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Energy Efficient Wireless Sensor Network Topologies and Routing for Structural Health Monitoring

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School of Aerospace, Transport and Manufacturing

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Abstract

The applicability of wireless sensor networks (WSNs) has dramatically increased from the era of smart farming and environmental monitoring to the recent commercially successful internet of things (IoT) applications. Simultaneously, diversity in WSN applications has led to the application of specific performance requirements, such as fault tolerance, reliability, robustness and survivability. One important application is structural health monitoring (SHM) in airplanes. Airborne Wireless Sensor Network (AWSN) have received considerable attention in recent times, owing to the many issues that are intrinsic to traditional wire-based airplane monitoring systems, such as complicated cable routing, long wiring, wiring degradation over time, installation overhead, etc. This project examines the SHM of aircraft wing and WSN design (ZigBee), and aspects such as node deployment and power efficient routing, vis-à-vis energy harvesting. Node deployment and power efficient routing protocol are related problems, and so this thesis proposes solutions using optimization techniques for Ant Colony Optimization (ACO), and power transmission profiling using Computer Simulation Technology software (CST).

There are three wing models; namely NACA64A410 model, Empty NACA64A410 model for the Wing, and Empty Prismatic model of the wing was specified and simulated in CST software. A simulation was carried out between the frequencies of 100 MHz to 5 GHz, and identified significant variations in the S_{ij} parameter between the frequency range 2.4GHz and 2.5GHz. Critical analysis of the obtained results revealed the presence of a significant impact from wing shape and the wing's inner structure on possible radio wave propagation in the aircraft wing. The different material composition of aircraft wings was also examined to establish the influence of aircraft wing material on radio wave propagation in an aircraft wing. The three materials tested were Perfect Electrical Conductor (PEC), Aluminium, and Carbon Fibre Composites (CFCs). For power transmission profiling (S_{ij} parameter), 130 nodes were deployed in regular and periodic compartments, created by ribs and spars, usually at vantage points and rib openings, so that a direct line of sight could be established. However, four sink nodes were also placed at the wing root, as presented in NC37 and NC38 simulations for aluminium and CFC wing models

respectively. The evaluation of signal propagation in aluminium and CFC aircraft wing models revealed CFC wing models allow less transmission than aluminium wing models.

A multiple Travelling Salesman (mTSP) problem was formulated and solved, using Ant Colony Optimization in MATLAB to identify optimal topology and optimal routes to support radio propagation in ZigBee networks. Then solving the mTSP problem for different regular deployments of nodes in the wing geometry, it was found that an edgewise communication route was the shortest route for a large number of nodes, wherein 4 fixed sink nodes were placed at the wing root. For a realistic wing model, the different possible configuration of ZigBee units were deduced using rational reasoning, based on results from empty wing models. Besides the determined S-parameter, aircraft wing materials and optimal nodes, the residual energy of each sensor node is also considered an essential criterion to improve the efficiency of ZigBee communications on the aircraft wing. Therefore, a novel hybrid protocol called the Energy-Opportunistic Weighted Minimum Energy (EOWEME) protocol can be formulated and implemented in MATLAB. The comparative results revealed the energy saving of EOWEME protocol is 20% higher compared to the Ad Hoc On-Demand Distance Vector (AODV) routing protocol. However, the need for further energy savings resulted in development of an improved EOWEME protocol when incorporating the clustering concept and the previously determined S-parameter, a number of nodes, and their radiation patterns. Critical evaluation of this improved EOWEME protocol showed a maximum of 10% higher energy savings than the previous EOWEME protocol.

To summarize key insights and the results of this thesis, it is apparent that the thesis addresses SHM in aircraft wings, using WSNs from a holistic perspective with the following major contributions,

- CST simulations identify power transfer (S-parameter) profiling in various wing models, with no internal structural elements to identify realistic wing with spars, and bars. With an average S-parameter of -107 dB at around 3 m, the communication or transmission

range of 1 m was identified to minimize loss of transmitted power. A range less than 1m would cause issues such as interference, reflection etc.

- Using a transmission range of 1 m, WSN nodes were assessed for shortest route commensurate with energy efficient packet transmission to sink node from the farthest node; i.e. near the wing tip. The shortest routes converged to travel along the length of the wing in the case of an empty wing model, however it was also observed in a realistic wing model, where internal structural elements constrained node deployment. An average distance of nearly 13 m required data transmitted from the farthest nodes to reach the sink nodes. Increasing the nodes however increased the distance required to up to 20 m in the case of 240 nodes.
- A new routing protocol, EOWEME was formulated, showing 20% greater energy savings than AODV in the realistic wing model.

Keywords: *ZigBee, wireless sensor network, radio wave propagation, aircraft wing, wing structure, wing materials, efficient energy routing, optimization*

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Acronyms

WSN	Wireless Sensor Network
RF	Radio Frequency
SHM	Structural Health Monitoring
CFC	Carbon Fibre Composites
MTSP	Multiple Travelling Salesman problem
CST	Computer Simulation Technology
NS	Network Simulator
IEEE	Institute of Electrical and Electronics Engineers
PSTN	Packet Switch Telephone Networks
WLAN	Wireless Local Area Network
ISM band	Industrial, Scientific and Medical radio band
FFD	Full Function Device
RFDs	Reduce Function Devices
SNR	Signal to Noise Ratio
dB	decibels
GAF	Geographical Adaptive Fidelity
CCP	Coverage Configuration Protocol
MAC	Medium Access Control
LR-WPAN	Low Rate-Wireless Personal Area Networks
AODV	Ad-hoc On demand Distance Vector
SPIN	Sensor Protocol for Information via Negotiation
LEACH	Low energy adaptive clustering hierarchy

Chapter 1: Introduction

1.1 Research Rationale

Based on the literature review in Chapter 2, the research gap is identified as determining the energy efficiency of signal behaviour in different materials. This is for the purpose of designing and implementing a new technique for the structural health monitoring of aircraft wings using wireless sensor networks. The problem addressed in this research concerns the design and implementation of a new routing protocol for the energy efficiency of aircraft wings. This is a novel proposal using wireless technology, which has not previously been used. It is expected this will demonstrate how to optimize energy in wireless sensor networks. Recent developments in the field of microelectronics and embedded sensors have led to the integration of sensors, Radio Frequency (RF) communications and microprocessors into one application [1]. This has revolutionized the way in which critical systems are monitored and maintained. Of the different types of networks available, Wireless Sensor Networks (WSNs) are extensively deployed in applications dealing with the monitoring and maintenance of critical systems [h2]–[4]. A Wireless Sensor Network (WSN) consists of many inexpensive wireless sensors that are capable of collecting, storing and processing environmental information, and communicating with neighbouring nodes. In the past, sensors were connected by wire lines. Over the past few years, WSNs have been widely applied in medical, military, industrial, agricultural and environmental monitoring applications [5]. The ability of the sensor nodes to sense information from their surroundings has led these WSNs to be extensively deployed in critical applications, such as forest fire detection, military applications and Structural Health Monitoring (SHM). Specifically, WSNs are highly used in aeronautical applications for the structural health monitoring of different parts of aircraft, which possess different design requirements. SHM involves monitoring structures using embedded or attached non-destructive evaluation sensors and utilizing the data in order to assess the state of the structure.

On the other hand, airline operators are currently facing significant pressure to minimize costs and improve profitability while running aircraft. This has led aircraft manufacturers to

continuously search for appropriate techniques and technologies that could be used to design aircraft effectively whilst reducing costs and fuel consumption. For example, the Airbus A380 has over 300 miles of cables consisting of approximately 98,000 wires and 40,000 connectors [6]. The set-up and regular maintenance of all these cables is very challenging, as well as costly for aircraft operators. The cable routing that occurs in the wired network set-up using various cables in these aircraft is quite a complex task, as the power cable and electrical signal cables should be physically separated to avoid electrical interference.

On the other hand, the aircraft environment is very dynamic and constantly changing, ranging from arid, humid and windy situations to extremely cold temperatures en route to Alaska and mountainous regions. Sensor systems for monitoring such environments are based on wired connections, which are complex and make it difficult to route communications. Furthermore, harsh environmental conditions impose physical restrictions on the use of a wire harness. This research mainly focuses on minimizing the cost of communication in the aeroplane by replacing wired loom with wireless connections [6]. One of the possible ways of reducing these costs would be by replacing wired cables by wireless links and conducting structural health monitoring of the aircraft wing using wireless sensor networks (WSNs).

Even though the use of WSNs for aircraft SHM applications can resolve the pressure on aircraft manufacturers to minimize aircraft manufacturing costs, these WSNs pose several challenges when used in SHM applications [7]. Some of these challenges have been reported in the literature [8] in the form of sensor node constraints, such as smaller battery size, low battery power, error-prone wireless links, limited energy and power, and deployment of sensor nodes. In these aircraft SHM applications, each sensor node is required to perform the sensing, data processing and data transmission over the wireless links. All these activities have to be completed using the limited battery power of each sensor node. As the sensor nodes are small, they have limitations in terms of battery size and power. This indicates that the power consumption of sensor nodes is one of the main issues in the design of WSNs for critical applications such as aircraft SHM [9], [10]. The use of wireless links that are highly error-prone to transmit the sensed and processed information also makes reliability one of the central issues in WSN design. The use

of wireless sensor networks in highly dynamic and fragile environments, such as forests, the military and aircraft wings, is achieved through the random deployment of the sensor nodes, which makes wireless communication efficiency very challenging [11]. Previous studies have emphasized the importance of placing the sensor nodes in optimum positions so that the antenna position on the aircraft wing does not have a negative impact on signal propagation in WSNs [12]. This research focuses on the structure of aircraft wings, which use a variety of structural components such as ribs, spars, and airfoils that are made of up composite materials such as Carbon Fibre Composites (CFCs), aluminium, or different alloys. Each of these composite materials has a different effect on signal propagation in WSNs, thereby posing a challenge for WSNs in SHM applications. There is a considerable need to address the many challenges faced by WSNs if they are to be used effectively in aircraft SHM applications and thereby minimize the aircraft's operating costs [13].

In typical wireless communication, the antenna plays a vital role in converting the guided wave to a free wave and vice-versa [14]. Analysing and evaluating the effectiveness and performance of wireless communication systems requires the effectiveness of the antenna to be assessed through simulations. Including antennas in the simulation requires the antenna to be represented in the form of a two-port network in which it supports wireless communication through two ports (the input and output ports) [15]. According to Yang (2015), the simulation measurements of the antenna are generally acquired regarding scatter parameter, radiation patterns, and antenna gains at different frequency levels. Of these simulation measurements, the S-parameter or scattering parameter (S_{12}) is considered in this research due to its ability to measure antenna efficiency based on the electrical behaviour and coupling that exists between port 1 and port 2 of the antenna in a two-port network [16]. Wang et al. (2014) indicates that the S-parameters mainly describe the input-output relationship between the two ports in an electrical system such as the antenna [17]. For example, S_{12} specifies that the power is transferred from port 2 to port 1, while S_{21} specifies that it is transferred from port 1 to port 2 [18].

The rationale for this research is to improve the efficiency of WSNs used in SHM applications by overcoming the different challenging issues currently faced by WSNs when used in SHM

applications in aircraft. This research considered an aircraft wing in order to design, simulate and show the effectiveness of sensor node communications to support SHM applications with reduced operating costs. Some of the key issues of relevance to WSN in SHM applications were considered, such as (1) the effect of antenna position on the wireless communication; (2) the effect of aircraft wing shape, inner structure and the aircraft wing materials on the wireless communications, (3) optimal topologies that dictate the best possible coverage and connectivity for energy limited settings, such as energy harvesting of the aircraft wing vibrations; (4) the effect of the structure of wings made from different composites on signal propagation, and thereby on the connectivity of different nodes; (5) the variation in different settings of structural materials and optimal topologies in very different conditions, such as extremes of temperature, air velocity, and pressure; and (6) the best routing protocol for WSNs used in SHM applications to deal with the energy shortage limitation of the sensor nodes. In the literature on WSN and SHM, some studies have reported the applicability of WSN for the structural health monitoring of the aircraft [19]. Somov et al. (2016) designed a supportive routing protocol that helps the sensor nodes deployed in different locations of the wing maintain energy-efficient communication in order to support structural health monitoring applications [20]. Singh and Sharma (2015), on the other hand, investigated the need to optimize the sensor network topology and design an energy-efficient routing protocol to support structural health monitoring applications [21]. Similarly, various studies in the literature have emphasized only one of the challenges faced by WSNs when used for SHM applications, rather than all the different challenges. However, the effective use of wireless sensor networks for structural health monitoring applications requires all these inter-related challenges to be resolved [22]. For instance, the optimum location of the sensor nodes can affect the amount of energy consumed by each sensor node, which may increase the importance of having an energy-efficient routing protocol for the sensor network. To the best of the researcher's knowledge, no existing study has yet focused on all the multiple issues and challenges faced by wireless sensor networks when used for SHM applications.

This thesis aimed to evaluate all these issues in an attempt to formulate appropriate solutions using powerful using Computer Simulation Technology suites of software (CST, 2015) for the modelling and simulation of aircraft wing structure and communication signals. Three wing

shapes were modelled using Gmesh software to experiment and four positions of the antenna were simulated using CATIA software. This helped identify the impact of wing shape, inner structure and antenna position on signal processing and wireless communication among the sensor nodes used for SHM applications. In order to address these WSN challenges, three main wing materials [23] were selected and simulated in order to identify their impact on signal processing and wireless communication among the sensor nodes used for SHM applications. The parameter S21 magnitude is used to present and evaluate these results, as it shows the coupling present between two ports of the antennas. Hence, this S21 parameter specifies the quality of the connection that is present between the antennas [24]. The other characteristic obtained from the estimation of the S21 parameter in this research is the presence of the cut-off range of the frequency band between the frequency range of 100MHz and 5GHz.

Different topology control settings were also experimented with, coupled with optimization strategies such as the Multiple Travelling Salesman problem (MTSP) to find the best topologies that can assure reliable connectivity across sensor nodes. Considering the unique constraints of the sensor nodes, an energy efficient routing protocol is proposed in this research. A combination of mathematical analysis and simulation studies were also carried out using Network Simulator (NS 2.33) software to show the effectiveness of proposed network routing protocol.

1.1.1 Wireless sensor network for SHM

Developments in the field of wireless technology have resulted in the extensive replacement of wired systems by wireless communication systems across a wide range of applications [25]. A wireless sensor network is formed through the deployment of a huge number of interconnected sensor nodes. The development of ad-hoc networking technologies allows tiny sensors to communicate through wireless links in a more convenient manner [[2], [6]].

Replacement of the current wired harness-based sensors with a wireless sensor network (WSN) can help achieve the goal of increasing the number of sensors, as well as the system redundancy. It will also reduce the weight of the aircraft system and lead to improved fuel efficiency and reduced carbon emissions [26]. European goals for 2020, for instance, include a 50% cut in CO₂ emissions. Replacing physical cabling by wireless connections also offers significant benefits in

terms of flexibility, interoperability, mass reduction and improved robustness. The use of WSN also enables a reduction in direct costs and maintenance costs [27]. WSN can be implemented through several existing platforms, such as MICA2, MICAz, TelosB Mote (Xbow, 2005), and Dust Network (DustNetworks, 2005), which cross-talk to each other using standard protocols such as ZigBee/IEEE 802.15.4. ZigBee/IEEE 802.15.4 is a global hardware and software standard designed for WSN that offers high reliability, low costs, low power use, scalability, and a low data rate. Table 1 compares ZigBee/IEEE 802.15.4 with several other wireless technologies.

Table 1: Comparison of different wireless technologies [28]

Standard	ZigBee/IEEE 802.15.4	Bluetooth	UWB	IEEE 802.11 b/g
Working frequency	868/915 MHz, 2.4GHz	2.4 GHz	3.1 - 10.6 GHz	2.4 GHz
Range (m)	30 – 75+	10 – 30	~10	30 – 100 +
Data rate	20/40/250 kbps	1 Mbps	100+ Mbps	2 – 54 Mbps
Devices	255 – 65k	8		50 – 200
Power consumption	~1 mW	~40 – 100 mW	~80 – 300 mW	~160 mW – 600W
Cost (\$US)	~2 – 5	~4 – 5	~5 – 10	~20 – 50

Some of the comparisons made in Table 1 are worth noting, as they are directly related to the present work. Firstly, power consumption is one of the significant constraints in WSNs. Table 1 indicates that ZigBee nodes have a power consumption of around 1mW, while even Bluetooth has a power requirement 40 times that of ZigBee. Cost-wise, ZigBee is the best option because the required nodes range from 100 to over 1,000. However, the working frequency of ZigBee compares favourably to that of Bluetooth and UWB, but at lower data rates as shown in Table 1. Based on this comparative analysis, the suitability of ZigBee nodes for use in a wireless sensor network is justified.

However, WSNs using ZigBee face issues related to power consumption, power management and, more importantly, the long system life of the sensor nodes. Ease of routing, cost reduction, configuration, and installation could also pose a problem, given the presence of internal structures and inaccessible areas in the aircraft wing. For example, increasing the number of sensor nodes affects energy-saving schemes, primarily if the energy harvesting modules are used [12]. Furthermore, in order to ensure coverage and connectivity for most the times in the operation of the WSN, reliability is ensured by having a higher number of sensor nodes, but this redundancy increases overhead energy costs.

This research focuses on one of the most commonly used wireless communication systems, ZigBee, which uses the IEEE802.15.4 standard. By providing low-cost designs with reduced power consumption [4], ZigBee has proved attractive to several applications in industry and the aircraft environment. The mesh network topology of ZigBee offers self-configurable and self-handling features that make it feasible for use in aircraft environments.

1.2 Scope of the Research

The scope of the current research is limited to the SHM of the aircraft wing using WSNs. There are various types of aircraft wings; this study examined an NACA64A410 model for the inner structure of the wing, an empty NACA64A410 model for the wing and an empty prismatic model of the wing. The deployment of different WSN designs in aircraft wings and the measurement of its experimental performance are very costly and unaffordable at an academic level. Therefore, the objective of this research was to study the design of WSN using computer simulations. Overall, this research focuses on identifying the following aspects:

- The effect of aircraft wing antenna position on the performance of ZigBee wireless communication between the frequency of 100MHz and 5GHz for three different wing model designs: an NACA64A410 model for the inner structure of the wing, an empty NACA64A410 model for the wing and an empty prismatic model of the wing.
- Identification of the effect of the shape and inner structure of the wing on the S21 parameter related to ZigBee wireless communications in an aircraft environment using CST software.
- The effect of the structural materials, shape and inner structure of the wing on connectivity control between the antennas in an aircraft wing.
- The optimal number of required sensor nodes (ZigBee) for a given aircraft wing structure, such as that of the Airbus A320 and Boeing 777.
- The optimal topology of these sensors over the aircraft wing based on CST simulations

coupled with MTSP optimization routines developed and coded in MATLAB.

- Change in optimal topology for different structural materials of the aircraft wing.
- Comparative assessment of different communication models, such as centralized and decentralized, to identify the suitability of adoption in an aircraft wing.
- Possible development of a generalized framework of CST simulations of communication signal strengths for optimal connectivity and reliability for any given aircraft wing.
- Mathematical modelling of an energy-efficient routing protocol for WSNs to help reduce energy consumption during SHM applications.
- Simulation studies of the effect of an energy-efficient routing protocol on WSNs to show its effectiveness in terms of reducing energy consumption during SHM applications.

1.3 Aims and Objectives

This research aims to identify the feasibility of using ZigBee wireless communications for SHM applications in an aircraft environment. This research also aimed to identify supporting factors, such as optimal network topology, suitable wing structure, wing materials and antenna position, that could increase the feasibility of using ZigBee wireless communications in aircraft environments. A further aim was to design, simulate and evaluate an energy-efficient routing protocol for ZigBee networks with an identified network topology and antenna position used in SHM applications.

The following objectives were used to help achieve these aims:

- To investigate the importance of ZigBee technology and WSN network topologies by analysing the advantages and the disadvantages of each of these network topologies.
- To investigate the effect of aircraft wing antenna position on the performance of ZigBee

wireless communication between the frequencies of 100MHz to 5GHz by designing a simulation environment based on the internal wing structure of an aeroplane.

- To investigate the influence of the shape, inner structure and composite materials of the wing on the control and quality of connectivity between the two antennas based on the S21 parameter.
- To develop an Ant Colony optimization method to identify the optimal sensor network topology, optimal number of nodes in a sensor network and the shortest route for any given cost function.
- To propose a hybrid energy-harvesting model for aircraft wings and to design and simulate a power-efficient hybrid routing protocol considering the Energy Opportunistic Weighted Minimum Energy protocol and Self-Healing Routing, evaluated in terms of a comparison of its performance with existing routing protocols.

1.4 Thesis Layout

The structure of the rest of the thesis is shown below and achieves the list of objectives presented above.

Chapter 2: Literature Review

This chapter describes the background to wireless communication systems. A brief explanation of wireless sensor networks and ZigBee technology is given with regard to the network topologies that are adopted by these networks. This chapter also reviews existing works related to connectivity design issues in sensor networks, routing methods in sensor networks and related works on the energy harvesting methods used in wireless sensor networks.

Chapter 3: Methodology

This chapter describes the methodology used to achieve the aim and objectives of this research. This methodology chapter specifies the design choices used to carry out the simulations to identify (1) the effect of the aircraft wing antenna position; (2) the effect of structural materials

on connectivity control; (3) topology control and WSN optimization; and (4) the aircraft wing power transfer characteristics.

Chapter 4: Antenna positioning in aircraft wings

This chapter provides a detailed description of the three wing models considered in this research. The different stages involved in the design of the three wing models using CATIA, Gmesh and CST software are detailed in this chapter. The results obtained from the simulations are discussed for each of the three wing models considered in this chapter. This chapter also critically analyses the results obtained from the simulation of wing models at the two different frequencies considered, namely 100 MHz to 5 GHz and 2.4 GHz to 2.5 GHz. This critical analysis identified the influence of wing structure and wing shape on the radio propagation of ZigBee communication. Additionally, this chapter investigates the influence of different structural materials used in aircraft wings on the control and quality of connectivity between the antennas present in an aircraft wing. The details of the simulation results obtained by considering aluminium and CFC as the two primary materials of aircraft wing are presented and compared in this chapter.

Chapter 5: Simulation Results for the Effect of Structural Materials on Connectivity Control

This chapter examines the effect of the different structural materials used in aircraft wings on the quality of the connection between the two antennas and thereby on the radio propagation signals. It considers the essential composite materials of aircraft wings; aluminium and carbon fibre composites are the two structural materials considered in this research. This chapter also covers the simulation of aircraft wings with aluminium and carbon fibre composites using CST, through which the influence of aircraft structural materials on the control of connectivity between the antennas was identified.

Chapter 6: WSN Design for Aircraft Wing Models

This chapter provides details of the optimization problem formulated to deal with the topology control and connectivity design issues associated with wireless sensor networks. The details of the actual optimization problem and the ant colony optimization method used to resolve this issue are presented by giving details of the different scenarios considered for these simulations.

This chapter also addresses the topology control and connectivity design of wireless sensor networks. The primary need to offer better topology control and to address various connectivity design issues in the wireless sensor network are identified in this chapter.

Chapter 7: Power transfer characteristics of an aircraft wing This chapter focuses on the power transfer characteristics of the aircraft wing. A set of simulation results carried out in Matlab and CST are presented in this chapter. The analysis of these results showed the need to reduce energy consumption during the process of routing information in the ZigBee network deployed on an aircraft wing.

Chapter 8: Efficient Power Routing in Aircraft Wing Model

The main purpose of this chapter is to describe the energy efficient routing protocols proposed for aircraft applications. Initially, an opportunistic routing protocol is detailed, and an improved version of this routing protocol is presented. Evaluation of the improved routing protocol was carried out using a combination of simulation studies and mathematical modelling.

Chapter 9: Conclusion and Future Work

The main findings of this thesis and the results obtained are summarized in this chapter. Details of possible future research are also suggested.

1.5 Contribution to Knowledge

This research work is unique in designing an optimized WSN that supports structural health monitoring applications of aircraft wings by overcoming all the major challenges of WSNs. This study contributes to the literature on WSN and SHM applications in aircraft by addressing a research gap. It involves a single study that addresses all the key challenges to make WSNs support highly efficient and effective communication for structural health monitoring applications. Another key contribution of this research is the identification of the effect of wing structure and shape, aircraft wing materials, and wing antenna position on the signal propagation of WSNs used in structural health monitoring applications. Mapping of the wing interior was carried out for radio propagation. A computational electromagnetic approach was used to find

the S parameters between deployed nodes in an aircraft wing. The best positions of nodes were inferred from the presence of rib holes that allow direct line of sight propagation. Therefore, the node positions have to be nearby rib holes. Using the identified number of nodes, 130 nodes along with redundant four-base nodes were evaluated for efficacy of communication. Based on s parameter characteristics, three paths to base sinks are identified and ranked.

Another key contribution of this research involves identifying the optimum topology of the sensor network. This is necessary to determine the number of nodes to be placed on the aircraft wing in order to support structural health monitoring applications. By formulating a multiple travelling salesman problem, optimum topology with 130 sensor nodes was identified and deployed in this research in the form of a sensor network on an aircraft wing. This research has also contributed to the literature by overcoming the energy constraint problem faced by the sensor nodes when used for structural health monitoring applications. The use of ranked paths based on the s parameter, along with residual energy criteria for successful transmission of signal and design, resulted in the implementation of a new routing protocol in Matlab. Preliminary simulation results for the new protocol showed a promising reduction of approximately 20% in energy usage in the overhead and rerouted control packages. However, further improvements to this protocol and results were investigated in NS2.

1.6 Conclusion

This chapter set out the rationale for the research by defining the research problem and elaborating on the research aim and objectives. In order to investigate the research aim, it is first necessary to locate it in the existing literature. The problems involved in improving the energy efficiency of aircraft wing structures have been studied previously. However, whether the actual wing issues have been addressed will be determined by reviewing the literature, since wings are an essential part of an aircraft. The research aim was established through a critical understanding of how to become wireless by studying the signal inside the structure and optimizing the routing protocol. This following chapter presents an analytical review of the relevant literature.

Chapter 2: Literature Review

2.1 Overview

In recent years, the use of wireless sensor networks in SHM applications has attracted considerable attention. This chapter comprises the literature review for this thesis, reflecting on current research assessing the feasibility of using sensor networks and ZigBee standard communications for aircraft SHM applications. The main purpose of the chapter is to detail the situation regarding current research into WSNs and ZigBee technologies, with regard to the structural health monitoring applications of aircraft specifically. It will investigate methods to evaluate wireless sensor networks for structural health monitoring, and study their signal behaviour in the cavity. It will also consider the best positioning of the sensor and antenna, and how energy efficiency can be improved. It is expected this will demonstrate how best to optimize energy in wireless sensor networks. Details of the wireless communication systems, and the topologies of WSNs and ZigBee networks are presented in this chapter. Based on the review of different WSN challenges reported in the literature, contemporary energy harvesting methods are presented in this chapter. The various harvesting techniques known to be suitable for aircraft SHM applications and current aeronautical projects relating to this study are detailed in this chapter

WSN design for aircraft monitoring has recently received widespread attention. Since the present work relates to SHM in aircraft wings, this chapter reviews the relevant literature on the following:

1. Wireless aircraft monitoring, Airborne Wireless Sensor Networks (AWSNs);
2. Power transmission, path loss in WSNs related to aircraft monitoring;
3. Energy-efficient routing protocols, optimization methods,

Based on critically assessed literature, research gaps have been identified and mapped into the research goals the present work.

2.2 Wireless Sensor Networks for Aircraft Monitoring

Wireless communication systems have become one of the fastest and highly growing components of the communication industry. Over the past decade, there has been an enormous growth in cellular systems, and they currently have nearly two billion users across the world [29]. In most developed and the developing countries, cellular phones have become part and parcel of everyone's life and have completely replaced wired landline systems [16]. Currently, several wireless communication systems are in operation. With the emergence of new systems, design details related to these new emerging systems are evolving at a constant rate [17]. Hence, it is important to identify the design aspects of these evolving wireless systems and some existing wireless communication systems are presented in this section.

2.2.1 Telephony system

Cellular telephone systems are very popular across the world and have created a revolution in the field of wireless communication systems [30]. Through these cellular systems, voice and data communication can be provided with both regional and international coverage. Initially, the design of these cellular systems aimed to support mobile terminals in the vehicles with antennas [31], [32]. Currently, these cellular systems offer support to several mobile terminals that work at any location at both vehicle and pedestrian speed. The main idea behind the development of cellular telephone systems is the frequency of reuse, which mainly exploits the fact that signal power will be less at a certain distance to utilize the same frequency spectrum at different locations [33].

2.2.2 Wireless LANs

A Wireless Local Area Network (WLAN) offers transmission of high-speed data in a particular region in which users can move from one location to the other [34]. The main unlicensed bands are the ISM bands 5.8 GHz, 2.4GHz and 900 MHz. When the industrial, scientific and medical radio bands (ISM) are considered, unlicensed users will be acting as secondary users and should deal with the interference which can occur with primary users [31], [32]. The interference problem in this wireless local area network can be resolved when the particular limit is provided on the power offered for the unit bandwidth of the unlicensed systems [13][26]. These wireless

local area systems can be deployed in different topologies, forming a star architecture, where the access points are placed across the complete coverage area or can form a peer-to-peer architecture in which self-configuration of the wireless terminals is used to form a network [32].

The second generation of WLAN has now come into existence, and operates with 2.4GHz of ISM band and 80 MHz of the spectrum. The standard associated with the second generation wireless LAN is the IEEE802.11b, which specifies the spectrum of a direct sequence, having data rates of 1.6Mbps and a range of 150 meters [35]. The network architecture of this standard can be presented using either star topology or peer-to-peer topology [36], [37]. The use of the IEEE802.11b standard grew slowly at first but has since experienced substantial drastic growth, which has led several organizations to develop products that rely on this standard. The standard IEEE802.11a works with the frequency of 5GHz and the spectrum of 300MHz. The data rate offered by this standard is between 20 – 70 mbps and depends on the multi-carrier modulation method [38]. The other standard, IEEE802.11g, provides 2.4 GHz of frequency and a data speed of 54 mbps. Similarly, several other standards in the IEEE802.11 family have come into existence by supporting higher data rates and better frequencies [39]. These standards include IEEE802.11n and IEEE802.11e. In order to avoid compatibility issues, all standards are supported by most access points and wireless local area networks [40].

2.2.3 Low Cost and Low Power Based Radios

In general, radios can be used to reduce the cost of equipment and power consumption, which makes them suitable for use in the various electronic devices used in highly sensitive applications such as sensor networks [41]. This trend is supported by the two main radios, Bluetooth and ZigBee. With the help of Bluetooth radio, connections can be established between wireless devices that are within a short range. This standard of Bluetooth depends entirely on a small microchip containing the radio transmitter that is present inside digital devices [42]. This Bluetooth utilizes the property of frequency hopping to provide multiple accesses with a carrier spacing of nearly 1 MHz [43]. When compared to this Bluetooth, the power consumption and cost of the ZigBee radio are much lower.

