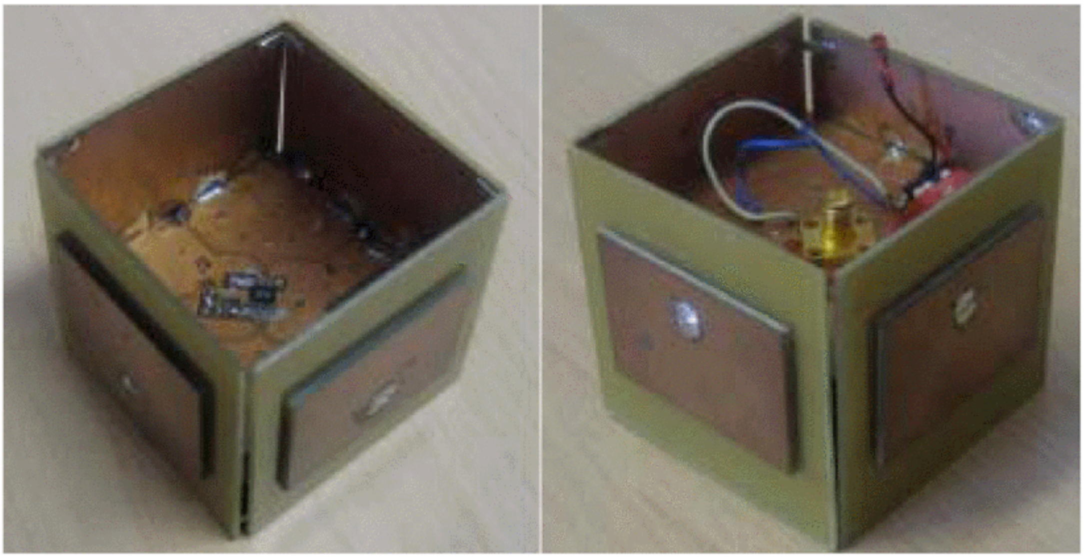


Figure 4.9: Four-beam patch antenna (FBPA) having dimensions of 56mm x 56mm and thickness of 2.4mm. (Source: [55])

Authors in [95] proposed the use of electronically steerable parasitic array radiator (ESPAR [94]) smart antenna for assessing adaptive routing performance in WSNs. ESPAR antenna operates in 2.4GHz and provides 4dBi gain with S11 around -35dB [94]. For the experiments, the proposed antenna with six steerable beams, connected to the CC2420 radio ship of the MicaZ sensor node. The antenna architecture can be seen in Figure 4.10. Experimental results from the paper showed that this type of directional antennas provided better reliability in communication compared to monopole antennas. Authors observed superior network performance compared to the monopole antennas with similar power consumption.

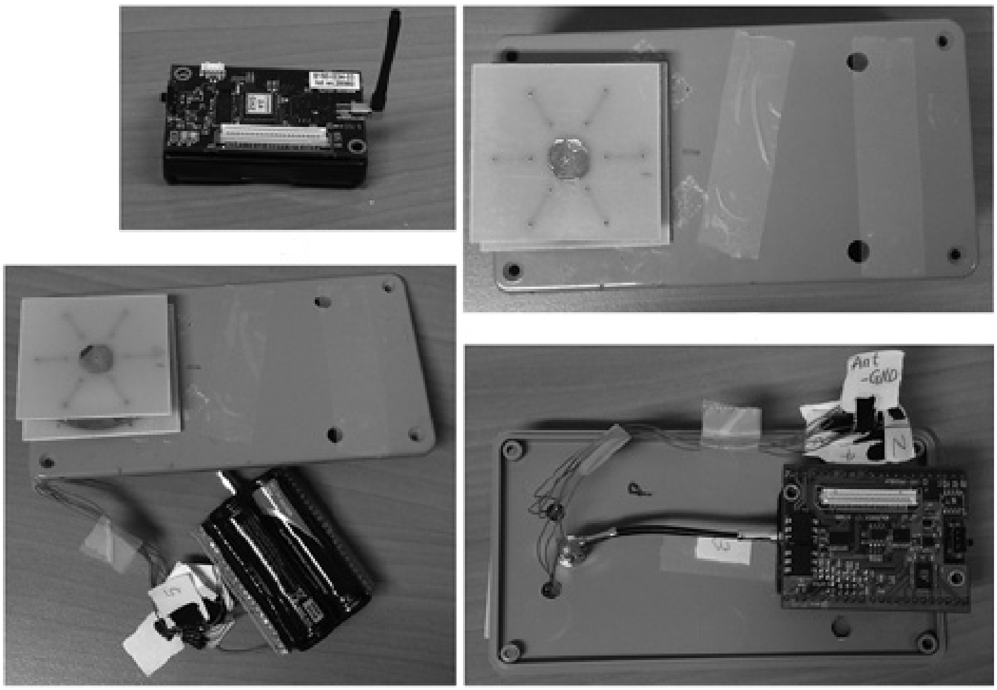


Figure 4.10: ESPAR smart antenna with MicaZ sensor node. (Source: [95])

While several papers offered specialized antenna designs, several others focused on the design of MAC and/or routing protocols. One such effort is the paper [38], in which authors proposed a directional MAC protocol for directional antenna utilization in ad hoc networks. The paper investigated and identified problems related to directional communication. In doing so, the paper offered valuable guidelines for the design of directional MAC protocols. The proposed MAC protocol benchmarked against standard IEEE 802.11 protocol. The benchmarked MAC protocol exhibited performance improvements over standard IEEE 802.11 protocol in terms of throughput and end-to-end delay. Authors stated the effect of the topology and the flow pattern on the performance of the directional MAC protocol. Paper suggested more aligned topologies being a cause of the performance degradations for directional antenna protocols.

In [50], authors proposed a customized cross-layer communication protocol for sectored antennas. The paper points out the interference and spatial reuse problems for omnidirectional antennas. The energy consumption problem is also considered in the paper. Authors proposed directional antennas for these problems. While the paper classified the directional antenna systems into two types as steerable beam and switched beam, it proposed Sectored-Antenna-Based Medium Access Control (SAMAC) protocol for the switched beam based antenna systems. The three objectives that the proposed SAMAC protocol is based on were, enhanced throughput by utilizing higher spatial reuse through directional antennas, high packet delivery ratio, extended battery lifetime through minimization of the transmission and reception power. Simulations are carried out for benchmarking SAMAC against several, energy efficient and baseline protocols like DMAC [87], TRAMA [121], BMAC [117], and baseline 802.11 [66]. Paper reported that SAMAC exhibited high energy efficiency and predictable end-to-end delay.

The study [150] is interesting in providing several caveats on the use of directional antennas in WSNs. The paper stated the benefits of the directional antennas such as the improved range in communication and less contention. However, situations are investigated in which negative effects on the performance are observed for directional antennas. Authors presented quantitative evidence on the negative effects of the directional antennas related to WSN convergecast protocols. They specifically pointed out two situations when it is not good to use directional antennas. Namely “tree shaped routing topologies” and “opportunistic channel access”. At the core of the issues, they listed “hidden terminal” problems. The paper presented important findings for protocol designers.

Several studies that are focused on the directional antenna design will be presented in the following paragraphs for the comparison purposes. The common property in all these studies is the use of patch antennas. Patch antennas combined in the form of 1D or 2D arrays, exhibit high combined gain, provided that the "feeding network" design is adjusted. Many factor should be considered for the design of the antenna. The operating frequency is one of them. Elements like, antenna geometry, substrate should be customized to the desired operating frequency. The rule of thumb for the size of the antenna is that the antenna dimensions should be close to half of the wavelength of the operating frequency [21, p. 542]. According to this rule for the antenna to operate in 2.4GHz frequency, the size should be about 6.25cm. The size of 2-by-2 patch can be as large as 12cm. However, in the literature, several size reduction techniques are proposed. These are discussed in the following paragraphs.

In [17] dual-band coaxial-fed 2-by-2 rectangular U-Slot microstrip patch antenna array for wireless sensor network applications is proposed. The schema of the antenna is shown in Figure 4.11. The antenna is designed as MIMO, so authors did not use a feeding network but utilized four ports for the excitation of the antenna.

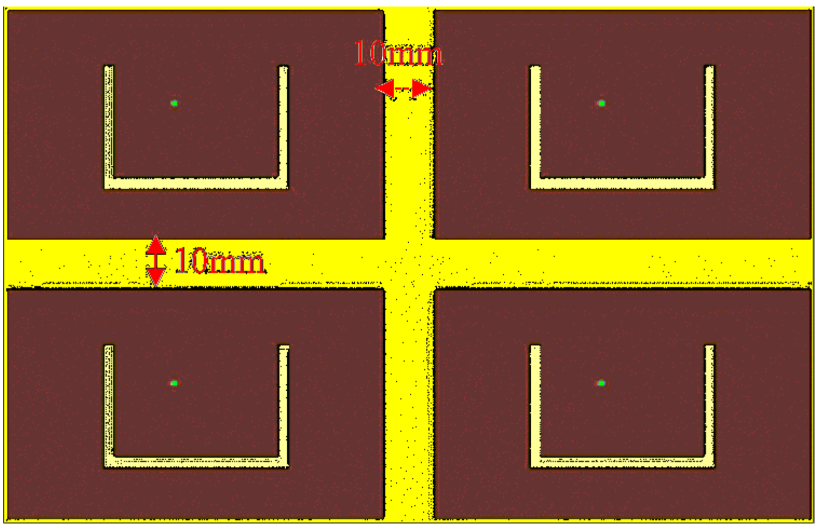


Figure 4.11: 2-by-2 microstrip patch antenna array designed in [17].

In [52] small (19.035mm $\times$ 20.035mm) circularly polarized square microstrip patch antenna designed for Zigbee communication (2.401GHz - 2.481GHz). Figure 4.12 shows the geometric details of the antenna. The paper reported return loss of 10dB and wide angle beamwidth. Authors did not specify the substrate that is utilized in the design. But they stated the dielectric constant as being 3.8, for both substrates that are shown in Figure 4.12 below.

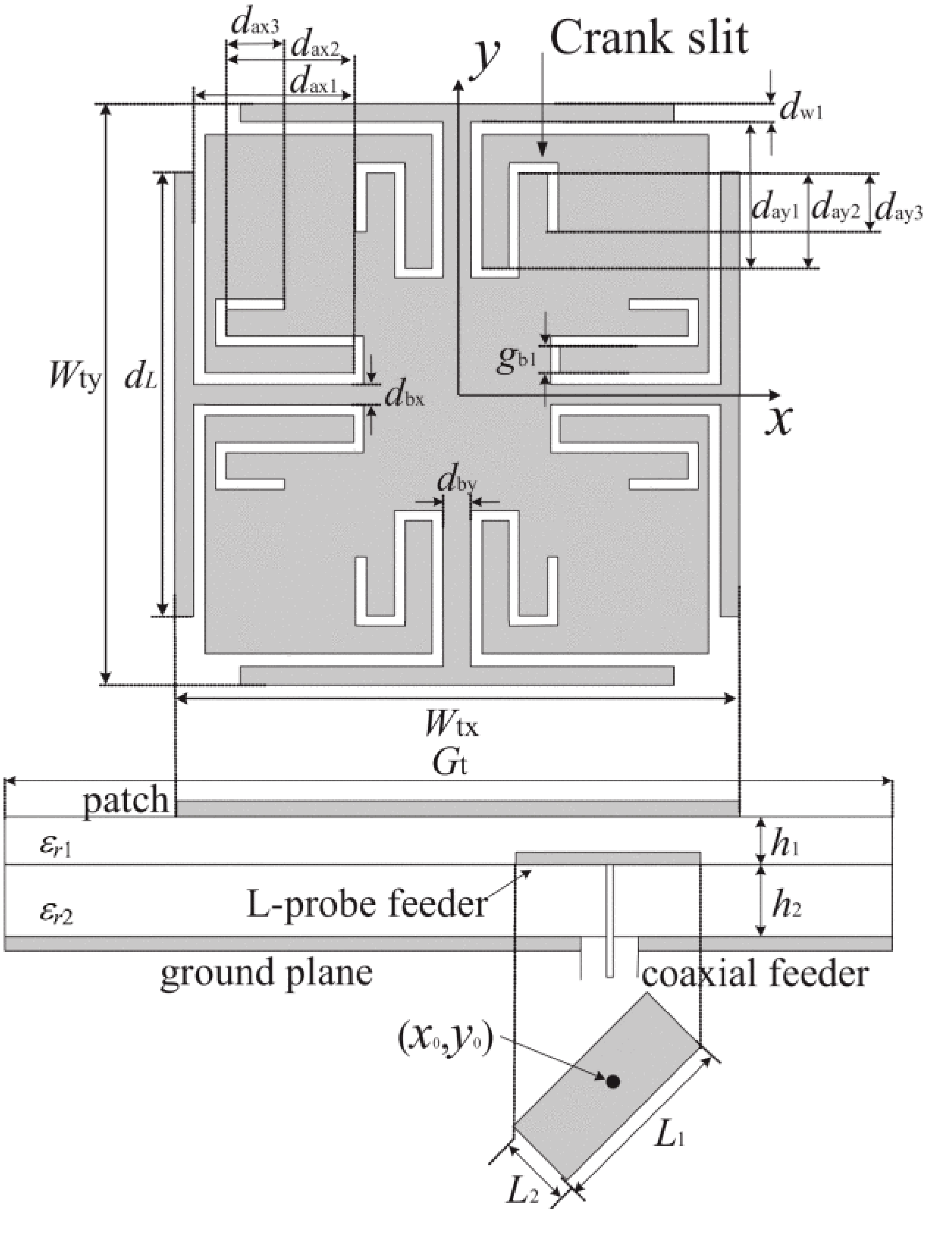


Figure 4.12: Circularly polarized microstrip patch antenna designed in [52].

