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ATILIM UNIVERSITY 2019

**COMPARATIVE ASSESSMENT OF SWITCHING OPTIONS FOR BACK
TO BACK ANTENNAS IN WIRELESS NETWORKS**

**A MASTER OF SCIENCE THESIS
IN
THE DEPARTMENT OF ELECTRICAL AND ELECTRONICS
ENGINEERING
ATILIM UNIVERSITY**

**THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
ATILIM UNIVERSITY**

**by
AHMET MERT DURUKAN
NOVEMBER 2019**

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**IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE
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NOVEMBER 2019

Approval of the Graduate School of Natural and Applied Sciences, Atilim University.

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ABSTRACT

COMPARATIVE ASSESSMENT OF SWITCHING OPTIONS FOR BACK TO BACK ANTENNAS IN WIRELESS NETWORKS

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This thesis mainly aims to provide bidirectional sensor node link communication with neighboring sensor nodes. The connection between the antennas to create a wireless sensor link is provided by using RF Switch and RF Splitter / Combiner designs. The performance evaluations of these two designs are determined as objectives. Measurements are also taken in the LOS and NLOS conditions. The data obtained from the measurement were evaluated in terms of total cost, energy consumption and maximum distance.

Keywords: Wireless Sensor Network (WSNs), LoRa, RF Splitter/Combiner, RF Switch, Coplanar Waveguide (CPWG). Wilkinson Power Divider

ÖZ

KABLOSUZ AĞLARDA ARKA ARKAYA OLAN ANTENLERİN BAĞLANTI SEÇENEKLERİNİN KARŞILAŞTIRILMASI

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Bu tez çalışması, çift yönlü sensör düğümlerinin birbirleriyle bağlantısını sağlamayı amaçlamaktadır. Bir alıcı-verici yonga setine sahip olan arka arkaya yönel antenlerin kablosuz sensör linki oluşturmak için antenler arasındaki bağlantı, RF Anahtarı ve RF Ayırıcı/Birleştirici tasarımları kullanarak sağlanmıştır. Bu iki tasarımın, performans değerlendirmeleri amaç olarak belirlenmiştir. Görüş mesafesinde ve görüş hattı dışındaki ortamlarda ölçümler alınmıştır. Ölçüm sonucunda elde edilen veriler toplam maliyet, enerji tüketimi ve erişilecek maksimum mesafe bakımından değerlendirilmiştir.

Anahtar Kelimeler: Kablosuz Sensör Ağları, LoRa, RF Ayırıcı/Birleştirici RF Anahtar, Eş düzlemsel Dalga Kılavuzu. Wilkinson Güç Bölücü

To My Family

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LIST OF SYMBOLS/ABBREVIATIONS

WSN:	Wireless Sensor Network
LOS:	Line of Sight
NLOS:	Non-Line of Sight
CPU:	Central Processing Unit
ISM:	Industrial Scientific Medical
UNB:	Ultra Narrow Band
RF:	Radio Frequency
LTE-M:	Ultra-Narrow Band
LoRa:	Long Range
FSK:	Frequency Shift Key
CSS:	Chirp-Spread-Spectrum
QoS:	Quality of Service
PCB:	Printed Circuit Board
VNA:	Vector Network Analyzer
CPWG:	Co-Planar Wave Guide
AWR-EM:	Electromagnetic Simulator

CHAPTER 1

INTRODUCTION

It is widely known that the term wireless corresponds to transmission of data without external electrical conductors over a short/long ranges. In relation to this, wireless communication can be conceived as one of the critical means for transmitting data from one to another device. The information desired to transmit through the air is then conveyed by means of electromagnetic waves in a wireless communication system. In retrospect, the initial wireless communication systems were presented at the end of the 19th century. Over the subsequent years, the technology has been developed in a considerable extent. Therefore, the term wireless has become attributed to a great variety of tiny devices and smart technologies such as tablets, smartphones, Bluetooth, computers, etc.

Nowadays, the wireless communication technology enables users or devices to communicate from even long ranges. Basically, it has various forms such as wireless network communication, satellite communication, Bluetooth communication, mobile communication, and infrared communication. Due to the unprecedented growing technological developments in wireless communication technologies, Wireless Sensor Networks (WSNs) maintain its importance for the researchers. Presently, WSN is the most common networking service that can be employed in various applications. Typically, a WSN is comprised of smart devices that are already known as nodes. These nodes consist a central processing unit (CPU), smart sensors, and limited computational power. With the help of these sensors, nodes are used for observing position, sound, heat, vibration, temperature, pressure, etc. Generally, in a WSN, a node contains a power unit, computing unit, sensor interface, and a transceiver unit. In order to have a communication between the nodes, a robust and efficient centralized system is required. Today, this gives rise to introduce the notion of Internet of Things (IoT).

In a typical WSN, it is desired to use low-powered nodes. These nodes being available as substructure for a deployment are expected to serve for a longer time. Yet, WSN is exposed to many inherited difficulties because of the constraints of the nodes. These constraints refer to communication bandwidth, energy capacity, and computational ability [1, 2]. In addition to these, security issues and network management also need consideration [3]-[6]. Thus, in practice, different types of deployment model along with various network parameters can be required. For example, a deployment of a network that allows to manage activity can be required in a smart transportation system, or, a deployment of a network that provides long range communication can be required in a smart environment, or, deployment of a network that enables to deal with natural disasters can be required in smart cities. When smart wireless systems are considered, these examples can be extended almost endlessly. For this reason, various wireless communication technologies have been developed in recent years. For short-range communication, ZigBee and 6LowPAN technologies have been introduced [7]. For medium- and long-range communication, several technologies such as Long Term Evolution for Machines (LTE-M), Ultra Narrow Band (UNB), Sigfox, Long Range (LoRa), etc. have been developed [8]. For long-range communication, the LoRa is the fastest growing wireless technology platform which uses the industrial, scientific and medical (ISM) band [9]. It provides several advantages like reducing device cost, enhancing network capacity, increasing devices' battery life, and supporting large number of devices. Whereas most of the wireless technologies use Frequency Shift Key (FSK) modulation, LoRa uses Chirp-spread-spectrum (CSS) modulation. This type of modulation provides low-power characteristics which yields to increase the range of wireless communication. It is also able to endure environmental obstacles/interferences. Therefore, LoRa technology allows transmitting data over long-distances in practice. Theoretically, in a typical wireless channel, relatively high transmission power is strictly required to transmit data over long-distances. However, with the help of LoRa, the data can be transmitted to a distance that is up to approximately 25 km even at 14 dBm output power in a line-of-sight (LOS) environment [8, 9]. For this reason, it has been preferably utilized in aerospace and defence industry.

To build WSN properly, fundamental design factors should be addressed. These can be classified as reliability, network size, connectivity, hardware constraints, energy consumption, security, self-configuration, data fusion, network dynamics, quality of service (QoS), transmission media, coverage, and sensor network topology. Among these factors, sensor network topology has vital importance. This is because, it directly affects the network capacity and latency, and network robustness. Besides, it also affects the complexity of data routing. Sensor network topology is comprised of two main topology type such as physical topology and logical topology. In physical topology, physical arrangement of the nodes is interested. In logical topology, data flow between the nodes in a network is concerned. Hence, various logical topologies can be established in identical physical topology. Physical topology has seven different models including point to point, bus, ring, star, mesh, tree, and hybrid. Point to point is the basic and simple network topology that connects two nodes directly. In bus topology, the nodes are connected each other through a cable which has terminators at each end of the bus. In ring topology, as its name indicates, the nodes are connected each other such a simple ring. In star topology, every nodes are connected to centralized node that can be a hub or switch with an optical or coaxial cable. Mesh network is slightly complicated than other topologies. It has two different types. In the first one, which is also called as fully connected mesh topology, all nodes in the network are connected each other. In the second one, which is partially connected mesh topology, some of the nodes are connected each other with point to point connection, while others are connected to another nodes presence in the network. In tree topology, there is a root node connected to sub-nodes in a hierarchical structure. In hybrid topology, more than two different topologies are combined where there is no standard structure. Thus, it is evident that there are various ways to achieve connection between the nodes. However, the geographic area where a WSN is desired to build, and the purpose have vital importance to decide the network topology.

In this thesis, a linear WSN system deployed in a rural setting is considered. In the system, sensor nodes are considered to be located on a pipeline where the range between the nodes is varying, but in some cases it is relatively high. It is also considered that a node on the line can communicate with both previous and next

sensor nodes. Hence, as this kind of arrangement is based on hierarchical structure, a spanning tree linear WSN is considered to be used. Under these circumstances, this study is the first that mainly aims to provide bidirectional sensor node link design where two back-to-back directional antennas with a transceiver chipset are used to provide communication with neighboring sensor nodes. For this purpose, two options have been offered to provide a connection between transceiver chipset and back-to-back directional antennas. In the first option, a radio frequency (RF) switch has been designed. In the second option, a combiner has been utilized. It is worth noting that, due to its efficiency in long-range wireless communication, LoRa module has been incorporated as a chipset in both options. For the performance assessment, measurements have been conducted in a rural environment. The measurement results have been then evaluated in terms of power consumption, total cost, and maximum achievable distance.

The rest of the thesis is organized in the following chapters. In Chapter 2, firstly, an overview of WSNs is given, and then, LoRa technology as a design option for sensor nodes in WSNs is briefly described. Chapter 3 presents the efforts for providing bidirectional sensor link design. In Chapter 4, measurement scenarios are explained, and measurement results are provided. In the last Chapter, results are discussed, and future work is outlined.

CHAPTER 2

AN OVERVIEW OF WIRELESS SENSOR NETWORKS (WSNs) AND LoRa TECHNOLOGY

Before describing the details of bidirectional sensor link design, it is necessary to comprehend the main concept of WSNs along with LoRa technology which is one of the growing wireless communication technologies. This also provides better understanding of the scope of the thesis. In this context, this chapter is divided into three stages. In the first stage, a detailed overview of WSNs is presented. In the second stage, LoRa technology is briefly discussed. In the last stage, scope of the thesis is presented.

2.1 Wireless Sensor Networks (WSNs)

2.1.1 Working Principle

A WSN could be described as a network of nodes which are employed cooperatively in order to control or sense the desired environment. Nodes in the network are linked with wireless media to communicate each other. Generally, a typical WSN architecture is comprised of observer (user), sensor nodes, and a gateway as shown in Figure 2.1.