2.2.4 Wireless sensor network

A Wireless Sensor Network (WSN) can be defined as an autonomous network that is formed with a collection of various sensor nodes [44]. The main purpose of wireless sensor networks is to gather information from the surroundings in which they are deployed. Random deployment of the sensor nodes and the ability to deal with dynamic topology have led these sensor networks to be used across a diverse range of applications, such as the military, habitat monitoring, forest fire detection and scientific exploration [45]. The working of a wireless sensor network with the different components present in each sensor node is given in Figure 1.

As shown in Figure 1, the collection of various sensor nodes results in the formation of a wireless sensor network [46]. The target node communicates with the base station that is external to the sensor network using multi-hop communication via a number of intermediate nodes. Figure 1 also presents the different components that are present within a sensor node and the different components that can help achieve the effective collection, sensing and transmission of the data [47]. The key components existing within a sensor node are the position finding system, mobilizer, sensing unit, a processing unit, power generator and the transmission unit. Each of these units possesses an individual responsibility; for example, the position finding system helps identify the position of the sensor node in relation to the other nodes in the network, the mobilizer helps mobilize the sensor node from one location to the other, the processing unit deals with processing activities, and the power unit supplies the required power to make the other components work [19].

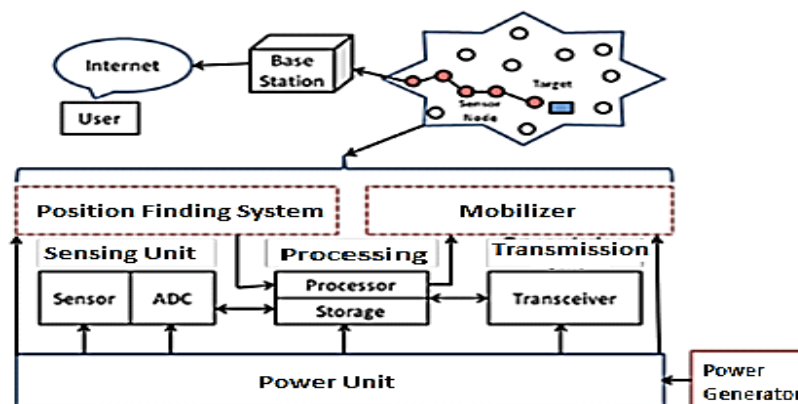


Figure 1: The different components of the sensor node and its interaction with the surrounding environment [8]

Although sensor networks are used in a wide range of applications, the sensor nodes that form part of these networks face some constraints [48], the most important of which are limited battery power, energy and memory. This is mainly because of the small size of the sensor nodes, which reduces memory size and battery size in the sensor nodes [49]. The working of the sensor nodes very much depends on the amount of battery power present within each sensor node, which to a large extent determines the lifetime of the wireless sensor network [50]. To ensure that the sensor nodes remain operational in the long term and to carry out sensing and data transmission activities, many studies [51] have been carried out to develop a different phase of minimizing energy consumption by each sensor node. For instance, a study carried out by [52] developed a routing protocol that helps sensor nodes to sense information from their surroundings and then transmit this to the base station whilst consuming less energy than usual [44].

2.3 WSN in an aircraft environment

Increasing improvements in the field of wireless sensor networks have led them to be used in several sensitive application areas, such as habitat monitoring and object tracking in the military [53]. This feature has also led the sensor networks to be used in aircraft environments. The utilization of wireless sensor networks inside aircrafts can offer several advantages by reducing the wiring problems, simplifying the aircraft design and increasing the payload weight [54]. The main reason for these advantages is the elimination of the wired technology. The feasibility of applying the IEEE 802.15.4 standard inside the aircraft is considered in this thesis.

However, certain challenges must be taken into consideration with regard to the application of the wireless sensor networks inside aeroplanes. These challenges are listed below [55]:

- ☐ Resistance caused by the interference in aircraft structures.
- ☐ Resistance caused the interference generated by another sensor.
- ☐ The security of the data that is transmitted.
- ☐ Provision of a non-failure work environment in which other wireless systems are

operational.

This study examines the practicability of applying the IEEE802.15.4 standard in terms of the resistance caused by the interference in the 2.4GHz frequency and the security offered to the data packets in the ZigBee standard [56]. It also helps identify that the IEEE802.15.4 standard provides proper resistance for the interference that arises in aeroplane environments using the 2.4GHz frequency band [57]. Furthermore, the use of this IEEE802.15.4 standard provides a higher security level for the data, as shown in this thesis. This research provides a detailed analysis of the use of wireless sensor networks in an aeroplane environment, and the different wireless communication systems available in the market are discussed [55]. Of these wireless communication systems, the wireless sensor network is selected and is utilized in this thesis to identify the wing structure and the integrity present in the cabin structure [20]. The figure below shows the configuration of the sensor network used in SHM (Structural Health Monitoring).

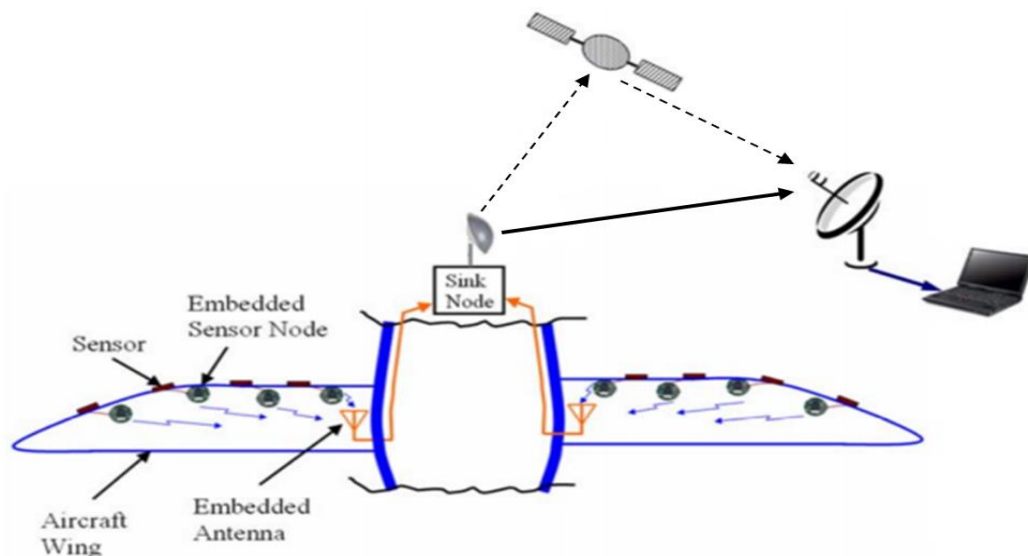


Figure 2: Configuration of WSN for the aircraft wing [32].

This configuration process considers wireless technologies that can operate at the frequency band of 2.4 GHz. The wireless nodes operating the frequency band of 2.4GHz must be checked in order to reduce any packet loss that may arise between the two nodes in the network [58]. This research also identifies the flexibility of using the IEEE802.15.4 standard for steganography. This steganography can be defined as hiding private information inside the signals to prevent an

unauthorized person from identifying this hidden message [59]. When private information needs to be encoded over the transmission signal, then the SNR (Signal to Noise Ratio) between the wireless nodes must be at an appropriate level of 1.95 dB (decibels) [60].

2.3.1 WSN in aircraft SHM applications

In a typical commercial aircraft, SHM is one of the foremost non-safety critical systems used in aircraft monitoring systems, which also include other aspects, such as engine health monitoring and the environmental control of the cabin. Apart from monitoring, critical safety aspects include the control systems used in aircraft engines and for flight [61]. At present, wired connections running along the length and breadth of the aircraft serve real-time sensors deployed across the aircraft. The popular Airbus A380 has around 40,000 connectors connected by 98,000 wires [62]. The length of the cables is around 300 miles [63]. This large number of sensors and wired connections renders the aircraft monitoring system inefficient and leads to shortcomings because of the long wires connecting sensors to a central unit [64]. Wired connections also create other problems, such as intricate cable routing, time-consuming installation in larger and inaccessible structures, the degradation of wired connections in harsh environmental conditions, and an increase in weight of the aircraft. One of the apparent advantages of WSN is thus a reduction in overall weight and thus in fuel consumption and the amount of maintenance required [65], [66]. Moreover, these weight reductions translate into savings of around \$15 to \$60 million per aircraft [67] (see Table 2 below for a comparison):

Table 2: Weight reduction due to the use of wireless sensors in aircrafts.

Aircraft/Flight	Weight reduction	Monitoring/control system	Source/Reference
Cessna 310R	90 lbs	Control systems	[68]
SH60 military helicopter	267 lbs	Control systems	[68]
Blackhawk helicopters	240 lbs	Wires	[69]

Therefore, the use of WSN-based aircraft monitoring (see Figure 3 below) was introduced by researchers in the late 20th century. For example, the initial prototypes for WSNs in aircraft monitoring had nodes with a low-processing microcontroller, a low sampling rate, and a low-resolution analogue-to-digital converter (ADC) with allied sensing elements. However, researchers in this field are actively addressing key issues such as routing protocols, passive sensing and hardware upgrades [70]–[74]. Developments in sensing technology and sensors have also kept pace. For example, advances in composite materials and piezoelectric materials have opened up new opportunities for the assessment of damage and impact and are an integral part of the SHM scheme [75].

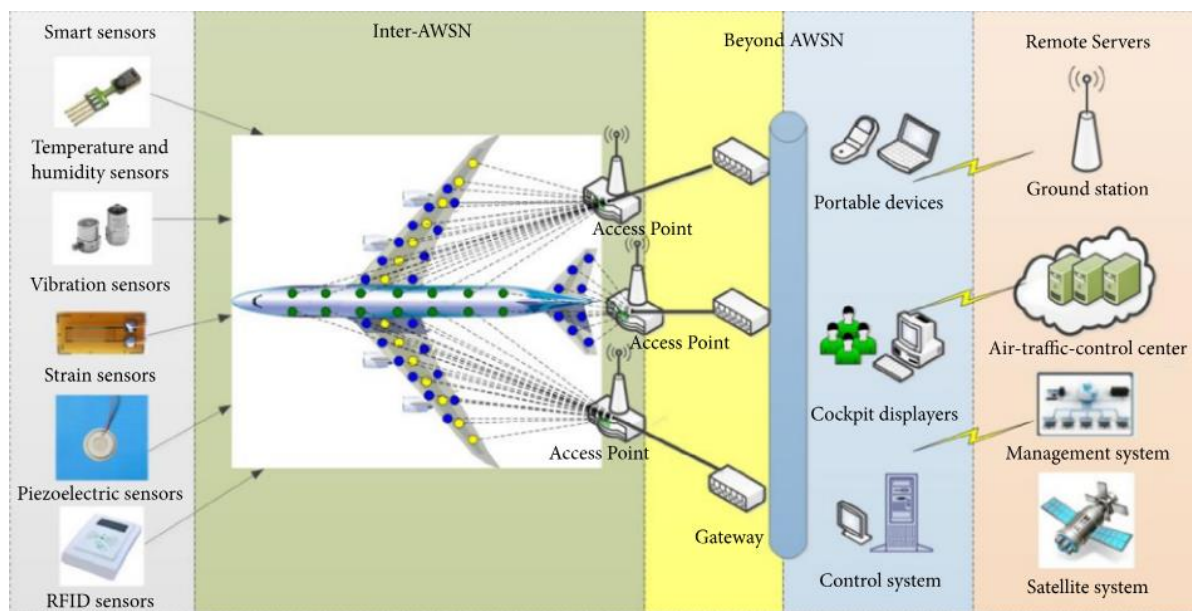


Figure 3: Aircraft monitoring system. Note that vibration and strain sensors deployed on the wings make the SHM WSN [61].

Major European research institutes have invested in WSNs for aircraft monitoring, prominent examples being:

1. The European Commission's Flite Instrumentation Test Wireless Sensor (FLITE-WISE) project for aircraft continuous monitoring [76];
2. The French research and development project SAHARA, supported by the ASTECH company [77];
3. NASA's Langley Research Centre's Fly-by-Wireless alliance project [78].

The unique properties of the wireless sensor network in sensing information from surroundings and transmitting the data have resulted in these networks being used across a wide range of applications, of which Structural Health Monitoring (SHM) applications for aircraft is the most important. A range of studies have been carried out to review the way in which wireless sensor networks are used for aircraft SHM applications and the different challenges that are associated with these SHM applications. Vujic et al. (2012) have indicated the importance of sensor networks to implement the health monitoring algorithms through which they will monitor any internal and external issues existing in the aircraft such as cracks and strains [51]. The use of these sensor networks in SHM applications necessitates the effective design of a sensor network that can overcome some of the critical challenging issues related to sensor networks. These challenging issues, as specified by Vujic et al. (2012), are the power transfer characteristics of the sensor node, the use of medium access control protocols for the sensor networks, and proper certification of the aircraft-based wireless systems in which wireless communication networks are used. Considering the energy constraints of the sensor nodes, there is a great need to implement an appropriate energy harvesting method to overcome the energy constraints and thereby increase the lifetime of the sensor network over an extended period.

Vujic (2014) examined the concept of designing a wireless sensor network for aircraft structural health monitoring applications [79]. This research indicated the need to design a sensor network capable of dealing with different parameters, such as energy efficiency, timeliness, testing reliability and scalability. Energy efficiency is one of the main design challenges of WSN when used for SHM applications because of the energy and power constraints faced by the sensor nodes. Adopting effective energy-saving mechanisms helps increase the lifetime of the wireless sensor node, from which the structural health of the aircraft can be monitored effectively. In another study, Vujic et al. (2012) focused on the use of sensor nodes for structural health monitoring applications of aircraft and identified the effect of using the IEEE 802.15.4 ZigBee standard in cluster and star topology on reducing costs and increasing energy-efficiency during the monitoring of the structural health of the aircraft [51]. Yedavalli (2012) examined the use of wireless sensor networks in control and the health monitoring applications of the aircraft. In this process, the existence of several technical challenges that must be resolved in order to effectively

use sensor networks effectively for aircraft were identified [80]. These technical challenges involve facilitating sensor node communication based on sensor nodes and flight-based control systems over the wireless network when it is bandwidth-limited. Other challenges include the use of a dedicated spectrum for communication purposes and the provision of an optimal level of a power source in the sensor node. The absence of such a power source can result in the poor design of wireless sensor networks.

2.4 ZigBee

The main aim of designing the ZigBee radio is to reduce power consumption and costs in comparison to Bluetooth devices. The ZigBee specification depends entirely on the IEEE802.15.4 standard. This ZigBee radio works on a similar ISM band to that of the Bluetooth and connects nearly 255 devices in each network. Through these ZigBee specifications, a data rate of nearly 255 Kbps is supported, with a transmission range of nearly 30 metres [36]. Even though ZigBee offers slower data rates, power consumption by ZigBee radios is lower, and it also offers a higher transmission range. The main aim of the ZigBee standard is to allow the radio to continue working for several months or years without the requirement of charging; this enables the ZigBee standard to be offered to the sensor network applications.

In a ZigBee network, three types of devices can be present: the network coordinator, router and end devices. The network coordinator acts as the central controller of the network and enables the complete ZigBee network to be effectively monitored. This network coordinator helps both start and end communication. At the same time, this network coordinator also preserves the security keys, which can be utilized for security purposes [81]. These network coordinators need a high range of memory and higher computation power when compared with other types of ZigBee devices.

The other type of device is the router, which is an FFD (Full Function Device). The main task of the router is to offer the synchronization of services for the network coordinators and end devices. These routers also help dynamically route the information and offer back-up routes if any of the ZigBee devices fail [82]. With the help of these routers, the network coverage area can

be increased in ZigBee networks. In addition, these routers can be used in devices that act as the edges of the network.

The third type of device that can be supported by these ZigBee networks is the end device. This end device does not have any functionality to route the information, but can quickly receive and transmit information [83]. These end devices are classed as RFDs (Reduced Function Devices) and hence are not required to deal with a large amount of data. These end devices have a simpler structure associated with a 64-bit address value. Due to minimum memory and power requirements, these end devices can also only have a 16-bit address.

2.5 Topology of ZigBee networks

The IEEE 802.15.4 ZigBee standard mainly exists in two different topologies. These topologies are utilized during the design of ZigBee networks. These two topologies include:

- ☐ Star topology;
- ☐ Mesh topology.

2.5.1 Star topology

Star topology is considered to be a very simple topology and is also treated as the less utilized topology in this ZigBee standard. In star topology, one network coordinator is present along with several RFDs. When network functioning is started by FFD, it creates the nodes and can become the network coordinator [84]. The transmission of data can take place from one RFD to another only with the help of the network coordinator. Here the coordinator acts as the router. Even though star topology can be constructed very quickly, it faces the limitation of being unable to establish the route when the connection between the RFD and network coordinator is removed. The presence of the network coordinator results in single point failures in star topology [85].

2.5.2 Mesh topology

Mesh topology, on the other hand, consists of the network coordinator, which has a connection with RFDs and FFDs [59]. In general, there is a connection between the router and the FFDs that enables rerouting between the nearest neighbouring nodes. As there is direct communication between the routers and FFDs, the rules of transmission and receiving are very flexible in mesh topology. The use of mesh topology improves the reliability of the network and packet propagation. In the event of any failure in the device, the router can re-route the data through the other FFDs [86]. The use of mesh topology also supports multi-hop communication, where messages are transmitted from one FFD to the other until the final FFD or RFD node is reached.

The use of mesh topology can increase the network coverage range, as this topology contains a large number of routers. In mesh technology, the occurrence of dead zones and weak signals can be easily resolved when the number of FFDs is increased. In the event of any device failure, the data can be re-routed using another FFD [30]. This topology can be self-configured and also self-organized, which increases the reliability and robustness of the network.

2.6 Connectivity design issues in WSN

In the literature, a significant number of studies have focused on topology control and on connectivity issues in sensor networks. From a connectivity perspective, an important aspect of design is the S parameter, since the WSN node operates at high frequency (~ 2.4 GHz) and the selected circuit elements/antenna for transmission have physical dimensions comparable to the wavelength [87]. The S parameter represents the input-output relationship (incident and scattered waves) between ports in an electrical system. The suffix, S_{ij} , would identify power transfer from the j th port to the i th port, measured in dB. For the WSNs, the suffix stands for the transreceiver of the i th node and j th node. For example, in the WSN, if $S_{ij} = -10$ dB, this would mean that if there is a 1 W power input at the j th node, then only 0.1 W would be received at the i th node. The S parameter is thus very useful in the analysis of power transmission in a WSN.

On the other hand, the efficient routing protocol complements power management, and many

routing protocols have been proposed. Maintaining the status of routing fidelity while switching off unwanted sensors that can prolong the network lifetime was presented by [10] in a new protocol called Geographical Adaptive Fidelity (GAF). This protocol uses a virtual grid for sensor nodes, and a sensor network to decide which nodes that should sleep and their sleep duration. Another protocol termed SPAN maintains connectivity by making sure that at least one connectivity link exists between the unwanted sensor nodes that have been put into sleep mode and all other active nodes [60], [88]. The maintenance of network connectivity is also essential in ensuring that the transmitting power of sensor nodes is energy-efficient [60], [88], [89]. [90] presented a coverage algorithm by studying how intersection levels between sensors' sensing ranges are covered by their neighbouring sensor nodes. It was found that coverage can establish connectivity if sensors' communication ranges are more than twice their sensing ranges' R_s . Another protocol, the Coverage Configuration Protocol (CCP) maintains connectivity but also gives different degrees of coverage. Cooperative transmission increases connectivity. Therefore, disconnected parts of a WSN, which had the disadvantage of the separation issue, are reconnected. Better connectivity (more than 50%) is offered by this approach compared to the multi-hop method, with a decreased number of nodes required to result in full coverage of up to 30% of an area [56], [91], [92].

To summarize, connectivity issues have been addressed in detail in both scenarios and abstract conditions. It is therefore important to examine relevant design solutions, which are discussed in the next section.

2.7 Relevant work on WSN

In the literature, various studies have focused on WSNs, but with a limited discussion of WSN propagation models. The primary targets of these papers are network behaviour, network topology and system-level modelling [92], general characteristics and applications [89], [94] WSN simulation, emulation or debugging tools [32], [39], [43], and cross-layer approaches for WSN problems [95]–[97]. The importance of the physical layer for signal propagation effects, signal detection, modulation, power efficiency, frequency selection, and generation is emphasized in [92]. Different aspects of signal propagation are investigated, and link quality metrics are

estimated in [89]. Furthermore, the application of WSN for underground water-based applications is the focus of the study by Akilydiz et al [98].

Sampigethaya et al. (2010) emphasized the importance of using WSNs in health management applications in aeroplanes [99]. This study indicated the importance of addressing two key aspects, one of which is related to security and the other to energy efficiency. The importance of designing a sensor network with proper power transfer characteristics and security features is noted in order to increase the effectiveness of using sensor nodes for structural health monitoring applications. Similar work was carried out by Kural (2014), who specifically focused on energy supply for sensor nodes when used for the structural health monitoring of aircraft wings. The use of the piezoelectric effect in the design of wireless sensor networks in order to supply electricity to the sensor node in structural health monitoring applications was examined. Lamb wave propagation was simulated in this research and the importance of using effective transfers to improve the design of a sensor network for structural health monitoring applications was identified.

Notay and Safdar [100] proposed a WSN topology design using ZigBee nodes specifically for the aircraft wing structure. However, the authors in [101] did not consider the development of a path loss model, but instead proposed the topology shown in Figure 4. The performance of the proposed network topology was validated in the OPNET Modeller 16 simulator using the ZigBee model as a platform. The main reason for the selection of the ZigBee model is its similarity with the wireless sensor network and the lack of a sensor model in the OPNET modeller. The IEEE 802.15.4 standard provided the specification for the physical and Medium Access Control (MAC) sublayer of Low Rate-Wireless Personal Area Networks (LR-WPAN) (both wireless sensor networks and the ZigBee networks are examples of LR-WPAN networks). Furthermore, both ZigBee and wireless sensor networks share the same physical and MAC layers.

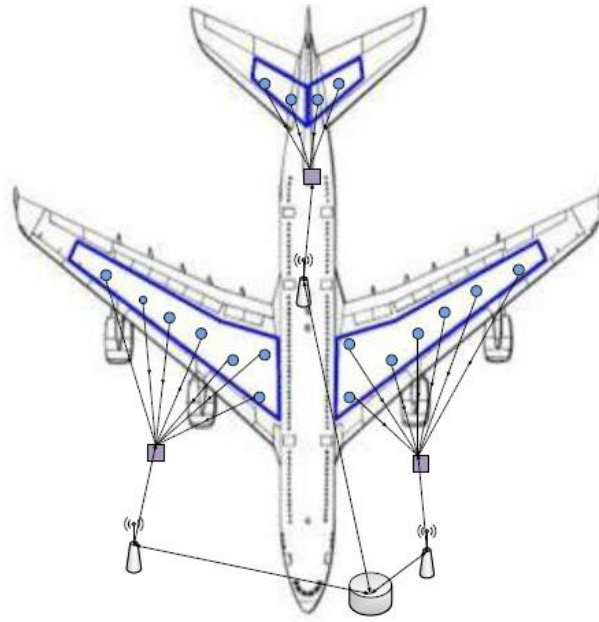


Figure 4: WSN deployment in an aircraft environment [101].

Realistic reconstruction of WSN topologies is possible if the path loss values among the sensor nodes are computed using proper propagation models [101]. Design of WSN routing protocols using simplistic path loss models would not show expected performance in practical applications, and the characterizations of these protocols under such assumptions would be questionable. Correct modelling of path loss is of utmost importance in determining the Signal-to-Noise Ratio (SNR) which in turn is the determining factor in transmission power control [45, 46]. The WSN lifetime is significantly affected by the optimal assignment of transmission power levels and by the extent of retransmissions due to packet failures, which are all dependent on the correct modelling of path loss. In general, path loss is stochastic rather than deterministic. Furthermore, it can vary over time and may change rapidly according to the frequency/scenario used. Therefore, path loss models include statistical descriptors such as mean values and standard deviations.

2.8 Routing in WSNs

Traditional routing protocols often use routing tables that indicate to each node the exact neighbour to which a packet should be sent in order to reach a specific destination. Prominent examples of such routing protocols are ad-hoc on-demand Distance Vector (AODV)[81], Mint

Route and Directed Diffusion [97]. This fundamental *unicast* routing approach intrinsically requires nodes to maintain knowledge of their neighbours and their neighbour states (such as *active, sleeping, and destroyed*). However, additional techniques are required to judge the quality of all available links [102]. For a highly dynamic network such as a WSN, this available unicast routing approach imposes a high algorithmic overhead. Requiring a node to continually learn the details of its local connectivity and notify its neighbours of its chosen state in a dynamic environment requires a significant amount of additional radioactivity that is not directly involved in transporting the sensor data [103]. Moreover, while routing messages to specific neighbours is adequate under ideal *static* network conditions, such an approach incurs an additional delay in a dynamic environment as nodes probe for new neighbours to forward the packet to and reconfigure the network's topology [104].

Figure 3 presents a broad classification of the WSN routing protocols into two main types, namely network structure-based routing protocols and protocol operation-based routing methods. Each of these routing protocols is further classified into different types, as shown in Figure 5.

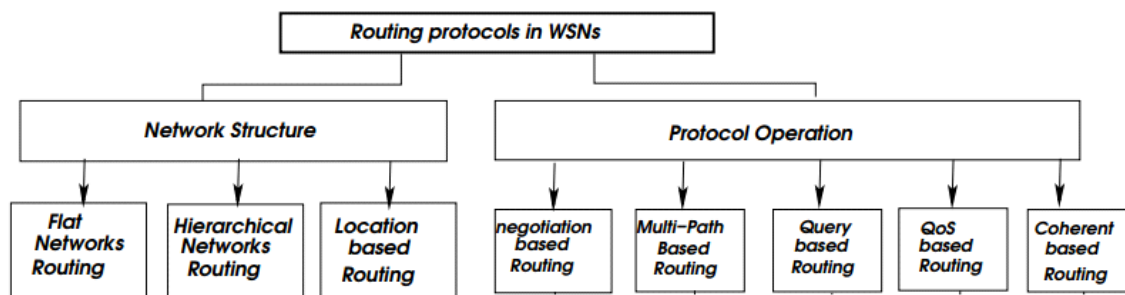


Figure 5: Routing protocols in WSN [89].

Some examples of important WSN protocols are:

Location-based protocols:- MECN, SMECN, GAF, GEAR, Span, TBF, BVGF, and GeRaF

Data-centric Protocols:- SPIN, Directed Diffusion

Rumour Routing:- COUGAR, ACQUIRE, EAD

Hierarchical Protocols:- LEACH, PEGASIS, HEED, TEEN, APTEEN

Multipath-based Protocols:- Disjoint Paths, Braided paths, N-to-1 Multipath Discovery

QoS-based protocols:- SAR, SPEED, Energy-aware routing

However, the availability of these different types of protocols does not resolve the routing issue in all cases. Application-specific routing protocols have to adapt often optimized tuning to the requirements and data available for the deployed nodes. Recent developments in research into energy-efficient routing protocols are either abstract or more specific to the underlying applications [65], [66], [68], [69], [105]. These protocols deploy various optimization and routing techniques, such as cluster-based [65], multi-hop clustering [69], improved Grey Wolf Optimizer [105], and the PEGASIS bacteria foraging protocol [67]. The further emergence of IoT has also stimulated interest in smart systems and power-efficient WSNs [71]–[75], [106]–[108]. However, deployment and energy optimized routing for WSNs in an airborne aircraft environment has not been rigorously studied in the literature, and addressing this gap is one of the main objectives of this study.

An aircraft wing environment, which is modelled as connected compartments by holes in ribs, presents a complex problem for routing [109]. As the recommended deployment of the wireless sensor nodes in the aircraft wing is ad-hoc, it is necessary to review the applicable routing protocols.

2.9 WSN Energy Harvesting Methods

The energy constraints of the sensor nodes must be resolved in order to use them for aircraft structural health monitoring applications. Energy harvesting is a widely adopted technique used to resolve the energy constraint problem of sensor nodes [110]. Energy harvesting is defined as the mechanism that is utilized for generating energy from the network surroundings in order to offer an uninterrupted supply of power to the sensor node and the wireless sensor network [111]. Several energy-harvesting opportunities exist to offer uninterrupted power supply for

WSNs in an aircraft environment, such as vibrational, thermal and electromagnetic energy harvesting [112]. The fuselage of an aircraft offers a proper temperature gradient across the inner and outer skin; hence, thermoelectric generation could be used to harvest a few megawatts (mW) of power. However, the different operations of the aircraft wing result in low-frequency vibrations through which the μW range of power can be harvested by the WSNs. The energy harvesting methods are listed below [113].

2.9.1 Vibrational Energy Harvesting

The vibrations of an aircraft wing are of different types: vibration, buffet, flutter, and noise. The vibrations are random, periodic oscillations of constant frequency and magnitude; buffets are aerodynamically induced vibrations and equally random [114]. Flutters are excited natural frequencies and an unstable aerodynamic condition that grows in magnitude. Noise, on the other hand, is an audible vibration that is random in nature, which manifests in tones like the whistling of a drain [115].

However, the experimental and computational studies on wing vibrations have classified vibrations according to their frequencies and modes [116]. The various modes of vibration, such as bending, and torsion have been identified, but high-frequency vibrations are undesirable for aircraft safety, even though they might be desirable for energy harvesting [117]. The low-frequency vibrations present in the aircraft are $<20\text{ Hz}$ [6].

The wing model is divided into three distinct regions, and the average frequencies inferred for each region are presented in Figure 6 and Table 3. Based on these frequencies, the estimated harvested energies have been computed [118].