The paper [100] proposed a microstrip patch antenna array for the sensor nodes. The paper claimed the superiority of the directional antennas over omnidirectional antennas by listing their high spatial reuse, low signal collision, high throughput, and less energy consumption properties. Authors presented the design of three different directional 2-by-1 microstrip patch arrays antennas (rectangular, triangular and E-shaped) by using FR4 substrate. The designed antennas are connected to MicaZ sensor node. In Figure 4.13 designed antenna can be seen. In Table 4.5 comparison of the performance characteristics of the proposed antennas is presented. Based on these measurement data from HFSS (High Frequency Structure Simulator[1]) simulator, authors proposed E-shaped type antenna as being the best one. The designed antennas are compared against omnidirectional antenna. In the benchmarking authors used metrics such as power consumption, RSSI, and packet delivery ratio. Benchmarks also showed the superiority of the E-shaped patch array.

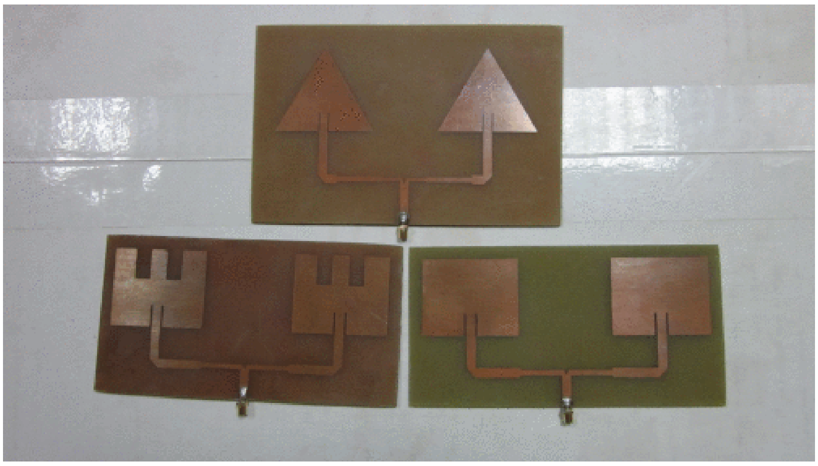


Figure 4.13: Microstrip patch antenna arrays designed in [100].

Table 4.5: Performance characteristics of two patch arrays designed in [100].

Type	Return loss (dB)	Gain (dB)	Area (L x W mm^2)
Rectangular	-24.46	2.648	113.5 X 57.91
Triangular	-25.83	2.017	117.55 X 76.63
E-shaped	-30.43	2.48	113.5 X 57.91

[1] https://www.ansys.com/Products/Electronics/ANSYS-HFSS

In thesis [32], techniques for size reduction and tuning are proposed for microstrip antenna design. One of the techniques is to put slits parallel to radiating edges of the patches. The thesis reported bandwidth improvements up to 30% and size reductions up to 49%. In Figure 4.14 various types of slits are shown for Planar Rectangular Multistrip Antenna (PRMSA).

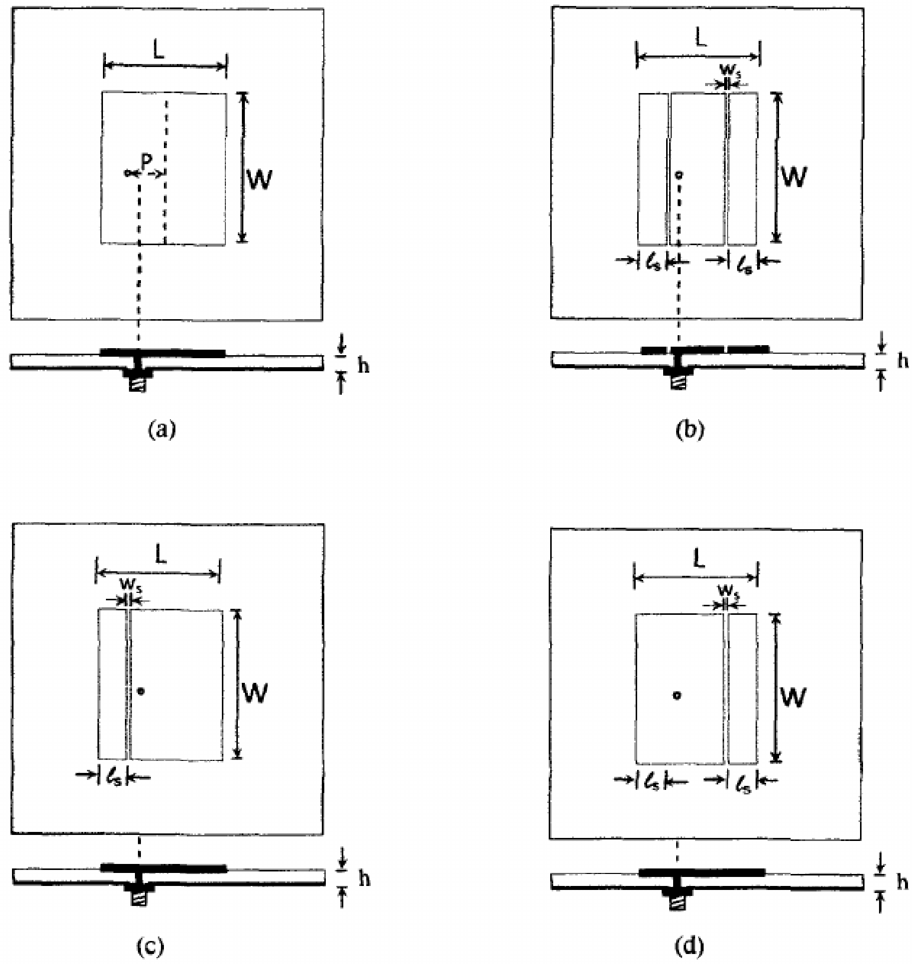


Figure 4.14: Types of slits studied in [32]. (a) PRMSA antenna, (b) PRMSA with double slit, (c) PRMSA with single slit near to the feed point, (d) PRMSA with single slit further from the feed point

Another size reduction technique is the use of fractal geometries. Extensive treatises on the use of fractal geometries in antennas can be found in [154] and in [157]. In [137] authors used Sierpinski Carpet fractal geometry for miniaturization of the inset-fed patch antenna operating at 2.45GHz. Authors reported 31% reduction for the first iteration of the Sierpinski Carpet fractal and 32% reduction for the second iteration of the Sierpinski Carpet, without any performance characteristic penalty related to reflection loss, impedance matching, and antenna gain. The substrate utilized in the designs was FR4 with the dielectric constant of 4.7, loss tangent of 0.019 and thickness of 1.6mm. Figure 4.15 shows the first two iterations of the Sierpinski Carpet fractal geometries for the inset-fed patch antenna used in the paper. The performance comparison of the base case and the iterations is given in Table 4.6.

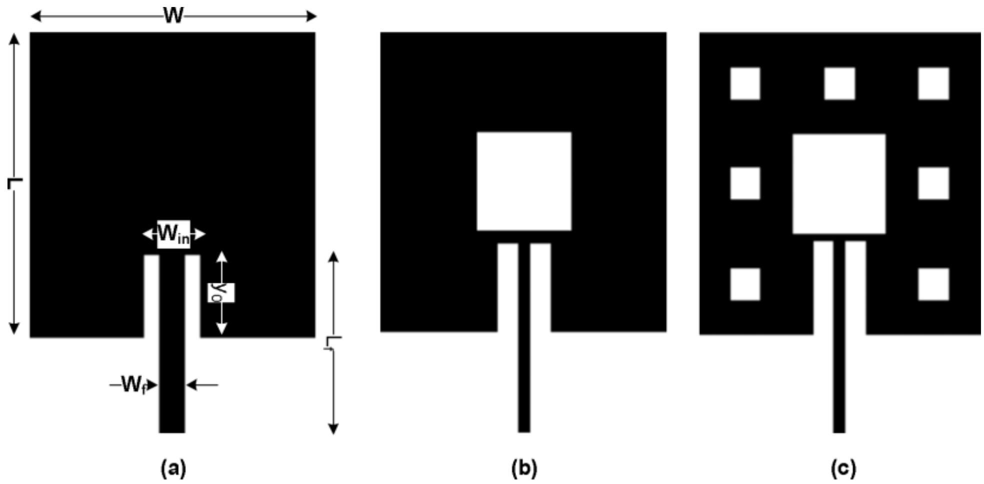


Figure 4.15: Inset-fed patch antenna and the first two iterations of the Sierpinski Carpet. (a) Base case, (b) The first iteration (c) The second iteration. (Source: [137])

Table 4.6: Comparison of the first two iterations of the Sierpinski Carpet geometries for the inset-fed patch antenna. (Source: [137])

Characteristic	Base case	Iteration 1	Iteration 2
Return Loss (dB)	29.08	28.42	24.28
Impedance BW (%)	70MHz	60MHz	60MHz
Bandwidth (%)	2.86	2.45	2.45
Gain (dB)	3.73	2.77	2.64
VSWR	1.07	1.08	1.13

CHAPTER 5

PROPOSED DIRECTIONAL ANTENNA AND ITS CHARACTERISTICS

In this section, the design of the proposed directional microstrip patch antenna array is presented. The section begins with the basic overview related to microstrip patch antennas. After that, the design of the proposed microstrip patch antenna array is explained and its performance characteristic is discussed.

The basic microstrip patch antenna consists of dielectric substrate sandwiched between the ground plane at the bottom and the patch itself at the top. The patch can be in various shapes. the substrate is chosen according to the desired frequency and according to the budget. Figure 5.1 shows the structure of a generic microstrip patch antenna.

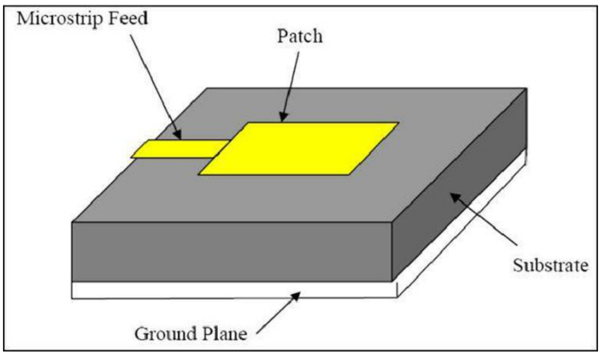


Figure 5.1: Structure of a generic microstrip patch antenna. (Source: [80])

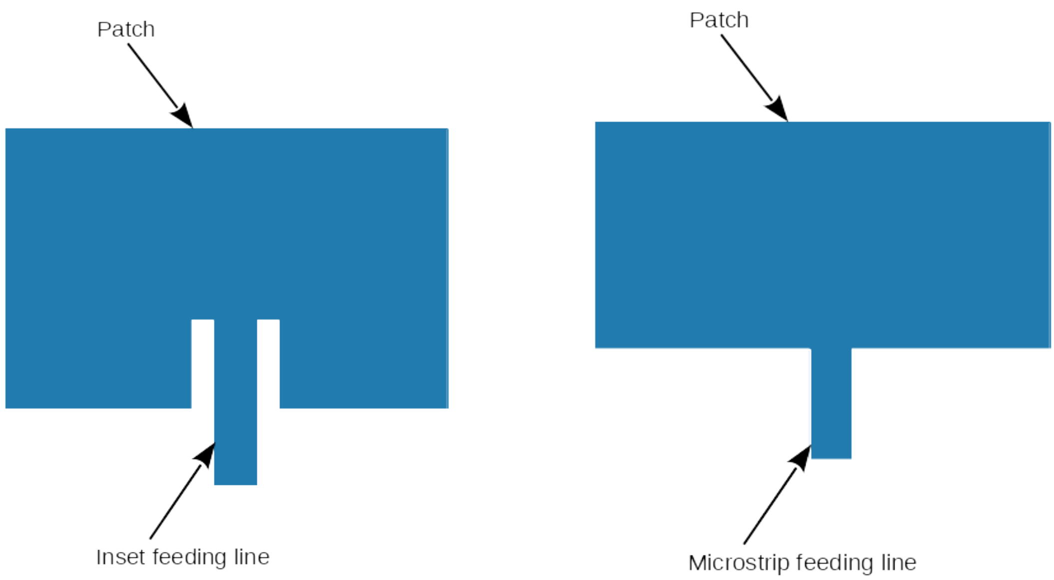
The decision for designing a microstrip patch antenna can be based on Table 5.1, in which advantages and disadvantages of the microstrip patch antennas are listed.

Table 5.1: Advantages and disadvantages of the microstrip patch antennas, considering design and performance characteristics. (Source: [70, p. 6])

Advantages	**Disadvantages**
Thin profile	Low efficiency
Light weight	Small bandwidth
Simple to manufacture	Extraneous radiation from feeds, junctions and surface waves
Can be made conformal	Tolerance problems
Low cost	Require quality substrate and good temperature tolerance
Can be integrated with circuits	High-performance arrays require complex feed systems
Simple arrays readily created	Polarization purity difficult to achieve

5.1 Design of the Proposed Directional Antenna

Patches of the proposed antenna are inset fed type. The study in [36], offers comprehensive analysis of the effects of the feeding techniques. Authors designed patch antennas with various feeding techniques for 2GHz resonant frequency and by using FR4 substrate. According to the paper, feeding techniques has important effects on various performance characteristics such as S11, impedance matching, total efficiency, directivity, and beamwidth. After experiments authors suggested that inset fed antennas having the highest directivity are more convenient for long distance communication. However, the paper stated that the spurious radiation from the feed line of the inset fed patches makes inset fed antennas worst in reflection loss, compared to aperture coupled and co-axial fed antennas. In Figure 5.2a the patch antenna with inset fed line is sketched. Microstrip fed patch is sketched in Figure 5.2b.