Here, user(s) and gateway(s) are connected through a network. Gateway(s) and sensor nodes, on the other hand, form a sensor field. Conceptual framework of a WSN is therefore based on sensing unit, CPU, and radio unit. In order to monitor the environmental conditions such as heat, pressure, or humidity. The sensing output is forwarded to CPU to perform the computations for achieving environmental data. These data are then conveyed by means of a radio unit with the help of wireless channels between the sensor nodes. Hence, all data are transferred to Gateway(s).

Thus, in a WSN, collection and transferring of data are completed in following stages: data collection, data processing, data packaging, and data transferring.



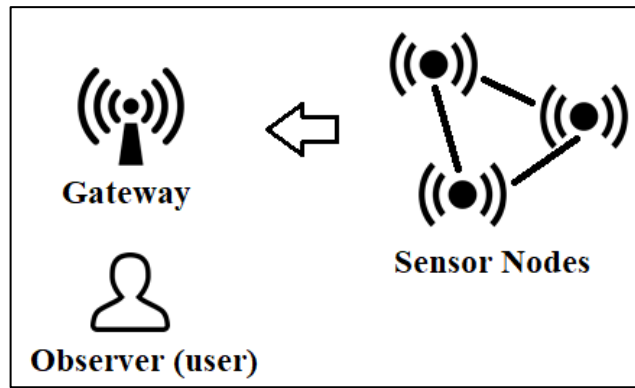


Figure 2.1 A typical illustration of WSN

2.1.1.1 Sensor Nodes

Typically, a WSN is a collection of sensor nodes which may be considered as separate small and tiny computers (devices). In order to create a network system, these devices work in cooperation. However, efficiency and functionality are basic requirements that should be met by the nodes. These nodes should also have predefined purpose. To provide data sharing and communication in a network, the nodes have a structure that should be synchronized. They are continuously processing, and have limited energy sources. Besides, these nodes are low-cost devices. Thus, it can be concluded that a sensor node is one of the fundamental components of a WSN. The main structure of a sensor node is shown in Figure 2.2.

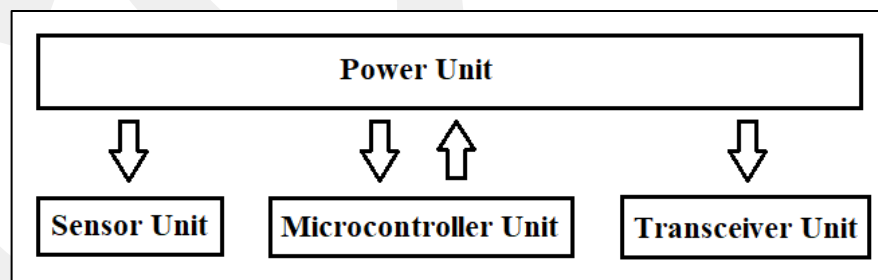


Figure 2.2 The main structure of a sensor node

As shown in Figure 2.2, power unit is centered at the main part (base) of the sensor node. Energy is supplied for sensor unit or sensor, microcontroller unit or CPU, and transceiver unit. This should be continuous process since the energy is required in all units while performing some specific tasks such as communicating, sensing or

computing. External sources such as batteries, solar cells or any other smart powering systems can be then utilized to power nodes.

In microcontroller unit or CPU, computing tasks are accomplished. It is comprised of a microprocessor and a memory unit. Mostly, connectors are included to connect external sources (units) to the main unit. The main functions of this unit are managing the gathered data. When sufficient data is gathered, microprocessor unit set the data as envelopes since they allow efficient data transmission. For broadcasting purposes, these are then forwarded to the radio. At the same time, CPU is connected to base, and also communicates with other sensor nodes to sustain efficiency in the system.

In sensor unit, sensing process is achieved. In fact, it is the most important part of the system. Sensors used in the unit converts different types of environmental data to electrical signals. Recently, several developments have been emerged to produce multi-functional sensors. These can be classified as LED sensors (ambient light sensors, proximity sensors, etc.), Micro-electro-mechanical systems (pressure sensors, acoustic sensors, etc.), and CMOS based sensors (temperature sensors, humidity sensors, etc.). These developments have made various type of sensors use in the sensor nodes.

Transceiver unit in a sensor node is mainly used to provide wireless communication. It has four states that can be listed as Sleep mode, Idle mode, Transmit mode, and Receive mode. It is important to note that Laser, Infrared, or RF technologies could be selected as a wireless media in the transceiver. Generally, RF technology is preferred in WSNs applications.

There is also an operating system that is used for WSNs. These can be mainly exemplified as Tiny OS [10], Contiki [11], and MANTIS [12]. Among these operating systems, Tiny OS can be preferred due to its efficiency.

2.1.1.2 Gateways

By means of gateways, system admins could be able to interface the sensor nodes to user computers (tablets, PCs, etc.). Generally, Gateways could be in three states

including active state, passive state, and hybrid state. When the gateway is in active state, it allows to transfer its data to the server of the gateway. However, when it is in passive state, it just send a request to sensor node. As their combination, when the gateway is in hybrid state, it performs all tasks in both passive and active state.

In order to connect the various gateways through a link or internet, task managers are utilized. These are comprised of data service and client data browsing. In fact, task managers yield to store and process of the collected data from the sensor nodes. These data can be analyzed by users with the help of an interface.

2.1.1.3 Communication Architecture

For communication tasks, a typical radio that is composed of a receiver and a transmitter can be used. These should be incorporated in sensor nodes in order to ensure bidirectional communication among the nodes. Fundamentally, while transmitting data, the data sent from the CPU is received, and then transmitted to the neighbor sensor node. Conversely, while in receiving data, the data sent from the neighbor sensor node is received, and then transmitted to the CPU. Here, it is worth noting that the collected data by the sensor node is forwarded to the parent node. To allow the accessibility between the user computer interface and the data collected by other nodes, this node is connected to a functional computer. Indeed, once a user lets out a directive, it will be forwarded to the functional computer through a wireless media like internet. Hence, the computer sends such directive to the parent node which will then send the received this directive to the other children nodes.

In Figure 2.3, the architecture of the protocol stack used by sensor nodes is shown. The protocol stack combines the data with network protocols. It is comprised of layers such as physical layer, data link layer, network layer, transport layer, application layer, and planes such as power management plane, mobility management plane, task management plane [13].

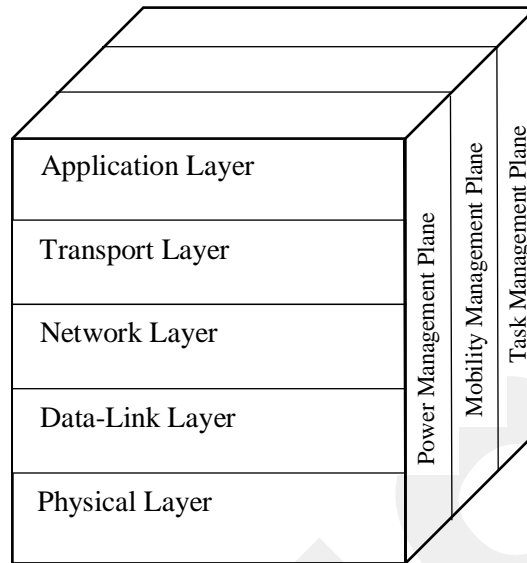


Figure 2.3 The architecture of the protocol stack used by sensor nodes

In the physical layer, some communication tasks such as choosing or generating of frequency, and modulation is managed. With the data link layer, error control is managed, and consistent connections in the communication network is guaranteed. In the transport layer, data flow is maintained. The provided data in this layer is routed in the transport layer.

In the power management plane, some tasks related to power consumption is managed. With the mobility management plane movement of each sensor nodes is identified, and then the mobility of these nodes are recorded. This provides to keep a route that comes back to a user. Thus, every node could be able to manage the power so as to accomplish a task. In the task management plane important events such as detection or sensing are controlled to avoid conducting similar tasks simultaneously.

2.1.2 Design Requirements

As discussed in Chapter 1, in order to build WSN properly, basic factors should be addressed. One these factors is reliability of a sensor node. This is the capability of a sensor that can continue the functions irrespective of external interferences. Density of the sensor nodes is another factor that highly affects the efficiency, coverage area, and reliability. Another is energy consumption that all sensor nodes require battery

operation, so life time of a sensor node is strictly relied on battery life times. The other one is data aggregation which is a function that provides to compress the size of the data. Another factor is the transmission (wireless) media that provides to construct the communication link between the nodes. Moreover, security of WSNs is another crucial factor as usual. Self-configuration is also important factor for WSN systems. If there is a failure in a node, new node should be integrated to the network. Network dynamics is another factor which is based on the mobility of the nodes. Due to this factor, some troubles in energy, routing stability, etc. may be emerged in practice. The other factor is QoS which is related to delivering the data within a specific latency. This could be important for some WSN application in practice. Network connectivity is another important factor that should be formed in a strict connection among the sensor nodes in a network. The other one is related to coverage which directly affects the system accuracy. The last one is sensor network topology. It is briefly discussed in the following.

2.1.2.1 Sensor Network Topologies

Sensor network topology is the schematic description the arrangement of all components in the network. Two different topologies are exist: Physical and Logical topology [14]. In the logical topology, data flow is concerned. In the physical topology, which is important for understanding this study, layout of the sensor nodes' connections are interested. There are seven different models for physical topology: a) point to point, b) bus, c) ring, d) star, e) mesh, f) tree, g) hybrid.

Point to point is the basic and simple network topology that connects two nodes directly. A simple illustration of this topology is shown in Figure 2.4

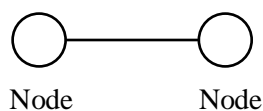


Figure 2.4 Point to point topology

In bus topology, which is shown in Figure 2.5, the nodes are connected each other through a cable which has terminators at each end of the bus. It can be considered as simple and low-cost. However, if the backbone cable is impaired, the network will become unusable.

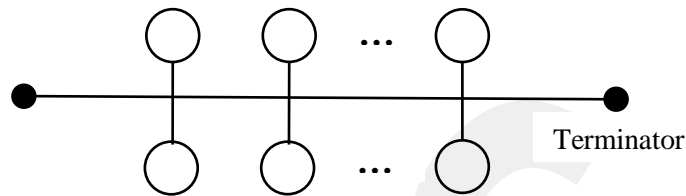


Figure 2.5 Bus topology

In ring topology, as its name indicates, the nodes are connected each other such a simple ring. It is faster than bus network. A typical arrangement is shown in Figure 2.6. This network has dual ring topology where data flow can be in both uni- and bi-directional. This network is relatively cheap, and is able to deal with high traffic in terms of data transfer. Yet, any type of failure in a node results in breakdown of all network.