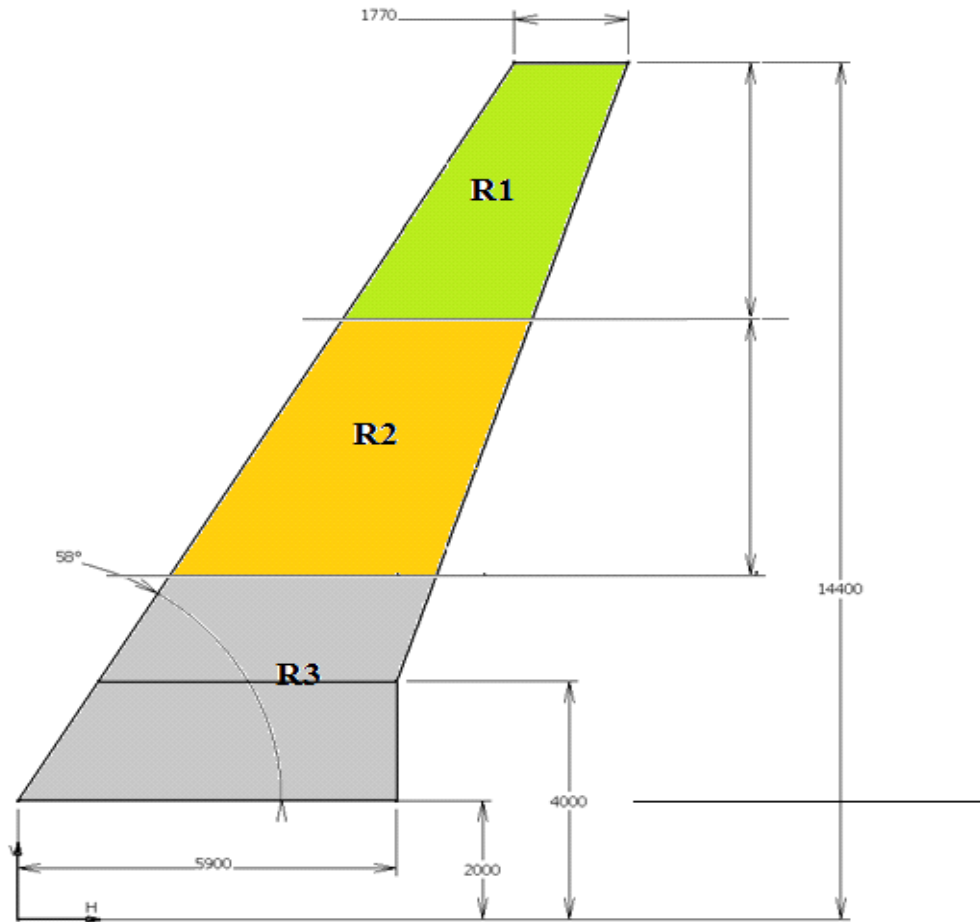


Figure 6: The wing model divided into three regions of an average length of 4m [119].

As shown in Figure 6, the aircraft wing considered in this research is divided into three main regions, namely R1, R2 and R3. The main reason for dividing the aircraft wing into three regions is to ensure that the average length of each region is equal to nearly four meters. It is essential to divide the aircraft wing into equal regions as indicated in [119] in order to estimate the average frequency level and amount of energy harvesting needed. The importance of dividing the aircraft wing into equal regions to effectively estimate and compare the amount of energy to be harvested, as indicated in [120], resulted in the decision to divide the wing model into the three regions shown in Figure 6. Wing model NACA64A410 was selected for this research in order to divide the aircraft wing into three principal regions [121].

Table 3: Frequencies and harvested energies from different regions of the wing model.

Region	Wing section length, m	Average Frequency, Hz	Energy harvested, mW**	Remarks
R1	4	15-20	7-9	Intermittent harvesting, as the vibrations last only for a particular length of time.
R2	4	10	3-5	Intermittent harvesting, as the vibrations last only for a particular length of time.
R3	4	<5	3-5	Continuous, since the vibrations are present throughout its operation.

Table 3 above presents the average frequency level and the energy harvesting requirements for each region present in the aircraft wing under consideration, as shown in Figure 6. All these calculated values apply to the aircraft wing model NACA64A410, although a wide variety of adopted wing models for different types of the aircraft exist, as indicated in [120]. Various studies in the literature, such as [122], were used to prepare Table 3. Critical analysis of the values presented in Table 3 indicates that despite the three regions of the aircraft wing being of equal length, the amount of energy to be harvested for the sensor nodes in each region is highly dependent on the average frequency. The region with a higher average frequency level, R1, was identified to supply a higher amount of harvesting energy when compared to that of the other regions. As these calculations are based on the aircraft wing model NACA64A410, these calculations can be easily applied to the other wing models considered in this research [123].

An example of the sequence of steps were used to calculate the harvested energies and frequencies based on the different regions of the wing model is given below.

Table 4: The frequencies based on the different regions of the wing model.

Assume the vibration 10-20 Hz will last for 5-6 seconds.
Assume the efficiency of the energy harvesting circuit is 90% [124].
Assume the piezoelectric device volume is cm ³ , specifically in reference to Table 3.
Power harvested = $2000 \times 0.90 = 1800 \mu\text{w} = 1.8 \text{ mW}$ per second.
If the vibrations of 20 Hz frequency last for 5 seconds, power harvested = $1.8 \times 5 = 9 \text{ mW}$.

The assumptions given in Table 4 were made based on the simulation analysis carried out by Jin et al. in [124]. As the simulation analysis was made on the basis of an aircraft environment, the frequencies and different values related to it were considered for this research. These assumptions were made in order to calculate the amount of power that has to be harvested for each type of aircraft wing. This way of considering the assumptions and then calculating the power harvested can be of significant help in undertaking the further analysis of power transfer characteristics in this research work.

The influence of piezoelectric device volume on the calculation of harvested energy/power facilitates the need to research the availability of piezoelectric (PZT) materials that can better extract and harvest vibration energy at these frequencies [120]. Piezoelectric polymer-based energy harvesters are suitable for applications with very low input frequencies. Although the intended applications that were researched in the literature are not directly related to the aircraft environment, it was assumed that suitable modification could be adopted [125][63]. Table 5 shows the possible harvested energies from piezoelectric materials at low frequencies.

Table 5: Piezoelectric materials for low-frequency energy harvesting.

Frequency, Hz	Material	Harvested Power, μW	Reference
2	PVDF	2	[63]
3	PVDF	610	[64]
1	PZT Ceramic	47	[126]
1	PZT Ceramic	265	[65]
2.5	PZT Ceramic	144	[66]
20	PZT Ceramic	2000	[66]
10	PZT Ceramic, Radial Field Diaphragms (RFD)	600	[68]

The harvested powers shown in Table 5 are the peak powers that exist at the specified natural frequencies. In order to balance the supply and demand for power by WSNs in the aircraft environment, the tentative energy harvesting circuit shown in Figure 7 was considered in this study. Considering this energy harvesting circuit makes it reasonable to assume an efficiency of 90% [127].

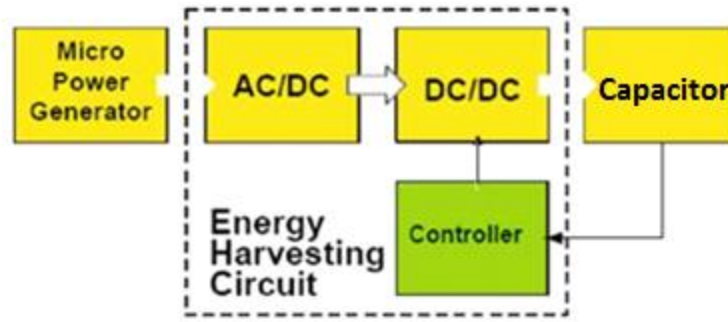


Figure 7: Energy Harvesting Circuit Block Diagram [128].

However, it is important to analyse whether the power supplied by these energy-harvesting techniques is capable of supporting the power requirements of various WSN components. For this purpose, the amount of energy consumed by various WSN components is identified and presented in Table 6.

Table 6: Energy consumption of various WSN components.

Component	Activity	Energy per activity	Remarks/Reference
Transceiver	Transmission	1 μ J/bit	RFM TR 1000 [69]
Transceiver	Reception	0.5 μ J/bit	RFM TR 1000 [69]
Microcontroller	Computation	1 nJ/instruction	[69]
Sensor	Sensing	-	-

The main objective of all these calculations is to evaluate the power consumption of sensor nodes for the transmission and reception of messages. From the NC37 CST simulation results, it is evident that three frequencies (2.4, 2.45 and 2.5 GHz) are accommodated. For all these frequency bands, ZigBee recommends a data rate of 250 Kbits/s or 250 kbps, as shown in Table 7.

Table 7: ZigBee recommended data rates in different regions [4], [129].

Band	Regions	Channels	Data rate
868 MHz	EU, Japan	1	20 kbps
915 MHz	US	10	40 kbps
2.4 GHz	Worldwide	16	250 kbps

Therefore, considering an RFM TR 1000 transceiver, the energy required for:

Transmission, $250000 \text{ bits/s} \times 1 \mu\text{J/bit} = 250 \text{ mJ/s} = 250 \text{ mW}$;

Reception, 125 mW.

Around 500 mW is required for transmission and reception when the transmission and reception radio are in an operational condition. Therefore, selecting a PZT ceramic operating at a frequency of 3 Hz [10] that outputs at around 500 μW every second helps optimize the energy harvested at a continuous rate. The duration required to make 500 mW available through energy harvesting is therefore 1000 seconds or 16.67 min. All these mathematical calculations indicate that continuous energy harvesting is feasible at the frequency of 3Hz. All the assumptions and the values calculated in the above tables help calculate the amount of the power to be harvested for each wing based on the model and inner structure of the aircraft wing.

2.9.2 Commercial Projects on Aircraft Energy Harvesting

Commercial projects such as Sentient in the UK and the Flightwise Advice project in Europe are engaged in designing the components and optimization solutions for the deployment of WSN in aircraft SHM applications. The Advice project [124] was launched in 2006 and ran for three years. This project received recognition from 10 different industries, research centres and various academic partners. The multidisciplinary Advice project aimed to develop state-of-art technologies for aircraft SHM carrying out vibration damping in the aeronautical structures of

the aircraft. Some of the main partners involved in the Advice project were INSA of Lyon in France, the Centre de Recherche en Aeronautique in Belgium, PZL Swidnik in Poland, and Aernnova Iberica in Spain.

One of the significant products developed from the ADVICE project is Vibrational and Damage Control Units (VDCus). The VDCus that were implemented in the frame of the project were used to prove the feasibility of objectives pursued by the ADVICE consortium. Even though these VDCus allow for a first evaluation of the energy balance on a representative composite structure, they still need to be optimized and robust.

The pictorial illustration of the VDCu electronics assembled on a 4x4cm PCB board is shown on the left of Figure, and the stiffened composite panel on a shaker used to characterize the VDCu system is shown on the right of Figure 8. The working of a VDCu is described below Figure 8.

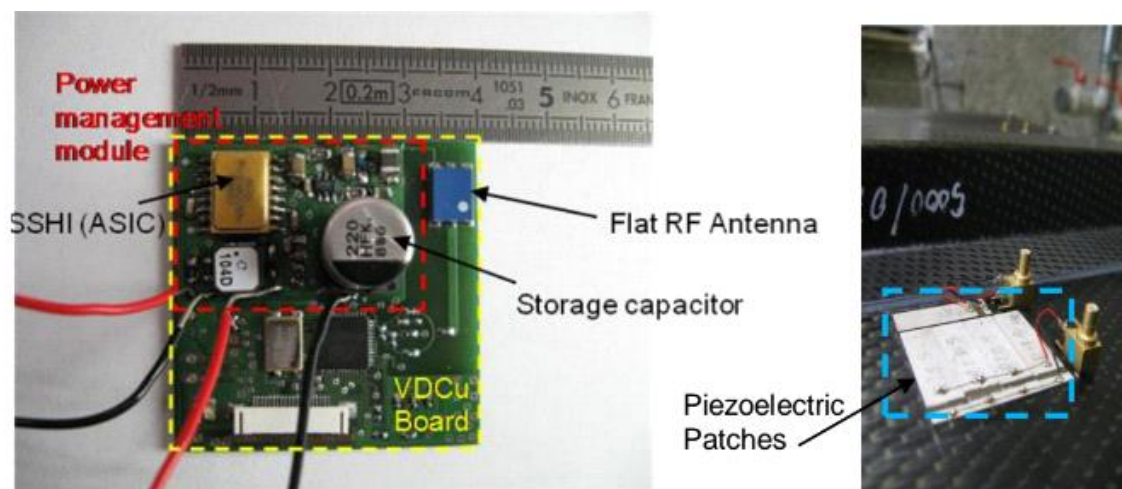


Figure 8: VDCu electronics and piezoelectric patches adapted from [130].

During the flight, the strain created by structural vibration in the piezoelectric elements is converted into a direct current that is stored in a capacitor. This allows the VDCu to operate for a short time during the flight until all the vibrations have stopped. To ensure proper functioning, the VDCu needs to harvest approximately 0.2mW (depending on the communication cycle), with a Lamb wave sent every 10 seconds. Tests carried out on a shaker with different vibration spectra representing aircraft structures showed that this is usually possible. The sensor, on the other hand, requires much more energy, as RF needs to be activated continuously (RF communication

is established with VDCu before any Lamb wave is transmitted), and the microcontroller has to handle more data. During the complete testing phase, the sensors were externally powered.

Major European research institutes have invested in WSNs for aircraft monitoring, prominent examples being:

4. The European Commission's Flite Instrumentation Test Wireless Sensor (FLITE-WISE) project for aircraft continuous monitoring [108];
5. The French research and development project SAHARA, supported by the ASTECH company [75];
6. NASA's Langley Research Centre Fly-by-Wireless alliance project [74].

The importance of providing energy-harvesting techniques for wireless sensor networks used for structural health applications has resulted in some commercial projects being undertaken by different aviation health monitoring institutes around the world. Menchur (2018) specified the details of an energy harvesting project called the EMRP project. The main intention of this project is to develop suitable approaches for energy harvesting based on thermoelectric conversion and electromechanical energy conversion technologies. The ability of this project to develop energy harvesting methods has resulted in its use in aircraft environments. Another commercial project was En-cone, a £1 million project undertaken by BAE Systems and engineers from the University of Lancaster. The main intention of this research project was to develop an aircraft that could stay in the air for longer without the need for refuelling. In this project, sensors made up of different macro-fibre composites were attached to an aircraft wing to collect vibrations from the wings. This project used simulations to analyse different forms of the vibration spectrums based on aircraft structure, especially aircraft wing structure. Based on this information, suitable energy harvesting methods have been developed for different aircraft based on different aircraft wing models.

Different real-time projects indicate the following uses of sensor nodes for structural health monitoring applications:

- (1) The WICAS PROJECT (Wireless Interconnectivity and Control of Active systems) aims to use sensor networks to achieve flow control in the aircraft wing.
- (2) The FLITE-WISE project (FLite Instrumentation TEst Wireless SEnsor), is supported by the European Commission. This project aims to use a wireless sensor network to make aircraft maintenance more efficient by removing the unnecessary costs associated with it.
- (3) The FBW alliance project (Fly by Wireless), is undertaken by NASA, which aims to fund four different research projects to apply wireless sensor networks in aircraft monitoring applications.
- (4) The ASMT programme (Advance Subminiature Telemetry System) by Eglin Airforce Base in Florida also aims to develop a wireless sensor network system for flight monitoring.

2.10 Research Gap

The issue addressed in this research is the efficiency of the wire loom and whether energy efficiency can be improved, for example improving the structural health of aircraft wings through the use of wireless technology. This is expected to contribute to maintenance activity and thus lead to cost savings, for example by replacing routine maintenance with on-demand maintenance.

Based on a review of existing studies in the literature of aircraft WSN usage in SHM applications, some of the key research gaps have been identified. These gaps are: (1) the absence of a systematic study of power transmission characteristics in aircraft wings or wing models; (2) WSN design for SHM applications focusing on node deployment and power-efficient routing; (3) the integration of energy harvesting into WSN designs and power management techniques.

2.11 Summary and Conclusion

This chapter reviewed the various energy harvesting techniques suitable for aircraft wings. The vibration source of energy harvesting was described, and mathematical calculations showed the feasibility of the power sustained through vibrational energy harvesting. Based on the review of previous studies of WSN usage in SHM applications in aircraft, some of the key gaps in the literature were identified. These gaps include the absence of a systematic study of power transmission characteristics in aircraft wings or wing models, WSN design for SHM applications focusing on node deployment and power-efficient routing, and the need to operationalize the integration of energy harvesting into WSN designs and power management techniques. Consequently, the next chapter on methodology will focus on suitable methods to study these issues. This will be done by understanding the precise data needed to understand the problem.

The following gaps were identified following the literature review:

1. The absence of a systematic study of power transmission characteristics in aircraft wings or wing models.
2. WSN design for SHM:
 - a. Node deployment;
 - b. Power-efficient routing.
3. Integration of energy harvesting into WSN design and power management.

3.1 Overview

The critical review of the existing literature has identified the lack of a single systematic study focusing on identifying the feasibility of ZigBee for use in aircraft in terms of power transmission characteristics, node deployment and power-efficient routing. Having identified this gap in the literature, the aim of this research was to identify the feasibility of using ZigBee for SHM applications in aircraft environments. This requires adopting a dedicated methodology detailing the selected aircraft wing models and providing a proper justification of the chosen wing models. This chapter provides all the details of the methodological decisions that were made in this research in order to help to assess the feasibility of ZigBee for SHM applications in aircraft environments. The wide range of applications of the NACA64A410, empty NACA64A410 and empty prismatic wing models across various aircraft, such as McDonnell Douglas, Airbus 320, DC-9-80 and Boeing 737-200 [131], resulted in these wing models being selected for the design described in this chapter. As this study investigated the feasibility of using ZigBee for SHM applications in aircraft environments in this report in terms of power transmission characteristics, node deployment and power-efficient routing, this methodology chapter specifies the design choices that were made to carry out the simulations to identify (1) the effect of aircraft wing antenna position; (2) the effect of structural materials on connectivity control; (3) identify topology control and WSN optimization; and (4) identify the aircraft wing power transfer characteristics.

The variance that might arise were another wing model used, for example a Boeing 747 wing, would be minimal, and would relate to inter spar spacing, and the length and breadth of the wing. This occurs because the best communication range is between 0.5-1m, according to simulation results reported by CST [132]. Therefore, results are very much independent of wing size and geometry. The number of nodes is expected to change but the overall methodology of the thesis remains applicable. Furthermore, these models were chosen to ensure the entire framework is consistent. The thesis considers different wing materials, and meshes comprising different numbers of nodes.

Spiral methodology was adopted in recognition of the importance of adopting a dedicated and structured methodology. The spiral model of software development mainly involves combining the features of the waterfall and prototyping models [133]. In this risk-driven process model, the project is carried out in the form of a cycle of spirals, with each spiral consisting of different stages, such as planning, risk analysis, engineering and the evaluation phase [134]. In this project, the spiral methodology was chosen in order to reduce the likelihood of any risks affecting the project, minimise project costs, develop software in the simulation studies in advance, and make the required amendments by testing in each iteration (spiral). The need for a long-term commitment, and the changes to and increasing complexity of the requirements, led to the selection of spiral methodology for this project.

3.2 Methodology for Antenna position in ZigBee communication

To assess the feasibility of using ZigBee for SHM applications in aircraft environments, this research examined the effect of the position of the aircraft wing antenna on the efficiency of ZigBee communication signals. This is mainly because previous studies [135] have emphasized the importance of identifying different factors, such as antenna position, on the transmission of ZigBee signals. In order to identify these factors, three different wing models were considered, designed and simulated using Gmesh and CATIA software packages [136]. These simulation packages were selected for this research based on the broad applicability of this software to simulate the aircraft wing models, as in previous studies [137][138]. The results obtained are presented between the frequency of 100 MHz and 5GHz; two transceivers are considered, one of which is fixed and the other movable. Despite the extensive use of a frequency of between 100 MHz and 5GHz for communicating signals on aircraft wings using the ZigBee network [139], the choice of this methodology was made as part of the overall methodology.

3.2.1 Wing Model Design

During the design aircraft wing design process, three wing models were created. These three models helped to create the simulation environment for the radio wave propagation. The software used to design these three wing models was CATIA, based on the work of Lapa [136].

As the simulation software considers over-wall gauges or wall surfaces, there is particular thickness for the external wing and the internal surfaces. The following three wing models were created in this study:

- **NACA64A410 model for the inner structure of the wing;**
- **Empty NACA64A410 model for the wing;**
- **Empty prismatic model of the wing.**

The different dimensions of the aeroplane wing were considered initially. The size of the wing was selected based on the passenger aeroplane design. This work is based on considerations of three different passenger aeroplanes: the McDonnell Douglas, Airbus 320, DC-9-80 and Boeing 737-200 [140],[136]. The first two wing models depend on the airfoil NACA64A410. However, the maximum thickness of the wing route in the third model is 598mm [136], [141], [142]. The selection of airfoil was based on the asymmetric airfoil that is most often used in the design of the passenger aeroplanes. The shape of the airfoil used is shown in Figure 9.

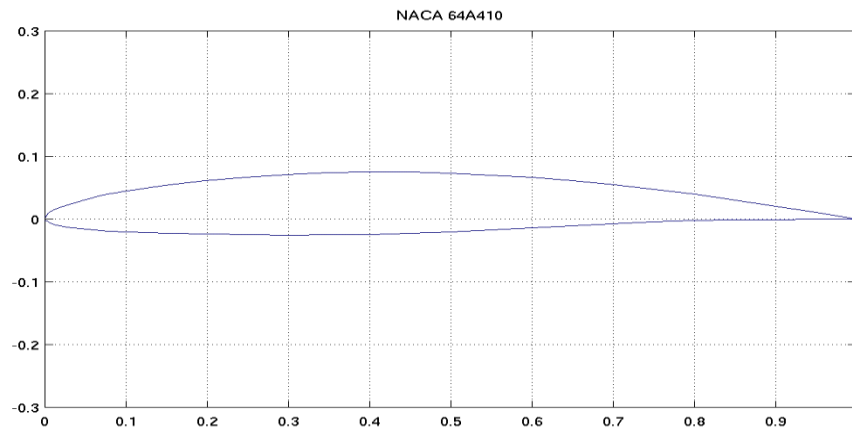


Figure 9: Shape of NACA64A410 air foil used in the design of an aircraft wing [136].

Based on the coordinates provided in [43], the creation of this airfoil was done by connecting the different points. By decreasing the number of points in a meaningful manner, the design of the airfoil was carried out using CATIA software. When preparing the airfoil, it is placed in different destination positions, such as root and tip of the wing. The NACA64A410 wing model was created for the inner structure of the wing. This model consists of four different spars, which

were placed based on [43], [136]. In the next step, the ribs and the openings were designed. The design of the kink rib was carried out using CATIA software, and its appearance is shown in Figure 10 below (the kink rib is the first rib created).

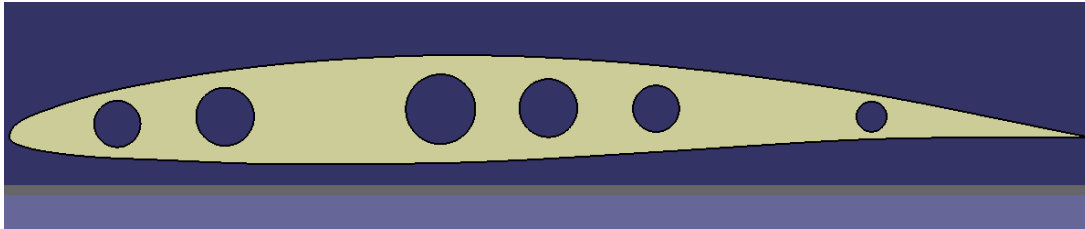


Figure 10: Created kink rib [136].

Later creation of five ribs was done with a distance of two meters. After completion of the design of the NACA64A410 wing model and the empty NACA64A410 model of the wing, the empty prismatic model of the wing was prepared [136].

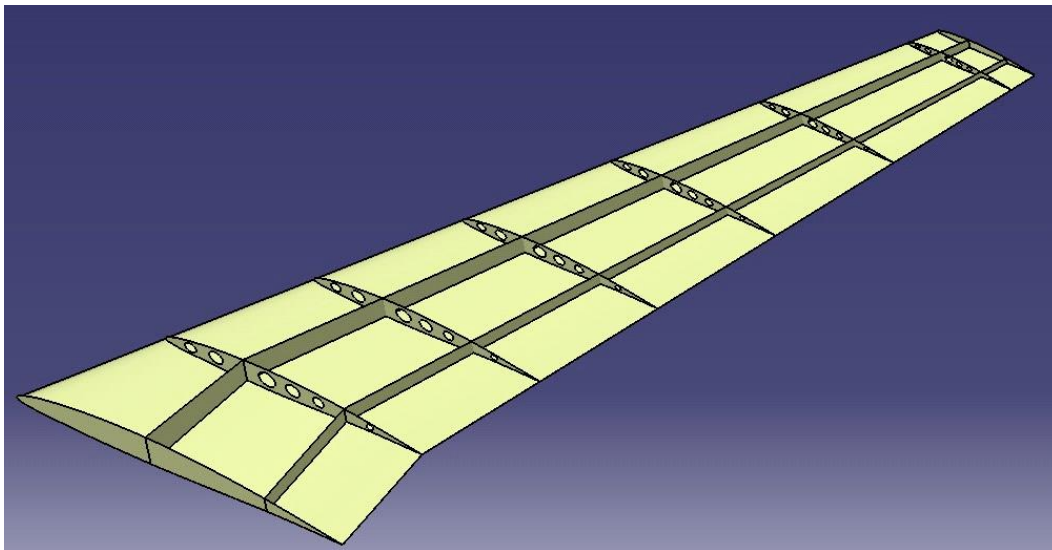


Figure 11: NACA64A410 model for the inner structure of the wing [136].

Figure 11 shows the creation of this NACA64A410 model of the wing model using the CATIA software. Here, the inner structure of the NACA64A410 model is created and modelled using CATIA software [136].

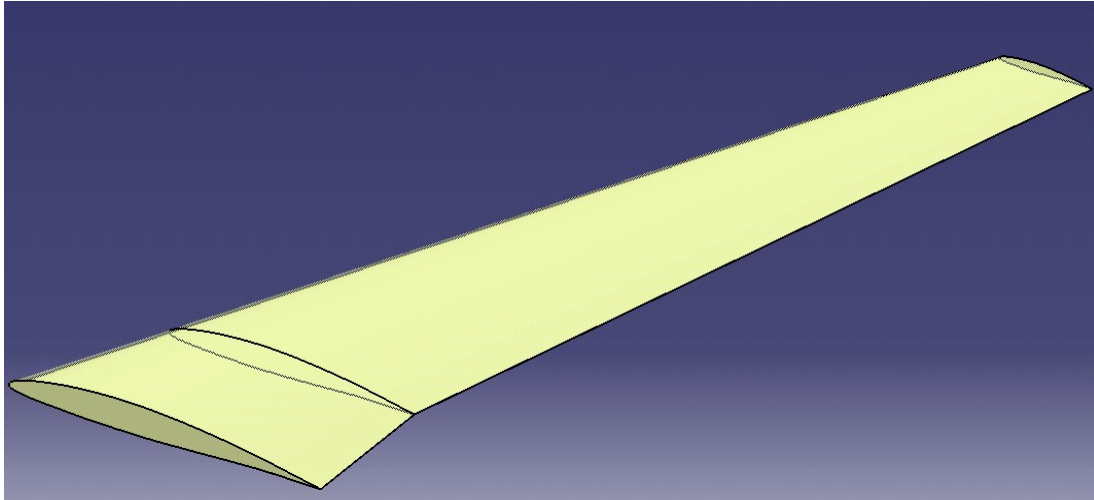


Figure 12: An empty NACA64A410 model for the wing [136].

Figure 13 shows the creation of the empty NACA64A410 model of the wing model using CATIA software [136].

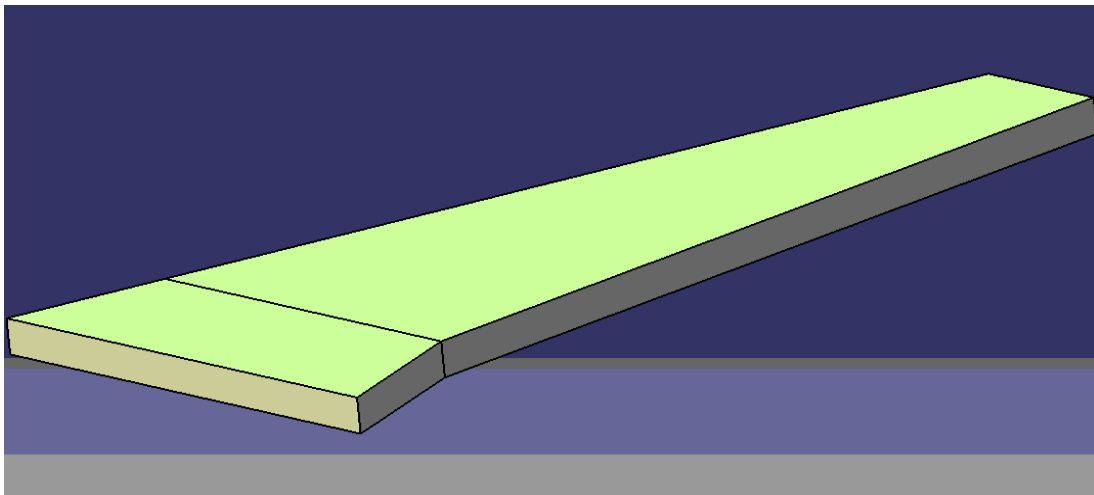


Figure 13: An empty prismatic model of the wing [136].

Figure 11 shows the creation of the empty prismatic model of the wing model using CATIA software.

This model can be used to identify the effect of the shape of the wing on radio wave propagation. This effect was studied based on the sketch execution, as indicated in Figure 14, below which the maximum thickness of 589mm is given to the root airfoil. Following the creation of required wing models, the next step of meshing wing models was carried out using Gmesh software.

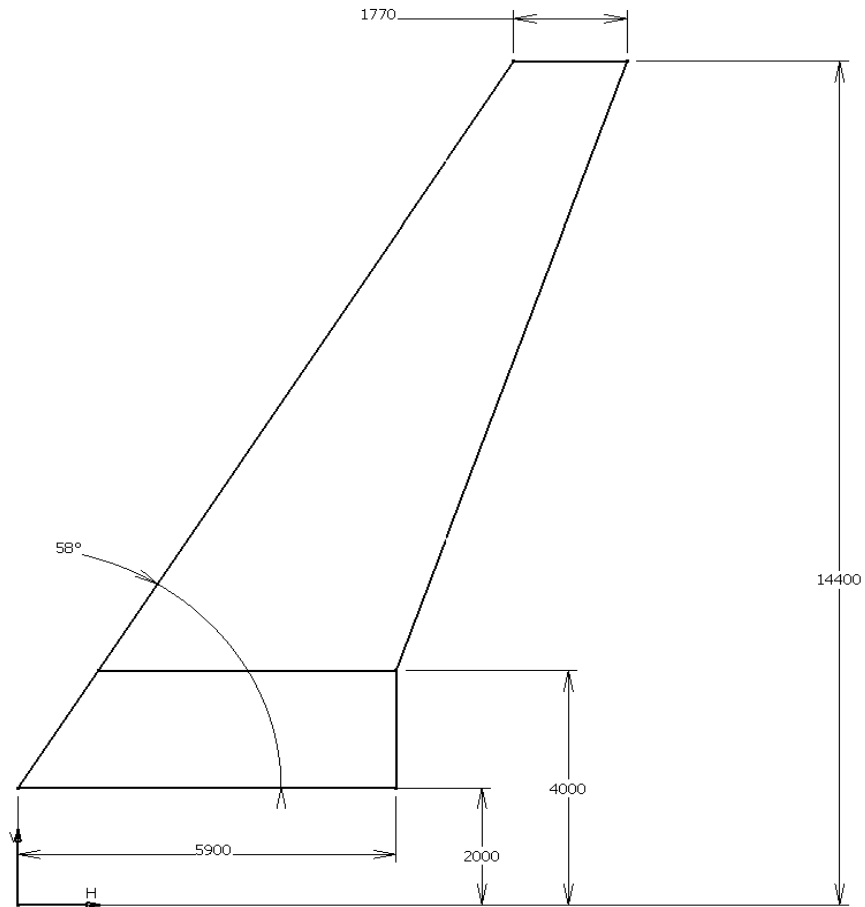


Figure 14: The various dimensions related to the wing model NACA64A410 [136].