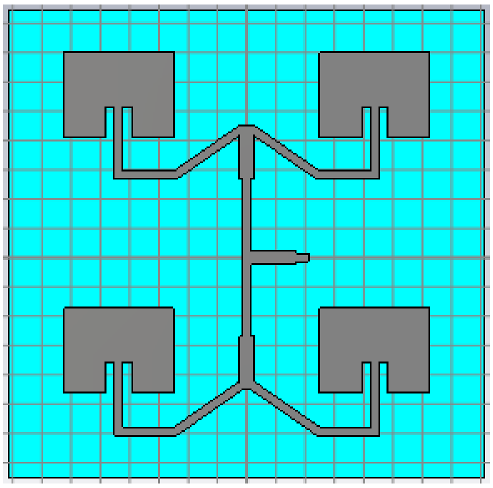


(a) The patch antenna with the inset fed line. **(b)** The patch antenna with the microstrip fed line.

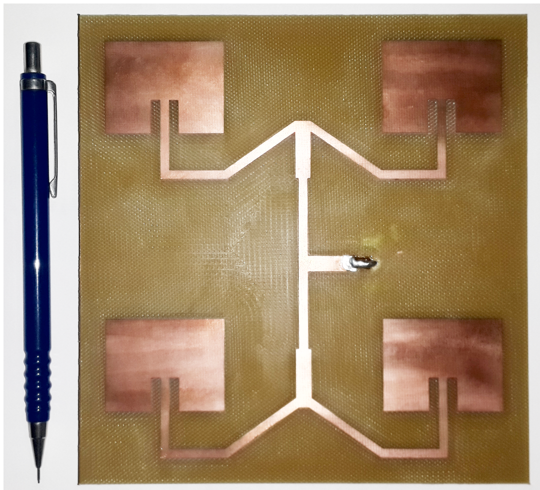
Figure 5.2: Various types of feeding lines for patch antennas.

The proposed antenna design includes corporate type feeding network for the patches. Corporate feeding networks provide equal amplitude and phase to each array element. They are easy to construct. However, there are some trade offs. According to [58] corporate feeding network is simple to design but presents performance degradations because of the feed radiation. Authors observed gain loss and degradations in side-lobe. They also reported cross polarization because of the resistive loss and feed radiation. The paper suggested the use of smoother feed discontinuities, thin substrates, and higher line impedance for alleviating these problems.

The two Ph.D. theses, [44] and [133], presented valuable discussions on the design and performance characteristics of the microstrip patch antennas. Books such as [48] and [155] can be proposed as valuable references on the design of microstrip patch antennas. For this thesis, a simple, cost effective, energy saving, and directional antenna design is considered. The proposed antenna is designed as 2-by-2 microstrip patch antenna array. Patches are inset-fed and the feeding network is corporate type. The schematic drawing and the actual photo of the designed microstrip patch array is shown in Figure 5.3a and Figure 5.3b respectively below in Figure 5.3. The design of the antenna is carried out in the Radio Frequency and Telecommunications Laboratory (RFTL) of METU NCC.



(a) Schematic drawing of the directional antenna designed.



(b) Photo of the directional antenna designed.

Figure 5.3: Drawing and the photo of the designed inset-fed 2-by-2 rectangular patch array with corporate feed.

The planar dimensions of the antenna are 124.9mm × 131.0mm (X and Y). FR4 substrate is utilized with the dielectric constant of 4.35, thickness of 1.5mm, and copper height of 0.018mm. SMA connector is added to the antenna for attaching to transmitter/receiver devices. Detailed design sketches and measures that are used for the design parameters of the antenna can be found in the Appendix A. The antenna design is carried out on the AntennaMagus[1] software package (version 2017). The software provided basic optimized template design for the microstrip patch antenna array, given the frequency and substrate requirements. It can also provide preliminary assessment for the performance of the template design.

[1] http://www.antennamagus.com/

5.2 Performance Characteristics of the Proposed Directional Antenna

The performance characteristics of the proposed antenna is assessed through simulations and actual measurements. Various parameters are adjusted and elaborate simulations are done with the CST[2] software package (version 2017). In this section mainly S11 and gain of the antenna will be presented to show the characteristics of the proposed antenna. In addition to the S11 assessments from the CST simulations, actual S11 is measured with Rohde&Schwarz® ZVB8 Vector Network Analyzer 2 ports, 8 GHz. As a representative practical usage performance assessment, the reception (download) and transmission (upload) data rate of the proposed directional antenna is benchmarked against the commercial omnidirectional antenna.

Since the antenna is designed for the practical usage in the existing standard 2.4GHz band protocols like IEEE 802.11 and IEEE 802.15.4, the frequency band allocation of these protocols is presented below. In Figure 5.4 the channel allocation schema of the IEEE 802.11 is depicted. Figure 5.5 depicts the channel allocation schema of the Zigbee frequency band, which represents one of the IEEE 802.15.4 based communication protocols. The designed antenna can operate in both standards, as it is targeted to communicate in 2.4GHz frequency. These figures are presented to depict the standard operating frequency bands of many commercial sensor nodes.

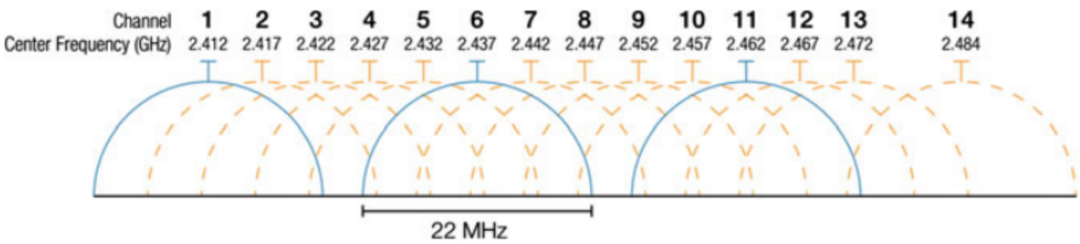


Figure 5.4: Wifi channel allocation.(Source: [135, p. 21])

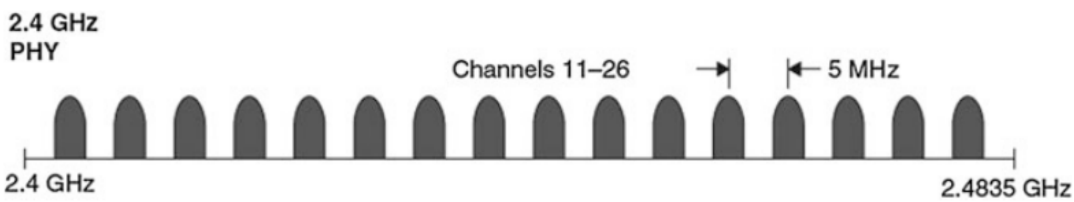


Figure 5.5: Zigbee channel allocation. (Source: [135, p. 12])

[2] https://www.cst.com/

The proposed antenna is designed to operate in 2.4GHz frequency. The impedance is set for 50 Ohm. The antenna has linear polarization. Return loss, S11, from the CST simulation of the antenna is shown in Figure 5.6 below. Measured S11 value, for 2.4GHz - 2.6GHz band, can be seen in Figure 5.7 below. In both figures the standard operating frequency for the IEEE 802.11 and the IEEE 802.15.4 are marked with gray regions.

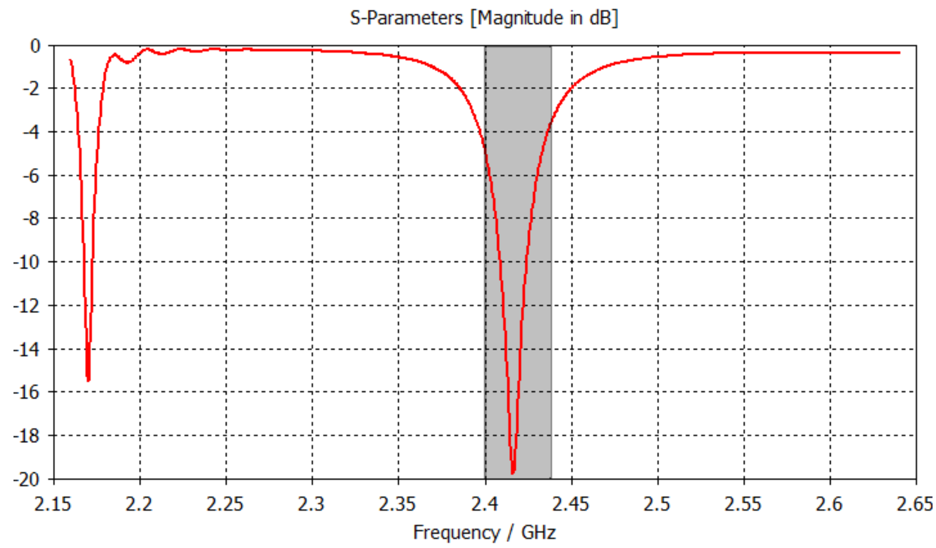


Figure 5.6: S11 plot from the CST simulation for the proposed antenna.

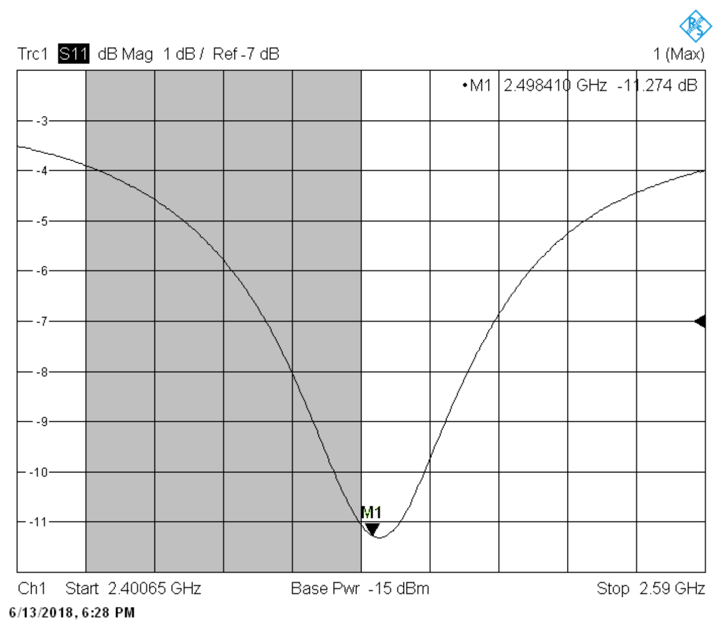


Figure 5.7: Measured S11 plot for the proposed antenna.

The designed patch array antenna has the maximum value of S11 about -10dB in the 2.4GHz - 2.48GHz frequency band. After post production tuning is carried out, the maximum value of the S11 in the 2.4GHz - 2.48GHz frequency band has reached -35dB. The tuning involved putting cross shaped copper tape pieces on the feeding lines near the SMA port level on the antenna layer. The tuned antenna and the resulting S11 measurements can be seen in Figure 5.8 and in Figure 5.9 respectively.

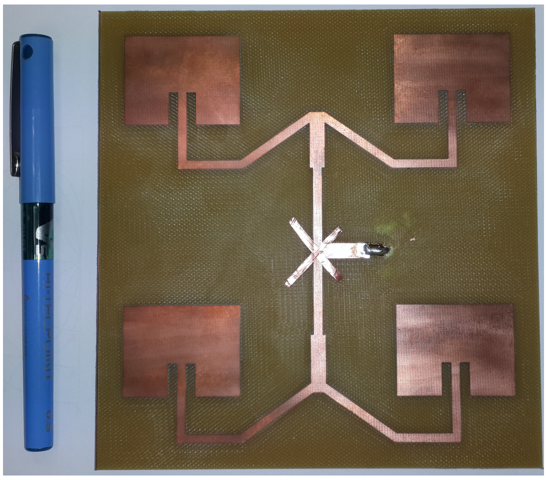


Figure 5.8: Designed antenna after tuning.

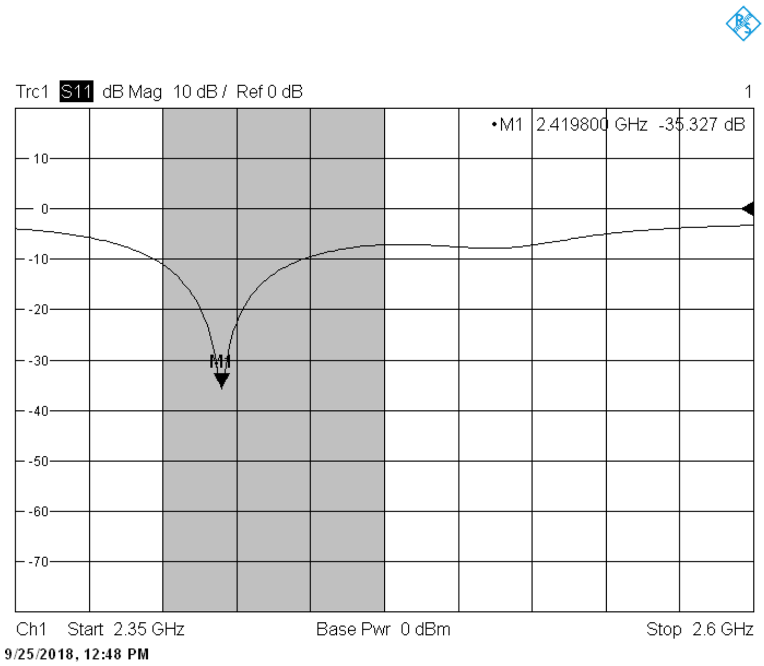


Figure 5.9: Measured S11 plot for the tuned antenna.