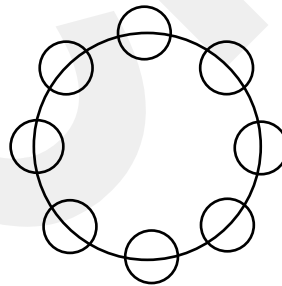


Figure 2.6 Ring topology

In star topology, every nodes are connected to centralized node that can be a hub or switch with an optical or coaxial cable. Typical ring topology is shown in Figure 2.7. Due to its high efficiency, this topology is widely used in many applications. Its management along with installment is also easier than the other topologies. However, its installment is expensive. Moreover, for large networks, central node may adversely affect the system performance if its capacity is low.

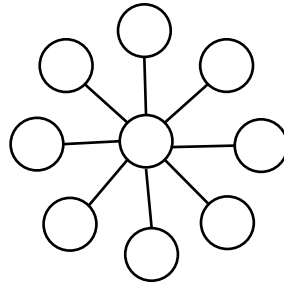


Figure 2.7 Ring topology

Mesh network is slightly complicated than other topologies. It has two different types. In the first one, which is also called as fully connected mesh topology, all nodes in the network are connected each other as shown in Figure 2.8.

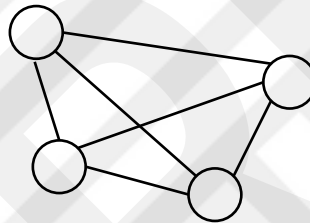


Figure 2.8 Fully connected mesh topology

In the second one, which is partially connected mesh topology, some of the nodes are connected each other with point to point connection, while others are connected to another nodes presence in the network. This is illustrated in Figure 2.9. In this network, there are two ways to transmit the data. First one is called as routing while second is known as flooding. When compared with the other topologies, mesh network ensures accuracy and security issues. But, it is expensive in total, and its installment is troublesome.

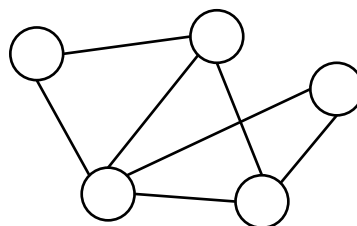


Figure 2.9 Partially connected mesh topology

In tree topology, there is a root node connected to sub-nodes in a hierarchical structure as shown in Figure 2.10. For this reason, it is not difficult to insert additional nodes to the network. Also, it is easy to manage the network. Moreover, troubleshooting is very simple. It is optimal when workstation groups are considered to be use. As a disadvantage, it is expensive.

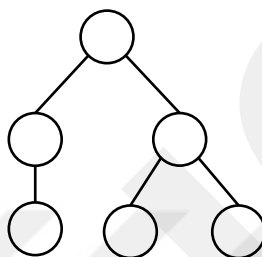


Figure 2.10 Tree topology

In hybrid topology, more than two different topologies are combined where there is no standard structure. Hence, it covers all advantages and disadvantages for the topologies that are mentioned above. Although its designing and installing phase is expensive, error detection is not difficult, and its structure is flexible. A simple illustration of a hybrid topology is shown in Figure 2.11.

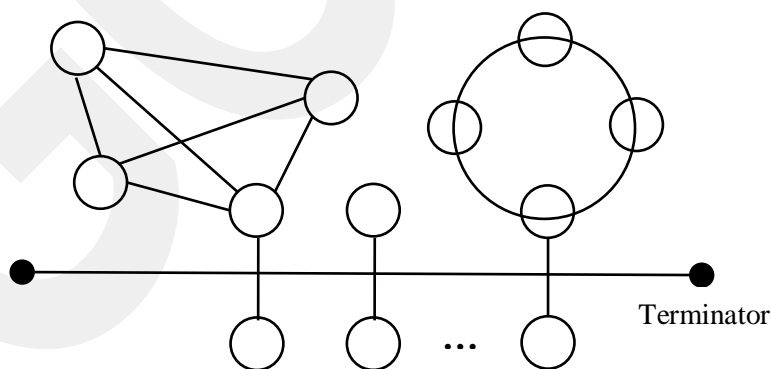


Figure 2.11 Hybrid topology

2.2 LoRa Technology

As discussed previously, low-power nodes are desired to use in a typical WSN. These nodes being available as substructure for a deployment are expected to serve for a longer time. In practice, deployment of a network is critical to provide efficient communication. For this reason, various wireless communication technologies have been developed in recent years. For short-range communication, ZigBee and 6LoWPAN technologies have been introduced. For medium- and long-range communication, several technologies such as LTE-M, UNB, LoRa), etc. have been developed. For long-range communication, the LoRa is the fastest growing wireless technology platform band.

LoRa is the physical layer that is used to provide long-range communication. As a physical layer, most of the wireless system use FSK modulation. However, LoRa uses CSS modulation which has similar power characteristics with FSK modulation but it provides longer communication distances. In fact CSS is used in military systems widely, however, with the help of LoRa, its usage becomes commercially useable.

Long range capability is the main benefit of LoRa technology. By a single station or a gateway, very large coverage such as hundreds of kilometers can be achieved. It should be noted that the environmental conditions may highly affect the range in a typical wireless application. However, according to [15], LoRa has a link budget which seems greater than the one that provided by other technologies. It should be noted that the link budget can be considered as an indicator that is used in determining the range in the environment.

LoRa allows various frequency channels and data rates to be used in communication. Here, selecting the data rate is critical since there is trade-off between the message duration and communication range. Typically, the data rates in LoRa technology is ranged from 0.3 kbps to 20 kbps, and, several data rates for each spreading factor could be observed [15]. These are listed in Table 2.1.

Table 2.1 Spreading factors attributes [15]

Spreading Factor	Bandwidth (kHz)	Spreading Factor (chips/symbol)	Bit rate (bits/sec)	Chip rate (chips/sec)	Time per symbol (sec/symbol)
SF7	125	128	5496	125000	0,001024
SF8	125	256	3125	125000	0,002048
SF9	125	512	1758	125000	0,004096
SF10	125	1024	977	125000	0,008192
SF11	125	2048	537	125000	0,016384
SF12	125	4096	293	125000	0,032768

In the literature, several studies on LoRa deployment have been presented [16-28]. In [16], LoRa devices are used to study on a scalable network for a smart city application. They aimed to provide a LoRa simulator (LoRaSIM) to capture link behavior. In [17], an experimental study has been conducted to study coverage of a LoRa network in the case that the distance between the transmitter and the receiver is high. It was aimed that to reach maximum communication range that can be achieved by the network setup. In [18], authors have conducted another experiment to assess the maximum emission that a node can produce. They have also analyzed the LoRa components in detail by using a testbed that is designed to assess the performance of both physical and data link layer. They used several channels and packets in their tests. Another experiment has been conducted in [19], to analyze the usage of the network in 5G. In [20], to test the capability of LoRa in indoor environment, experiments have been conducted. The main purpose was to evaluate the maximum range than can be achieved by LoRa. Another LoRa based setup has been designed in [21] named as FABIAN. It was deployed in a city, and experimented by focusing the traffic between the base stations and the nodes. Assessments were carried out to measure QoS. In [22], in order to achieve long-range communication and high data transmission with low power, Wi-Fi and LoRa are combined in a multi interface module design. In [23], the performance of LoRa network which is based on channel access has been scrutinized. In [24], a low-cost system to monitor the greenhouse gas

emissions in an around the Nordic cities. In [25], a device based on LoRa module that can be used to provide plug and play for none expects in IoT systems has been presented. Another study introduces a system that is designed for monitoring water level through a WSN by deploying LoRa [26]. Similarly, the study in [27] was conducted to monitor road condition of a bridge by using a WSN that deploys LoRa. Lastly, a smart water management system has been proposed through a water distribution network [28]. All studies introduced above are summarized and compared in the following table.

Table 2.2 LoRa applications [8]

Ref.	Node	Range	SF	Band MHz	BW kHz	Payload bytes	Tx Power dBm	App.	LoRa Module
[16]	2	100m	7-12	868	125 250 500	20	2-17	Smart city	NetBlocks XRange SX1272
[17]	2	30km	-	868	125	50	14	Testbed	Semtech SX1272
[18]	1	2.8km	7-12	868	125	51	14	Testbed	Semtech SX1276 MBED
[19]	9	60m	12	863- 870	125	4	14	Indoor experiment	Microchip RN2483
[20]	1	-	12	433 868	125	-	20	Indoor experiment	IMST iU880A
[21]	-	-	7-12	-	125	64	-	Testbed, Smart city	Froggy Factory LoRa Shield
[22]	-	6km 20km	12	-	125	-	-	Testbed	Waspote SX1272
[23]	-	-	7-12	-	125	64	-	Testbed	-
[18]	-	2.8km	7-12	-	125	-	2	Testbed	Semtech SX1276 MBED

Table 2.3 LoRa applications [8] (cont'd)

[24]	10	-	-	-	125	54	-	Testbed, Smart city	Libelium's plug & sense
[25]	-	3.5km	12	868	125	-	-	Monitoring system	Microchip RN2483
[26]	5	1km 5km	12	915	125	26	14	Monitoring system	Atmel HopeRF RFM95
[27]	3	-	12	433 868	125	8	14	Monitoring system	Microchip RN2483
[28]	15	1.25km	7-12	868	125	18	-	Manageme nt system	Microchip RN2483

2.3 Scope of the Thesis

Obviously, it can be concluded from Chapter 2.1 that there are several ways to connect the nodes in a WSN. However, the geographic area where a WSN is desired to build is an important factor that should be taken into account while deciding the network topology. Besides, the purpose of the WSN application has considerable importance. Furthermore, WSNs require sensor nodes that should be energy efficient and are able to communicate over long ranges. As can be inferred from Chapter 2.2, it is clear that deployment of LoRa could be a best choice to meet these requirements.

In this thesis, on the other hand, it is aimed to provide bidirectional sensor node link design in linear WSN system deployed in a rural environment. As an illustration, distribution of n nodes is shown in the Figure 2.12.