Figure 14 shows the details of the NACA64A410 model of the wing model given in the form of different dimensions.

□ Meshing Wing Models

Gmesh software was used to mesh the three wing models. For this purpose, the files with an IGS extension were imported using the grading tool in CATIA software. In all three models, the following similar parameters were taken into account:

- Default shape of the grid patches;
- The default 3D function for meshing;
- Mesh refinement.

Using the 3D meshing functions provides a particular shape is provided for the grid and for different patches of the wing model. Using the mesh tool, the patch size is reduced depending on the accuracy needed. In order to obtain the appropriate level of precision in the simulation, the same parameters are used for different models [136].

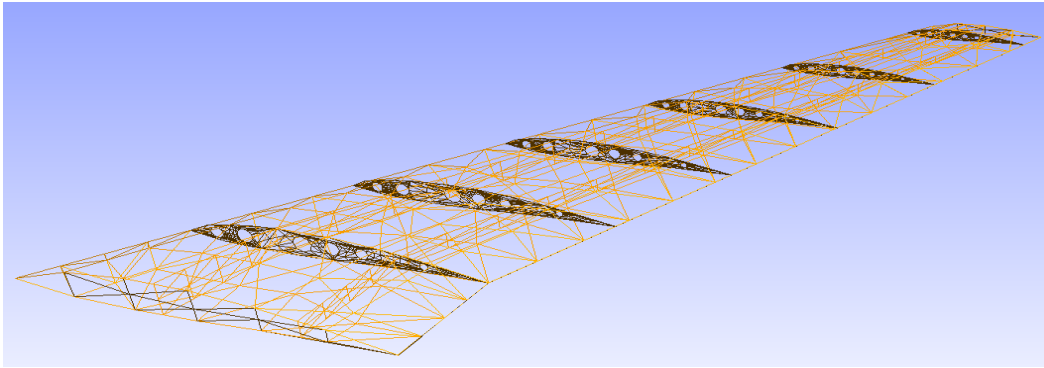


Figure 15: NACA64A410 model for the inner structure of the wing [136].

Figure 16 shows the result of meshing the NACA64A410 wing model using the adopted Gmesh software [136].

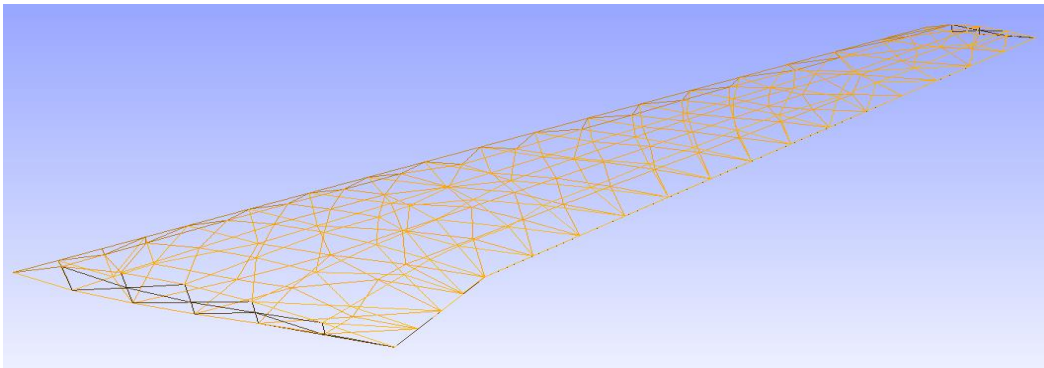


Figure 16: an Empty NACA64A410 model for the Wing [136]

Figure 16 shows the result of meshing the empty NACA64A410 wing model using the adopted Gmesh software [136].

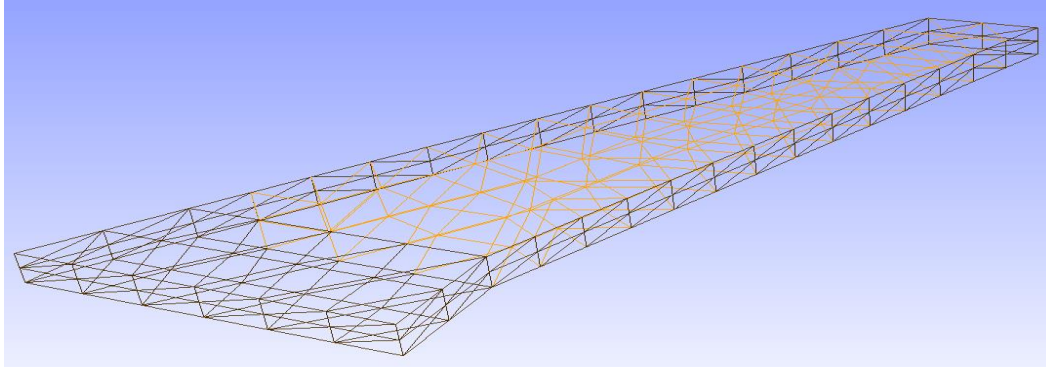


Figure 17: Empty prismatic wing model [136].

Figure 17 shows the result of meshing the empty prismatic wing model using the adopted Gmesh software [136].

3.3 Methodology for effect of structural materials on connectivity control

As part of the process of assessing the feasibility of using ZigBee networks in aircraft environments for the SHM applications, the effect of structural materials of aircraft wing on the connection quality between the two antennas was also identified. Considering the key compositions of the aircraft wing shown in Figure 17, aluminium and carbon fibre composites were the two structural materials considered in this research. In this way, the effect of aluminium and carbon fibre composites on the quality of the connection between the two antennas existing on aircraft wings is intended to be identified in this research. The details of the design methodology used to identify the influence of aircraft structural materials on connectivity control and the quality of the connection between the antennas are given in this section.

3.3.1 Structural materials of an aircraft wing

The three designed wing models (the NACA64A410 realistic wing model, the empty NACA64A410 wing model and the empty prismatic wing model) were used to determine the gradual effect of radio signal attenuation on the aircraft wing. This is mainly due to wing shape and the presence of inner structural elements, such as ribs and spars in the wing, where the interior and the structural elements of aircraft wing are indicated. The empty wing models act as reference models to quantify and calibrate the loss of radio wave signals in the realistic wing. Furthermore, the presence of these inner structural elements, as in the case of the NACA64A410 realistic wing

model, presents challenges for the design of WSN topology. One example of such a challenge is hindering the radio wave signal propagation from the transceivers in the remote locations, such as those near the wing tip or nodes at the wing root.

An aircraft body, especially the aircraft wing, is composed of structural materials such as aluminium, titanium, steel and carbon laminate, as well as other composites. The composition of each of these structural materials in the aircraft wing is shown in Figure 18, indicating that composites account for nearly 50% of the total structural composition. As the radio wave signal travels from the wing tip region to the wing root, the characteristic impedance of the transmission channel (in the inside region of the wing) depends on the materials present in the aircraft wing structures. These materials may be metals like iron, copper or aluminium, or dielectrics like plastics, paper and wood. The composite materials used for aircraft wing structures (Figure 18) exhibit modified properties that differ from those of the materials of which they are made. Metals are good reflectors, while dielectrics offer transmission of some radio wave signals depending on the attenuation coefficient [143]. This attenuation coefficient indicates the proportion of lost signal and the thickness of the structural elements. Therefore, advantageous materials used as structural materials would be dielectric due to the lower reflection of radio waves, but also consist of lower attenuation coefficients, which allows the transmission of signals.

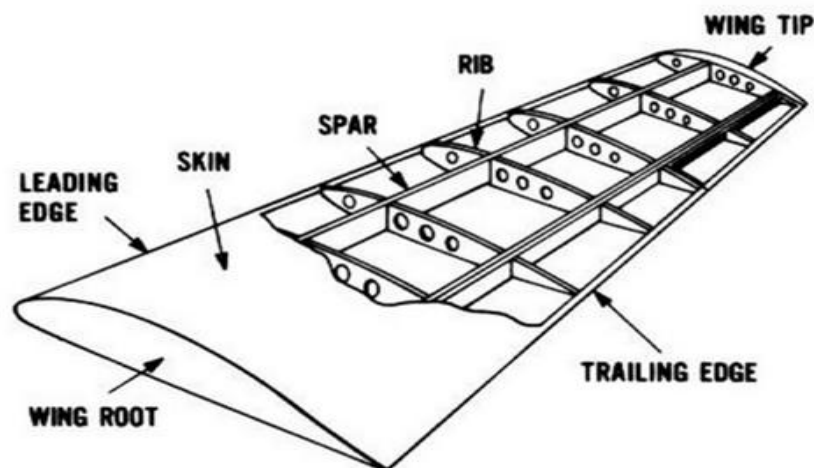


Figure 18: Aircraft wing interior and structural elements [136].

However, the selection of structural materials does not always favour the excellent transmission of radio signals on the aircraft wing. Mechanical and flexural properties, such as high specific weight, higher corrosion resistance, cost and fabrication also determine the selection of materials and composites for wing structure. Moreover, the aircraft wing is not made up of a single material, but is instead a heterogeneous structure made up of different materials and composites, as shown in Figure 19.

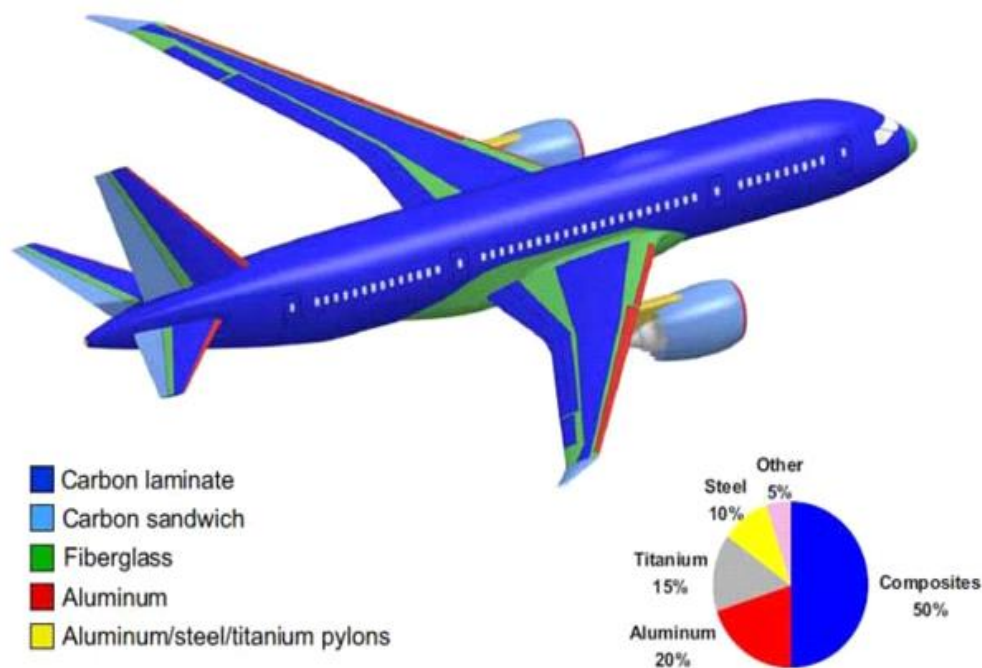


Figure 19: Structural materials in an aircraft body [144].

Therefore, it is essential to characterize radio wave propagation through the different composites of materials used in an aircraft wing. This is because of the usefulness of characterized propagation behaviour during the design and optimization of WSN topology [145]. The primary materials considered for this work are Carbon Fibre Composites (CFCs) and aluminium. The impact of these materials on the radio wave signal propagation and radio wave attenuation between the antennas present on the aircraft wing is identified in this chapter.

3.3.2 Radio Wave Attenuation through Materials

Radio wave propagation over any kind of medium suffers attenuation of intensity, which thereby results in path loss. This is mainly because reflection, refraction, coupling loss and absorption can affect the line of sight propagation. Path loss (L) is characterized by the path loss exponent n .

$$L = 10 n \log_{10}(d) + C \quad (3.3.2)$$

In Equation (3.3.2), L is path loss in dB, d is the distance in meters and C is a constant representing system loss. The equation above is an example of path loss in free space because of the square law of propagation in space.

In the case of aircraft wings made up of different structural elements, the propagation of radio wave signals can suffer from attenuation based on the composition of structural elements. The path loss model was used in this research in order to assess the impact of different structural elements on the propagation of the radio wave signals and on radio wave attenuation. The path loss models can be statistical/empirical or analytical/deterministic [146]. Empirical models are based on measured or averaged path losses along different radio links in the media, whereas deterministic models are based on the use of physical laws of radio propagation through media [147]. The wireless sensor networks used in the interior part of the aircraft wing are generally characterized as small range systems [148], which makes deterministic modelling both feasible and possible, because of the analytical tractability of signal propagations. For example, as ribs have holes, the wireless sensor nodes are placed so that the line of sight propagation is along the line perpendicular to the plane of spars and spacing between nodes is in the range of 600-800cms. Therefore, ray tracing over a region of 600-800cms in range is not a complex problem, especially when the tracing consists of a significant component of diffraction rib holes, apart from reflection and refraction from the compartment walls [148]. In addition, routing or significant transmission of data across spars is insignificant and hence not considered in this research. Figure 20 shows the ribs, spars and direction of signal propagation and routing paths.

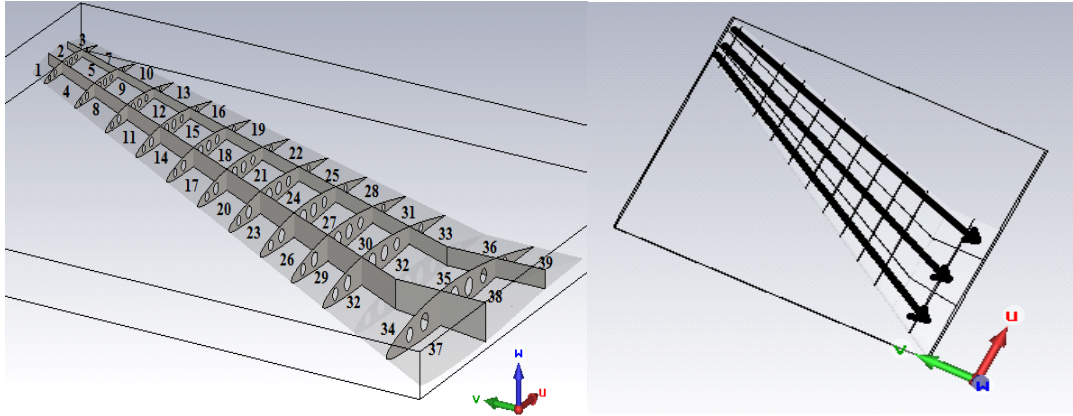


Figure 20: Realistic wing model with node positions near rib holes and the direction of routing or signal propagation.

Alternatively, a simulation approach can yield a path loss model, based on the scattering parameter [149]. The variation of the scattering parameter (S_{21}) across frequency range and distance was investigated for aluminium, CFC and PEC, as shown in the next section.

3.4 Methodology for the optimal topology of WSN in aircraft wing

This study involved identifying the need for optimal topology and the optimal number of nodes in a WSN deployed for structural health monitoring applications in the aircraft wing. The various issues faced by sensor networks in relation to topology control and connectivity design are described as part of the methodology.

3.4.1 Topology Control in WSN

The primary objective of topology control in wireless sensor networks is to maintain network connectivity and optimize network lifetime and throughput. Network conditions need to be monitored in a timely manner by the system operator upon the successful deployment of the sensor network. Compared to wired networks, wireless communication presents a different set of challenges, the main one being supporting WSN services in environments suffering from channel attenuation; another challenge is the limited (narrow) bandwidth of these sensor networks. A range of studies [150] investigating the challenges of wireless sensor networks have indicated the need to address these two key challenges in order to support the use of these sensor networks across a wide range of applications. For instance, WSNs face the difficulty of properly addressing limited bandwidth and operating in a channel attenuation environment if

they are to be used effectively on aircraft wings for the SHM applications. In the literature on wireless sensor networks, several studies have developed different solutions to address the challenges faced by these networks [151]. One of the solutions proposed in the literature to overcome these key challenges of WSN involves the selection of a suitable transmission range for each sensor node, algorithms for efficient network services, and suitable energy-saving mechanisms such as the effective scheduling of sensor's sleep-wake cycles to improve the prolonged lifetime of the network [152]. WSN network services have the important goal of supporting reliable connectivity between communicating sensor nodes across the network topology at different times. Coverage and connectivity control in WSNs helps complement the design goals of a sensor network that is intended to be used in aircraft SHM applications, as indicated in this chapter. Therefore, the primary function of or consideration for the topology control in this research is to answer the two following questions: (1) How effective are the sensors? Moreover, (2) how reliable is their connectivity for the transmission of sensor data? Some of the key topology control issues that occur in a wireless network such as WSN are shown in Figure 21.

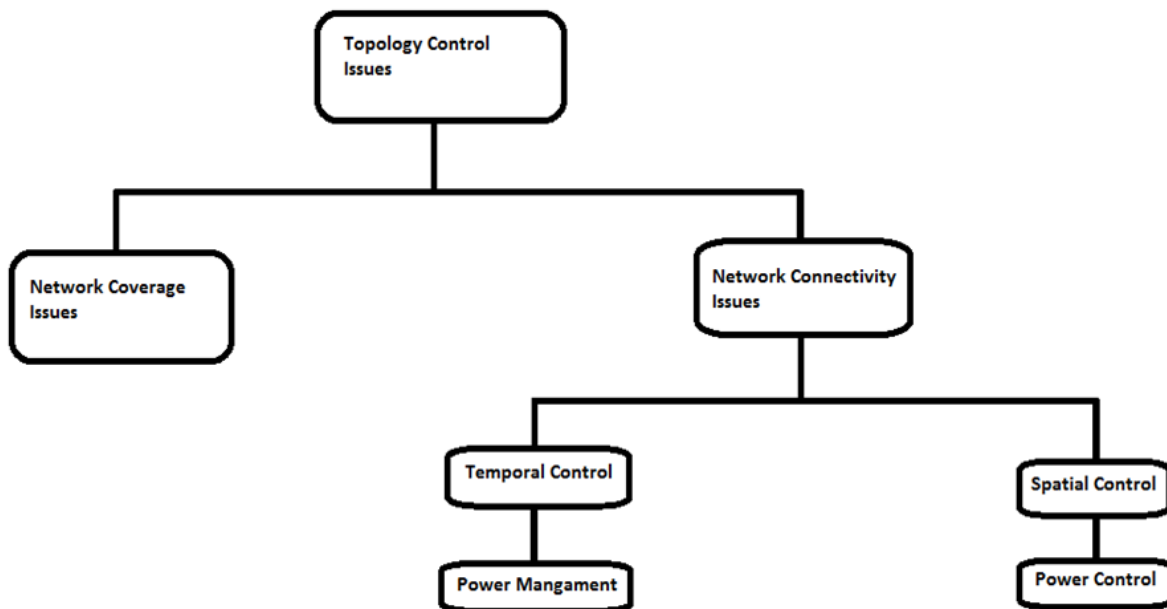


Figure 21: Topology control issues relating to coverage and connectivity [153].

The latter design consideration of connectivity is explored in detail for the aircraft wing. Moreover, it is anticipated that primary design challenge is in the realistic wing model compared

to empty wing models because the presence of different structural elements impedes signal propagation in particular ways that are specific to shape and type of material. Table 8 presents the design stages of and challenges for the three different wing models based on previous studies in the literature [154].

Table 8: Topology control – Connectivity consideration and challenges in design for wing models.

<i>Attribute</i>	<i>Description</i>	<i>Possible Values/Description</i>	<i>Remarks, if any</i>
Node deployment	Regular grid or lattice for the arrangement of nodes or random deployment of nodes over the monitoring or sensing region.	The regular square grid is suitable and adopted for all wing models.	Regular is preferred due to the predefined geometry of the environment to be monitored.
Communication range	A circle of reliable communication distance between two nodes.	50 cm to 1 m, very low compared to the ZigBee range for standard deployment scenarios.	Can be inferred from the density of nodes selected for the wing models.
Node/link heterogeneity	It describes whether sensors are of different types transmitting different types of data.	The present scenario has a homogeneous link. All sensors transmit data related to SHM using similar sensors.	The purpose of WSN is SHM, and all nodes are similar.

Scalability	Capability to enlarge or handle a growing amount of transmissions in WSN.	Scalable WSN.	The number of nodes is bounded since the region of the aircraft wing does not exceed 60-70 m ² .
Transmission Media	Characterization of the surrounding environment for a description of attenuation of the signal.	Prevailing wing structural materials and components (CFC, aluminium etc.).	
Data aggregation	Different mechanisms and routing protocols ensuring the avoidance and implosion of data transmission.	SPIN, SPAR, Gossiping, LEACH etc.	Selection of routing schemes and protocols will be dictated by optimization of WSN connectivity.
Energy considerations	Powering each sensor node and power decay across space and time.	2 AA batteries or rechargeable batteries with each node power-up. Further energy harvesting can also be considered.	Rechargeable or disposable batteries; the primary concern will be efficient energy use and the connectivity quality of WSN for the significant operation time of the flight.

During the process of designing an effective wireless sensor network for aircraft wing models, the need for proper node deployment, identifying a suitable communication range, increasing scalability, data aggregation, transmission media, node heterogeneity and energy considerations have been identified as very important in this research. Concerning the transmission media, the effect of wing structural materials and components like CFC and aluminium must be considered. The possible communication range for the sensor network has been identified as 50cm to 1m, which is low when compared to the ZigBee communication range as used in different deployment scenarios. As part of identifying the key challenges in designing a WSN for wing models, the possibility of using SPIN, SPAR, Gossiping, LEACH and similar methods were identified from previous studies [155]. In the same way, energy considerations for the sensor network were identified as one of the key challenges that must be considered in order to minimise the total amount of energy consumed by each sensor node, with the main intention of maximizing the lifetime of the sensor network. Based on the identification of all these different connectivity issues, some of the most important ones that arise for different wing models are assessed in the next section.

3.4.2 Modelling connectivity design issues in WSN

If at least a single link is achieved between each pair of sensor nodes, a WSN can be considered to be connected. Here, connectivity relies on the existence of such a communication link between each pair of sensor nodes [156]. The connectivity in wireless networks is affected by changes in network topology due to mobility or the failure of sensor nodes and attacks. A loss of connectivity implies that no link exists between nodes, or that nodes are isolated because of failure; however, rerouting and partitioning can be considered as alternatives [157].

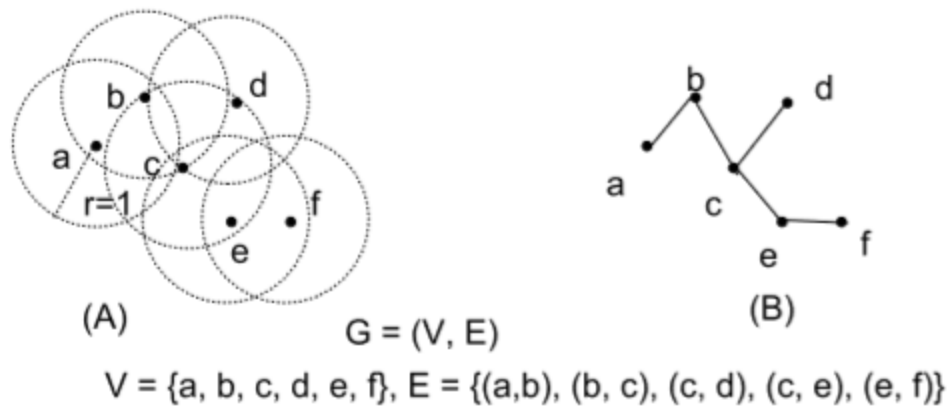


Figure 22: Topology control issues of coverage and connectivity [156].

Mathematical modelling of connectivity is performed using a graph $G = (V, E)$, where V is the set of vertices that are the sensor nodes and E is the set of edges that act as links. If any two sensor nodes 'a' and 'd' are considered, k represents the number of links between them, and all of them are not duplicated, the network is termed k -connected. Connectivity and the quality of service measure for fault tolerance are often used to measure the quality of a WSN service. For a connected network, k thus has at least to be equal to 1. In Figure 22, r is the radius of transmission, and the number of nodes is denoted by " N ".

3.5 Methodology for topology control and WSN optimization

This study also identified the optimal topology, number of nodes and routing paths for a ZigBee network used in aircraft applications. The methodology details the multiple travelling salesman problems for topology control and WSN optimization.

3.5.1 Topology control and optimization of WSN

Topology control and the optimization of the sensor mesh topology used in aircraft wing models are presented in this chapter. Topology control refers to the primary objectives of WSN design that are necessary to ensure the connectivity of the network. Connectivity of the network is ascribed to the network condition; sensor nodes stay connected to enable the collected information to be relayed back to the controllers or stationary/mobile sinks. For example, a network is said to be fully connected when each pair of sensors can communicate with each

other. The sensor communication in a pair of nodes can be direct or occur through relay nodes. The density of nodes (the number of nodes per unit space to be monitored) can be as high as 20 nodes/m³, which is recommended for prolonged network life [158]. However, at such node density a large amount of data is generated, and as many sensors can monitor the same region, data redundancy emerges as another issue. In addition, at high node densities, the total cost of nodes can be high; this also needs to be considered in the present case of sensor deployment in an aircraft wing. Higher node density also equals greater weight added to the structure. Reducing the weight of wiring around the aircraft wing is one of the advantages of using WSNs, as described earlier; this therefore suggests a trade-off between connectivity requirements and node density or the number of nodes to use. Therefore, one of the goals of optimization is to find the minimum number of nodes required in a WSN to achieve efficient connectivity. Furthermore, since knowledge of aircraft wing structure, especially intervening elements such as ribs and spars in the wing, is suggestive for the deterministic deployment of WSN, the deployment grid (for example square or triangular) must be optimized to find the optimal distances between nodes. Such optimal distances will also conform to power levels at nodes; higher power levels and smaller distances between nodes will result in interference; lower power levels can jeopardize the connectivity of the network [104], [159]. Therefore, the connectivity of the designed WSN can be assessed using the spatiotemporal powers of nodes or sensors, which can be simulated by CST modelling of sensor deployment in various aircraft wings. Further connectivity of the network in a proposed ad-hoc (multi-hop) WSN can be assessed by formulating a Multiple Travelling Salesman Problem to investigate the smallest time and shortest path between any arbitrarily picked sensor and gateway. The chapter is organized into sections to describe the problem formulation, solution approach, implementation using MATLAB code, and the discussion of results.

3.6 Methodology for Aircraft Wing power transfer characteristics

This study also aims to identify the power transfer characteristics of the aircraft wing. Details of the methodology are presented in this section. Aircraft wings in commercial airliners such as Airbus have spars and ribs as integral elements. Spars and skin are mostly made of high-grade

aerospace aluminium alloy, while some spars are made of Carbon Fibre Composites (CFC). The substantial share of aluminium and CFC has become the main reason for formulating NC37 and NC38. Evaluation of the radio propagation in aircraft environments is very challenging due to the intricate geometry and the structural elements of the aircraft. However, following recent developments in WSN, the deployments of these sensor networks for SHM applications requires the characterization of power transfer and radio propagation in the aircraft wing. In the literature, few studies have investigated the path loss model or radio propagation in an aircraft environment [160].

The methodology adopted in this study is the radio propagation simulation in the aircraft wing model. Figure 23 shows the node deployment at the rib holes that facilitates the direct line of sight communication. Two nodes are deployed, one on either side of the rib hole, to remove the possibility of link failure and introduce slight redundancy in the node deployment.

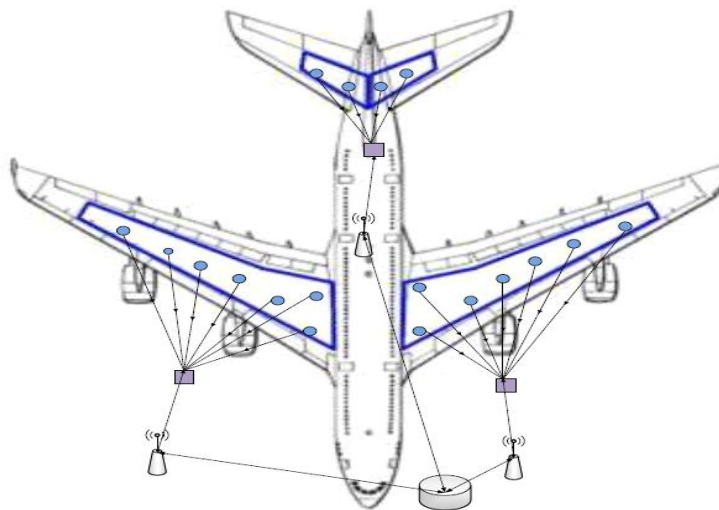


Figure 23: WSN topology for aircraft SHM [101].

As the rib holes also carry wires and fuel lines, placing two nodes across the holes eventually helps to improve the reliability of the network. This model shown in Figure 23 excludes the fuel tank and wiring that runs around the aircraft wing. The design of the simulations aimed to investigate the following goals:

- To map the S parameter, as each node communicates with every other node in the network.

- To investigate the effect of different construction materials, such as Carbon Fibre Composites (CFCs) and aluminium.

A. Number of nodes

As previously mentioned, the placement of two nodes on either side of the node near the hole specifies the number of nodes deployed. This study deployed a total of 130 nodes around 65 rib holes and four base station nodes at the wing root. The decision to have 65 rib holes in the simulated aircraft wing model was made based on the modelling and meshing of the aircraft wing models as shown in Figures 24 and 25. A total of 130 nodes was considered to be included on the wing, *mostly at vantage points of rib openings to establish direct line of sight. Another critical decision made in this research was to have four base stations, each of which dealt with data collection and data aggregation of the nearby nodes such. All the base stations were able to deal with data collection and data aggregation from the 130 sensor nodes present in the wing model.*

The following two deployments were simulated:

- NC37: Realistic wing made of aluminium with 130 nodes and 4 base nodes.
- NC38: Realistic wing made of Carbon Fibre Composites (CFCs) with 130 nodes and 4 base nodes.

Table 9 presents the other planned simulation scenarios in this study.