According to the CST simulation, the gain of the designed antenna is 12.74dB at 2.4GHz. In Figure 5.10 and in Figure 5.11 the gain characteristics of the designed antenna can be seen in 2D and 3D farfield plots respectively.

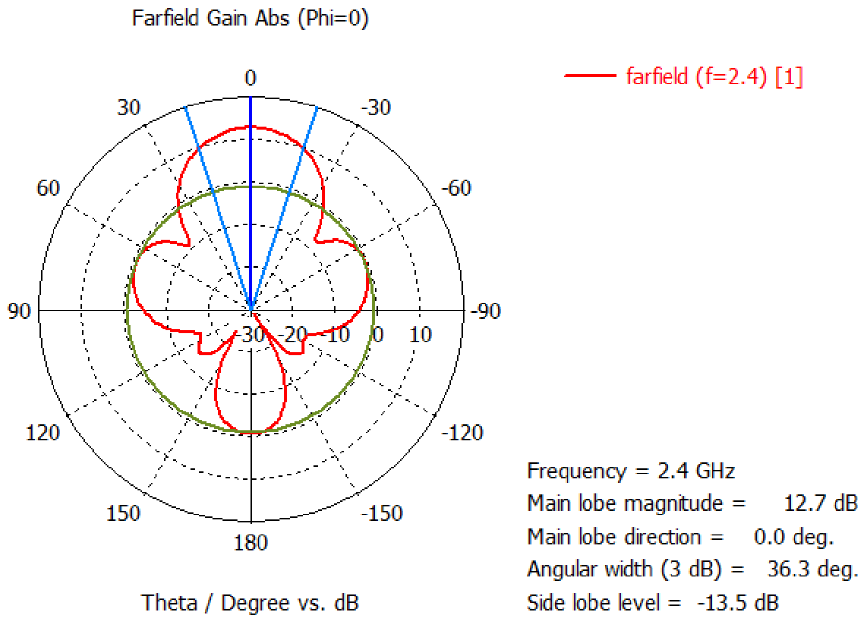


Figure 5.10: 2D Far field plot from the CST simulation for inset-fed 2-by-2 rectangular patch array with corporate feed network.

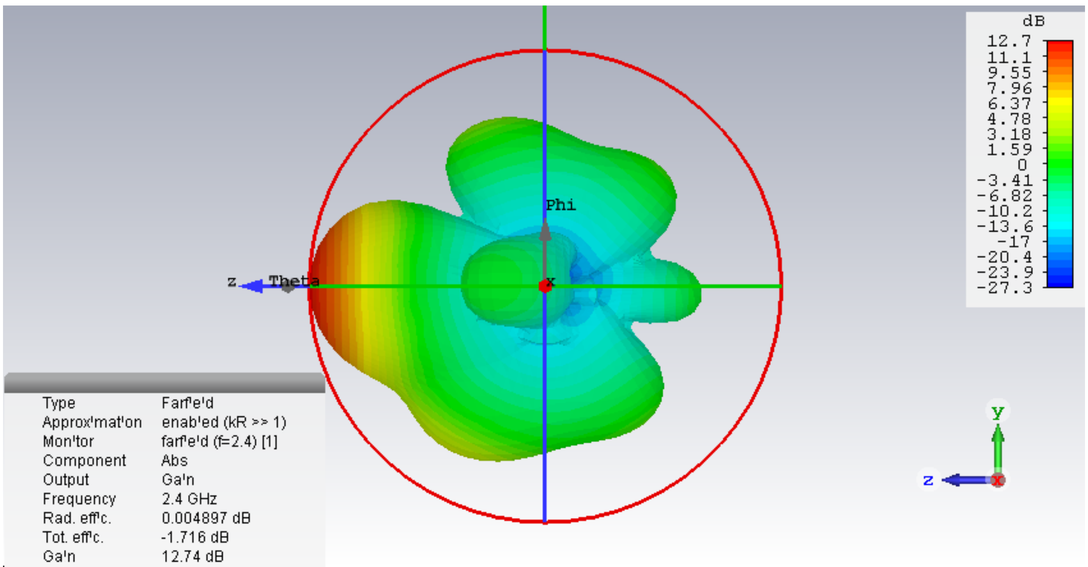


Figure 5.11: 3D Far field plot from the CST simulation for inset-fed 2-by-2 rectangular patch array with corporate feed network.

After determining the performance characteristics of the proposed patch antenna, it is benchmarked against the commercial 4dBi omnidirectional antenna. In Figure 5.12 both antennas can be seen side by side. The S11 measurements of the omnidirectional antenna is plotted in Figure 5.13.

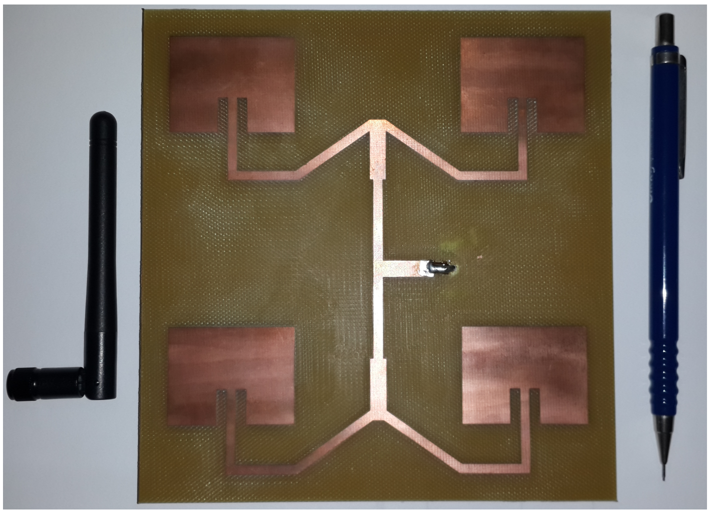


Figure 5.12: Omnidirectional (left) and directional antennas (right) used in benchmarking.

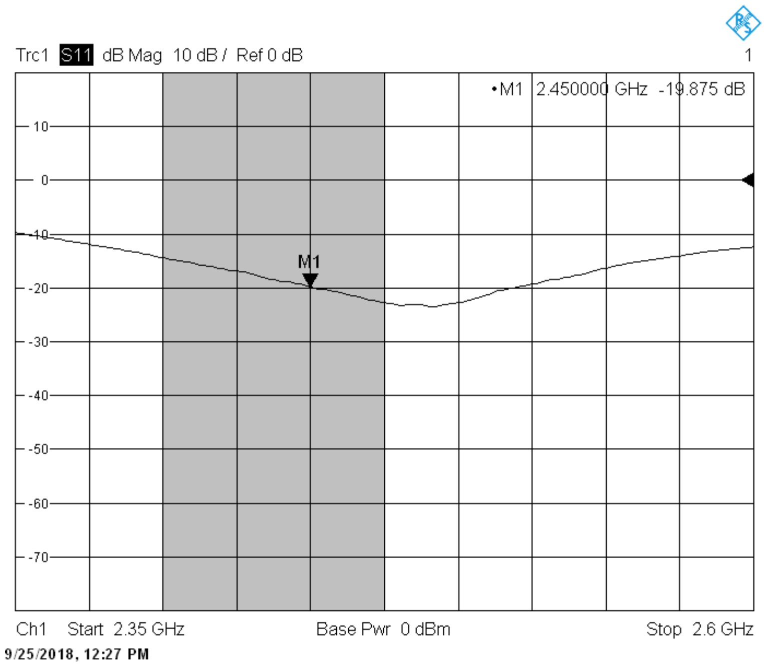


Figure 5.13: Measured S11 plot of the omnidirectional antenna used in benchmarking.

For the benchmark setup, two computers are utilized. The commercial USB wireless communication adapter with the omnidirectional antenna is connected to the server machine and “iperf3[3]” server is started. In the second machine, the client iperf3 is started. The benchmarked antennas at the client side are connected to the identical USB wireless adapter that is used for the server machine. The server machine is used in receiver and transmitter modes for both tested antennas. With the iperf3 benchmarking utility data rate is recorded at every second. 130 observations are made for statistical analysis. Reported data rates (Mbps) are plotted for comparison.

Through the statistical analysis, the performance differences and similarities are verified. The details of the analysis and the related R codes for the statistical tests can be found in Appendix B. The exploratory data analysis that is given in Appendix B, covers descriptive plotting of the observed data sets and hypothesis testing of the pair wise comparisons. The normality of the observations are tested by looking at QQ plots and density plots. None of the observed data were fitting to “Normal” distribution. To depict the nature of the observed distributions, boxplots are also provided in Appendix B. The differences between means are tested by applying pair-wise “Welch Two Sample t-test”. Pair-wise “Two-sample Kolmogorov-Smirnov” test is applied to see if any of the two observed data sets are coming from the same distribution. Results of the mentioned statistical tests are summarized in Table 5.2.

Table 5.2: Summary of the statistical tests results.

Test Group	Test	Tested property	Result
Reception	Welch Two Sample t-test	Means are same?	No
	Two-sample Kolmogorov-Smirnov	Distributions are same?	No
Transmission	Welch Two Sample t-test	Means are same?	Yes
	Two-sample Kolmogorov-Smirnov	Distributions are same?	Only Directed and DirectedX

[3] https://iperf.fr/

In Figure 5.14 the results of the reception benchmark can be seen. According to the plot proposed patch antenna reaches the maximum communication speed faster than the commercial antenna. It can also sustain higher level reception rate with lower jitter. The tuned version of the proposed antenna exhibited improved performance.

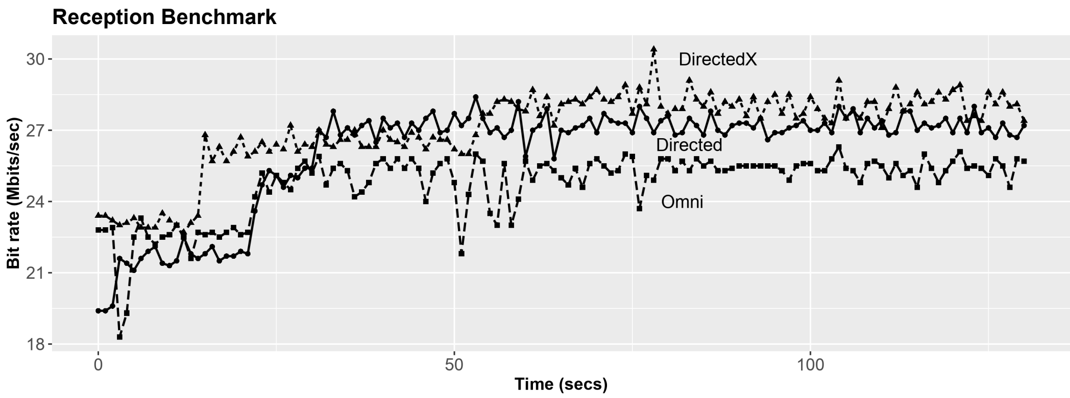


Figure 5.14: Antenna reception benchmark plots. “DirectedX” is the tuned version of the proposed directional antenna.

Table 5.3: Antenna reception benchmark statistics (Mbits/sec) for 130 observations.

Type	Min	Max	AVG	STD
Omni	18.3	26.3	24.73	1.35
Directed	19.4	28.4	26.06	2.24
DirectedX	22.7	30.4	27.04	1.66

The result of the transmission benchmark is plotted in Figure 5.15. For the transmission benchmark, there is no significant differences in the transmission performance of the benchmarked antennas.

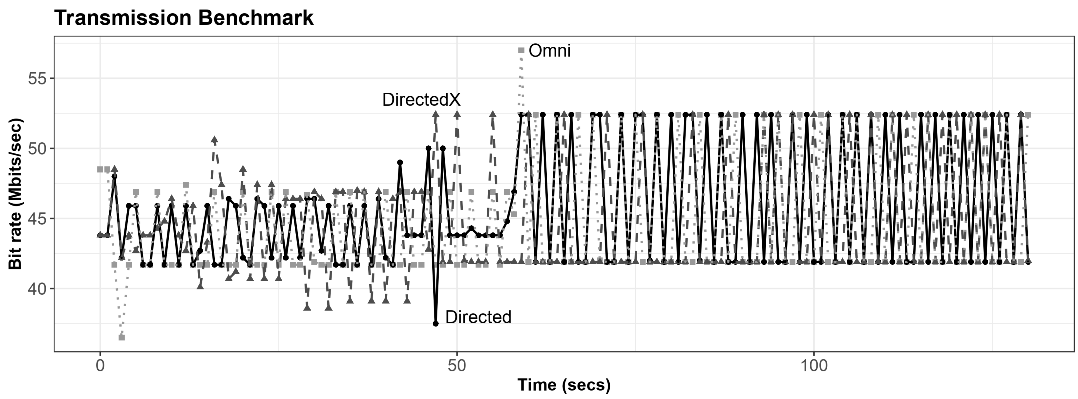


Figure 5.15: Antenna transmission benchmark plots.

Table 5.4: Antenna transmission benchmark statistics (Mbits/sec) for 130 observations.

Type	Min	Max	AVG	STD
Omni	36.5	57	44.82	4.44
Directed	37.5	52.4	45.72	4.45
DirectedX	38.6	52.4	44.75	4.31

In order to show individual antenna performances clearly, separate transmission plots are given in Figure 5.16 for the omnidirectional, in Figure 5.16 for the directional, and in Figure 5.16 for the tuned directional antennas.