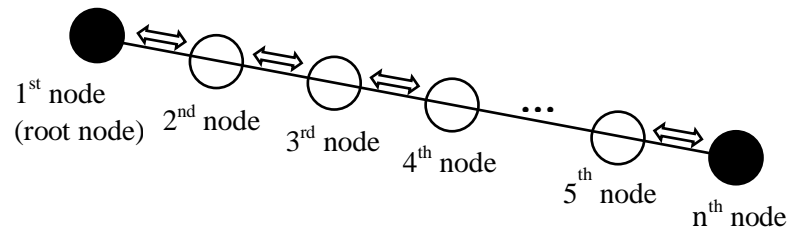


Figure 2.12 Spanning tree network of nodes

As can be seen in Figure 2.12, distribution of the nodes follow the bus topology. Yet, in the considered WSN system, there is a root node (node 1) while other nodes are hierarchically connected to it. The more feasible topology in this case is a combination of tree and partially mesh topology which can be considered as a spanning tree network of sensor nodes. In this network, the structure of parent to child is built in from root to last node. Indeed, root node is parent whereas the last node is child in this structure. However, other nodes can be parent and child. Moreover, each of nodes in the network has single ID which is utilized in while determining the parent-child relation.

For the considered network, it is necessary to use two back-to-back directional antennas with a transceiver chipset in order to provide communication with neighboring sensor nodes. Therefore, the study presented in this thesis offers two options to provide a connection between transceiver chipset and back-to-back directional antennas. In both options, LoRa module has been incorporated as a chipset due to its efficiency. Designing of these options are described in the following chapter.

CHAPTER 3

SWITCHING OPTIONS

As mentioned before, the study presented in this thesis mainly aims to provide bidirectional sensor node link design where two back-to-back directional antennas with a transceiver chipset are required to provide communication with neighboring sensor nodes. For this purpose, two options have been offered to provide a connection between transceiver chipset and back-to-back directional antennas. These options are described in the following sections.

3.1 RF Switch

The first option is based on RF switch which has been designed for the combining antennas with the chipset. In the design, some methods and approaches to provide active RF switch and matching circuits with minimum insertion loss have been investigated. The system structure includes RF transceiver module, impedance matching circuit, RF switch (chip) and supply components for switching as shown in Figure 3.1. In addition, the goal of design is to provide an impedance matching circuit which is a critical component with the appropriate RF switch selection.

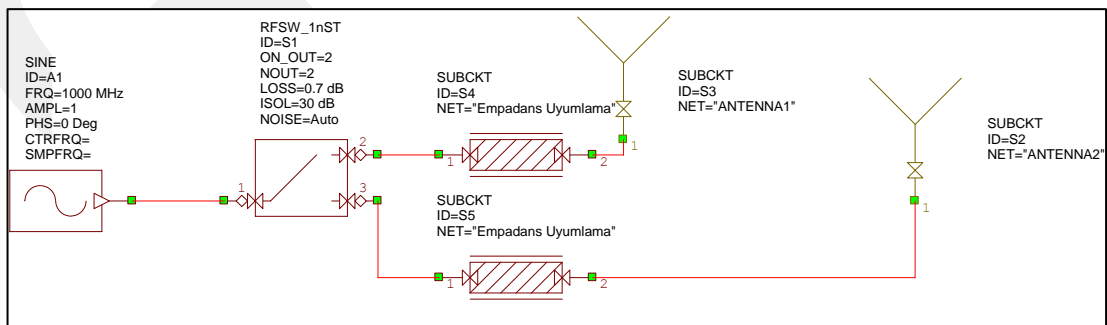


Figure 3.1 System Structure and RF Switch Designing

There are several methods in the literature to draw the transmission line. These are Microstrip Line, Coplanar Wave Guide Line (CPWG), and Stripline [30]. In this study, CPWG has been used as described in the following.

3.1.1 Coplanar Wave Guide Line

When circuitry of RF switch circuit which can be reached from its datasheet is considered, CPWG can be an appropriate method to create the transmission line. One of the important advantages over the other methods is its compatibility with the size of RF Switch pins.

In order to create an impedance matching circuit or line, firstly, the “AWR TXLINE” calculator has been used. According to the desired characteristic impedance of the line and its operating frequency, this tool gives the width of the line along with the spacing between the line and ground. It should be noted that, as reported in [31], the physical length of the line (distance of the line) only change the phase of the signal, and does not change the characteristic impedance [31].

The interface of the “AWR TXLINE” calculator tool is shown in Figure 3.2. Here, values are entered in accordance with RF Switch pin input (Length 0.5 mm) to calculate the line and gap value with the help of directions in [32]:

- Selected line: CPWG
- Height: 1.6 mm
- Frequency: 868 Mhz
- Material used: FR4 (Insulator Constant = 4.5 Loss Tangent = 35um)

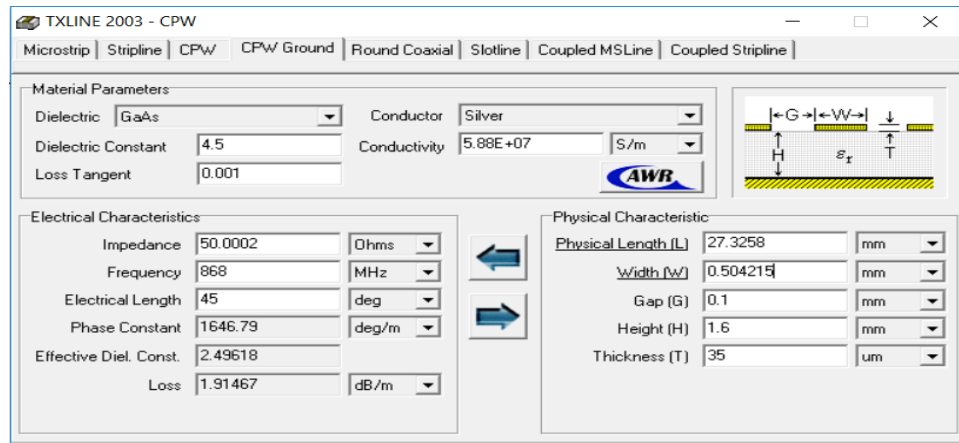


Figure 3.2 Microwave Office TXLINE Calculator

The calculation is based on 50-ohm impedance and 868 MHz operating frequency. In this regard, the parameters of FR4 circuit board has been examined and impedance compatibility has been ensured. Figure 3.3 shows the corresponding schematic design of CPWG.

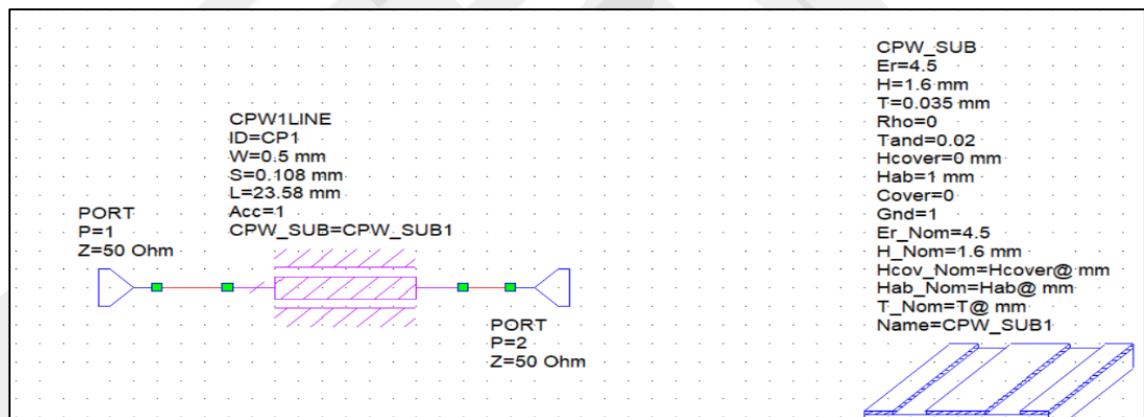


Figure 3.3 CPWG Schematic Design in AWR-MWO

The printed circuit board (PCB) is then designed by using Altium as shown in Figure 3.3. The design parameters are listed in Table 3.1 to find the loss of FR4 board on the line.

Table 3.1 “CPWG” Parameters

Characteristic Impedance	50 ohm
Line Width	0.5 mm
Space between line and ground	0.1 mm



Figure 3.4 Measurement Loss on Line using FR4

Furthermore, the simulation results of the “CPWG” design in AWR environment have been provided as shown in Figure 3.5. As a benchmarking, simulation results have been compared with the test results achieved by Vector Network Analyzer (VNA).

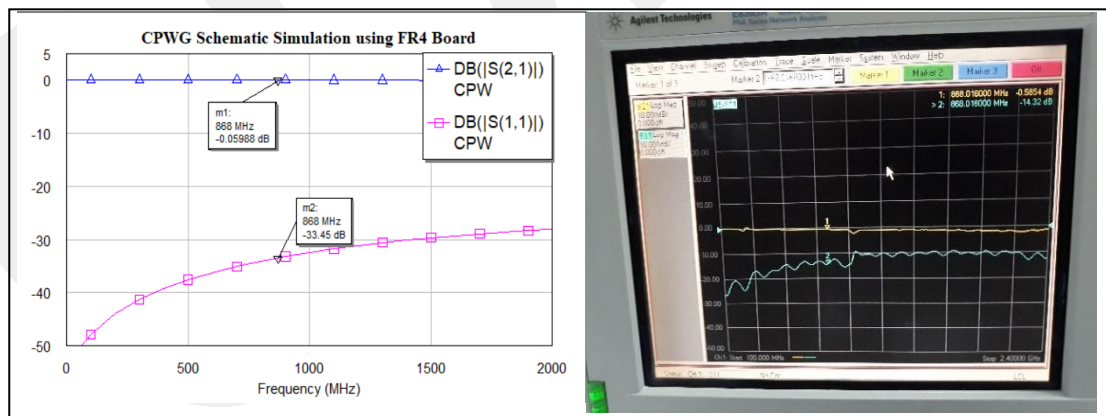


Figure 3.5 CPWG Schematic Simulation and Experiment Result

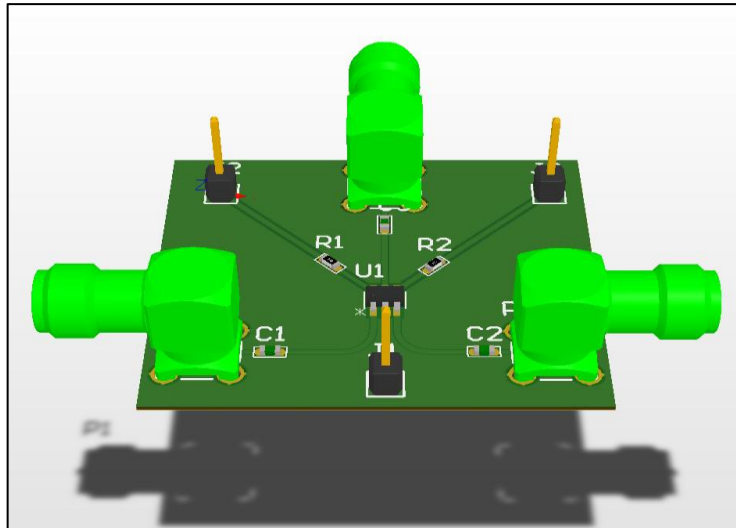


Figure 3.7 PCB Design of RF Switch

Then, the simulation and experimental results have been compared with the RF switch ON and OFF state. The results are shown in Figure 3.8.