Table9 : Simulation Scenarios

Scenario	File name	Centralized	Non-Centralized	CST result File	Text File
Realistic wing aluminium	NC37		√	√	√
Realistic wing CFC	NC38		√	√	√

Realistic empty wing aluminium	NC39		✓	✓	✓
Realistic empty wing CFC	NC40		✓	✓	✓
Prismatic empty wing aluminium	NC41		✓	✓	✓
Prismatic empty wing CFC	NC42		✓	✓	✓
Realistic wing aluminium	C37	✓		✓	✓
Realistic wing CFC	C38	✓		✓	✓
Realistic empty wing aluminium	C39	✓		✓	✓
Realistic empty wing CFC	C40	✓		✓	✓
Prismatic empty wing aluminium	C41	✓		✓	✓
Prismatic empty wing CFC	C42	✓		✓	✓

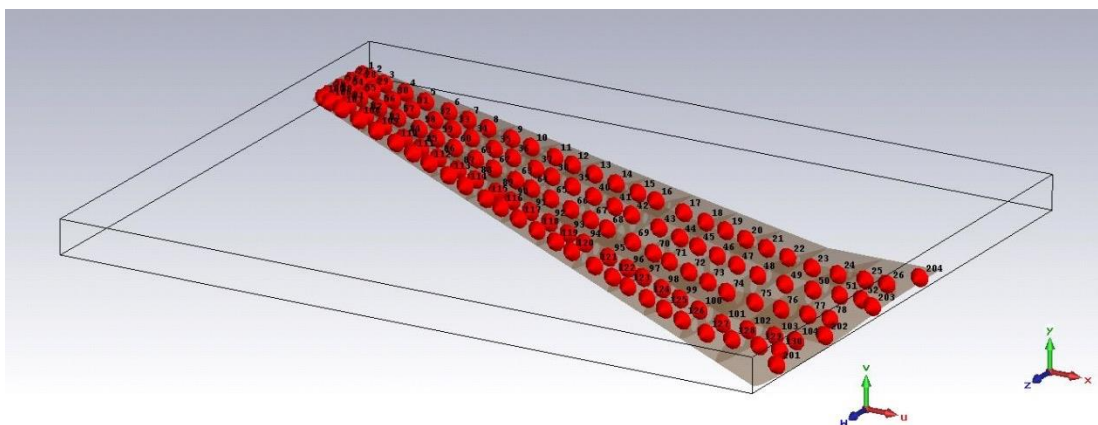


Figure 24: Node deployment, discrete ports.

Figure 24 shows the position of the 130 deployed nodes with numbering.

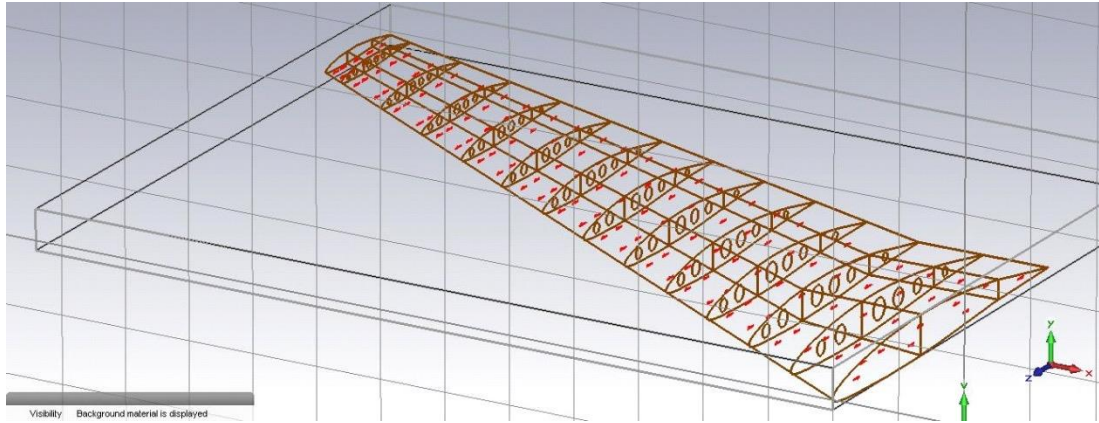


Figure 25: Ribs and inner structure of the wing.

Figure 25 shows the inner structure of the wing model in the form of ribs.

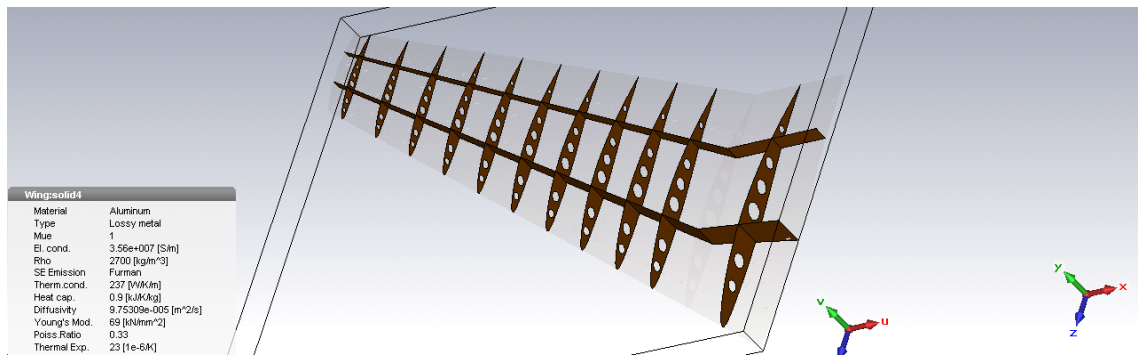


Figure 26: Aircraft realistic wing model with the inner structure.

Finally, Figure 26 presents the inner structure of the realistic aircraft wing model.

3.7 Summary and Conclusion

This chapter has described the spiral methodology adopted in this study and the design process of three wing models (the NACA64A410 model, empty NACA64A410 model and empty prismatic model) using Gmesh and CATIA software. The justification of the design choices made as part of this methodology was presented in this chapter in order to assess the feasibility of using ZigBee for SHM applications in aircraft environments. The meshing of the three selected wing models helped to identify the inner structure, various dimensions and the inner shape of the three selected wing models. With regard to the composition of the inner structure, aluminium and CFC were considered in this chapter in order to identify their impact on radio signal attenuation. In

the same way, with regard to the challenges involved in designing a WSN for an aircraft wing model, the methodology modelled a sensor network and made decisions regarding a number of nodes, base stations, rib holes and the number of simulations for topology control and optimization of the sensor networks. Using these design methodology choices, the simulation set-ups and studies were carried out using the required software. The simulation results obtained by putting these methodological choices into practice are presented in the following chapters of this thesis.

Chapter 4: Antenna position on an aircraft wing

4.1 Overview

The methodology chapter detailed the study and design process of three wing models (the NACA64A410 model, the empty NACA64A410 model and the empty prismatic model) using Gmesh software. The meshing of the three chosen wing models helped in identifying the inner structure, various dimensions and the inner shape of the wing model. Based on this information, the different positions on which to place the antenna on the three aircraft wing models have been identified in this chapter as 1/4, 1/2, 3/4 and the tip of the wing. The identification of these four different antenna positions and the simulation of the three designed aircraft wing models were essential in order to determine the effect of the position of the antenna on the aircraft wing on the efficiency of ZigBee communication signals. Gmesh and CATIA software packages were used in this chapter to simulate the three aircraft wing models with four antenna positions. The simulation results obtained are presented in this chapter between the frequency of 100MHz and 5GHz; two transceivers were considered, one of which was fixed and the other movable. The critical analysis of these simulated results is very important in order to identify the effect of the position of the antenna on the aircraft wing on the communication efficiency of ZigBee. This critical analysis of the simulation results obtained from Gmesh and CATIA software did not identify any considerable impact of wing shape on antenna position between the frequency range 2.4GHz and 2.45GHz. When the frequency level is higher than the value of 2.6 GHz, a large difference was identified on coupling at the placement of the antenna near the 1/2 position of the wing. This critical analysis also identified the influence of the wing's inner structure, with the highest coupling difference of 30dB being present at a frequency of nearly 2.465GHz, when there is a large difference between the first and second transceiver antennas.

4.2 Positioning of Antenna

For all the selected test cases, one antenna model was utilized. The selected antenna model consists of the following characteristics:

- Vertical orientation;
- Every antenna acts like the transceiver;
- The bottom edge of the antenna is placed at the lower level of the wing plane;
- An impedance of 50 ohms;
- Input provision at the center of the antenna having 1 mW value.

Based on previous studies in the literature [49], [161], the propagation of radio waves and radio wave signal attenuation were identified as being affected by the antenna position. Therefore, to assess the feasibility of using ZigBee for SHM applications in an aircraft environment, the impact of antenna positions on ZigBee communication was investigated in this research. Dipole antenna makes it conceivable to get the proper simulation. The reason is that the dipole antenna is placed more in direction of the metallic bottom. It permits to quantify in the two cases (of higher and lower frequencies). Hence, for every simulation, two transceivers were used. Using the different dimensions of NACA64A410 wing model as identified in the methodology (Figure 12) and the inner structure of the three wing models (the NACA64A410 model, the empty NACA64A410 model and the empty prismatic model) (Figures 13, 14 and 15) through meshing, four different positions were identified in which to place each of these four transceivers. In other words, based on the identified inner structure, various dimensions, and the inner shape of the wing models, the different positions on which to place the antenna on the three aircraft wing models were identified in this chapter as 1/4, 1/2, 3/4 and the tip of the wing. Therefore, the selection of these positions for the transceiver greatly helped in achieving coverage the complete wing in the three aircraft models considered. The effect of the antenna position on radio wave propagation was identified by following the steps below:

- Placing the first transceiver near to the wing root, which acts as the control device for the complete aircraft cabin;
- Placing the second transceiver at the 1/4 of the wing length;

- Run the simulation;
- Placing the second transceiver at the 1/2 of the wing length;
- Run the simulation;
- Placing the second transceiver at the 3/4 of the wing length;
- Run the simulation;
- Placing the second transceiver near to the tip of the wing;
- Run the simulation.

Repetition of this procedure was done for different radio wave propagation environments. In addition, these steps were repeated for all the three wing models. This process therefore helped identify the effect of wing structure and shape on the changing position of the antenna.

4.3 Antenna position on three wings

- **Realistic NACA64A410 Wing Model**

Port 1 – Fixed Transceiver

Surface current distribution @ 2,405GHz – position 1 – 1/4 wing

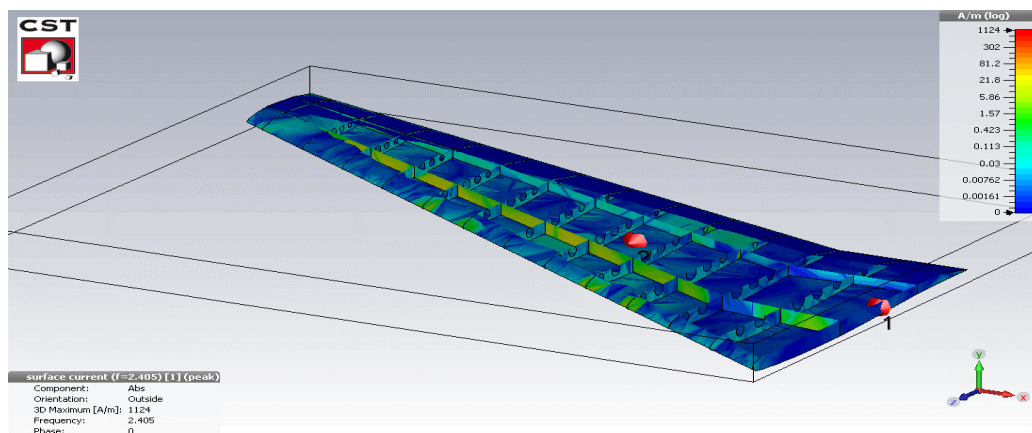


Figure 27: Surface current distribution @ 2,405GHz 1/4 wing – fixed transceiver.

The CST simulation result of the wing when the antenna is placed at the 1/4 length of the wing is shown in Figure 27 above.

Port 2 – Movable Transceiver

Surface current distribution @ 2,405GHz – position 1 – 1/4 wing

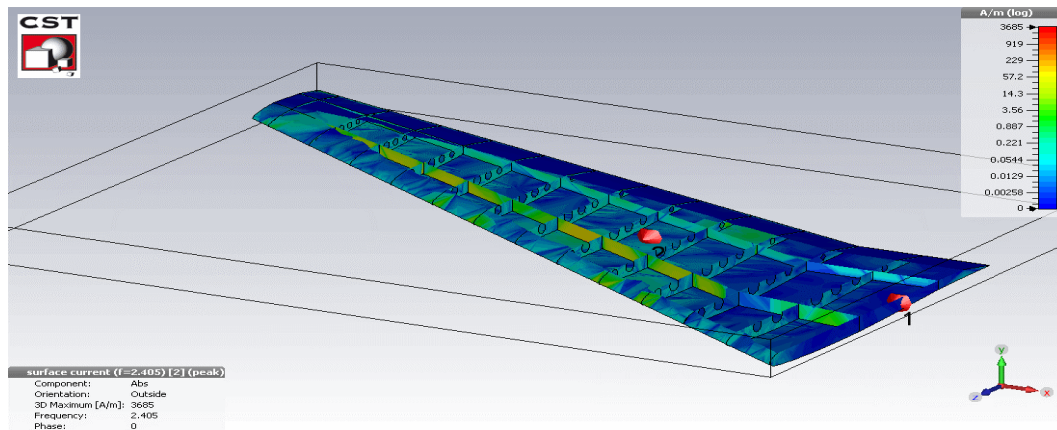


Figure 28: Surface current distribution @ 2,405GHz 1/4wing –moveable transceiver.

After the CST simulation result of the wing when the antenna is placed at the 1/4 length of the wing, the placement of a fixed transceiver was made as shown in Figure 28.

For the Realistic NACA64A410 Wing Model, two transceivers (one fixed and the other moveable) were initially placed. The movable transceiver was placed at the 1/4 position of the wing length, as shown in Figures 27 and 28, with the other fixed at the wing root position.

Port1 – Fixed Transceiver

Surface current distribution @ 2,405GHz – position 2 – 1/2 wing

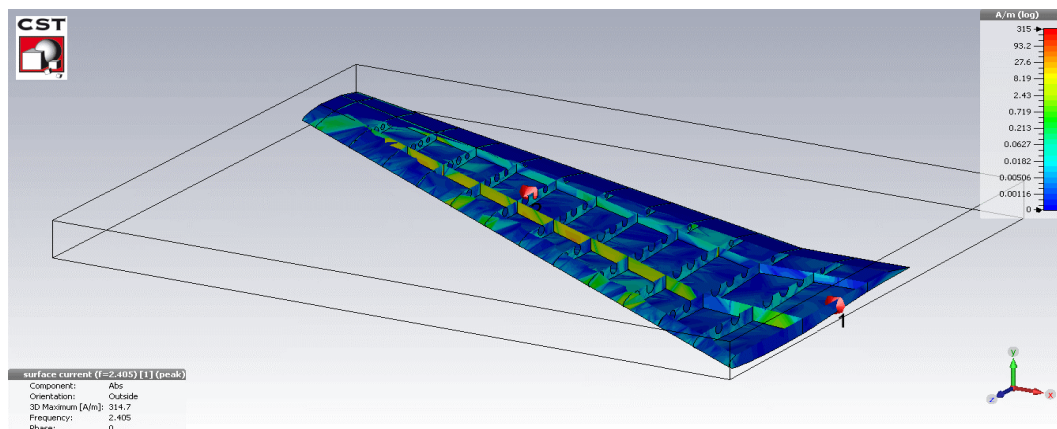


Figure 29: Surface current distribution @ 2,405GHz 1/2 wing –fixed transceiver.

The location of the transceiver is movable in this wing model, with a surface current distribution @ 2,405GHz – position 2 – 1/2 wing, as shown in Figure 29.

Port2 – Movable Transceiver

Surface current distribution @ 2,405GHz – position 1 – 1/2 wing

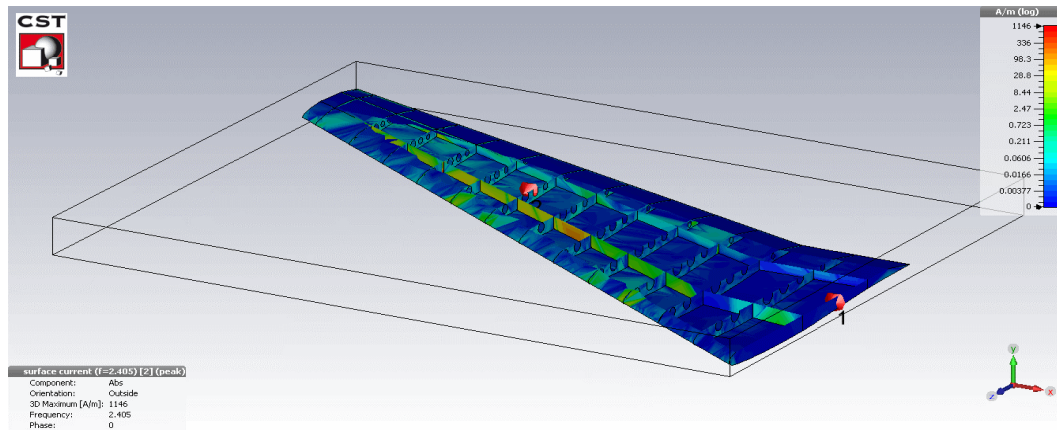


Figure 30: Surface current distribution @ 2,405GHz 1/2 wing –movable transceiver.

At the same frequency range of 2.45 GHz, the transceiver is fixed at the position of 1/2 of the wing length as indicated above.

For the Realistic NACA64A410 Wing Model, two transceivers (one fixed and one movable) were placed. The movable transceiver was placed at the 1/2 position of the wing length, as shown in Figures 29 and 30, with the other fixed at the wing root position.

Port1 – Fixed Transceiver

Surface current distribution @ 2,405GHz – position 1 – 3/4 wing

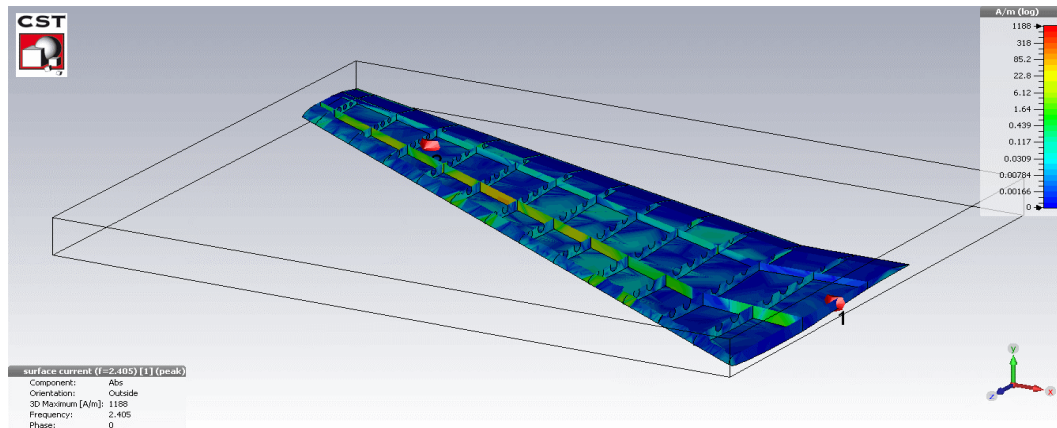


Figure 31: Surface current distribution @ 2,405GHz 3/4wing – fixed transceiver.

The antenna placed on the 3/4 of the wing length was also fixed at the given position.

Port 2 – Moveable Transceiver

Surface current distribution @ 2,405GHz – position 1 – 3/4 wing

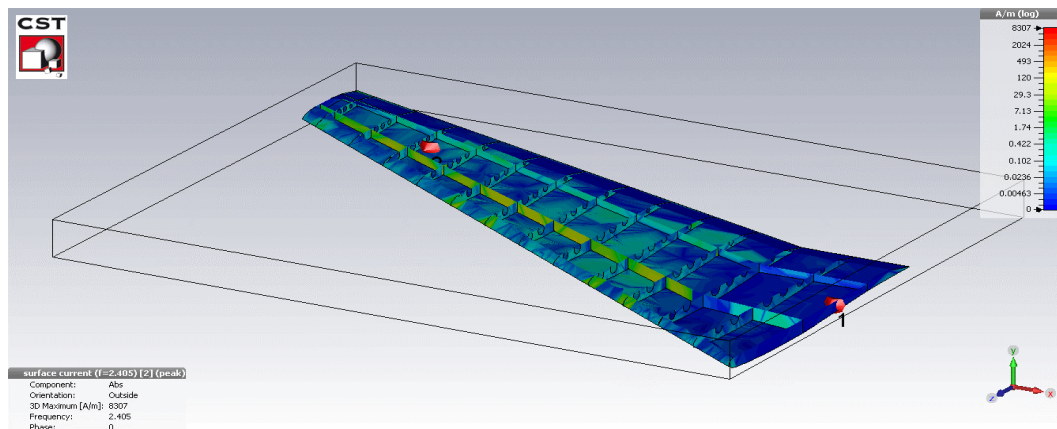


Figure 32: Surface current distribution @ 2,405GHz 3/4wing – moveable transceiver.

Here the moveable transceiver was placed at the 3/4 length of the wing. The surface current distribution was @ 2,405GHz – position 3 – 3/4 wing.

For the Realistic NACA64A410 Wing Model, two transceivers (one fixed and one movable) were placed. The movable transceiver was placed at the $\frac{3}{4}$ position of the wing length, as shown in Figures 31 and 32, and the other fixed at the wing root position.

Port 1 – Fixed Transceiver

Surface current distribution @ 2,405GHz – position 1 – 4/4 wing

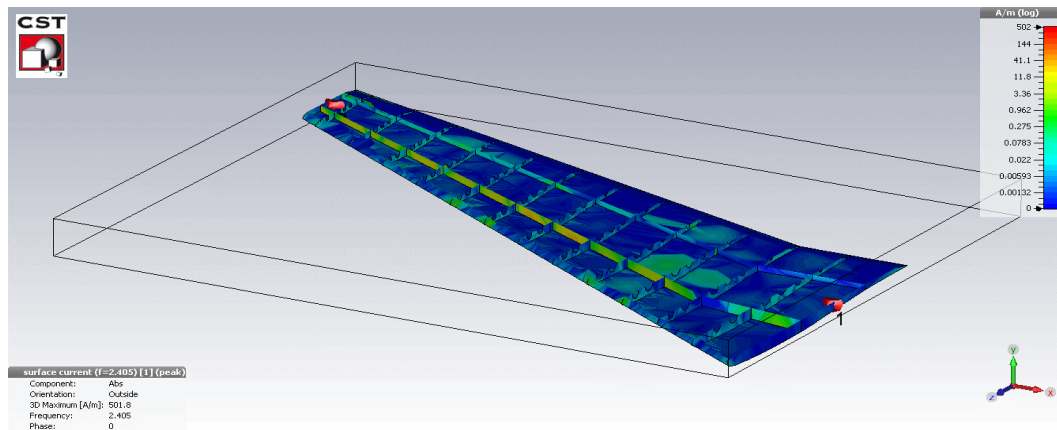


Figure 33: Surface current distribution @ 2,405GHz tip of wing – fixed transceiver.

The fixed transceiver was placed at the tip of the wing, and the simulated wing model is shown above.

Port2 – Moveable Transceiver

Surface current distribution @ 2,405GHz – position 1 – 4/4 wing

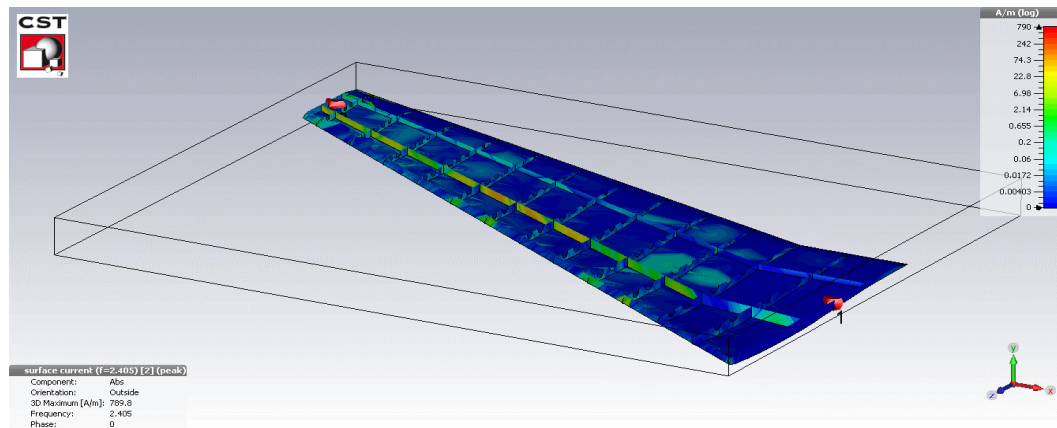


Figure 34: Surface current distribution @ 2,405GHz tip of wing – moveable transceiver.

The moveable transceiver was placed at the 4/4 the length of the wing and the simulated wing model is shown above. Surface current distribution @ 2,405GHz – position 4 – 4/4 wing (tip of the wing).

For the Realistic NACA64A410 Wing Model, two transceivers (one fixed and one movable) were placed. The movable transceiver was placed at the 4/4 position of the wing length, as shown in Figures 33 and 34, and the fixed one was placed at the wing root position.

- **Empty NACA64A410 Wing Model**

Surface current distribution @ 2,405GHz – pos1 – ¼ wing

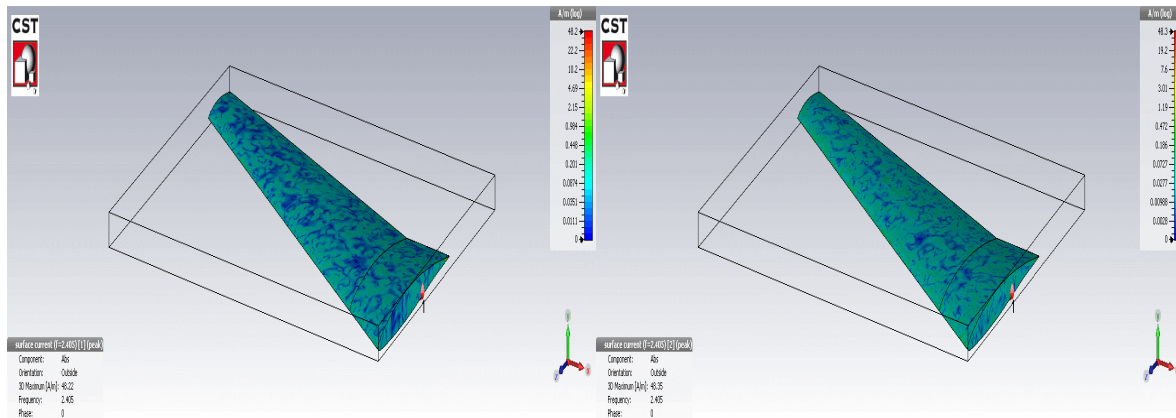


Figure 35: Surface current distribution @ 2,405GHz –1/4 wing - fixed and moveable.

Port 1 – Fixed Transceiver

Port 2 – Moveable Transceiver

For the Empty NACA64A410 Wing Model, two transceivers (one fixed and one movable) were placed. The moveable transceiver was placed at the 1/4 position of the wing length, as shown in Figure 35, with the other fixed at the wing root position. For the frequency of 2.45GHz, the antenna was placed at the 1/4 length of the wing, and the simulations of this placement are shown above.

Surface current distribution @ 2,405GHz – position 2 – 1/2 wing

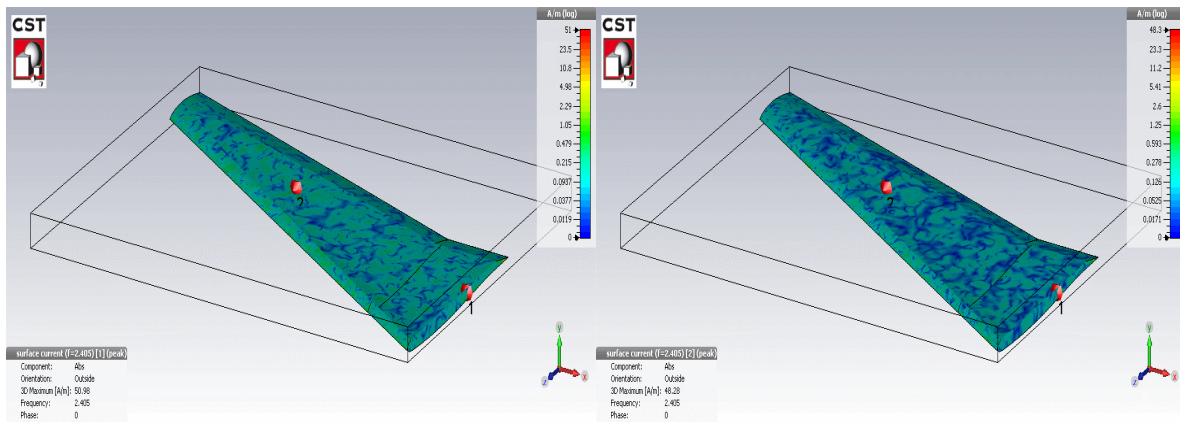


Figure 36: Surface current distribution @ 2,405GHz –1/2 wing - fixed and moveable.

Port 1 – Fixed Transceiver

Port 2 – Moveable Transceiver

For the Empty NACA64A410 Wing Model, two transceivers (one fixed and one movable) were placed. The movable transceiver was placed at the 1/2 position of the wing length, as shown in Figure 36, with the other fixed at the wing root position. For the frequency of 2.45GHz, the antenna was placed at the ¼ length of the wing, and the simulations of this placement are shown above. Both the fixed transceiver and the movable transceiver were placed at the 1/2 length of the wing.

Surface current distribution @ 2,405GHz – position 3 – 3/4wing

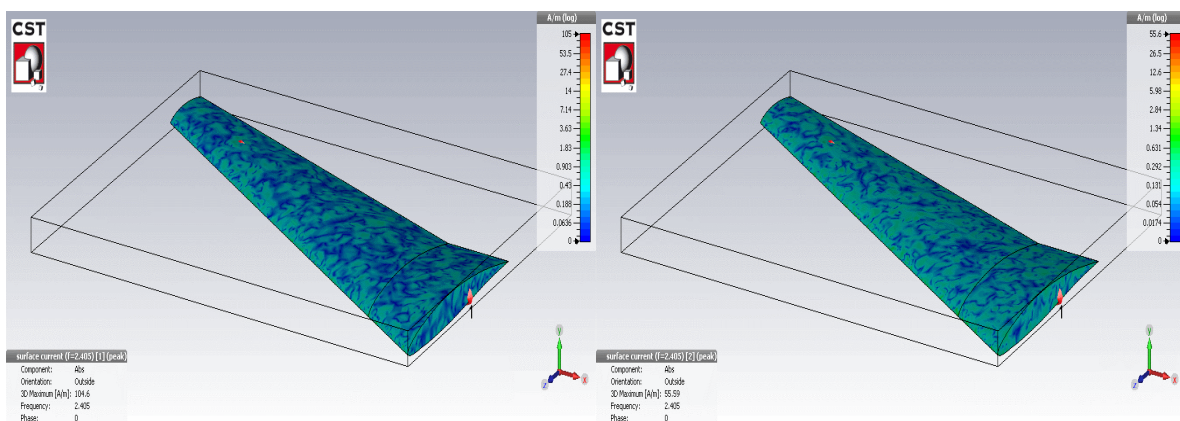


Figure 37: Surface current distribution @ 2,405GHz –3/4 wing - fixed and moveable.