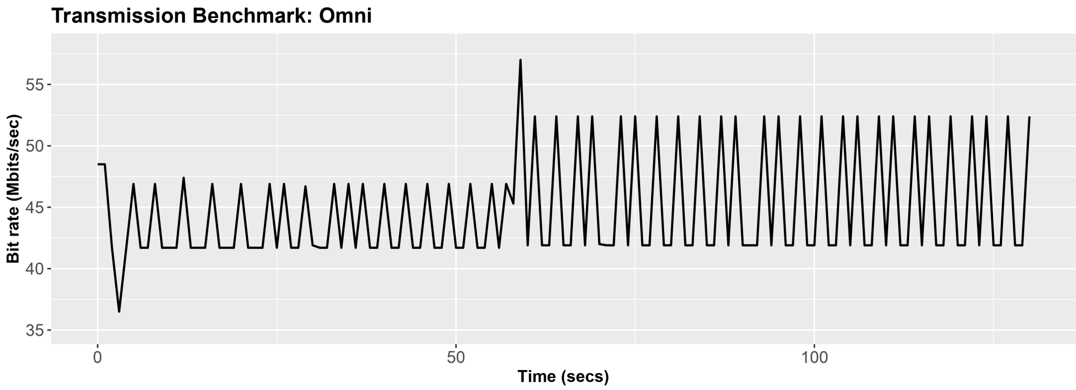


Figure 5.16: Performance of transmission for the omnidirectional antenna.

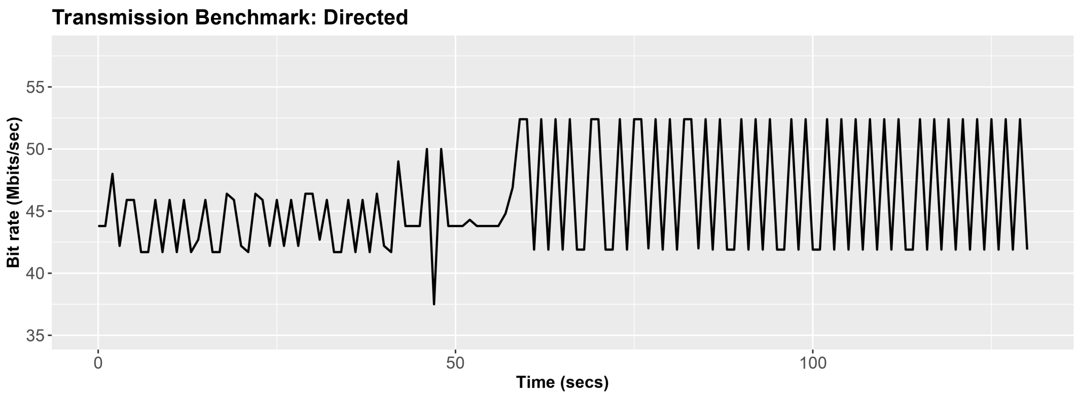


Figure 5.17: Performance of transmission for the proposed directional antenna.

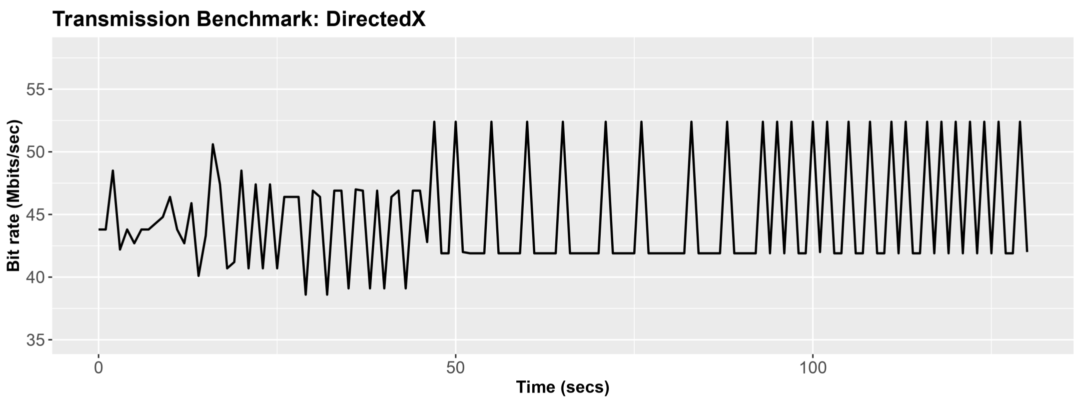


Figure 5.18: Performance of transmission for the tuned version of the proposed directional antenna.

5.3 Size Reduction Experiments

Size reduction through the fractal iteration is applied on the proposed antenna to decrease the overall size. For the fractal geometry the first iteration of the “Sierpinski Carpet” [162] is utilized. The idea is borrowed from the paper [137]. While the authors in the paper applied the size reduction to the single patch, in this thesis, size reduction is applied to the 2-by-2 patch antenna array. 62.5% size reduction in X-Y plane, is achieved, but because of the insufficient tuning for the feed line, antenna gain from the CST simulation is not as good as the original design. Table 5.5 lists the dimensions of the original patch array and the first iteration of the “Sierpinski Carpet”. This size reduction method is proposed for the sensor node design in which the overall size constraint is very crucial. In such cases, antenna geometry can be reduced by using fractal iteration method.

Table 5.5: Size comparison of the original patch array and the 62.5% reduced version.

Dimension	Original value	62.5% reduced value
X	124.9mm	78.06mm
Y	131.0mm	81.88mm

The schema of the first iteration patch array can be seen in Figure 5.19 below.

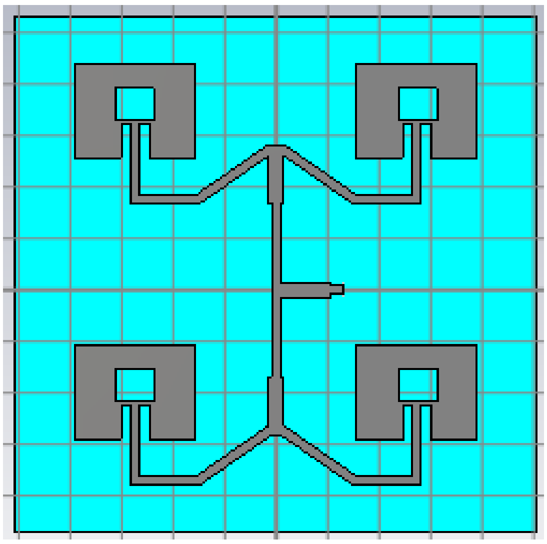


Figure 5.19: The first iteration of the “Sierpinski Carpet” fractal on the proposed antenna.

S11 plot from the simulation is presented in Figure 5.20 and the 3D gain plot for 2.4GHz is given in Figure 5.21. Fractal version achieved the maximum S11 value of -10dB and the gain for 2.4GHz is 7.32dB.

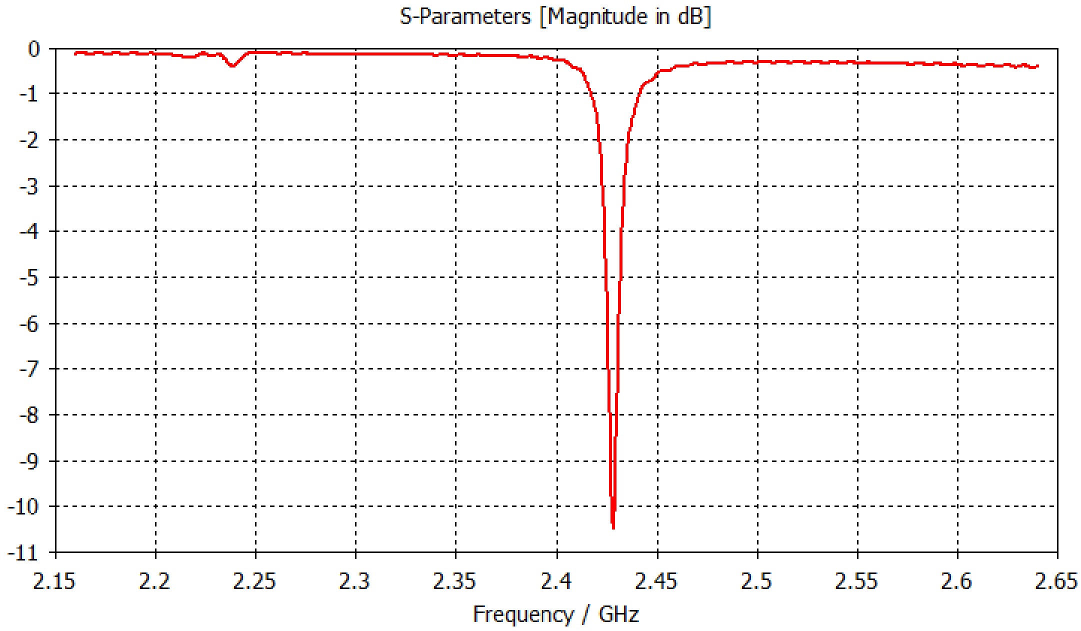


Figure 5.20: S11 plot from the simulation for the first iteration fractal version.

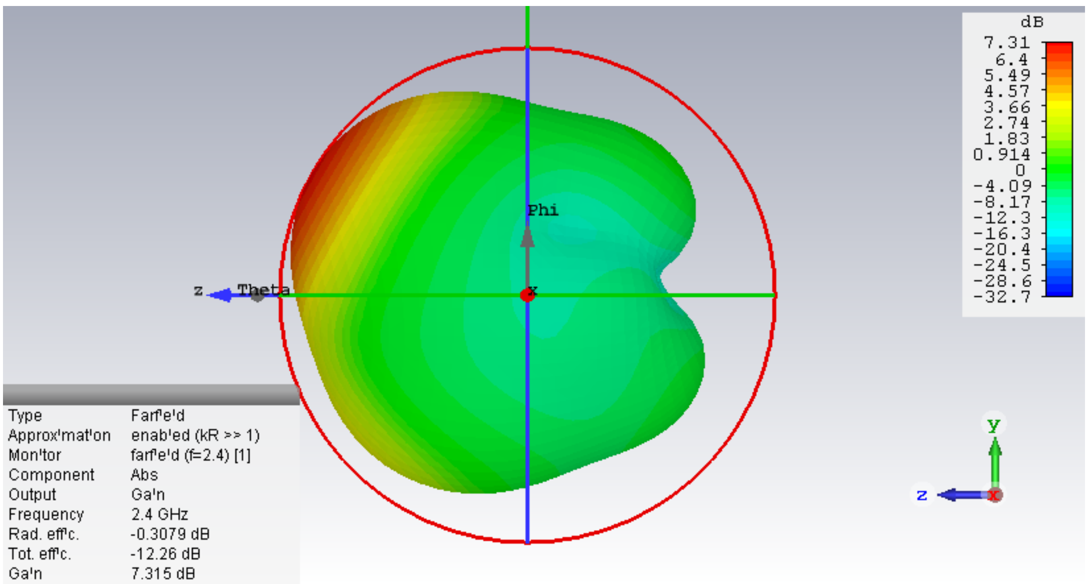


Figure 5.21: 3D gain plot for 2.4GHz for the first iteration fractal version.

5.4 Contributions of the Thesis to Directional Antenna Research

The practical novelties of the thesis related to the directional antenna research can be listed as:

- The proposal of using “inset-fed 2-by-2 rectangular patch array with corporate feed” type antenna system with a sensor node.
- The utilization of the Sierpinski Carpet fractal iteration technique for reducing the size of the 2-by-2 patch antenna.

The practical tuning method of applying adhesive copper tape was a result of ad hoc modification based on the “on the fly observations” of the changes related to the S11 measurements. However, the data rate benchmark proved the statistical significance of this ad hoc tuning. This simple process can be regarded as the “post production tuning” phase that further improves the design phase of the antenna with software package. The next step after this tuning, which in this thesis was not followed, is the modification of the design model based on this feedback.

On the theoretical side, a statistical framework is suggested to interpret the results of the benchmarks. In the case of this thesis, the benchmark was related to download and upload data rate comparison. The thesis proposed a statistical analysis framework that goes beyond the parameters that can be easily estimated such as the mean and the standard deviation. The framework consists of:

- Test to see if the distributions of the observations are coming from the Normal Distribution (Gaussian) with qq-plots, density plots. If the distribution of the data is not a Gaussian, this can easily be seen from the density plot, which will be different than the “symmetric bell shape”.
- Verification or rejection of the “sameness” of the means through “Welch Two Sample t-test”, in which null hypothesis is “the means do not have statistically significant difference”.
- Verification or rejection of the “sameness” of the distributions of the observations through “Two-sample Kolmogorov-Smirnov test”, in which null hypothesis is “two groups are coming from the same distribution”.

CHAPTER 6

CONCLUSION AND FUTURE WORK

The thesis proposed LaGOON routing protocol as a simple and energy-aware routing protocol for WNSNs and for WSNs. Algorithms for omnidirectional and directional versions are given and are explained with the examples. Simulation results for the omnidirectional antenna version in WNSNs are presented to show the relative performance over the baseline cases (flooding and random routing). Improvements over the plain flooding and random routing suggest that the omnidirectional LaGOON protocol has potential uses in real life scenarios. The algorithm designed as simple as possible considering computation and memory space resources. Energy is a very critical constraint in WNSNs. As the literature survey showed in Section 2.1, the research in the field of WNSNs is in need of more elaboration and further studies. Still, no routing algorithm is matured towards standardization. In this context, the proposed routing algorithm is an important contribution towards the more efficient algorithms. The same situation is valid for the nanoantenna design. The energy efficient antenna research in THz band specialized for WNSNs is still need of further studies. However, graphene based THz antenna applications seem to be promising [41, 76, 77]. In any case, new technologies in the nanosensor architecture will be required, which will, in turn, bring out the necessity of the radical designs in routing and MAC software. The principles of the simple synergistic design of the routing and directed antenna that the thesis based on, are beneficial for the further research in WNSNs and in WSNs as well.