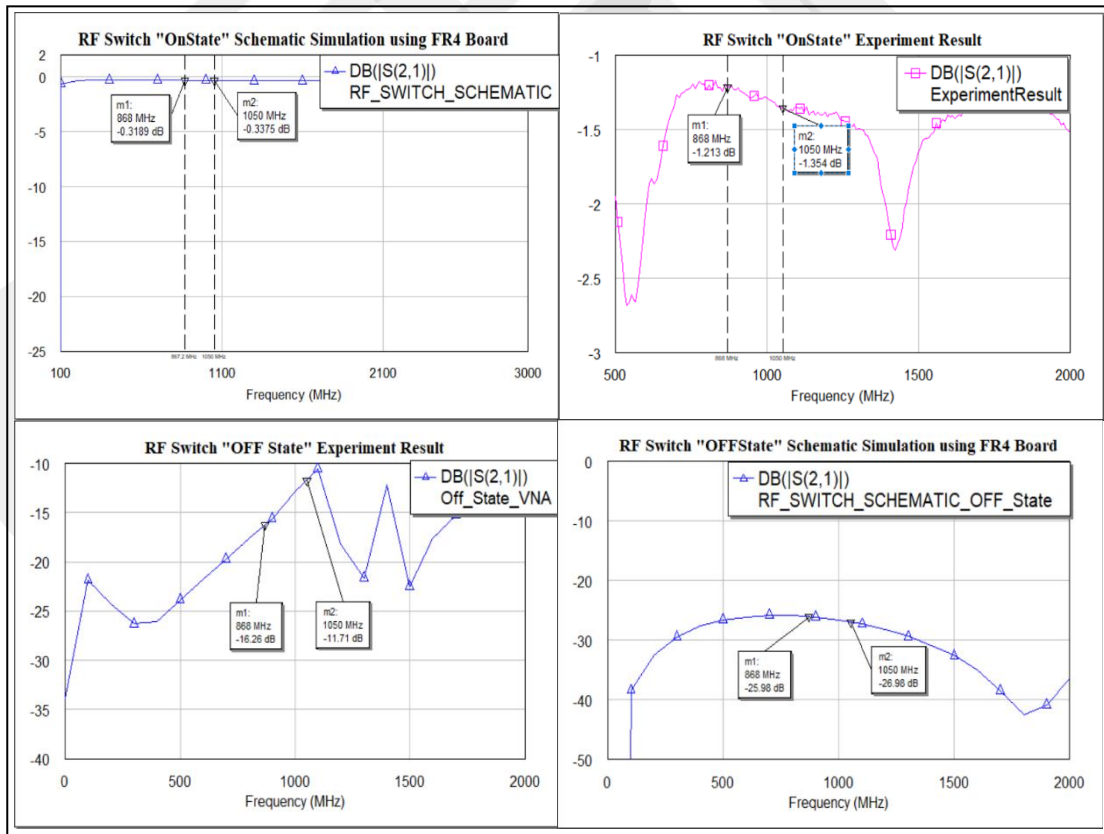


Figure 3.8 Comparison Results

3.1.3 Integration of RF Switch Design

As discussed in the previous chapter, WSNs require sensor nodes that should be energy efficient and are able to communicate over long ranges. Accordingly, using of LoRa transceiver chips could be an efficient way to meet these requirements. Therefore, a system design is required to integrate RF switch that matches LoRa module to the antenna. In this section, this system design is briefly explained.

The basic structure of the system is shown in Figure 3.9 where microprocessor controls the DC pins of the RF switch.

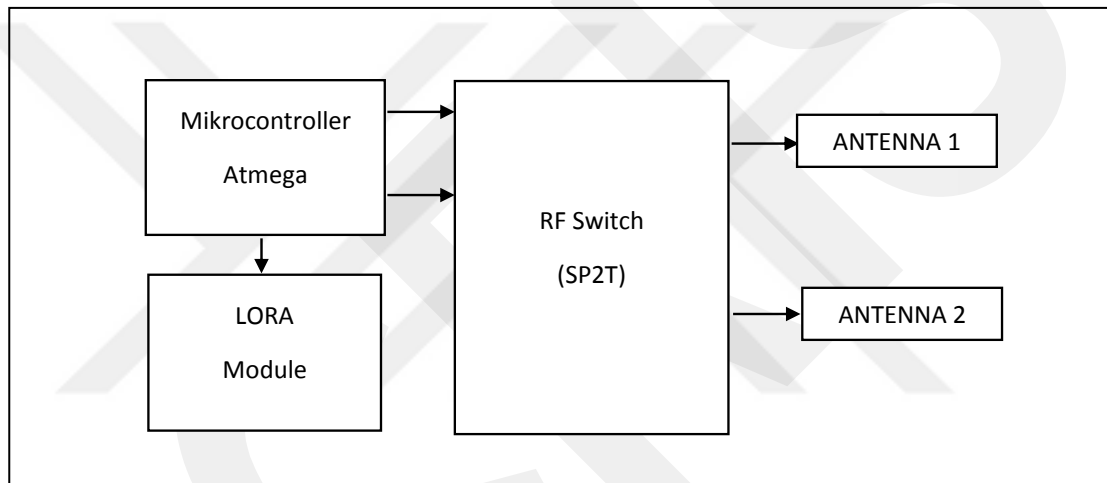


Figure 3.9 System Design

For the PCB design of this system that is compatible to Arduino Mega, Altium has been used. While doing this, the parameters for impedance matching should be properly selected. As listed in Table 3.3. the distance between the line and ground is 0.3 mm. This is because, the output pins of the LORA module have a length of 1.5 mm. Besides, the length between the line and ground should be 0.1 mm as the size of the pins of the RF switch is 0.356 mm. Using these parameters, the designed PCB layout is shown in Figure 3.10.

Table 3.3 Selected Parameters for 50-ohm Matching

Length	Transmission Line(mm)	Space between Line and Ground(mm)
L1	1.5	0.3
L2-L3	0.356	0.1

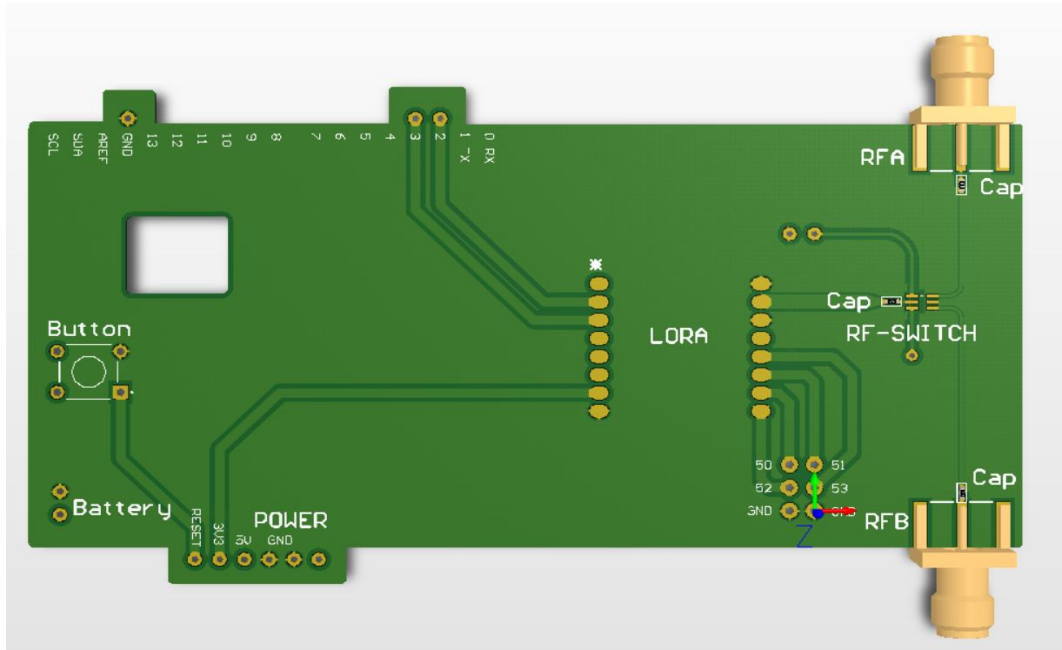


Figure 3.10 RF Switch Unit with Arduino Mega

Moreover, in Table 3.4, the gain and the loss has been measured for the design at 915MHz when the RF1-RF2 is both ‘on’ and ‘off’ state. The results are listed at Table 3.4 and Table 3.5, respectively.

Table 3.4 The Measured Values in the RF1-RF2 ON State

RF1-RF2	Transmit Power(dBm)	Received Power(dBm)	Loss(dB)
S21(Insertion Loss)	17.74	17.15	0.59
S31 (Isolation)	17.74	2.42	15.32

Table 3.5 The Measured Values in the RF1-RF3 ON State

RF1-RF3	Transmit Power(dBm)	Received Power(dBm)	Loss(dB)
S31(Insertion Loss)	17.74	17.02	0.72
S21(Isolation)	17.74	-3.38	21.12

3.2 RF Splitter

In this section, another switching option based on power divider is explained. As is known, power dividers have various topologies, such as Lange, Wilkinson or a simple T-junction [33]. For this design, Wilkinson power divider has been selected. Moreover, the methods and techniques followed in this design have been provided. Also, the results achieved from simulations and the measurements have been compared.