Port 1 – Fixed Transceiver

Port 2 – Moveable Transceiver

For the Empty NACA64A410 Wing Model, two transceivers (one fixed and one moveable) were placed. The moveable transceiver was placed at the 3/4 position of the wing length, as shown in Figure 37, with the other fixed at the wing root position. For the frequency of 2.45GHz, the antenna was placed at the 1/4 length of the wing, and the simulations of this placement are shown above. The fixed transceiver and the movable transceiver were placed at the 3/4 length of the aeroplane wing, as shown above.

Surface current distribution @ 2,405GHz – position 4 – 4/4 wing (tip of the wing)

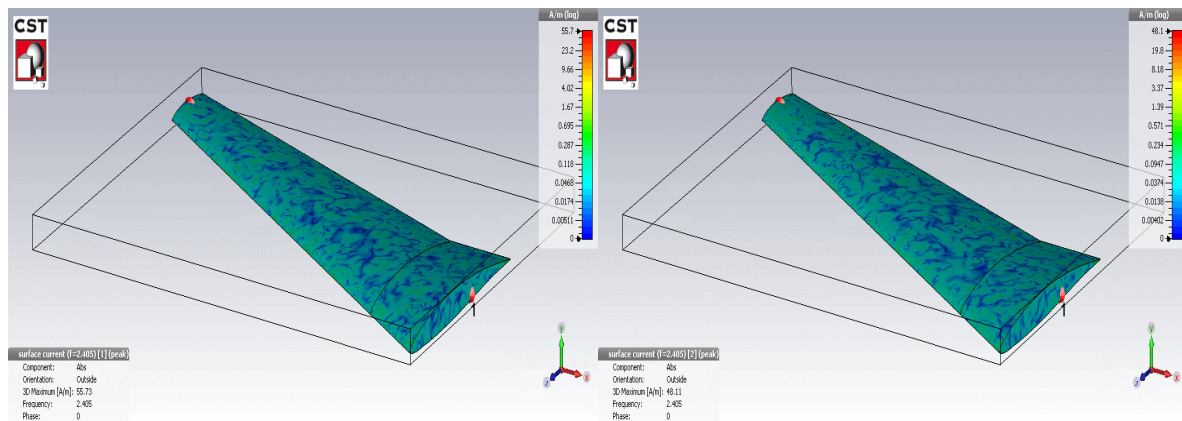


Figure 38: Surface current distribution @ 2,405GHz – tip of wing - fixed and moveable.

Port1 – Fixed Transceiver

Port2 – Moveable Transceiver

For the Empty NACA64A410 Wing Model, two transceivers (one fixed and one moveable) were placed. The moveable transceiver was placed at the 4/4 position of the wing length, as shown in Figure 38, with the other fixed at the wing root position. For the frequency of 2.45GHz, the antenna was placed at the 4/4 length of the wing, and the simulations of this placement are shown above. In this empty wing model, the placement of the antenna is now at the tip of the wing, and can either be fixed or moved.

- **Prismatic Wing Model**

Surface current distribution @ 2,405GHz – pos1 – 1/4 wing

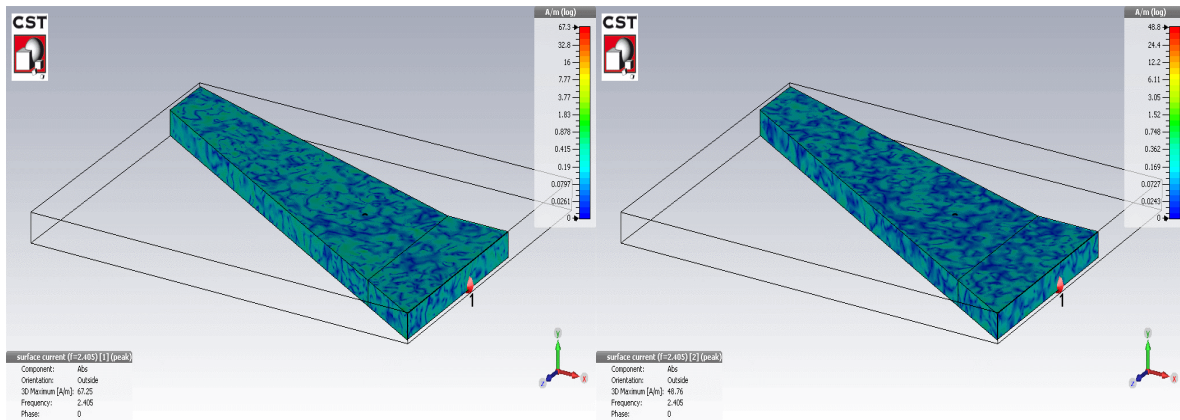


Figure 39: Surface current distribution @ 2,405GHz – 1/4wing - fixed and movable.

Port 1 – Fixed Transceiver

Port 2 – Moveable Transceiver

For the Prismatic Wing Model, two transceivers (one fixed and one moveable) were placed. The moveable transceiver was placed at the 1/4 position of the wing length, as shown in Figure 39, with other one fixed at the wing root position. For the frequency of 2.45GHz, the antenna was placed at the 1/4 length of the wing, and the simulations of this placement are shown above.

Surface current distribution @ 2,405GHz – position 2 – 1/2 wing

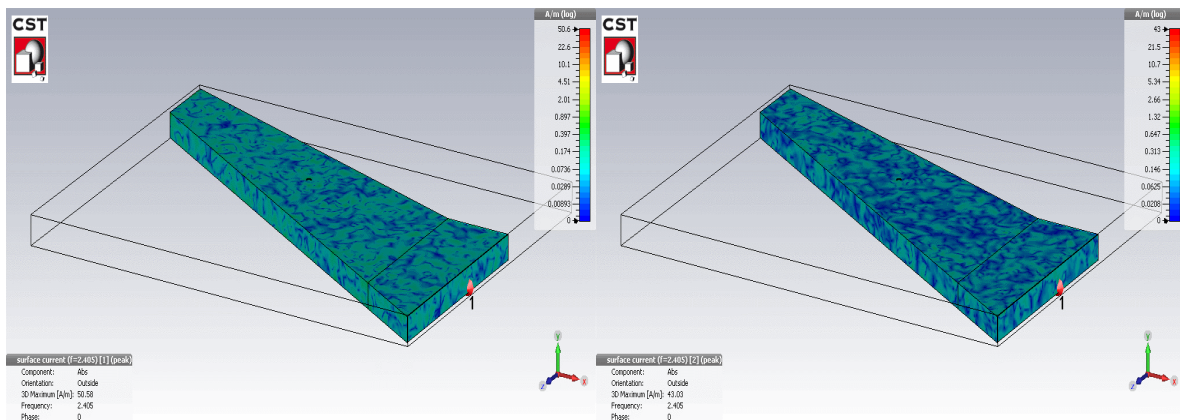


Figure 40: Surface current distribution @ 2,405GHz –1/2 wing - fixed and movable.

Port1 – Fixed Transceiver

Port2 – Moveable Transceiver

For the Prismatic Wing Model, two transceivers (one fixed and the other moveable) were placed. The moveable transceiver was placed at the 1/2 position of the wing length, as shown in Figure 40, with the other fixed at the wing root position. For the frequency of 2.45GHz, the antenna was placed at the 1/2 length of the wing, and the simulations of this placement are shown above.

Surface current distribution @ 2,405GHz – position 3 – $\frac{3}{4}$ wing

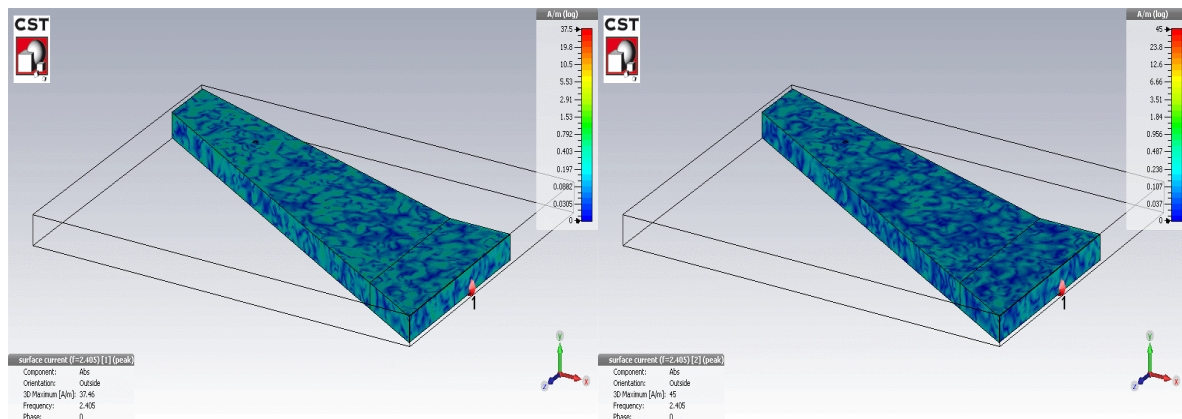


Figure 41: Surface current distribution @ 2,405GHz –3/4 wing - fixed and movable.

Port 1 – Fixed Transceiver

Port 2 – Moveable Transceiver

For the Prismatic Wing Model, two transceivers (one fixed and the other moveable) were placed. The moveable transceiver was placed at 3/4 position of the wing length, as shown in Figure 41, with the other fixed at the wing root position. For the frequency of 2.45GHz, the antenna was placed at the $\frac{1}{4}$ length of the wing, and the simulations of this placement are shown above. The surface current distribution when the antenna is placed at the $\frac{3}{4}$ length of the wing is indicated in the above screenshot.

Surface current distribution @ 2,405GHz – position 4 – 4/4 wing (tip of the wing)

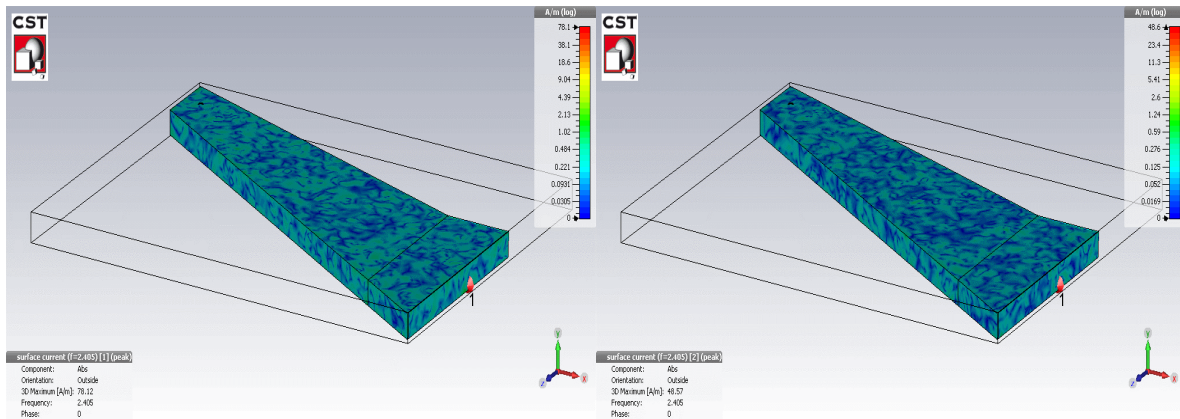


Figure 42: Surface current distribution @ 2,405GHz – tip of wing - fixed and moveable.

Port 1 – Fixed Transceiver

Port 2 – Moveable Transceiver

For the Prismatic Wing Model, two transceivers (one fixed and one moveable) were placed. The moveable transceiver was placed at 4/4 position of the wing length, as shown in Figure 42, with the other fixed at the wing root position. For the frequency of 2.45GHz, the antenna was placed at the 4/4 length of the wing, and the simulations of this placement are shown above. The antenna position is now moved to the tip of the wing and the surface current distribution is shown in the above screenshot.

4.4 Simulation of Aircraft Wing Models

Software requirements of the simulation

The simulations of this work were run on a desktop computer with the following specifications:

- Intel quad-core processor;
- 16GB of RAM;
- 1TB of hard drive;
- Windows 7 operating system.

CST (Computer Simulation Technology) software offers a highly accurate and efficient solution

for electromagnetic design and analysis. This CST offers a user-friendly based three-dimensional simulation software that allows users to select the appropriate technique for the design and optimization of the devices present in the wide frequency range. The simulation was run for all three wing models of the aircraft with the help of the different test cases. These test cases were performed by placing the antennas on different positions simultaneously. The mesh file that was initially created was later converted to a simulation file using the CST software.

- **Simulation Parameters**

In this project, during the simulation process two different test cases were performed in order to perform the following:

- Identification of the effect of the antenna positions on the performance of ZigBee;
- Investigating the performance of the ZigBee wireless sensor network on the sensors present in the aircraft engines.

The test case numbers initially used in this simulation were slowly increased to four for all three different wing models. In all these test cases, different antenna positions were used on the aircraft wing in order to identify the positions that could offer better ZigBee performance. All these test cases were performed with the same frequency range of 0 to 5GHz. At this frequency itself, all three wing models were simulated using the CST software.

- **Assumptions of Simulation**

In this simulation, some assumptions were considered. To run the simulations, one of the environments considered was free space-based radio wave propagation. During the operation of the wing structures, several types of the medium will be present, namely air, lubricants and fuel [16]. All these different types of the medium will have a high impact on radio wave propagation. To minimize the effect of this medium on radio wave propagation, the free space medium was considered in this project. The materials used for the external and internal surface models were considered to be metallic for all the wings. In this simulation, several parameters were considered in order to minimize the effect of the different materials, such as composites and

plastics, on electromagnetic radiation. Selecting only one metallic material with the default level of conductivity significantly reduces the influence level.

4.5 Presentation of the Results

After running the simulation, the S-parameter was estimated for the different positions of the antenna on the different models of the wing. In this section, each wing model is considered, and the differential positioning of the antenna was carried out in order to estimate the S-parameter. In addition, the effect of the wing shape and the inner structure of the wing on the antenna position are identified in this section. Figure 43 presents the S21 parameter value with a change in the antenna position in the three wing models considered in this research. Parameter S21 magnitude presents the coupling that is present between the two ports of the antennas. Hence this S21 parameter specifies the quality of the connection that is present between the antennas placed on the simulated aircraft wing models.

- **Realistic NACA64A410 Wing Model**

Frequency: 100MHz to 5GHz

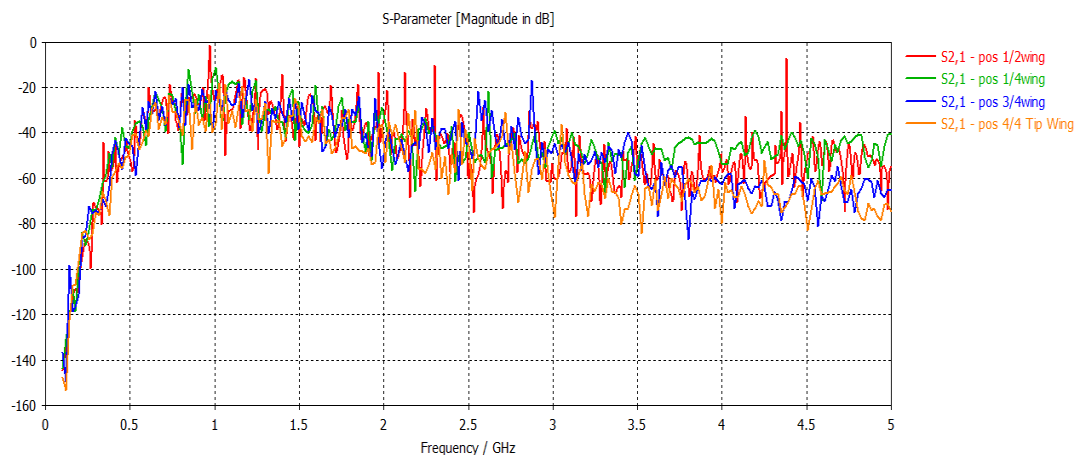


Figure 43: Realistic NACA64A410 Wing Model: 100MHz to 5GHz.

The above graph presents the results for the realistic wing model between the frequency ranges of 100 MHz to 5 GHz. In this model, the second transceiver is placed on four different positions on the wing, and the value of the S21 parameter for each case is identified. Initially, the value of

the S21 parameter remained the same, but later changed slightly. When the second transceiver was placed at 1/4 wing length, the value of the S21 parameter increased the minimum value of ZigBee SNR. The characteristic feature obtained from this result is the presence of the operational ISM band related to ZigBee between the frequency ranges of 100 MHz to 5GHz.

Frequency: 2.4GHz to 2.48 GHz

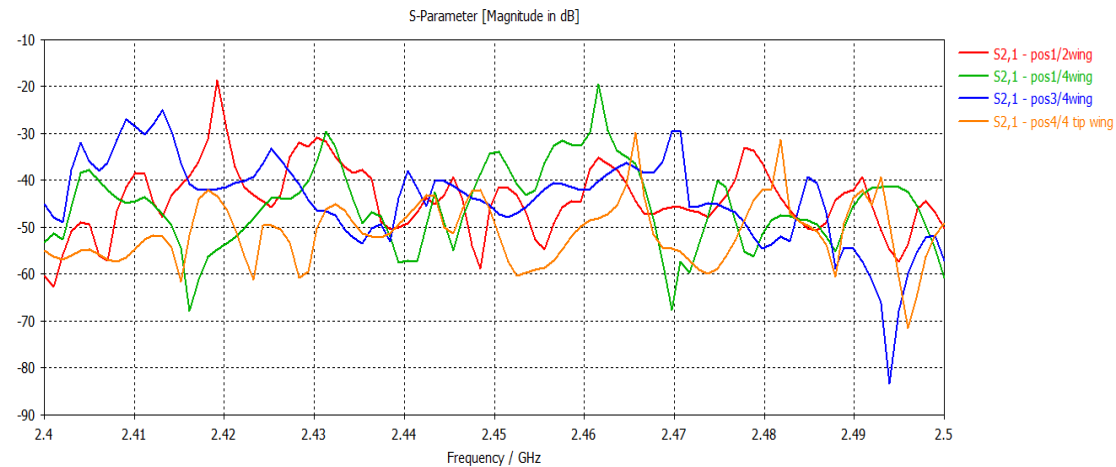


Figure 44: Realistic NACA64A410 Wing Model: 2.4GHz to 2.5GHz.

The other characteristic obtained from the estimation of the S21 parameter is the presence of the cut-off range of the frequency band in the range of 100MHz to 5GHz, which is 2.4- 2.5GHz. The frequency range changed from 2.4 GHz to 2.5GHz for the realistic wing model. The value of the S21 parameter between this frequency range was identified for all the four different positions of the antenna on the wing. The changes in the value of the S21 parameter can be easily identified in this frequency range. When the transceiver was placed at 3/4 of the wing, the S21 parameter value initially increased before undergoing a steep decrease between 2.49 and 2.5. From the simulations, it was identified that the coupling existing between the transceivers with the frequency range of 2.4- 2.5GHz was significantly low, which is the typical minimum value for the ZigBee SNR (Signal to Noise Ratio). This reduced the performance of ZigBee, and the data transmitted between the antennas was delivered at 2.49GHz.

- **Empty NACA64A410 Wing Model**

The second model, the empty wing model, was simulated by placing the antenna at four different positions of the wing. **Frequency: 100MHz to 5GHz.**

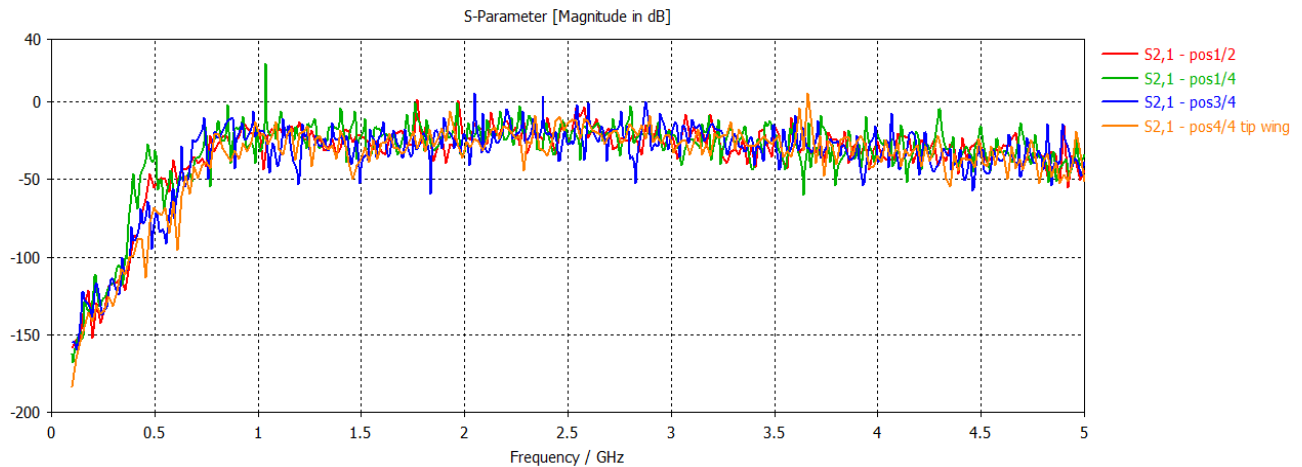


Figure 45: Empty NACA64A410 Wing Model: Frequency: 100MHz to 5GHz.

The CST results for the empty wing at the frequency range of 100MHz to 5GHz is shown above. Between the frequency range of 2.4GHz to 2.5GHz, there are variations between these two results in terms of the S21 parameter values. However, the fluctuations were identified as being similar for all the different positions in the wing, as shown above. Estimation of the S21 parameter helped identify the presence of the cut-off range of the frequency band between the frequency range of 100MHz and 5GHz as 2.4- 2.5GHz.

Frequency: 2.4 GHz to 2.5GHz

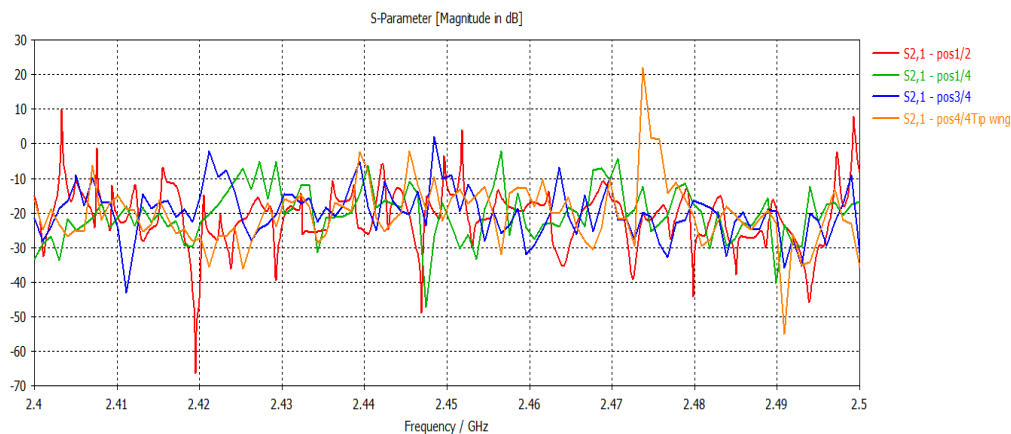


Figure 46: Empty NACA64A410 Wing Model: Frequency: 2.4GHz to 2.5GHz

The frequency range 2.4GHz to 2.5GHz is considered, and the variations in the S21 parameter value are shown alongside some variations in the parameter value. When the second transceiver was placed at the 1/4 positions of the wing, the value of the S21 parameter increased drastically to between 2.47 and 2.48 GHz. At 2.42GHz, the value of the S21 parameter decreased when the second transceiver was placed at half of the wing positions. From the simulations, it was identified that the coupling existing between the transceivers with the frequency range of 2.4 - 2.5GHz is significantly low, which is the typical minimum value for the ZigBee SNR (Signal to Noise Ratio). This lowered the performance of ZigBee, and the data transmitted between the antennas was delivered at 2.42GHz.

- **Prismatic Wing Model**

The third wing model is the prismatic wing model, in which the antenna was placed at four different positions on the wing to identify the effect of these positions on the S21 parameter.

Frequency: 100MHz to 5GHz

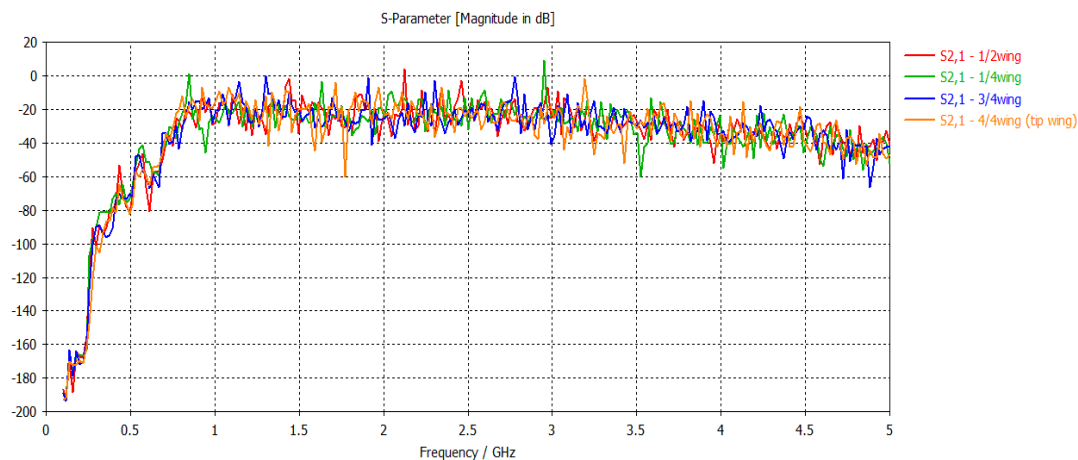


Figure 47: Prismatic Wing Model: Frequency: 100MHz to 5GHz.

The value of the S21 parameter between the frequencies of 100 MHz to 5 GHz is shown above. The value of the S21 parameter showed considerable similarity between all the different positions of the second transceiver. Estimation of the S21 parameter helped identify the presence of the cut-off range of the frequency band as 2.4-2.5GHz, which is within the frequency range of 100MHz and 5GHz.

Frequency: 2.4 GHz to 2.5 GHz

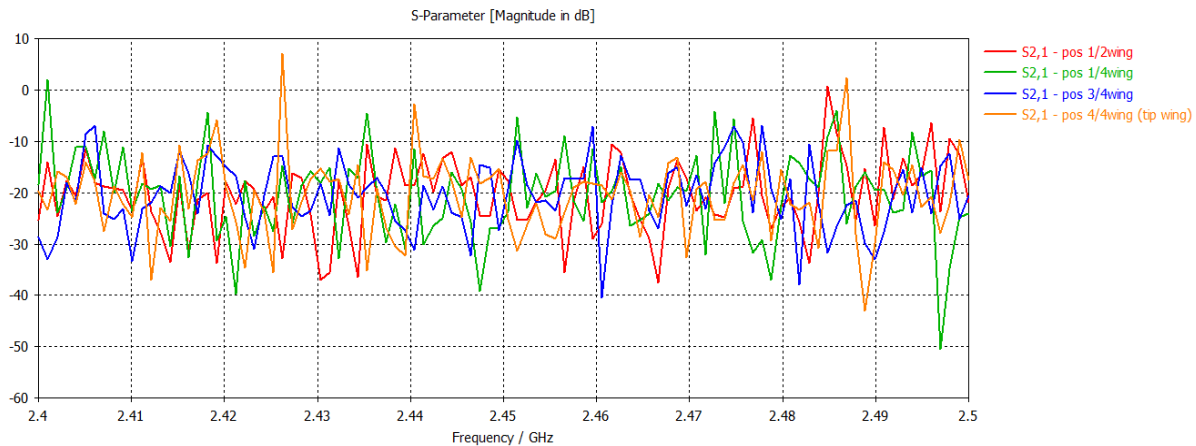


Figure 48: Prismatic Wing Model: Frequency: 2.4 GHz to 2.5GHz.

The variations of the S21 parameter between the frequency range 2.4GHz to 2.5GHz is shown in the above graph. The variations for all the different positions of the antenna are given above. Between the range of 2.48GHz and 2.49 GHz, the positions at 1/4th of the wing and 1/2nd of the wing underwent a steep increase. Between 2.49 and 2.5 GHz the S21 parameter value decreased when the second transceiver was placed at the 1/4 position of the wing. From the simulations, it was identified that the coupling existing between the transceivers with the frequency range of 2.4-2.5GHz is significantly low, which is the typical minimum value for the ZigBee SNR (Signal to Noise Ratio). This meant that the performance of the ZigBee was reduced, and the data transmitted between the antennas was delivered at 2.48 GHz.

4.6 Influence of wing shape and inner structure

The analysis of the different antenna positions on the wing shows that it has a considerable impact on radio wave propagation. In particular, the comparison of the realistic and prismatic wing models shows the difference with respect to coupling between the transceivers at different positions of the antenna. This is based on the theory that the signal strength between the antennas should be high when they are closer and lower when they are further apart. The simulation suggests that the coupling that is present between the transceivers is high when they are far away. The main reason for this effect is the high reflection and resonance caused by the ribs and also based on the shape of the wing.

Table 10: Variations in S_{21} parameter in various transceiver positions.

Wing Model	Second Transceiver Position	S_{21} Value [dB]
Realistic NACA64A410	$\frac{1}{4}$ Wing Length	-42
	$\frac{1}{2}$ Wing Length	-35
	$\frac{3}{4}$ Wing Length	-47
	Wing Tip	-50
Empty NACA64A410	$\frac{1}{4}$ Wing Length	-14
	$\frac{1}{2}$ Wing Length	-20
	$\frac{3}{4}$ Wing Length	-11
	Wing Tip	-20
Prismatic Model	$\frac{1}{4}$ Wing Length	-17
	$\frac{1}{2}$ Wing Length	-26
	$\frac{3}{4}$ Wing Length	-25
	Wing Tip	-22

In the simulation the lowest value of coupling -82dB is when the second transceiver is placed at the $\frac{3}{4}$ length of the wing in the realistic wing model at the frequency of 2.495 GHz. Another lowest value is at the $\frac{3}{4}$ length of the wing at nearly 2.485 GHz, which is -60 dB. In the case of the prismatic model, the lowest coupling value was obtained when the second transceiver was placed at the $\frac{1}{4}$ length of the wing. In case of the first ZigBee channel, the best coupling value was -30dB and the worst value -63dB, which was obtained between the antennas that are present at $\frac{3}{4}$ of the wing length in the prismatic wing model. This is because of the lower levels of resonance and reflection when compared with the highly complex shapes. The comparison of S_{21} parameter values for the different position of the antenna in different wing models is shown in the above table. In the case of each wing model, three positions were selected for placement of the transmitter. For all these three positions, the value of S_{21} parameter is calculated and given in decibels (dB).

4.7 Influence of the wing shape

With regard to wing length, the initial analysis regarding the coupling of two antennas is the identification of the influence of the shape of the wing on performance. The figure below shows the comparison of the value of S_{21} parameter for different models of the wing, namely the empty

model, prismatic model and realistic model.