Although the LaGOON protocol is presented without any enhancements, several improvements can be done to make it more efficient. One of the improvements, as it is mentioned at the end of Chapter 3, is the inclusion of the neighbor selected by the source node in the message, for optimization of the “Forward” path. In addition to this improvement, to control the traffic amount that may increase due to “ACK” packets (in the case of Reliable transmission scheme), nodes can decide to send with some preset probability parameter, similar to persistence schemes of the CSMA protocols. Another improvement can be done for the routing tables. While routers can store the whole routing table (for each node), nanonodes can use “caching” type storage scheme to optimize the routing table size. Using more elaborate simulator that includes a directional antenna model can be another crucial future work that can be suggested.

The proposed antenna is designed to be simple to produce, cost effective, energy saving, and directional above all other desired performance characteristic. FR4 is chosen as the economical substrate. Patch antenna arrays offer a simple and elegant way to increase the overall gain by combining individual patches in an easy way. However, the feeding network is the most crucial and hardest part of the design. In the design process, many novelties are tried like fractal iterations for antenna geometry, slits, ground defects, and cuts. But results were not good and small improvements were requiring the expensive process of designing prototypes and carrying out parametric sensitivity analysis, which was contrary to the principles that were set forth from the beginning of the thesis. For that reason, the antenna design process was kept as simple as possible. The idea was to produce a “proof of concept” and assess the performance characteristic through simulations and measurements. Yet the fractal iteration technique is found to be rather promising for size reduction, which it can be suggested as the first future work as a continuation of this thesis. In a possible future work, the second improvement that can be suggested is the assessment of the trade offs between using more expensive substrate and designing more effective feeding network. Through the data rate tests, the practical usage of the proposed antenna was tested. In the results of the tests, the higher data rate is observed for the proposed antenna compared to the commercial omnidirectional product.

The main motivation of the thesis was to design a directional antenna and routing protocol that exploits directional communication. With such directional communication, it is possible to prolong the lifetime of the sensor node for more sustainable sensor networks. Yet one of the difficulties encountered was the impossibility of the power adjustments related to the output of the radio chip sets. Modern small scale computing units such as Onion Omega2+ [1] and Particle Photon [2] with the possibility of an external wireless antenna interface is considered as platforms for experiments. But due to the FCC Rules [3], the design of these platforms does not allow any adjustment for the output power level to the external antennas. As a result, in the thesis, energy consumption benchmarks were not included.

In addition to the platform limitations, freely available WSN and WNSN simulators still in their infancy for the directional antenna and for the elaborate physical medium modeling. These restrictions limited the thesis for including comprehensive benchmarks and extensive comparisons on the routing performance of the directional and omnidirectional antennas.

However, in the thesis novel routing algorithm is proposed for the WNSNs and performance assessment is carried out by simulations. The possibility of the directional antenna adaptation for the proposed routing algorithm is shown with example scenarios. The thesis discussed the design of a microstrip patch antenna array as a “proof of concept” directional antenna. Brief literature survey and design guidelines are presented for a simple to produce, cost effective, energy saving directional antenna design. The designed antenna benchmarked for the practical usage through data rate tests. At the end this thesis tried to point out issues and principles related to the design of a sustainable sensor network, which is a vital part of a universal Sustainable Development as the working of the nervous system is important to the body, by presenting a novel routing algorithm and proof of concept application of a directional antenna.

[1] https://docs.onion.io/omega2-docs/omega2p.html

[2] https://docs.particle.io/datasheets/photon-(wifi)/photon-datasheet/

[3] https://www.ecfr.gov/cgi-bin/text-idx?SID=e7c92954653bca93eda68aa445ede077&mc=true&node=se47.1.15_1247&rgn=div8

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APPENDIX A

ANTENNA DESIGN SKETCHES AND PARAMETERS

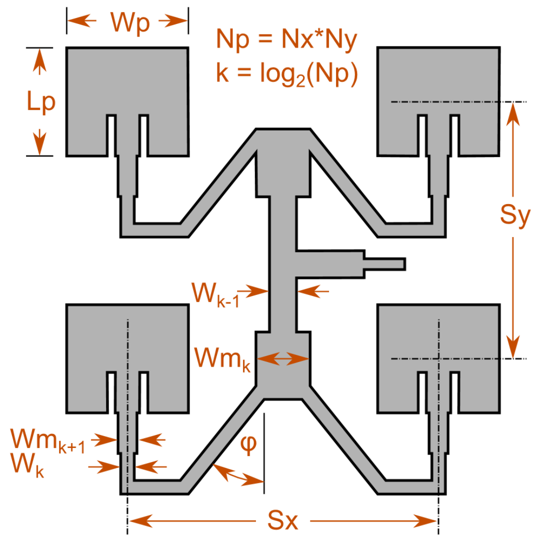

Figure A.1: Top view of the antenna design. (Source: AntennaMagus software V2017.)

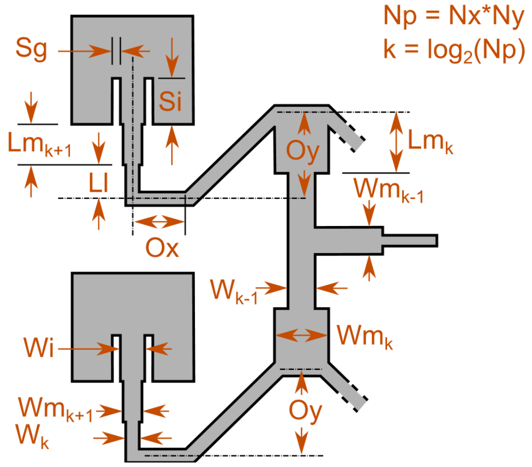

Figure A.2: Detailed top view of the antenna design. (Source: AntennaMagus software V2017.)

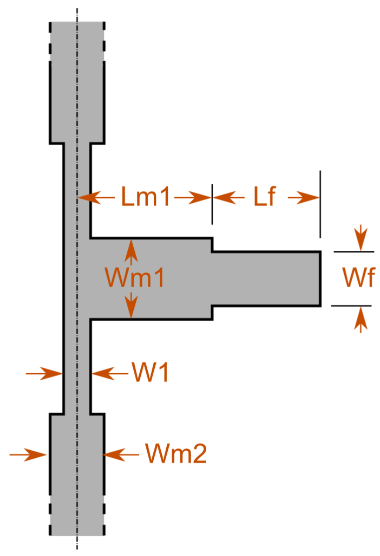

Figure A.3: Feeding network details of the antenna design. (Source: AntennaMagus software V2017.)

Figure A.4: Side view details of the antenna design. (Source: AntennaMagus software V2017.)

Table A.1: Antenna parameters and objectives used in the design. (Source: AntennaMagus software V2017.)

Type	Description	ShortName	Value	Unit
Objective	Centre frequency	f_0	2.4	GHz
Objective	Input resistance	Rin	50	Ω
Objective	The substrate name.	Name	FR4	-
Objective	The substrate manufacturer	Manufacturer	Generic	-
Objective	The thickness of the substrate	Substrate Thickness	1.5	mm
Objective	The relative permittivity of the substrate	Relative Permittivity	4.35	-
Parameter	Number of patches in X-direction	Nx	2 patches	-
Parameter	Number of patches in Y-direction	Ny	2 patches	-
Parameter	Patch width	Wp	37.50	mm
Parameter	Patch length	Lp	29.09	mm
Parameter	Patch spacing between patch centres in the X-direction	Sx	87.44	mm
Parameter	Patch spacing between patch centres in the Y-direction	Sy	87.44	mm
Parameter	X-offset of patch element	Ox	18.75	mm
Parameter	Y-offset of patch element	Oy	15.65	mm
Parameter	Substrate height	H	1.5	mm
Parameter	Relative permittivity	εr	4.35	-
Parameter	Loss tangent	tanδ	0	-
Parameter	Matching line 1 length	Lm1	16.81	mm
Parameter	Matching line 2 length	Lm2	16.81	mm
Parameter	Matching line 3 length	Lm3	8.68	mm
Parameter	Matching line 4 length	Lm4	18.05	mm
Parameter	Matching line 5 length	Lm5	18.05	mm
Parameter	Matching line 6 length	Lm6	18.05	mm
Parameter	Matching line 7 length	Lm7	18.05	mm
Parameter	Matching line 1 width	Wm1	4.933	mm
Parameter	Matching line 2 width	Wm2	4.933	mm
Parameter	Matching line 3 width	Wm3	2.892	mm
Parameter	Matching line 4 width	Wm4	673.9	µm
Parameter	Matching line 5 width	Wm5	673.9	µm
Parameter	Matching line 6 width	Wm6	673.9	µm
Parameter	Matching line 7 width	Wm7	673.9	µm
Parameter	Network line 1 width	W1	2.892	mm
Parameter	Network line 2 width	W2	2.892	mm
Parameter	Network line 3 width	W3	673.9	µm
Parameter	Network line 4 width	W4	673.9	µm
Parameter	Network line 5 width	W5	673.9	µm
Parameter	Network line 6 width	W6	673.9	µm
Parameter	Network line length	Ll	4.339	mm
Parameter	Feed line length	Lf	4.339	mm
Parameter	Feed line width	Wf	2.892	mm
Parameter	Feed inset from edge of patch	Si	10.53	mm
Parameter	Width of patch feed line	Wi	2.892	mm
Parameter	Spacing between feed line and patch	Sg	2.892	mm
Derived	Device X-dimension	X	124.9	mm
Derived	Device Y-dimension	Y	131.0	mm
Derived	Device Z-dimension	Z	1.5	mm
Derived	Angle of diagonal lines	φ	56.36	°

APPENDIX B

STATISTICAL ANALYSIS FOR THE ANTENNA BENCHMARKS

B.1 Tests and Hypotheses for the Statistical Analyses

1. Testing if the means are same with Welch Two Sample t-test
   - H0: True difference in means is equal to 0
   - H1: True difference in means is not equal to 0
2. Testing if the data are coming from the same distribution with Two-sample Kolmogorov-Smirnov test
   - H0: Two distributions are same
   - H1: Two distributions are not same

B.2 Summary of the Benchmark Results

Table B.1: Reception Benchmark summary.

Type	Count	Mean	SD	Median	Min	Max	IQR
Omni	130	24.7313	1.3544	25.3	18.3	26.3	1.2
Directed	130	26.0618	2.2429	27.0	19.4	28.4	1.1
DirectedX	130	27.0435	1.6653	27.6	22.7	30.4	1.9

Table B.2: Transmission Benchmark summary.

Type	Count	Mean	SD	Median	Min	Max	IQR
Omni	130	44.8198	4.4378	41.9	36.5	57.0	5.2
Directed	130	45.7252	4.4499	43.8	37.5	52.4	10.5
DirectedX	130	44.7481	4.3086	41.9	38.6	52.4	5.0

B.3 Descriptive Plots of the Reception Data

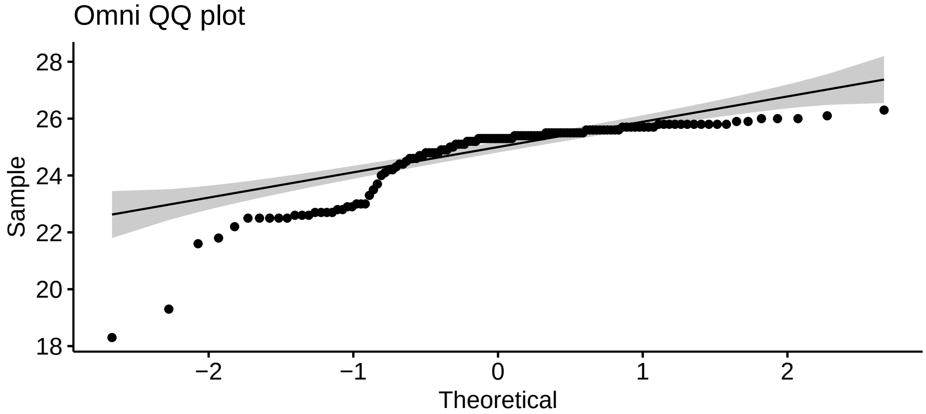

Figure B.1: QQ plot of the data rate observations for the Omnidirectional Antenna.

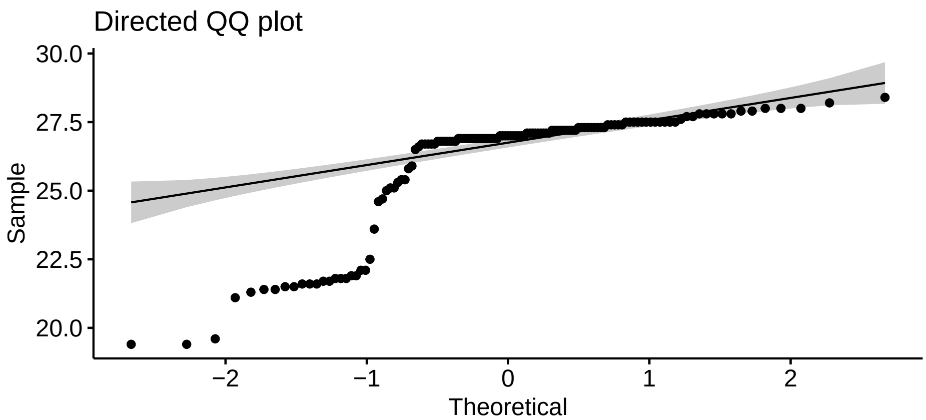

Figure B.2: QQ plot of the data rate observations for the Directional Antenna.