3.2.1 Ideal Wilkinson Power Divider and Phase Angle

The important parameters when designing the power divider are characteristic impedance of the electrical length of the line, and the balance resistance used to provide isolation between ports. Characteristic impedance of the transmission line should be 70.7-ohms for a 90-degree angle between the ports, and the electrical length of the line should be selected according to the 90-degree angle [34]. Using the “AWR TXLINE” tool shown in Figure 3.11, the length (W) and the physical length (L) of the selected line has been decided as 1.49 mm and 48 mm, respectively.

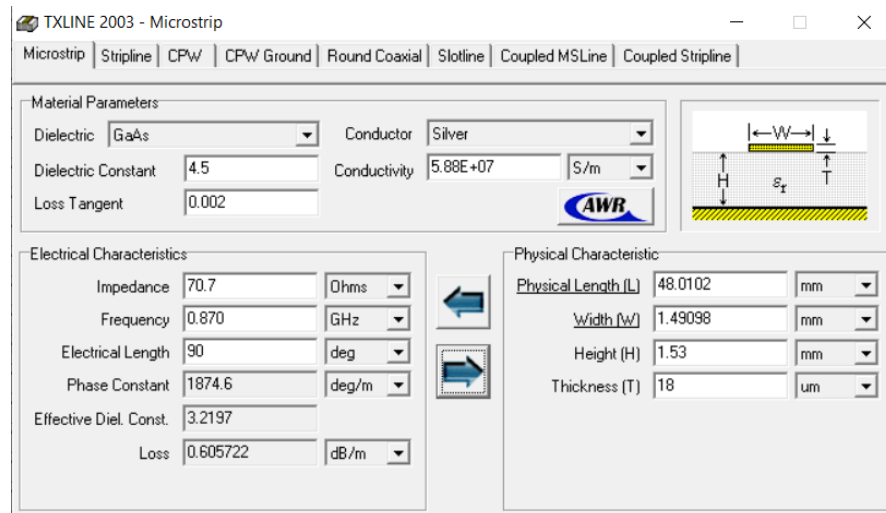


Figure 3.11 Microwave Office TXLINE Tool

Here, the required impedance of each quarter wave transmission line is equal to $\sqrt{2}$ of the characteristic impedance of the input transmission line ($Z_0 = 70.7 \Omega$). In addition, the balance resistance connecting the two output ports equals to double of the characteristic impedance of the input transmission line ($R = 2 \times 50$) [30]. The ideal Wilkinson power divider design in AWR is shown in Figure 3.12.

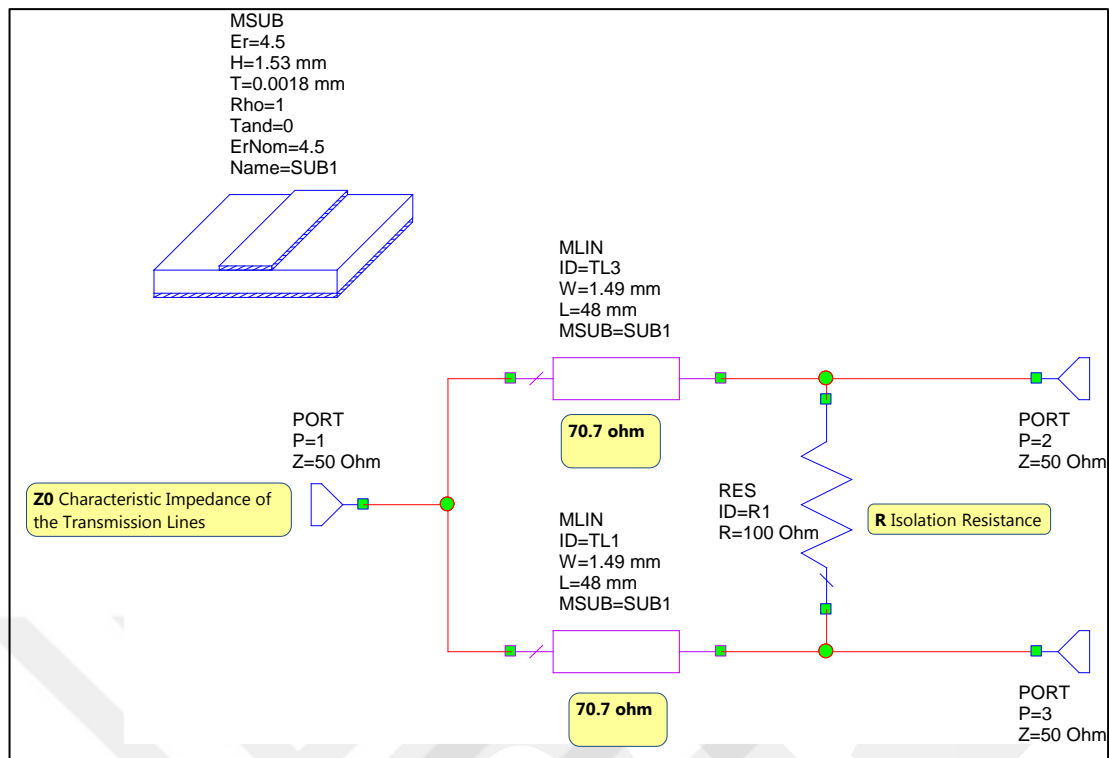


Figure 3.12 The ideal Wilkinson Power Divider

In Wilkinson power divider design, the reflection on the output port should be basically the same with the signal on the other output port. The signal reflected from the one of ports backs to the other output port through a resistive path, or the input. Since the transmission lines are quarter wavelengths, the signal passing through the resistor reaches a certain phase, while the signal (two 90° phase shifts) moving along the two quarter wave lines reaches 180° phase. When these are out of phase, the reflections have equal amplitude, and are completely canceled out (isolation between the output ports). Therefore, an ideal Wilkinson power divider can be observed as a 90° phase shift and half the amplitude of the input port as shown in Figure 3.13 [35].

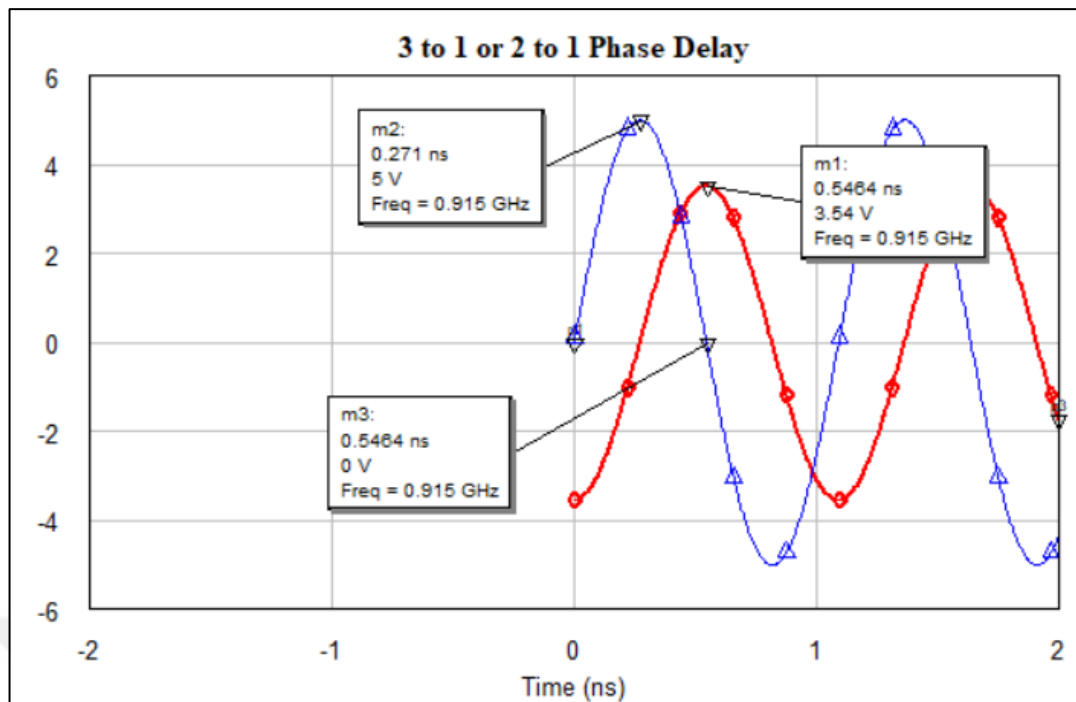


Figure 3.13 Phase Difference Between Input and Output

3.2.2 Wilkinson Power Divider Design and EM Simulation

The Wilkinson power divider consists of three topologies. These are conventional straight-split method, the circular split method and the elliptical split section [30]. In this design, conventional straight split method has been selected.

The schematic design of the power divider in AWR environment is shown in Figure 3.14. The lengths of the microstrip line elements have been selected to operate at 870MHz frequency band. In order to observe phase angle as 90° , the physical length has been selected as 48mm.

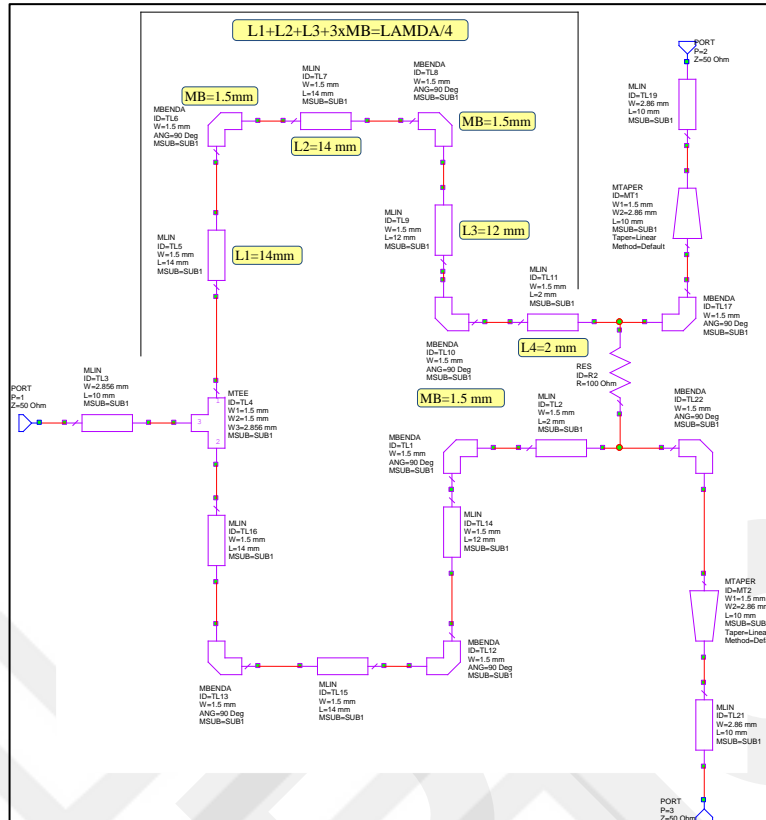


Figure 3.14 Wilkinson Power Divider in AWR-MWO

In order to increase the accuracy of the schematic results, the design has also been simulated in the AWR-EM environment. Figure 3.15 shows the EM layout of the circuit and the PCB.