Position: $\frac{1}{4}$ length of the wing

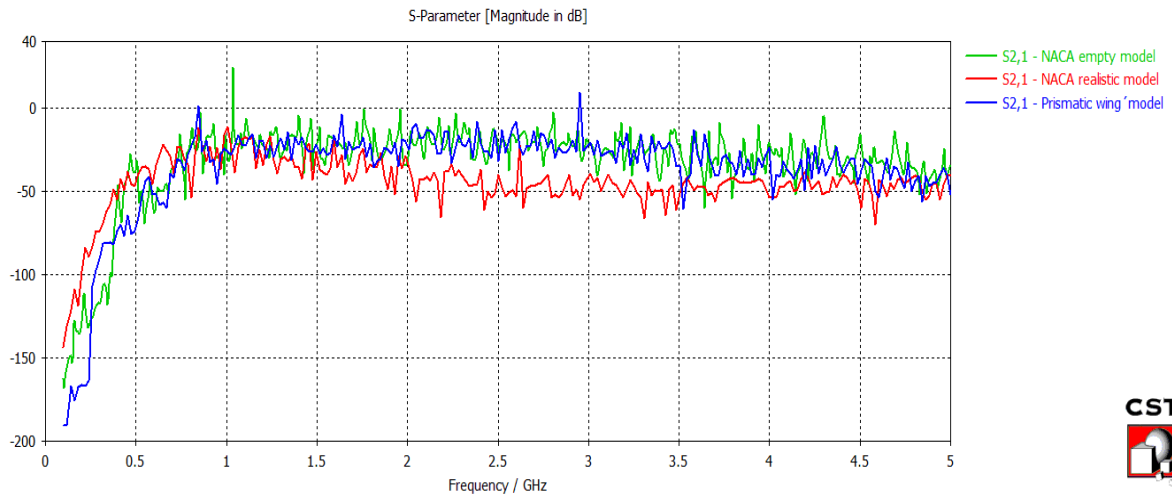


Figure 49: Effect of three wing models on wing shape: 100MHz to 5GHz: 2nd transceiver position at $\frac{1}{4}$ wing length.

The CST results were compared for the three wing models when the second transceiver was placed at the $\frac{1}{4}$ length of the wing length. The empty wing model and the prismatic wing model showed similar results, with the major difference of the realistic model. Between 2GHz and 3.5 GHz, the S21 parameter value of the realistic model decreased when compared to the other two wing models.

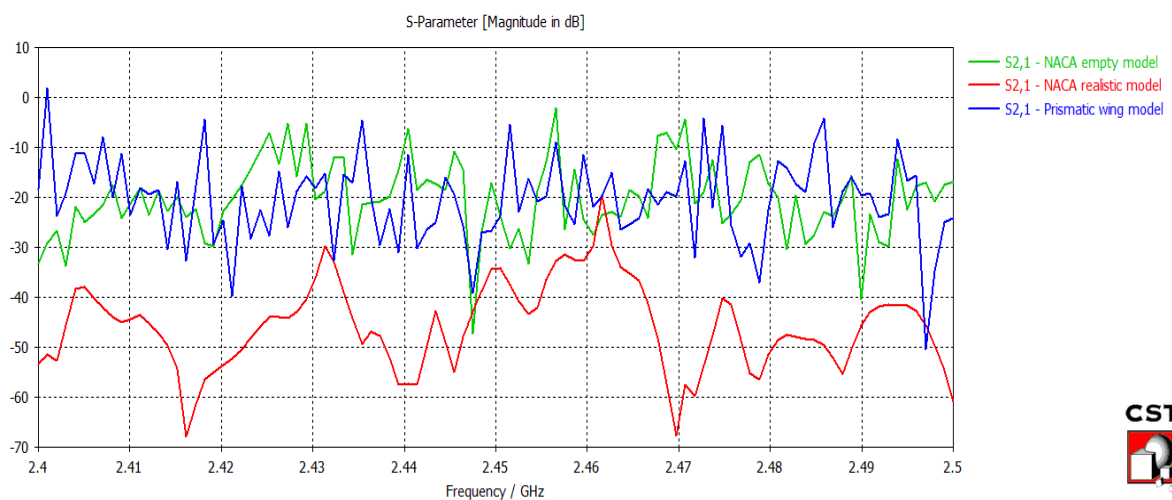


Figure 50: Effect on wing shape of three wing models: 2.4GHz to 2.5GHz: 2nd transceiver position at $\frac{1}{4}$ wing length.

The above figure represents the comparison of the three wing models. The wing inner structure has ribs that consist of different holes and spars. The presence of these structures has a considerable impact on the coupling that exists between the antennas. These structures can result in the formation of resonance effects, along with the reflections from these surfaces. In such a case, the placement of the transceiver is done out of site and the differentiation of radio waves is done from the holes to the ribs. The above graph represents a comparison of the S21 parameter for the three wing models, and the effect of the wing shape and inner structure on the performance of ZigBee.

Position: $\frac{1}{2}$ length of the wing

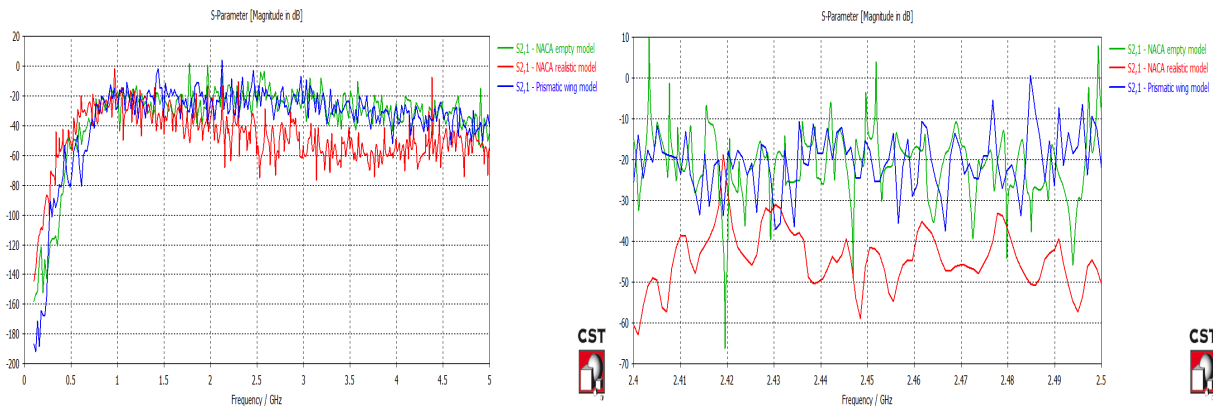


Figure 51: Influence of wing shape and inner structure – 2nd transceiver positions at $\frac{1}{2}$ wing length.

The second transceiver was placed at the $\frac{1}{2}$ position of the wing. At this position, the effect of the shape and inner structure of the wing on the variation in the S21 parameter is shown in the above graph. In the realistic wing model, the S21 parameter value was considerably affected by the wing structure, but this effect was much lower for the empty wing model and the pragmatic wing model.

Position: $\frac{3}{4}$ length of the wing

The second transceiver was placed at the $\frac{3}{4}$ position of the wing. At this position, the effect of the shape and inner structure of the wing on the variation in the S21 parameter is shown in the above graph. In the realistic wing model, the S21 parameter value was considerably affected by the wing structure, but this effect was much lower for the empty wing model and the pragmatic wing model.

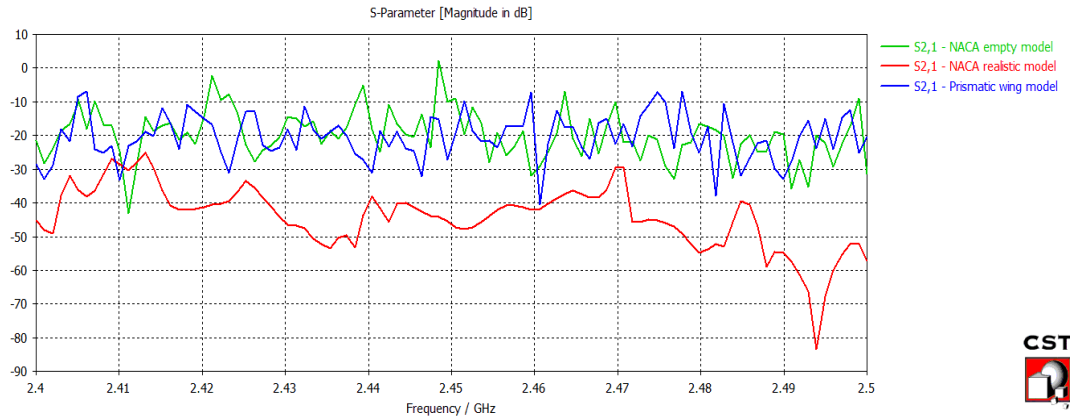


Figure 52: Influence of wing shape and inner structure – 2nd transceiver position at $\frac{1}{4}$ wing length: 2.4GHz to 2.5GHz.

The effect of the inner structure and shape of the wing on the value of the S21 parameter in the case of all three wing models is shown in the above graph. In the case of the realistic wing model, the S21 parameter value decreased, but maintained a constant value and did not undergo any changes for the empty wing model and the prismatic wing model.

Position: Close to wing tip

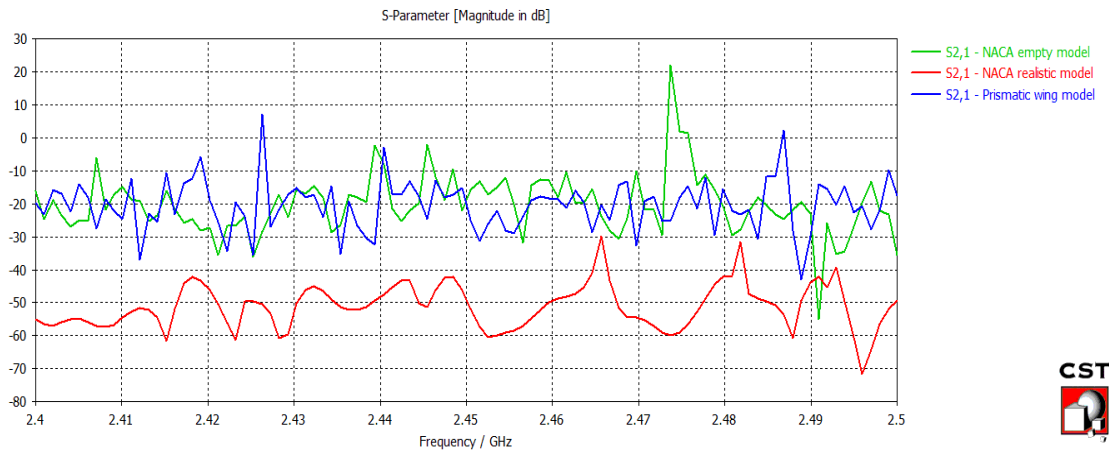


Figure 53: Influence of wing shape and inner structure – second transceiver close to wing tip: 2.4to 2.5GHz.

The inner structure and shape of the wing had a considerable impact on the S21 parameter value in the realistic wing model. However, whilst the S21 parameter value decreased for the realistic wing model, in the empty and prismatic wing models it did not undergo drastic changes.

4.8 Results of Analysis

The main result obtained from this case study is the presence of the rectangular shape caused by the presence of less coupling when compared to the real wing shape. The shape of the wing had more of an effect on resonance over radio wave propagation and also over the several reflections from the rounded shapes. There were no significant differences between the various nodes that coupled between the frequency range of 2.4GHz and 2.45GHz. For this particular range, the wing shape did not have a considerable impact on the positions of the antennas. When the frequency level was higher than the value of 2.6 GHz, a large difference in terms of coupling was observed when the antenna was placed near the $\frac{1}{2}$ position of the wing. The presence of these large differences clearly shows the main reason for the presence of the varying coupling between the different antennas. They occurred mainly on the higher part of the 2.4GHz of ZigBee. In both the realistic and prismatic wing models, there was an increase in coupling when the frequency increased in the ZigBee band. The graphs show that the most substantial coupling difference of 30dB was present when the second receiver was situated at the $\frac{3}{4}$ length of the wing. At the same time, the smallest coupling difference (5dB) occurred when the antenna was placed at half of the wing length. This is mainly because of the difference in the thickness of the wing along the its length.

With regard to the influence of wing inner structure, the highest coupling difference of 30dB was present at the frequency of nearly 2.465GHz when there was a large difference between the first and second transceiver. The presence of resonance by the wing's inner structure increases the coupling that is present between the nodes when compared to that of the empty wing model. In the case of the first ZigBee channel, the coupling difference exists between 7dB and 15dB, and is highly dependent on the antenna location. In this particular channel, the estimated values of the S21 parameter are lower for the realistic model when compared to the empty wing model. This is because of the presence of a local minimum related to the ZigBee band for the complete, tested range of frequency.

4.9 Summary and Conclusions

As part of assessing the feasibility of using ZigBee communications for SHM applications in an aircraft environment, the effect of antenna position on the efficiency of ZigBee signal communications has been identified in this chapter. In order to identify the effect of antenna position on the efficiency of ZigBee signal communications, three wing models, namely the NACA64A410 model, the empty NACA64A410 model and the empty prismatic model of the wing, were considered in this chapter. During the simulation of these three wing models using the Gmesh and CATIA software packages, the frequency range of 100MHz to 5 GHz was initially considered. A dedicated frequency of 2.4GHz to 2.5GHz was then considered in this chapter in order to identify the impact of the wing antenna position on the S21 parameter. Critical analysis of the CST results obtained identified the way in which aircraft wing shape and structure can affect the radio propagation signals used in ZigBee communication. This analysis showed that wing shape has a more significant influence on the resonance of ZigBee radio propagation signals than the inner structure of an aircraft wing. In both the realistic model and the prismatic wing model, an increase in coupling was identified when the frequency was increased in the ZigBee band. In the case of the wing's inner structure, this analysis identified the presence of higher resonance for the empty wing model when compared to the other wing structures that were considered. Having studied the different material structures, it is necessary to now examine the effect of the signal in these different materials in the next chapter.

Chapter 5: Simulation Results for the Effect of Structural Materials on Connectivity Control

5.1 Overview

In order to assess the feasibility of using ZigBee communication for SHM applications in an aircraft environment, this research aimed to investigate the effect of wing shape, inner structure, antenna position and wing composition on radio wave propagation. The previous chapter identified the effect of wing shape, inner structure and antenna position on the radio propagation signals of ZigBee networks. With regard to antenna position, the results showed the presence of changes in the S21 parameter of the aircraft wing between 2.4GHz and 2.5GHz based on the changing position of the antenna. The results in the previous chapter also showed the significant influence of wing shape on the resonance of ZigBee radio propagation signals compared to the inner structure of an aircraft wing.

In this chapter, the effect of the different structural materials used in aircraft wings on the quality of the connection between the two antennas, and by extension on radio propagation signals, is identified. Based on the previous studies in the literature [162][158], aircraft, especially wing models, were found to be made of different materials with different compositions. In terms of the composition of an aircraft wing, aluminium and carbon fibre composites were the two structural materials considered in this research. The main aluminium combinations utilized in aircraft are the 2xxx, 3xxx, 5xxx, 6xxx and 7xxx series[195]. The 2000 series is suggested for use in high temperature situations and in conditions with an expanded yield coefficient. The 7000 series compound are utilized for lower temperature situations in parts presented to expanded burdens and in parts that need to convey high consumption obstruction under high voltage. 3xxx, 5xxx and 6xxx compounds are utilized in low load parts, and additionally in water driven, grease and fuel frameworks. On the other hand, CFC aircraft can be either graphite , turbostrate , or a hybrid structure, depends on manufacture process[196]. A turbostratic structure, which is the essential structure of numerous carbon strands, comprises of subjectively stacked, parallel graphene sheets

that may even be part. A turbostratic structure may expand layer separating as much as 0.344 nm, consequently, additionally diminishing the aggregate of the fascination powers[197].

We consider 7075 alloy for this research. It comprises of aluminum, zinc, magnesium and copper. It's the most grounded of all aluminium composites and practically identical in that regard with steel, anyway it weighs just 33% of what steel gauges. Additionally, we consider hybrid structure of CFC for this research. In this chapter, CST was used to simulate aircraft wings composed of aluminium and carbon fibre composites to examine the influence of aircraft structural materials on connectivity control between the antennas. These results helped to design an optimal topology of WSN by identifying the approximate best locations for sensor nodes in the wing model presented in this chapter.

5.2 CST Simulations

For the CST simulations, a test case matrix was prepared, as shown in Table 11. All the test cases were repeated for wing models using aluminium and CFC materials. However, different parameters were set for meshing and computational efficiency, and are shown in Table 11. The actual aircraft wing is a heterogeneous made partly from aluminium and glass fibre, with a significant proportion made from CFC. However, this study used a complete wing model made up of aluminium or CFC. This is because the wing component in the model is cast as a single unit, as shown in Figure 54.

Table 11: Test case matrix for CST simulations.

Material	Wing Model	Position of Movable Transceiver	Status
	Realistic	$\frac{1}{4}$ wing length	Complete
	NACA64A410	$\frac{1}{2}$ wing length	Complete

Aluminium	model Empty NACA64A410 model	$\frac{3}{4}$ wing length	Complete
		Full wing length	Complete
		$\frac{1}{4}$ wing length	Complete
		$\frac{1}{2}$ wing length	Complete
		$\frac{3}{4}$ wing length	Complete
		Full wing length	Complete
	Empty prismatic model	$\frac{1}{4}$ wing length	Complete
		$\frac{1}{2}$ wing length	Complete
		$\frac{3}{4}$ wing length	Complete
		Full wing length	Complete
Carbon Fibre Composites	Realistic NACA64A410 model	$\frac{1}{4}$ wing length	Complete
		$\frac{1}{2}$ wing length	Complete
		$\frac{3}{4}$ wing length	Complete
		Full wing length	Complete
	Empty NACA64A410 model	$\frac{1}{4}$ wing length	Complete
		$\frac{1}{2}$ wing length	Complete
		$\frac{3}{4}$ wing length	Complete
		Full wing length	Complete
	Empty prismatic model	$\frac{1}{4}$ wing length	Complete
		$\frac{1}{2}$ wing length	Complete
		$\frac{3}{4}$ wing length	Complete
		Full wing length	Complete

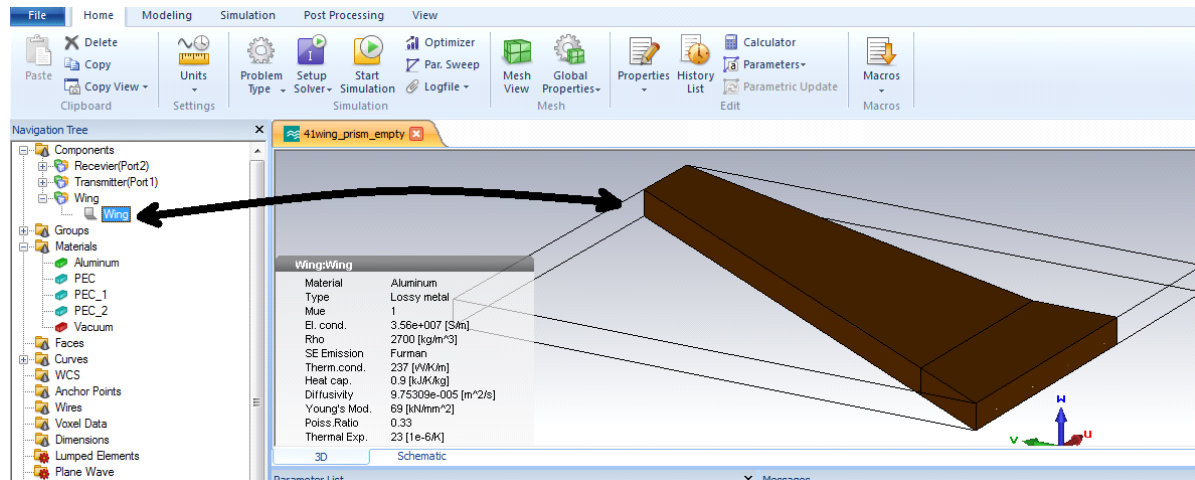


Figure 54: Screenshot showing the wing component in the model as a single seamless unit.

As the aircraft wing was considered as a single seamless unit in the CST simulation, as shown above, aluminium and CFC were the two key aircraft structural materials considered for investigation in this chapter.

The CST simulations were run on desktop machines and cloud computers, and are described further in Tables 12 and 13.

Table 12: Effective parameters for refined mesh and solver efficiency.

Mesh Settings		Solver Settings	
Mesh Density Control			
Steps per wavelength	1	Solver Accuracy Stopping	1e-3
Min. number of steps	10	Multithreading	Upton 48
Average quality	0.8986	Min Box size in wavelength	0.1

Table 13: Computational resources used for CST Simulations

Hardware/Software	RAM	Processor	Storage	Version	Remarks, if any
Desktop PC	16	Intel i7, 3 rd generation	2 TB	Not applicable	4 such desktop PCs were used.
Cloud Computing	-	-	-	-	
CST suite	Not applicable	Not applicable	Not applicable	2016 release	University Personal Use License
Desktop PC	32	Intel i7, 3 rd generation	2 TB	Not applicable	-
HPC	-	-	-	-	-

5.3 Simulation Results

The simulation results were essentially the S21 parameter value for the frequency range of 2.4-2.5 GHz. The characteristic variation of the S21 parameter in a different setting of the wing and the positions of the second transceiver are presented and analysed in the following sections.

Test case 1: Aluminium.

All the parts in the empty wing, realistic wing and prismatic wing models were composed of aluminium in this case. A suitable conducting material, aluminium is expected to attenuate the signal significantly. The penetration is low, and therefore, the transmission across spars is not reliable for communications.

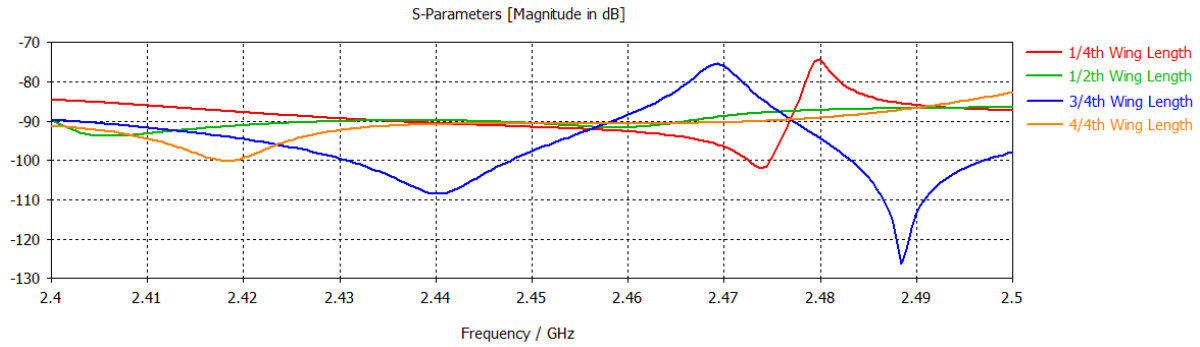


Figure 55: S21 parameter in the empty prismatic wing (aluminium).

The above graph presents the variations in an S21 parameter of an empty prismatic wing model made of aluminium with different positions of the antenna on the wing. Figure 55 shows the S-parameter at various distances from the fixed transceiver at the wing root. The S parameter obtained for coupling at the 3/4 wing length position shows a wide range of variation between 2.43 to 2.5GHz compared to the values at other distances. The average S parameter values are around -90dB.

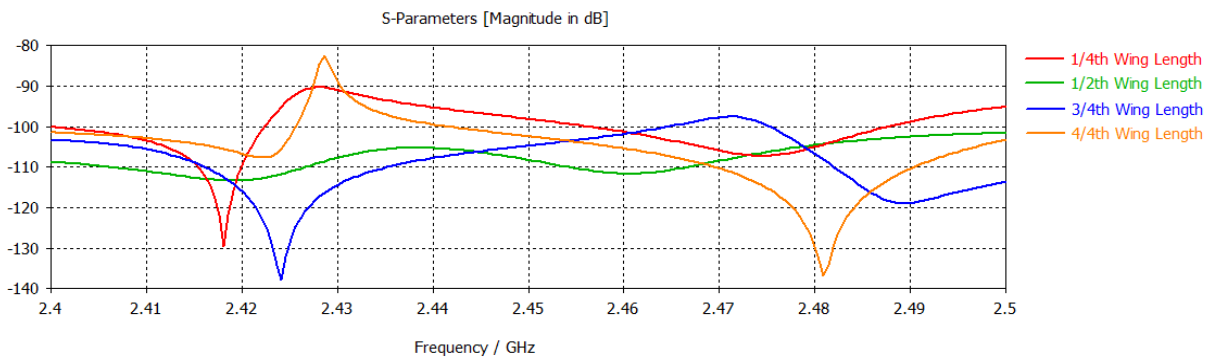


Figure 56: S21 parameter in empty wing, Aluminium.

The above graph presents the variations in the S21 parameter of an empty wing model made of aluminium with different positions of the antenna on the wing. While only the 3/4 wing length position shows wide variation in the prismatic wing, in the case of the empty wing model, all positions show absolute variations of around -40dB at frequencies 2.425 and 2.48GHz, as shown in Figure 56.

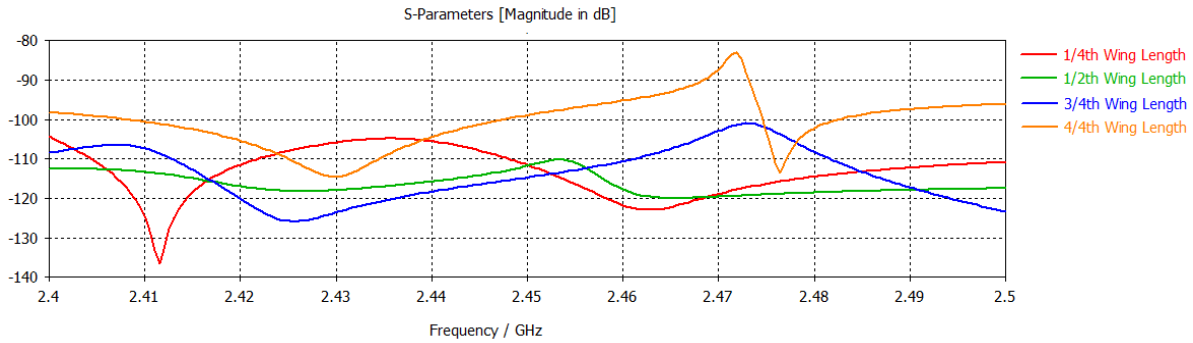


Figure 57: S21 parameter in the realistic wing, Aluminium.

The above graph presents the variations in the S21 parameter of the realistic wing model made of aluminium, with different positions of the antenna on the wing. The scenario is further reflective of increased variation in the case of the realistic wing, as shown in Figure 57. Here, the S parameter variation did not show any pattern and varied according to the different positions of the second transceiver. In addition, the average S parameter drops to -110 dB.

Test case 2: CFC

CFC stands for Carbon Fibre Composites, which are laminated composites reinforced with carbon fibres. CFC is a dielectric material, and its properties are derived from the properties of the laminates and epoxy system used as a binding matrix. Recent years have witnessed an upsurge in the use of these composites in aerospace and aeronautical industry, and it was therefore used in simulations.

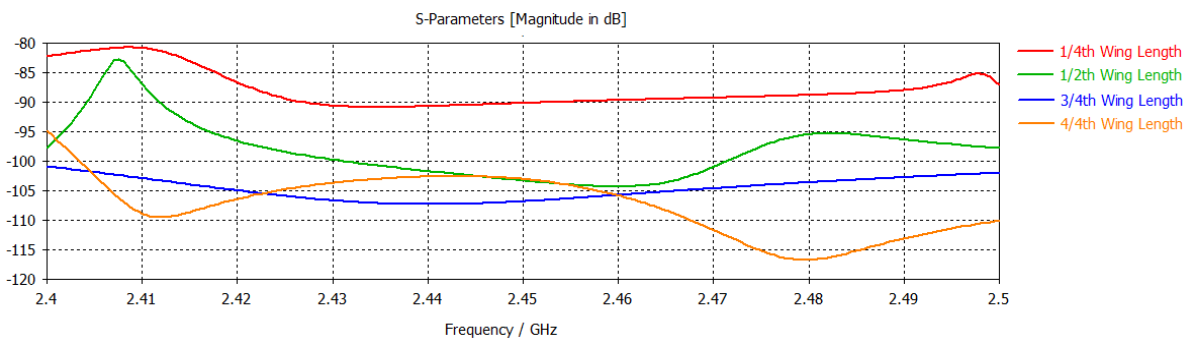


Figure 58: S21 parameter in empty wing, CFC.

The CFC empty wing model results for S parameter are shown in Figure 58. It shows a wide variation from around -90 to -105dB for the different positions of the second transceivers. The variation is similar to that in the case of an empty wing composed of aluminium, but the variation is across all frequencies in the case of CFC.

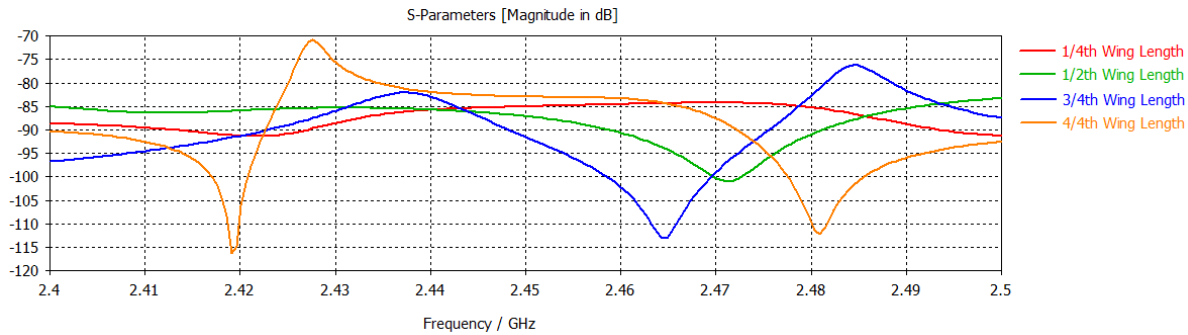


Figure 59: S21 parameter empty prismatic model, CFC.

Figure 59 depicts the S parameter for the prismatic model, and is mostly constant at -85 dB, which is higher than for the prismatic model of aluminium.

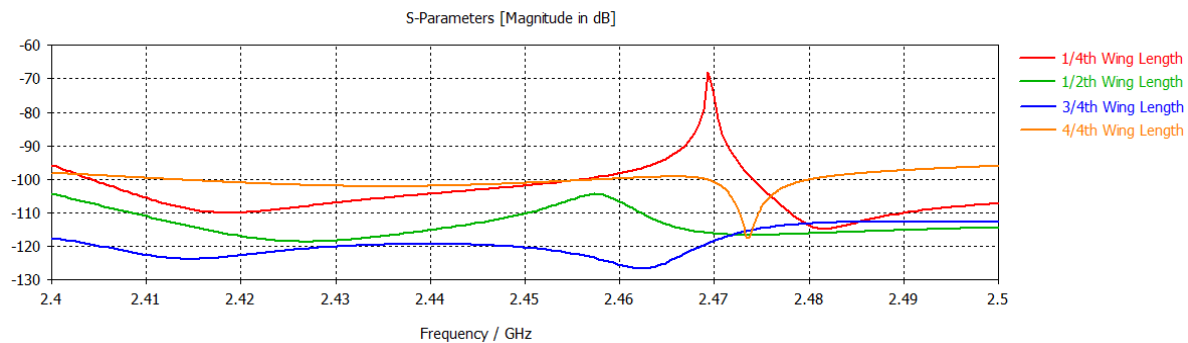


Figure 60: S21 parameter for the realistic wing, CFC.