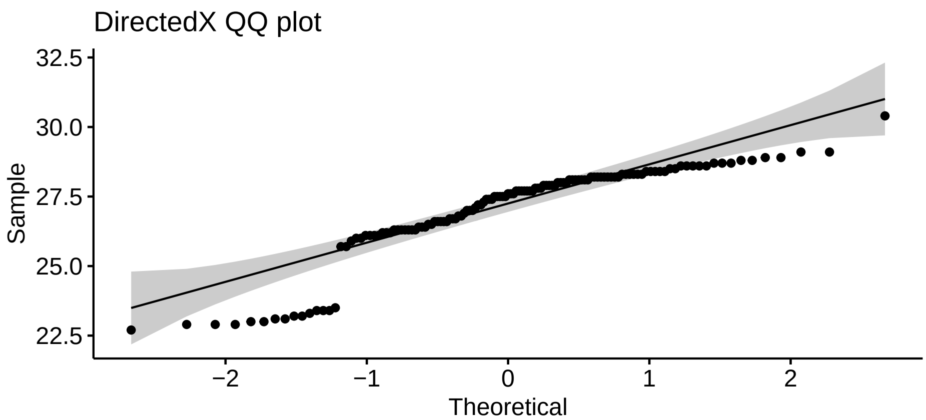

Figure B.3: QQ plot of the data rate observations for the Directional Antenna (tuned version).

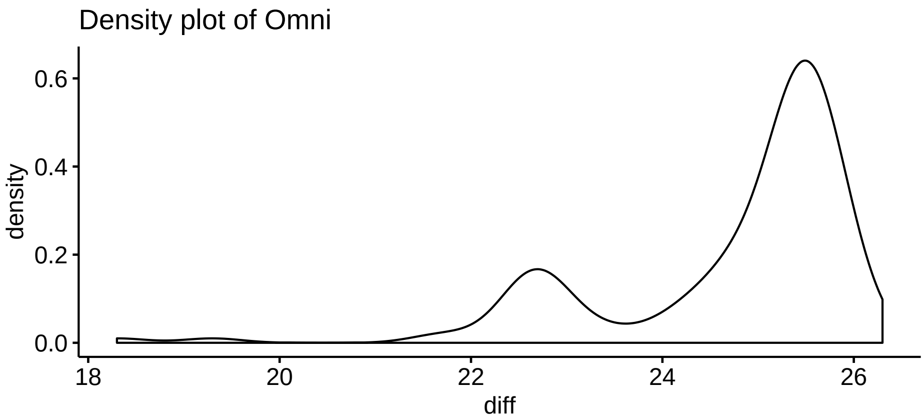

Figure B.4: Density plot of the data rate observations for the Omnidirectional Antenna.

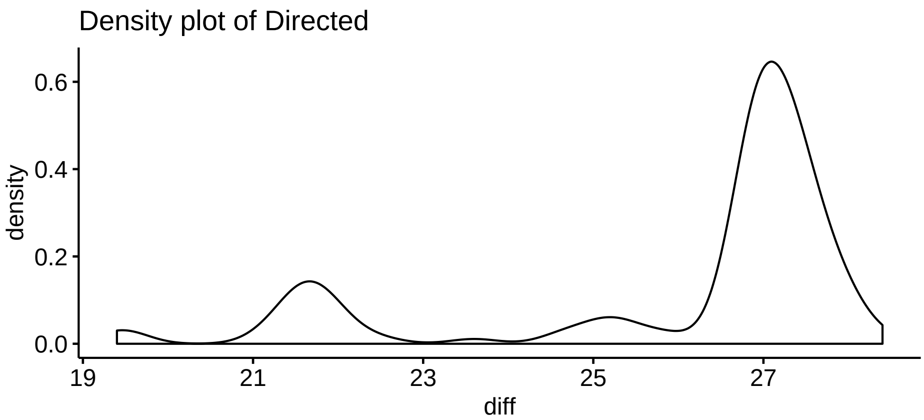

Figure B.5: Density plot of the data rate observations for the Directional Antenna.

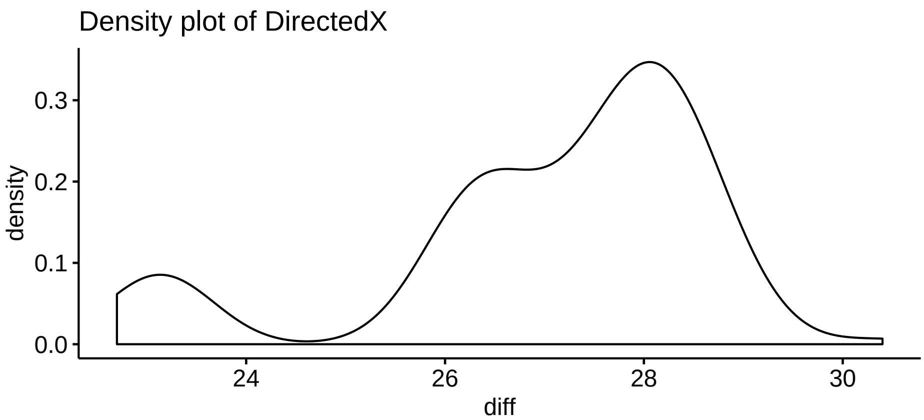

Figure B.6: Density plot of the data rate observations for the Directional Antenna (tuned version).

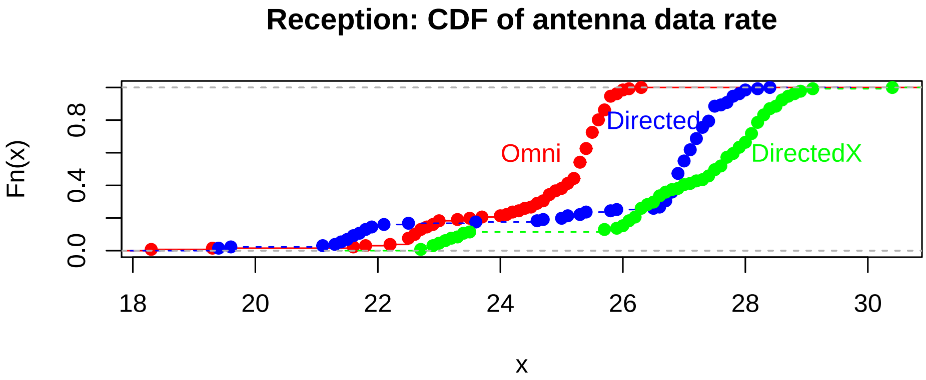

Figure B.7: Cumulative Distribution Function for the data rate observations.

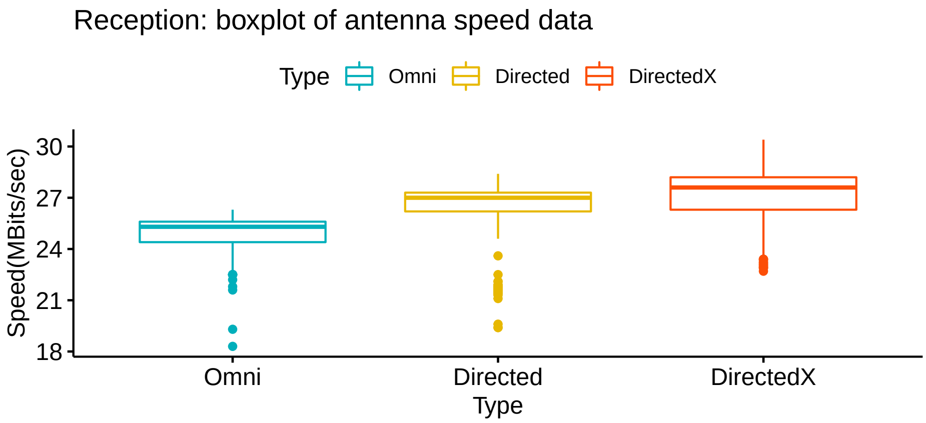

Figure B.8: Boxplot for the data rate observations.

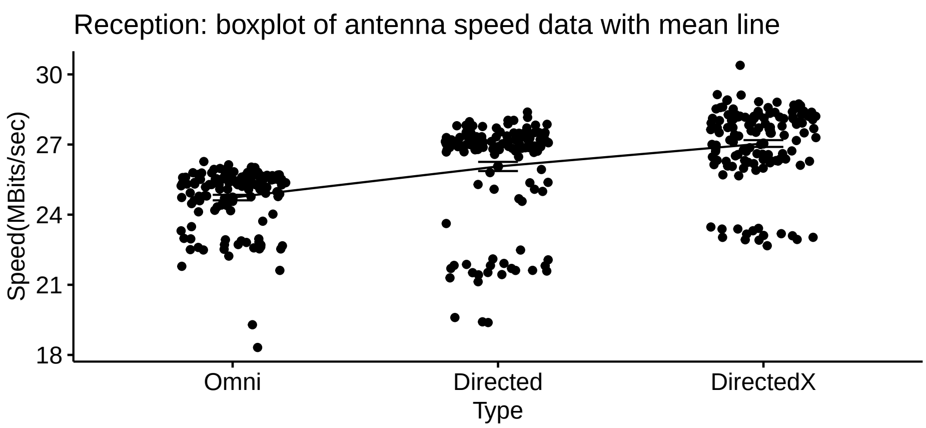

Figure B.9: Boxplot for the data rate observations with the mean line connected.

B.4 R Codes and Results for the Statistical Tests on the Reception Data

```r
# Testing if the means are same with Welch Two Sample t-test
# H0: True difference in means is equal to 0
# H1: True difference in means is not equal to 0
# If the p-value of the test is less than the significance
# level alpha = 0.05.
# We reject the Null Hypothesis that:
# The means do not have statistically significant difference
t.test(Omni,Directed, alternative = "two.sided")
```

```
##  Welch Two Sample t-test
## data:  Omni and Directed
## t = -5.8122, df = 213.69, p-value = 2.221e-08
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -1.7817661 -0.8793026
## sample estimates:
## mean of x mean of y
##  24.73130  26.06183
```

```r
t.test(Directed,DirectedX, alternative = "two.sided")
```

```
##  Welch Two Sample t-test
## data:  Directed and DirectedX
## t = -4.0221, df = 239.93, p-value = 7.732e-05
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -1.4624757 -0.5008831
## sample estimates:
## mean of x mean of y
##  26.06183  27.04351
```

```r
t.test(Omni,DirectedX, alternative = "two.sided")
```

```
##  Welch Two Sample t-test
## data:  Omni and DirectedX
## t = -12.329, df = 249.64, p-value < 2.2e-16
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -2.681588 -1.942840
## sample estimates:
## mean of x mean of y
##  24.73130  27.04351
```

```r
# Testing if the data are coming from the same distribution with
# Two-sample Kolmogorov-Smirnov test
# H0: Two distributions are same
# H1: Two distributions are not same
# If the p-value of the test is less than the significance
# level alpha = 0.05.
# We reject the Null Hypothesis that two groups are coming
# from the same dist.
ks.test(Omni,Directed, alternative = "two.sided")
```

```
##
##  Two-sample Kolmogorov-Smirnov test
##
## data:  Omni and Directed
## D = 0.74809, p-value < 2.2e-16
## alternative hypothesis: two-sided
```

```r
ks.test(Directed,DirectedX, alternative = "two.sided")
```

```
##
##  Two-sample Kolmogorov-Smirnov test
##
## data:  Directed and DirectedX
## D = 0.38931, p-value = 4.766e-09
## alternative hypothesis: two-sided
```

```r
ks.test(Omni,DirectedX, alternative = "two.sided")
```

```
##
##  Two-sample Kolmogorov-Smirnov test
##
## data:  Omni and DirectedX
## D = 0.83206, p-value < 2.2e-16
## alternative hypothesis: two-sided
```

B.5 Descriptive Plots on the Transmission Data

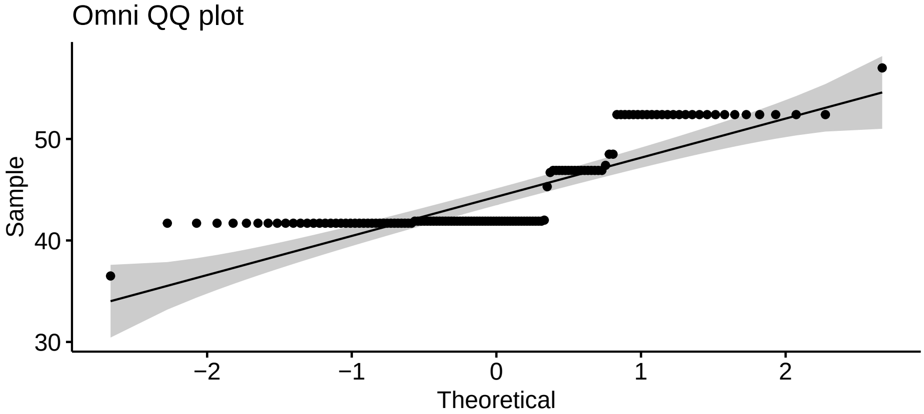

Figure B.10: QQ plot of the data rate observations for the Omnidirectional Antenna.