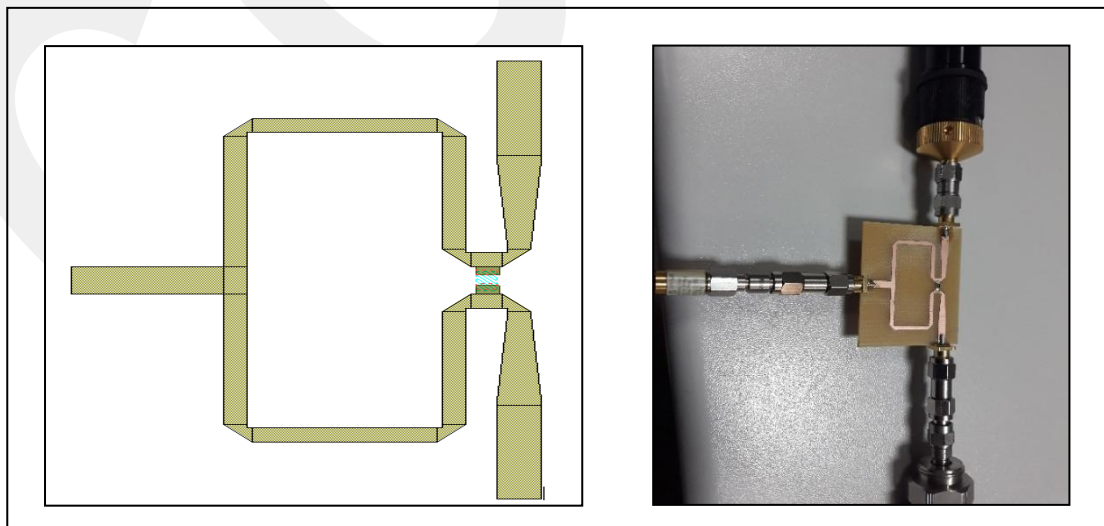


Figure 3.15 AWR-EM Design and Printed Circuit Board

Wilkinson power divider has been designed at ISM-868Mhz band. The reflection and insertion loss graphs have been plotted by means of AWR. The results have been observed as shown in Figure 3.16.

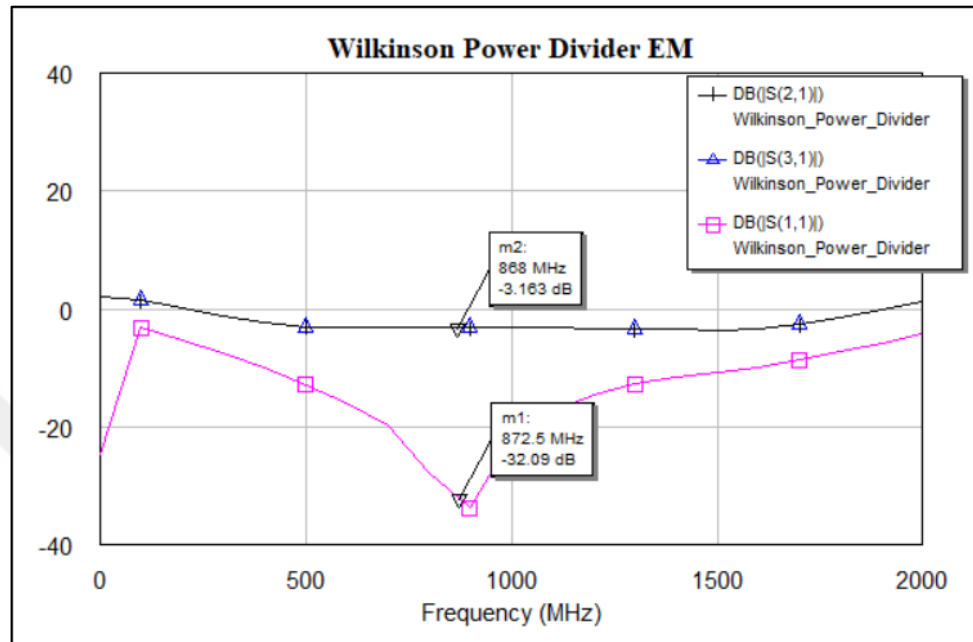


Figure 3.16 Wilkinson Power Divider - S21, S31 and S11

PCBs have been then designed. To control these designs, VNA has been utilized. Results are shown in Figure 3.17.

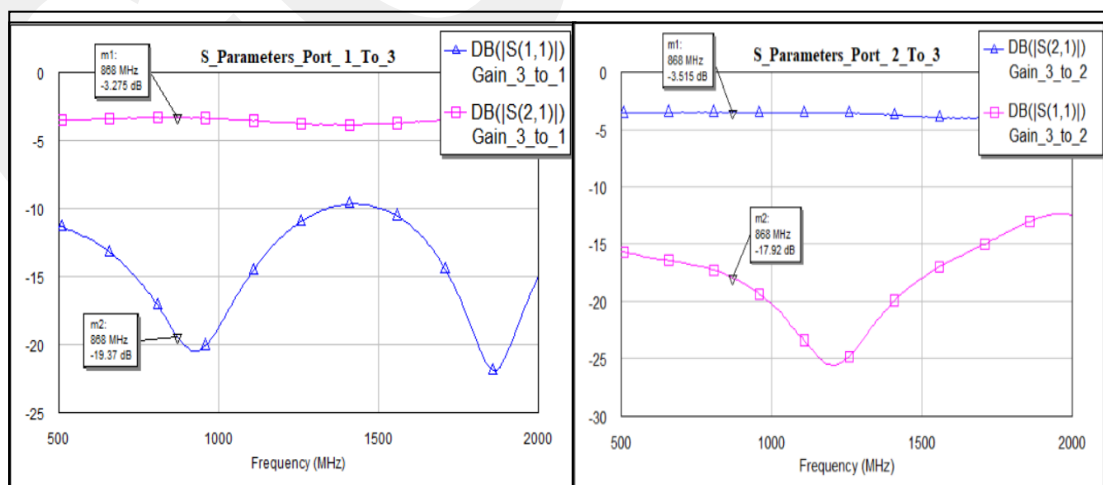


Figure 3.17 Experimental Results of Wilkinson Power Divider S21, S31 and S11, S22

In the circuit design, it is intended to operate two antennas simultaneously using a Wilkinson power divider. From the simulation results, insertion loss is observed as 3.163 dB. According to the results obtained by VNA, $S_{21} = 3.275$ dB and $S_{31} = 3.515$ dB. Although the desired results have obtained in the simulation results, there was a 0.3 dB loss obtained during the implementation. It is believed that the reason of this loss stemmed from the connector type used in the implementation or soldering process.

CHAPTER 4

PERFORMANCE MEASUREMENTS

For the performance assessment, measurements have been conducted in a rural environment. In this chapter, the measurement results have been evaluated in terms of power consumption, total cost, and maximum achievable distance.

During the measurements, firstly, 100 packages were transmitted. Then, the number of received packages were analyzed by varying the distance between the nodes. To do this, two different measurements were conducted.

For the first measurement, as shown in Figure 4.1, a one-meter SMA cable and a microstrip antenna [36, 37] were connected to one antenna port of the node. 50-ohm flat antenna was also connected to the other antenna port to avoid the reflection.

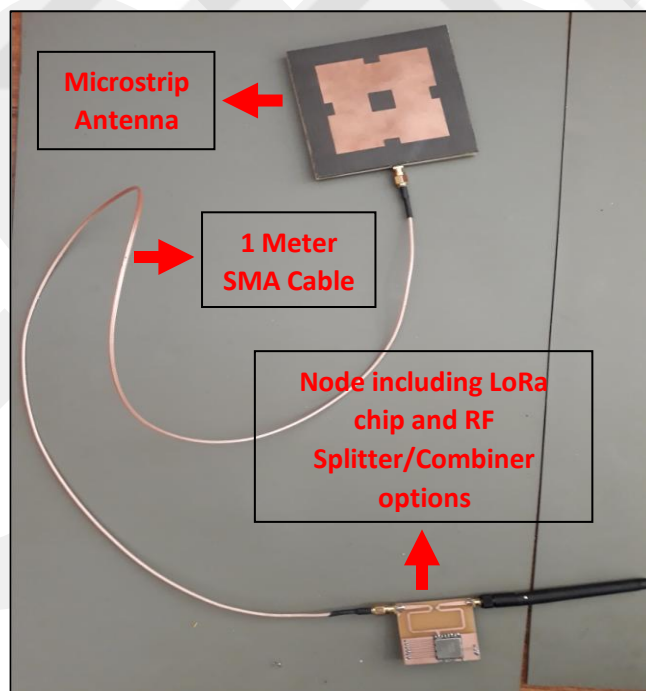


Figure 4.1 Measurement Setup

Before the measurements, the LoRa parameters were identified as listed in Table 4.1 below.

Table 4.1 LoRa Parameters

Spreading Factor	7
Bandwidth	125 kHz
Coding Rate	4/5
Output Power	17.7 dBm
Center Frequency	915 MHz
Payload Length	8 Bytes
Preamble	6 Bytes

According to the LoRa parameters, the bit rate and sensitivity were theoretically calculated as provided in Table 4.2.

Table 4.2 Lora Modem Theoretical Outputs

Bit Rate	5468.75 bps
Time on Air	34.05 ms
Sensitivity	-123 dBm
Link Budget	140 dBm

Range measurements were performed in İncek - Ankara. The communication module used in the system was SX1276 RF Module. Firstly, eight measurement points were identified to deploy the nodes under line-of-sight (LOS) condition as shown in Figure 4.2 and Figure 4.3. At these points, RSSI (Incoming Signal Strength) values were recorded by repeating measurements five times. For each measurement points, the averaged RSSI values and the calculated Packet Error Rate (PER) are listed in Table 4.3. It should be also noted that while the output power from the combiner and antenna was taken as 15.3 dBm, the output power of RF Switch and antenna was taken as 17.7 dBm.



Figure 4.2 Measurement Points under LOS Condition

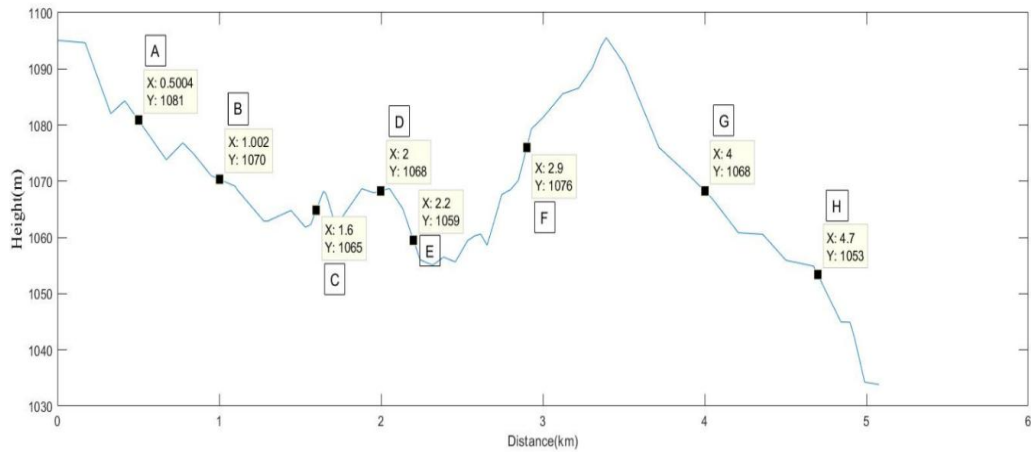


Figure 4.3 Altitude Values of Measurement Points

Table 4.3 RSSI and PER Results

REF	Altitude	Distance	LoRa: 125 kHz BW, SF = 7 Splitter Output Power:15.3 dBm		LoRa: 125 kHz BW, SF = 7 Output Power:17.1 dBm RF Switch	
	(Meter)	(km)	RSSI	PER (%)	RSSI	PER (%)
A	1081	0.5	-102	87,93,83,96,97	-102	87,93,83,96,97
B	1070	1	-110	91,97,93,93,83	-110	91,97,93,93,83
C	1065	1.6	-112	99,100,100,100,100	-111	99,100,100,100,100
D	1068	2	-113	99,100,100,100,100	-112	99,100,100,100,100
E	1059	2.2	-127	99,100,100,100,100	-126	99,100,100,100,100
F	1076	2.9	-106	99,99,99,100,100	-105	99,99,99,100,100
G	1068	4	-113	99,84,95,100,100	-112	99,84,95,100,100
H	1053	4.7	-120	81,78,95,97,98	-118	81,78,95,97,98
I	1045	5	-128	35,20,10,10,10	-128	40,35,35,45,50

The second measurements were conducted under Non-Line-of-Sight condition, at Atilim University Campus – Ankara. The measurement points were identified as shown in Figure 4.4 and Figure 4.5. PER and RSSI values obtained from the measurements are listed in Table 4.4.



Figure 4.4 Measurement Points under NLOS Condition

Table 4.4 RSSI and PER Results by Distance and Altitude

REF	Altitude	Range	LoRa: 125 kHz BW, SF = 7 Output Power:14.2 dBm Splitter		LoRa: 125 kHz BW, SF = 7 Output Power:17.1 dBm RF Switch	
	Meter	(km)	RSSI	PER (%)	RSSI	PER (%)
A	1168	0.1	-73-72-73	100,99,98	-74 -72- 73	100,100,100
B	1164	0.4	-112-110-117	99,100,100	-120 -120- 115	98,100,100
C	1170	0.72	-125-123-121	41,100,97	-115 -117- 116	48,92,66
D	1186	1.1	-114-117-116	100,100,100	-100-100-100	100,100,100
E	1175	1.5	-99-102-102	99,100,99	-122-124-121	100,100,100
F	1183	1.9	-120-123-121	100,100,99	-116-116-117	100,98,100
G	1164	2.46	-112-113-113	100,100,100	-126-126-126	100,100,100
H	1180	2.96	-120-125-127	86,100,100	-122-119-121	100,100,98
I	1163	3.2	-	-	-	-
J	1130	3.47	-	-	-	-

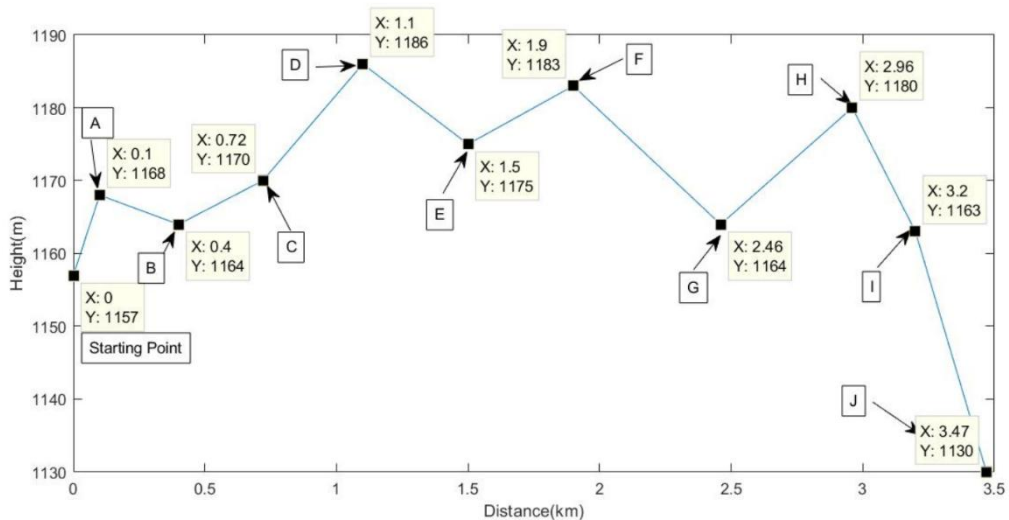


Figure 4.5 Altitude Values of Measurement Point

4.1 Comparison of RF Switch and RF Splitter/Combiner

In this subsection, RF Switch and RF Splitter/Combiner designs have been compared in terms of insertion loss, the isolation, power dissipation, and the total cost in order to analyze their feasibility. Firstly, according to obtained insertion loss and the

isolation values presented in Table 4.5, it is clear that RF Switch has less insertion loss and provides better isolation.

Table 4.5 Comparison results between RF Switch and RF Splitter / Combiner in terms of insertion loss and isolation values

Option	RF1-RFOUT		RF2-RFOUT	
	Insertion Loss (dB)	Isolation (dB)	Insertion Loss (dB)	Isolation (dB)
RF Switch	0.72	15.32	0.59	21.12
RF Splitter/Combiner	3.275	19.32	3.515	17.92

Then, the designs have been compared according to power dissipation rates. For RF Switch, the control pins require a bias voltage up to ~3V and drain a current of several microamperes. This results in a power dissipation of 10 μ W. However, in a switching solution where an RF switch is employed, it is not possible to observe power dissipation.

Furthermore, the designs have been evaluated by comparing their total cost. In RF switch design, the RF switch chip along with the DC blocking capacitors increase the total cost. However, in RF Splitter/Combiner design, only the additional circuit element is a balance resistor which does not affect the cost significantly. In Table 4.6, the total cost of both designs is provided. Obviously, RF switch design required higher cost when it is compared with RF Splitter / Combiner design.

Table 4.6 Comparison results between RF Switch and RF Splitter / Combiner in terms of total cost

Option	Cost
RF Switch(Chip-Capacitor)	\$3-5
RF Splitter (Balance Resistor)	\$0.01

On the other hand, there are still some drawbacks needed to discuss in using RF Switch. For proper usage of RF switch, the switch position should be set to the

correct port so that RF signal can propagate through the switch. In fact, this can be accomplished by software solutions. However, as a disadvantage, this puts an additional burden on the software developer. For this reason, it is also highly prone to programming errors. Yet, using a RF Splitter/Combiner will not cause any coding difficulties.

CHAPTER 5

CONCLUSION

The study presented in this thesis aims to provide bidirectional sensor node link design. In this design, two back-to-back directional antennas with a transceiver chipset are considered to be used that allows communication with neighboring sensor nodes. To provide a connection between transceiver chipset and back-to-back directional antennas, this study, which is the first report in the literature, offers two options. In the first option, a RF switch has been designed. In the second option, a combiner has been utilized. While coplanar wave guide line technique is applied to design the RF Switch, Wilkinson power divider is utilized to achieve RF Splitter.

For the performance assessment, the measurements were conducted under LOS and NLOS conditions. In these measurements, RSSI values were obtained, and then PER values for each measurement were calculated. Then, the results have been evaluated in terms of power consumption and maximum achievable distance.

Firstly, it is worth noting that environmental conditions highly affect the maximum achievable communication range. For both options, the maximum coverage range was observed as 4.7 Km and 3 Km for LOS and NLOS conditions, respectively. The effects of environmental conditions can also be observed in PER results. Especially in NLOS environments, it becomes difficult to achieve accurate results. Still, according to measurement results, using RF switch may provide better coverage range although there are slight differences in the observed ranges.

On the other hand, when two options are compared in terms of power consumption, it has been observed that lower power consumption can be achieved when RF splitter is used. This is because, in the RF switch design, there is a power unit which adversely affects the power consumption.

Besides, RF switch and RF splitter/combiner designs have been compared in terms of insertion loss, the isolation, power dissipation, and the total cost in order to analyze their feasibility. According to results, RF switch has better insertion loss and isolation when compared to RF combiner. On contrary to RF combiner, the power dissipation is not an issue for RF switch design. But still, RF combiner offers some advantages over RF splitter. For instance, its design cost-effective, and does not require programming tasks to operate.

Therefore, the proposed options can be easily integrated to sensor nodes to be used in a linear WSN system where bidirectional communication between the sensor nodes is required. This system may be then used in several applications especially in monitoring of pipelines in unattended environments. However, the environment conditions or system requirements still have a significant importance while deciding one of these designs. For low-cost communication, RF combiner would be a reasonable choice to implement. However, RF switch has advantages in terms of insertion loss, isolation, and power dissipation. Thus, it is believed that this study offers useful information to design bidirectional links in linear WSNs.

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