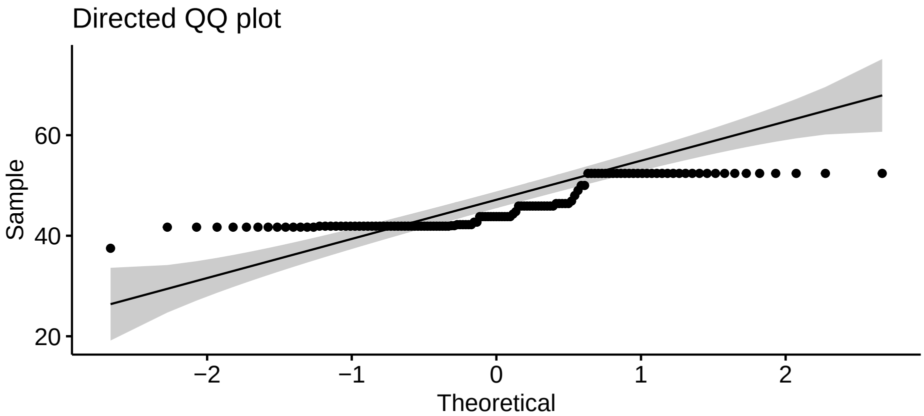

Figure B.11: QQ plot of the data rate observations for the Directional Antenna.

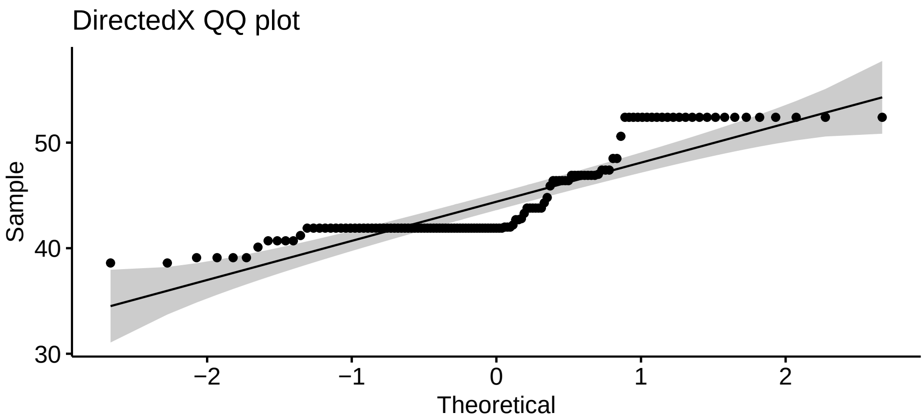

Figure B.12: QQ plot of the data rate observations for the Directional Antenna (tuned version).

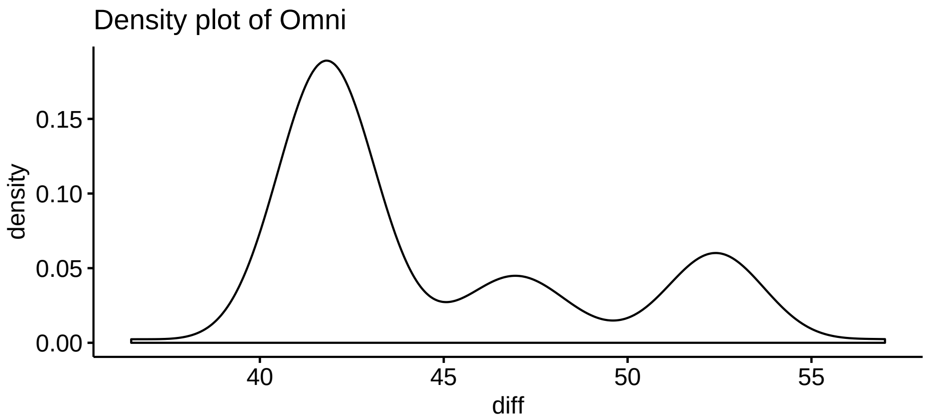

Figure B.13: Density plot of the data rate observations for the Omnidirectional Antenna.

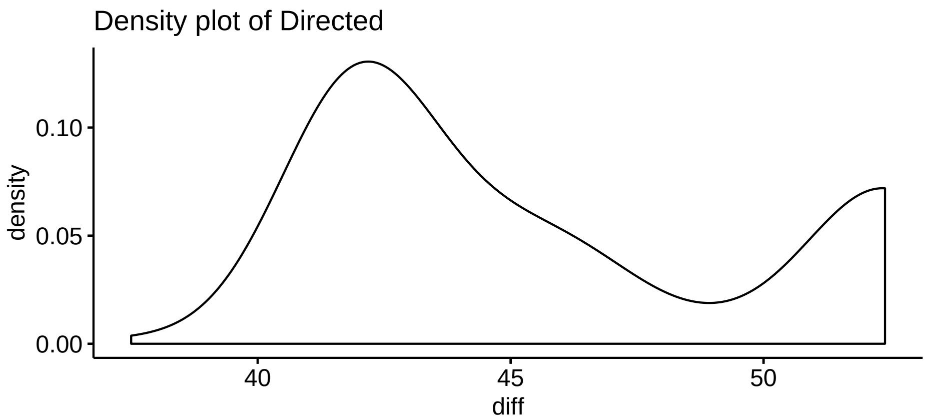

Figure B.14: Density plot of the data rate observations for the Directional Antenna.

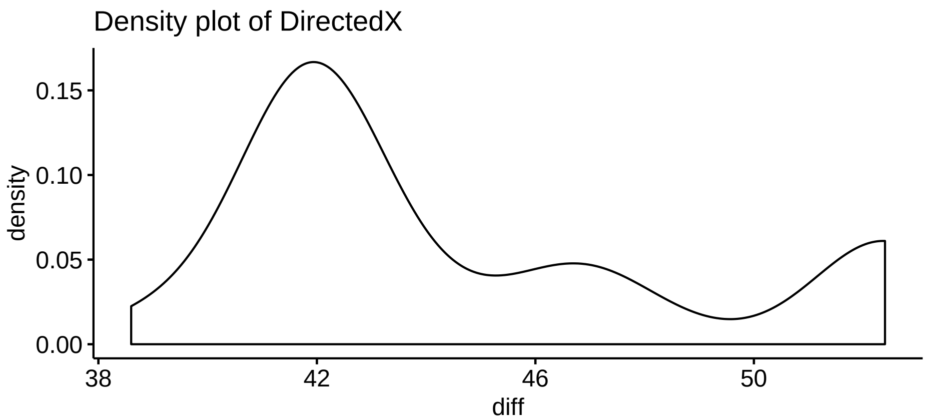

Figure B.15: Density plot of the data rate observations for the Directional Antenna (tuned version).

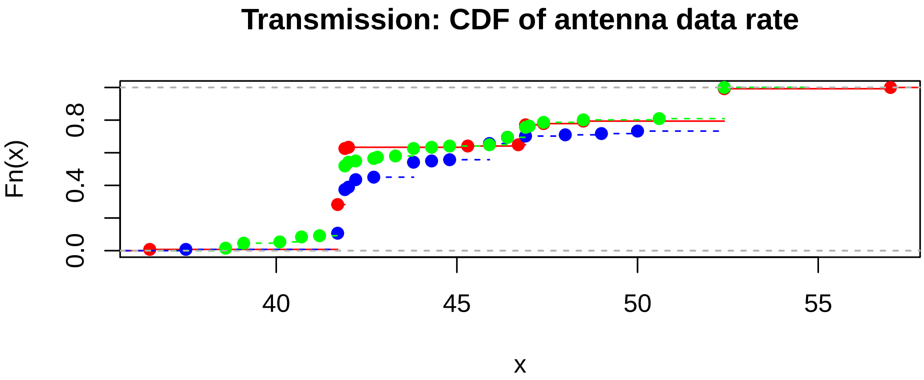

Figure B.16: Cumulative Distribution Function for the data rate observations.

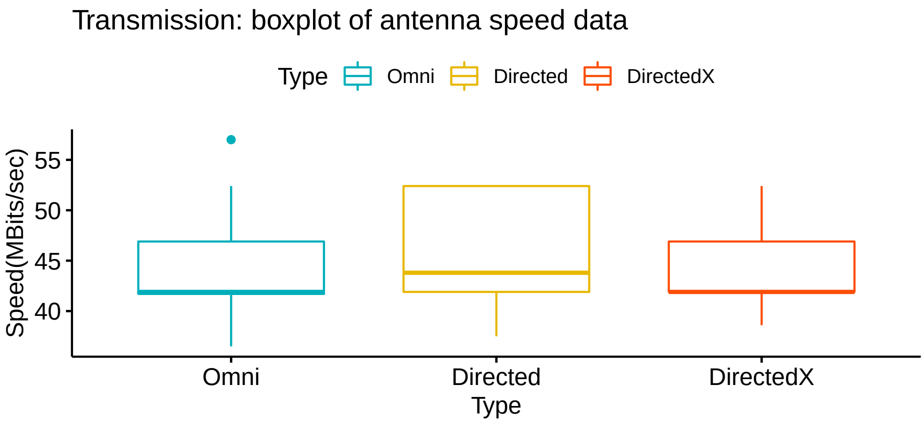

Figure B.17: Boxplot for the data rate observations.

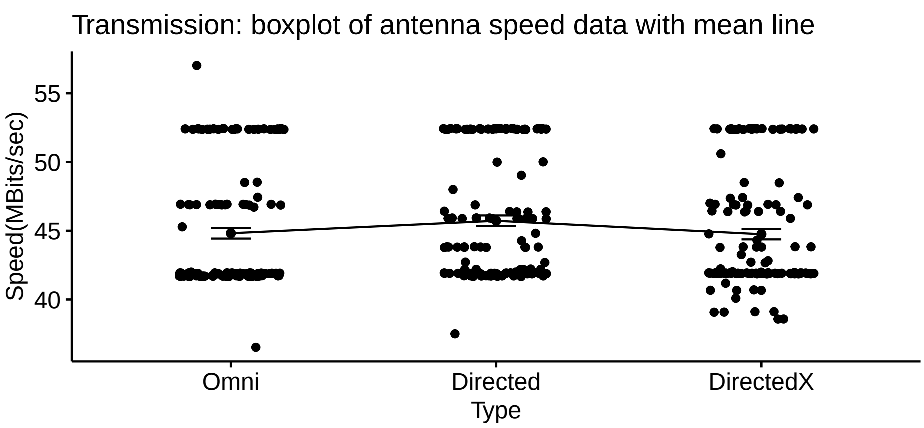

Figure B.18: Boxplot for the data rate observations with the mean line connected.

B.6 R Codes and Results for the Statistical Tests on the Transmission Data

```r
# Testing if the means are same with Welch Two Sample t-test
# H0: True difference in means is equal to 0
# H1: True difference in means is not equal to 0
# If the p-value of the test is less than the significance
# level alpha = 0.05.
# We reject the Null Hypothesis that:
# The means do not have statistically significant difference
t.test(Omni,Directed, alternative = "two.sided")
```

```
##  Welch Two Sample t-test
## data:  Omni and Directed
## t = -1.6488, df = 260, p-value = 0.1004
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -1.9865682  0.1758812
## sample estimates:
## mean of x mean of y
##  44.81985  45.72519
```

```r
t.test(Directed,DirectedX, alternative = "two.sided")
```

```
##  Welch Two Sample t-test
## data:  Directed and DirectedX
## t = 1.8055, df = 259.73, p-value = 0.07215
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -0.08854895  2.04274743
## sample estimates:
## mean of x mean of y
##  45.72519  44.74809
```

```r
t.test(Omni,DirectedX, alternative = "two.sided")
```

```
##  Welch Two Sample t-test
## data:  Omni and DirectedX
## t = 0.13278, df = 259.77, p-value = 0.8945
## alternative hypothesis: true difference in means is not equal to 0
## 95 percent confidence interval:
##  -0.9923951  1.1359066
## sample estimates:
## mean of x mean of y
##  44.81985  44.74809
```

```r
# Testing if the data are coming from the same distribution with
# Two-sample Kolmogorov-Smirnov test
# H0: Two distributions are same
# H1: Two distributions are not same
# If the p-value of the test is less than the significance
# level alpha = 0.05.
# We reject the Null Hypothesis that two groups are coming
# from the same dist.
ks.test(Omni,Directed, alternative = "two.sided")
```

```
##
##  Two-sample Kolmogorov-Smirnov test
##
## data:  Omni and Directed
## D = 0.25191, p-value = 0.0004906
## alternative hypothesis: two-sided
```

```r
ks.test(Directed,DirectedX, alternative = "two.sided")
```

```
##
##  Two-sample Kolmogorov-Smirnov test
##
## data:  Directed and DirectedX
## D = 0.15267, p-value = 0.09438
## alternative hypothesis: two-sided
```

```r
ks.test(Omni,DirectedX, alternative = "two.sided")
```

```
##
##  Two-sample Kolmogorov-Smirnov test
##
## data:  Omni and DirectedX
## D = 0.19084, p-value = 0.01694
## alternative hypothesis: two-sided
```

APPENDIX C

TEZ FOTOKOPİSİ İZİN FORMU

PROGRAM

SEES	X
PSIR	
ELT	

YAZARIN
Soyadı: Kılıç
Adı: Kemal
Bölümü: Sürdürülebilir Çevre ve Enerji Sistemleri Programı

TEZİN ADI (İngilizce): Energy Efficient Routing With Directional Antennas in Wireless Sensor Networks

TEZİN TÜRÜ: Yüksek Lisans [X] Doktora [ ]

1.Tezimin tamamından kaynak gösterilmek şartıyla fotokopi alınabilir.	X
2.Tezimin içindekiler sayfası, özet, indeks sayfalarından ve/veya bir bölümünden kaynak gösterilmek şartıyla fotokopi alınabilir.	X
3.Tezimden bir bir (1) yıl süreyle fotokopi alınamaz.	

TEZİN KÜTÜPHANEYE TESLİM TARİHİ: 26 Ekim 2018