The S parameter decreased considerably for the realistic wing, as the distance of the second transceiver increased from the first node at the root wing, as shown in Figure 60.

5.4 Comparison of Results

The S parameter, S21, can be compared for a fixed antenna location for aluminium, CFC and PEC.

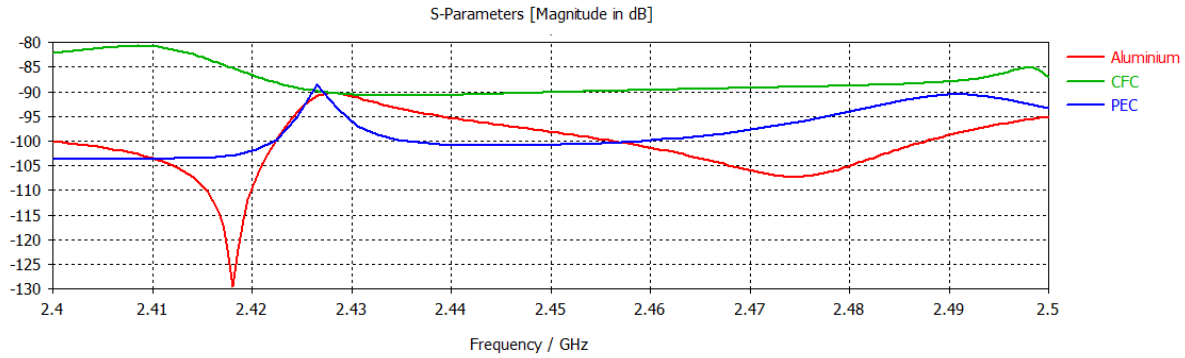


Figure 61: Second transceiver 1/4 wing length, empty wing.

Whilst PEC is the perfect conductor, CFC being dielectric, favours comparatively good transmission, as shown in Figure 61. The parameter drops suddenly at around 2.418GHz in aluminium. It does not fall so suddenly for PEC or CFC.

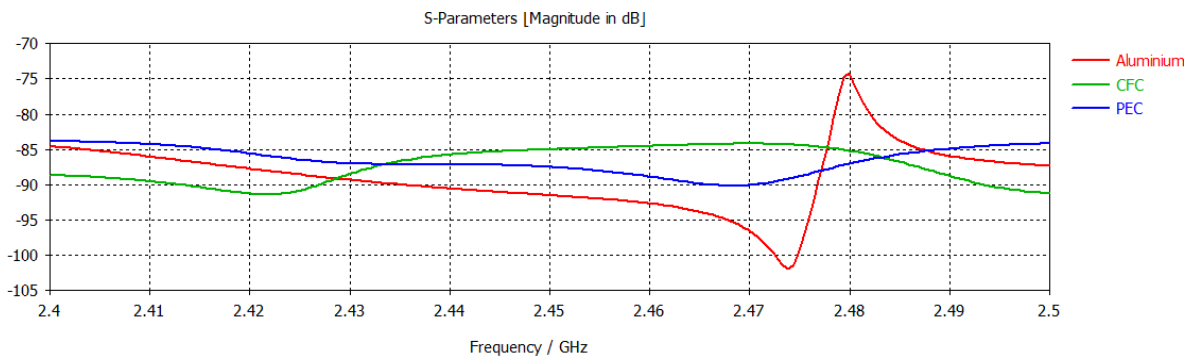


Figure 62: Second transceiver at 1/4 wing length, prismatic wing.

Compared to the empty wing, the prismatic wing, however, shows steady S21 values for almost all frequencies except for aluminium, as shown in Figure 62.

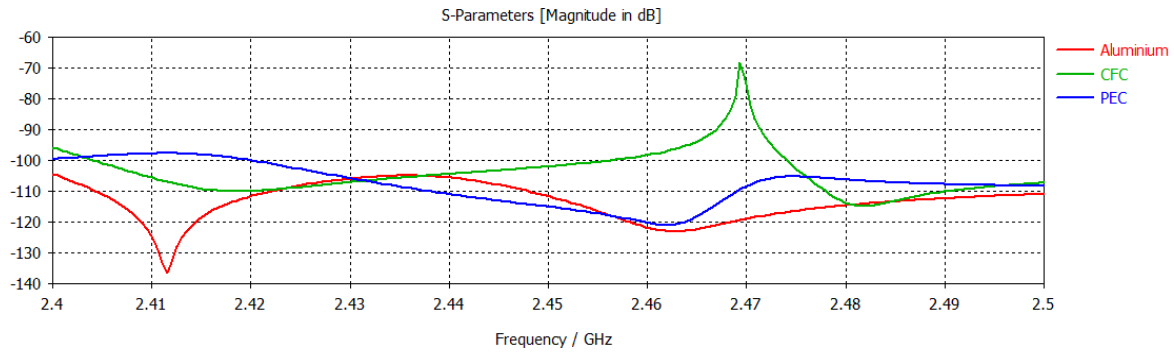


Figure 63: Second transceiver at 1/4 wing length, realistic wing.

From the above figure, it is also evident that CFC shows a favourable peak at 2.47 GHz for the realistic wing in Figure 63, while aluminium shows a low at around 2.41 GHz.

For other positions, the salient features are presented in the figures and reflect different patterns of variation, but overall CFC indicates a good coupling through the S21 parameter compared with conductive materials. Hence, it can be concluded that WSNs tend to show better connectivity in CFC wings compared to conductors.

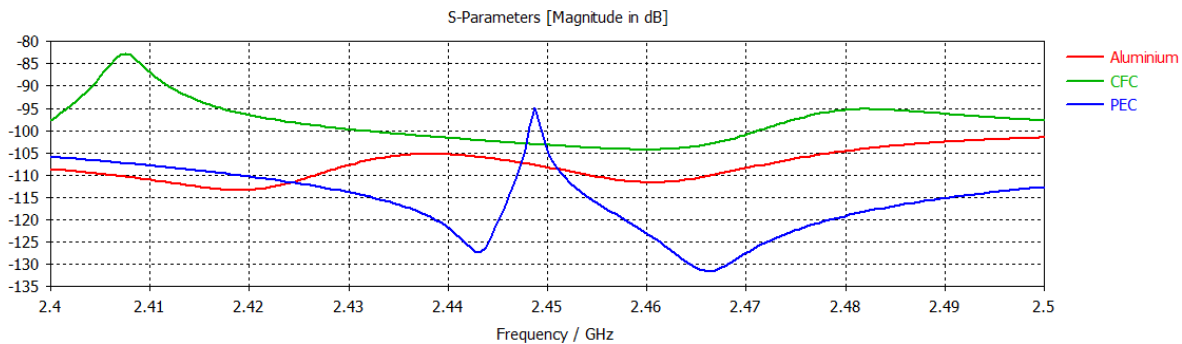


Figure 64: Second transceiver at 1/2 wing length, empty wing.

The variation in the link budget (S21) value when the second transceiver is placed at half length of the empty wing is given in Figure 64. Here, the PEC material wing recorded the highest value at 2.45GHz.

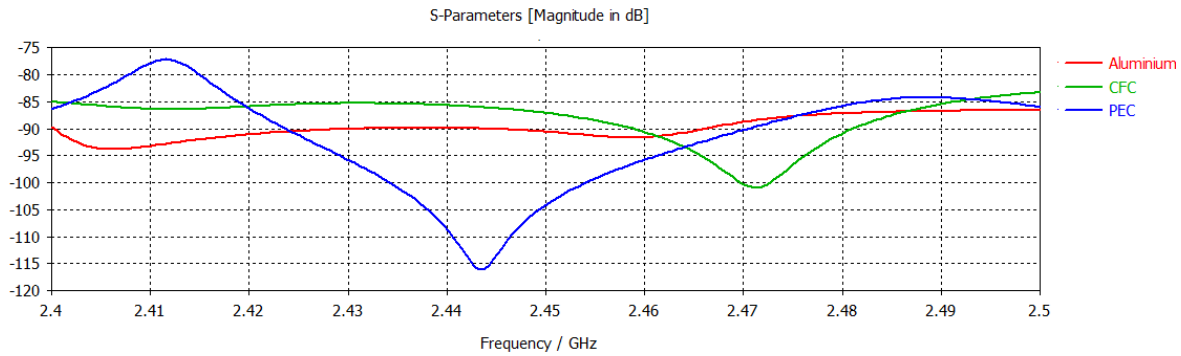


Figure 65: Second transceiver at 1/2 wing length, prismatic wing.

The variation in the link budget (S21) value when the second transceiver is placed at half length of the prismatic wing is shown in Figure 65. Here, the PEC material wing recorded the lowest S21 value, followed by CFC and the aluminium material at 2.45GHz.

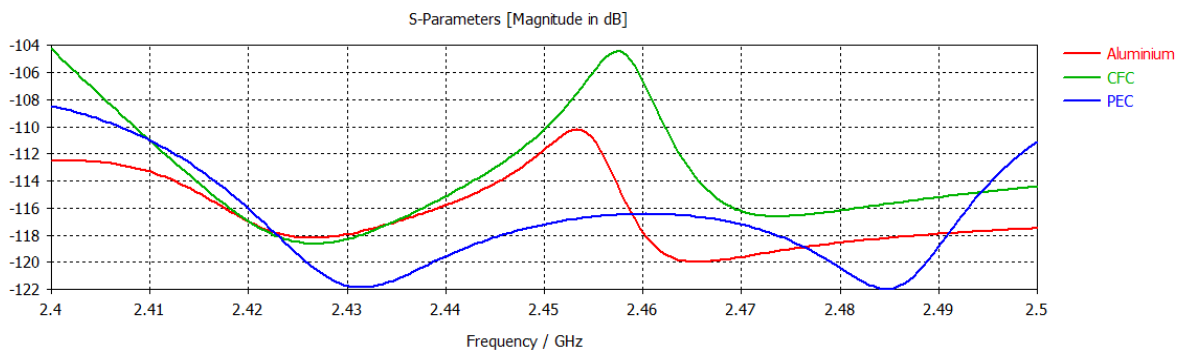


Figure 66: Second transceiver at 1/2 wing length, realistic wing.

The variation in the link budget (S21) value when the second transceiver is placed at half length of the realistic wing is given in Figure 66. Here, high fluctuations in the S-parameter value are identified for three materials: aluminium, CFC and PEC.

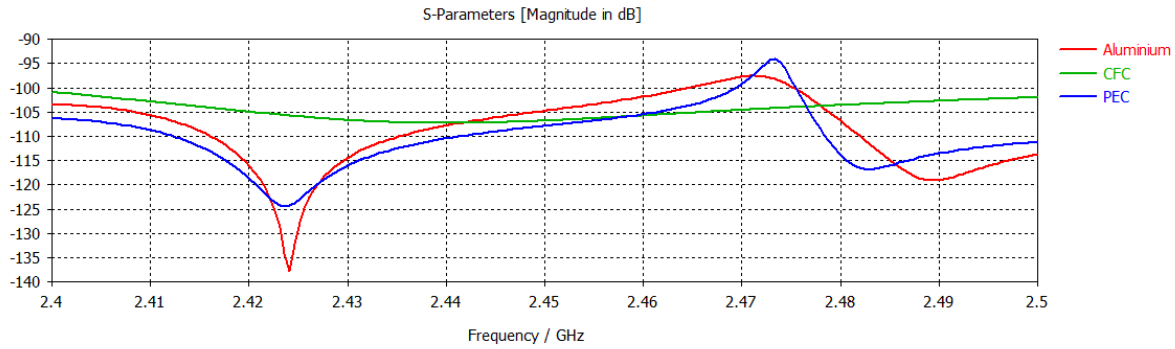


Figure 67: Second transceiver at 3/4 wing length, empty wing.

The variation in the link budget (S21) value when the second transceiver is placed at the 3/4 length of the empty wing is shown in Figure 67. Here, the aluminium wing recorded the lowest S21 value of between 2.42 and 2.43 GHz.

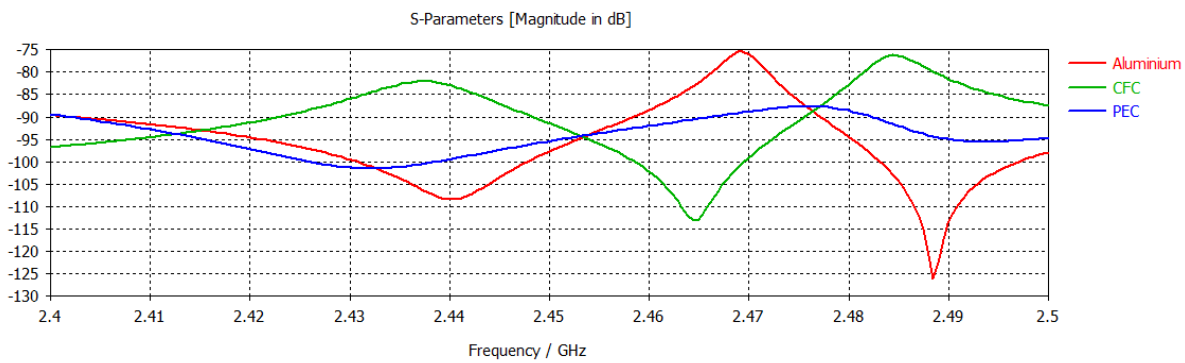


Figure 68: Second transceiver at 3/4 wing length, prismatic wing.

The variation in the link budget (S21) value when the second transceiver is placed at the 3/4 length of the prismatic wing is shown in Figure 68. Here, the aluminium wing recorded the lowest S21 value at 2.49GHz.

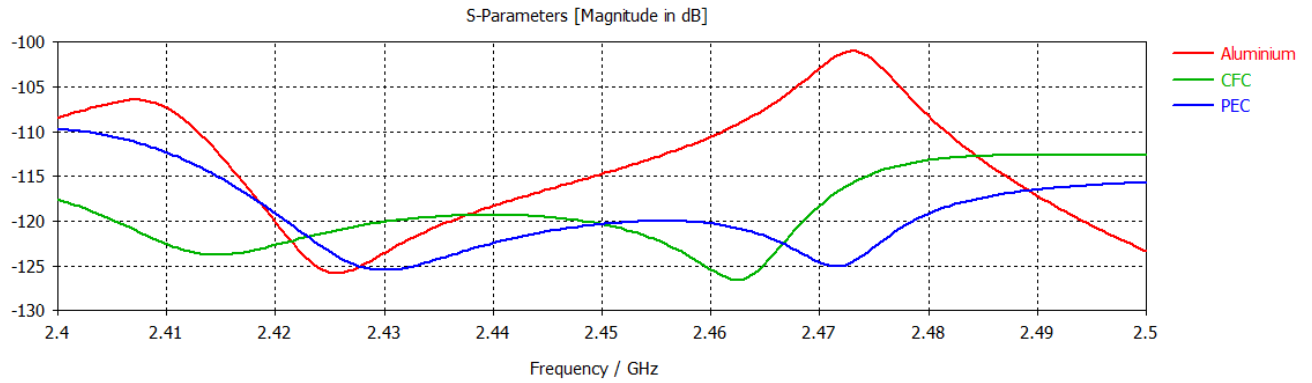


Figure 69: Second transceiver at 3/4 wing length, realistic wing.

The variation in the link budget (S21) value when the second transceiver is placed at 3/4 length of the realistic wing is shown in Figure 69. The aluminium wing recorded a high S21 value of between 2.47 and 2.48GHz.

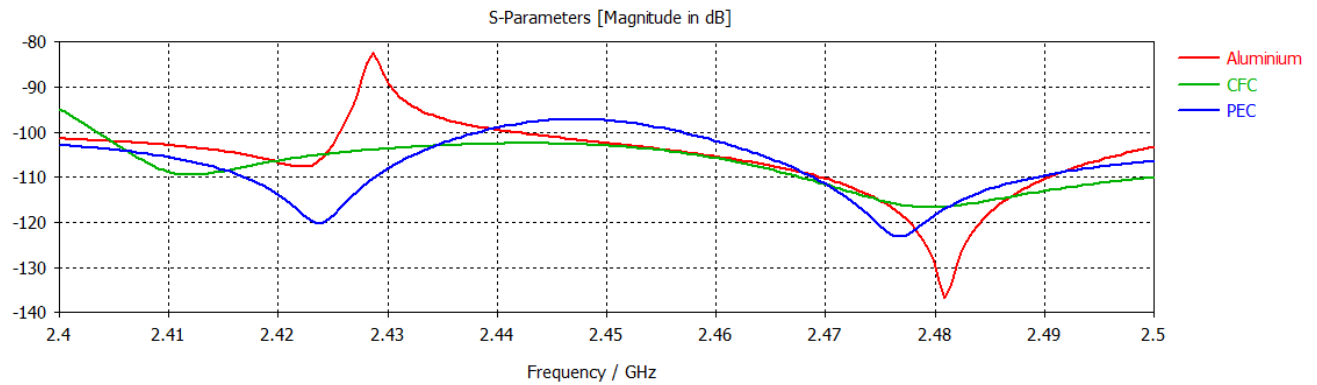


Figure 70: Second transceiver at 4/4 wing length, empty wing.

The variation in the link budget (S21) value when the second transceiver is placed at 4/4 length of the empty wing is shown in Figure 70. The highest S21 value for the aluminium wing was 2.43GHz and the lowest 2.48GHz.

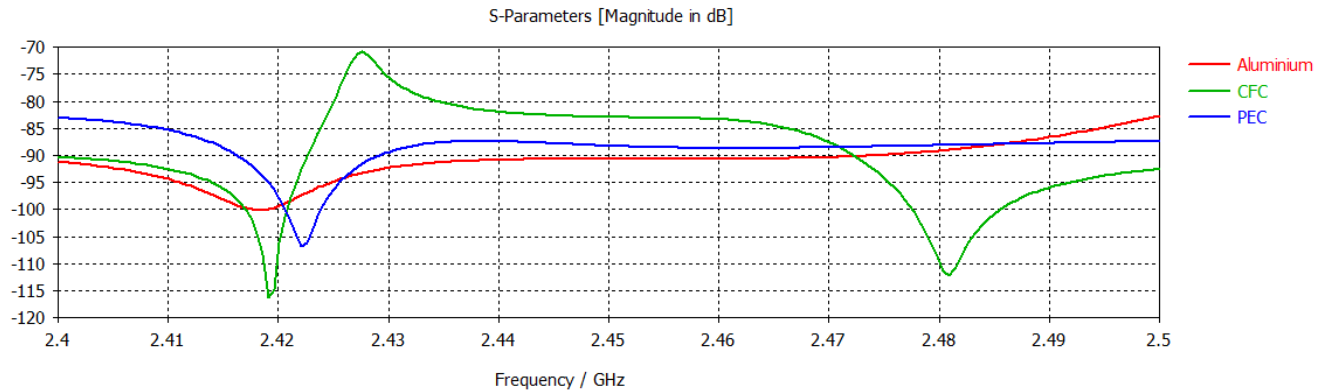


Figure 71: Second transceiver at 4/4 wing length, prismatic wing.

The variation in the link budget (S21) value when the second transceiver is placed at 4/4 length of the prismatic wing is shown in Figure 71. The highest S21 value for the CFC wing was 2.43GHz and the lowest 2.48GHz.

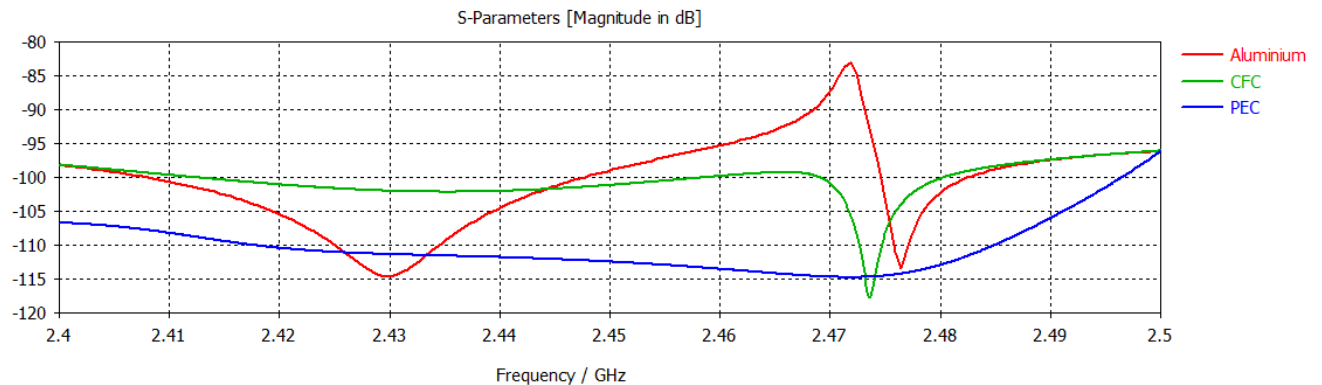


Figure 72: Second transceiver at 4/4 wing length, realistic wing.

To conclude the comparison, the salient point is that S21 was between -90 to -120dB in all cases, and CFC exhibits higher values. These simulations are complemented by an increased number of nodes that all communicate to the base nodes at the root wing. Through these simulations, it is easy to map the communication range in each case.

5.5 Explanation of Results

All the graphs obtained from the CST simulation have identified the significant influence of wing material on the S parameter (S21). On the other hand, a comparison of the CST simulation results obtained for each case (aluminium, CFC and PEC) showed that the value of the S parameter (S21) varied according to the position of the second antenna on the wing and with the change in wing model. For empty prismatic, empty and realistic wing models made of aluminium, the average S parameter values were found to be -90dB, -45dB and -100dB respectively. This average S parameter value was obtained by considering the variations in S21 value with the change in the antenna position placed on the aircraft wing. In the case of CFC, for the empty prismatic, empty and realistic wing models, the average S parameter values were found to be -100dB, -85dB and -110dB respectively. Considering the results of the previous chapter regarding the significant changes in S21 parameter value between the frequency range of 2.4 and 2.5GHz, this frequency is only considered in this chapter to identify the effect of aircraft wing composition on the radio wave signals and signal strength value. From this comparison, the ability of aircraft wing models made of CFC to record higher S21 values has been identified, which shows that this material is able to support better connectivity and antenna communication on ZigBee networks. The S21 parameter values of an aircraft wing composed of aluminium and CFC materials were compared with a wing in which PEC material was used during its manufacture. This comparison of S21 values for different aircraft wing models based on changing the antenna positions revealed a significant fall in the link budget value for aircraft wing made of aluminium than other materials CFC and PEC. This is mainly because of the unique and favourable properties of PEC and CFC materials compared to aluminium. PEC is a perfect conductor and CFC is dielectric, which helps favour good transmission.

5.6 Summary and Conclusion

To assess the feasibility of using ZigBee communications in an aircraft environment, the impact of wing model composition on radio wave propagation was identified. Among the different material composition of aircraft wing, the influence of aluminium, CFC and PEC wing materials

on the connectivity quality levels were identified in this chapter. For each wing material considered, CST simulations were carried out by changing the antenna position. This way of conducting several simulations helped identify that CFC exhibits a higher S21 value when compared to other wing structure materials. A comparative analysis of the link budget value exhibited by the aircraft wing when different materials are used indicated that CFC material is highly effective in improving connectivity between the antennas in ZigBee communication. The next chapter aims to determine where to deploy the sensors to achieve the optimal position at the lowest cost.

6.1 Overview

The performance of WSNs in any given application depends on two aspects: the deployment of sensor nodes and energy consumption. Whilst the deployment of WSN addresses problems such as optimization and node topology, the aspect of energy consumption decides the lifetime of the node/network. The main purpose of the present chapter is to present systematically, both the design aspects for the monitoring of aircraft wing structural health. The chapter is organized as follows,

Section 9.2 discusses and finalizes various node deployment aspects in terms of their application in wing models. One of the main results is CST simulations that identify communication range and a path loss model for node deployment. However, it is also argued that realistic wing model node deployment is somewhat constrained by the internal structural elements. Section 9.3 describes the Multiple Travelling Salesman Problem for communication between nodes. The problem is open tour, which means that the source and destination nodes are not the same. In the present case, the signals originate at the wing tip nodes and travel to the sink nodes at the wing root. This optimizes the travel distance from farthest node in an energy-efficient manner. The travel distance is also the best routing path for the ZigBee nodes of this WSN. Section 9.4 describes the implementation and results obtained for mTSP using Ant Colony Optimization. Finally, Section 9.5 concludes the salient findings of this chapter.

6.2 Node Deployment

Node deployment addresses how many nodes to deploy and how to deploy them. Various deployment methods practised in the design of WSN are shown in Figure 73. The wing model dimensions and geometry are shown in Figure 74, and the area that needs to be monitored for structural health ranges from 1.77m to 5.9m (width) and 12.4m (length). The total area is therefore around 47.55m². Constant or variable node densities can be evaluated over this area,

considering the empty models of the prismatic and NACA64A410 airfoil. The optimal node densities will be constrained by the sensing and transmission range. The structural health, efficiency and coverage of the monitoring sensors will affect optimization, especially given the many different choices of these sensors, and it is complicated to treat each one independently. However, that is not the concern in the present work. In terms of the selection of nodes and the determination of node density, ZigBee units are considered for the reception, transmission and processing of sensor data and their transmission range, specifically in the wing model environment.

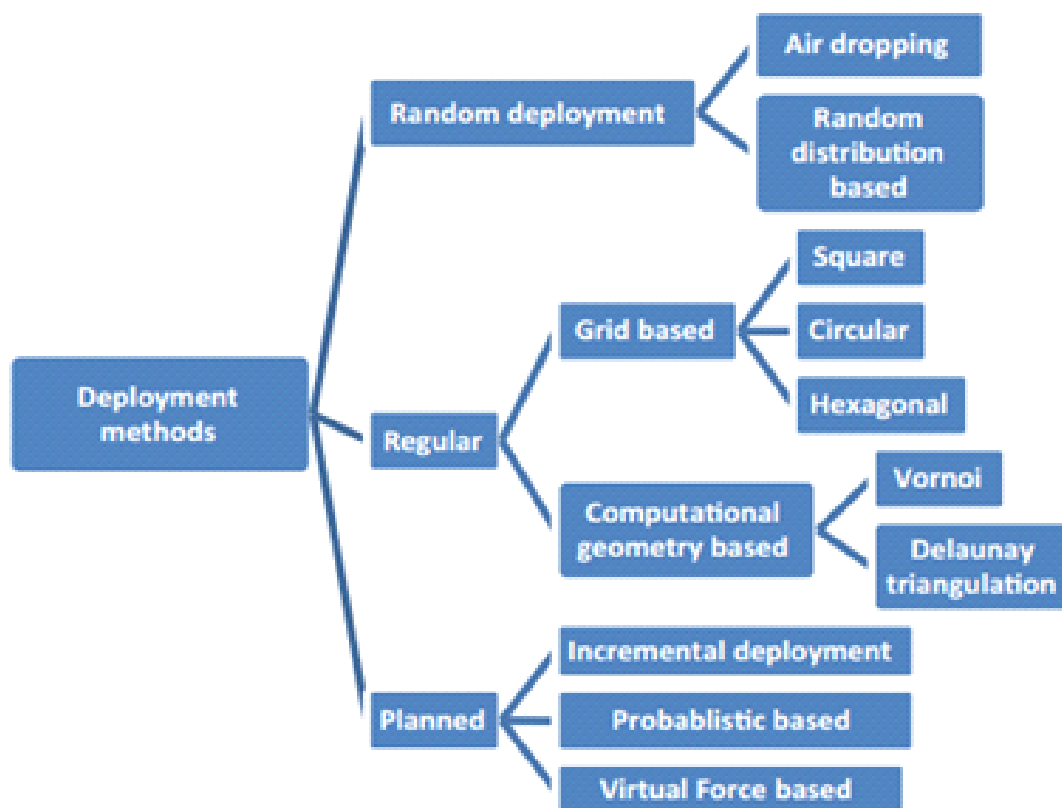


Figure 73: Deployment Methods.

The transmission range for ZigBee units will be inferred from CST simulations of two-transceiver and multiple transceiver scenarios in different settings of centralized and distributed communications. An example of such an exhaustive simulation programme is presented in Table 14.

Table 14: CST simulation programme.

Wing Model/Comments	Number of Transceivers	Communication model	Node density, number of nodes / m ²	Remarks
Across all wing models inclusive of different materials.	2	Distributed	0.0421	Fixed node at wing root and movable at different distances from wing root.
Prismatic wing mode	79	Decentralized	1.6629	Four nodes fixed at the wing root and others uniformly distributed over the wing. Each node communicates to every other node.

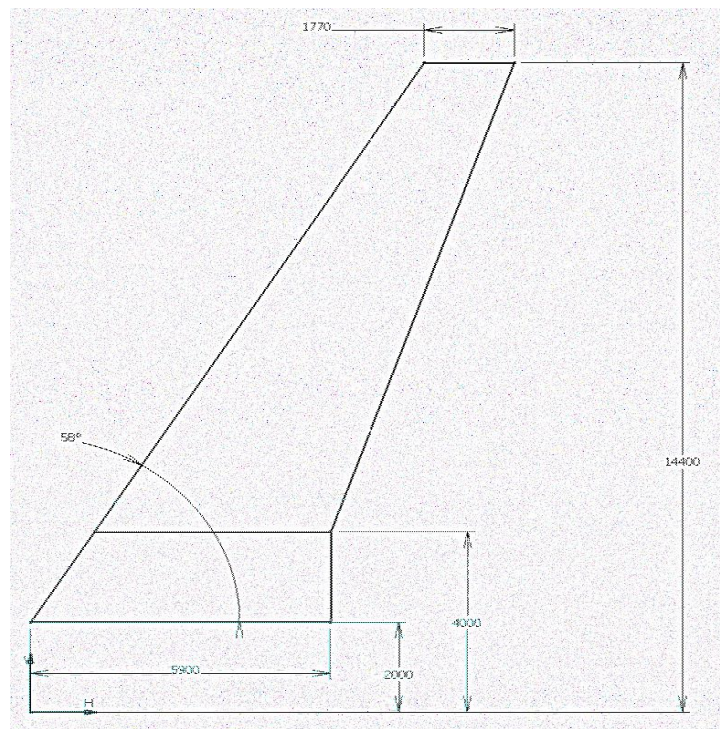


Figure 74: Wing model geometry

Based on such a simulated model for path loss and transmission range for ZigBee units, it is justified to make the following assumption:

Assumption 1: While designing WSNs, the trade-offs between selecting the sensing and transmission range is important. However, the present case is restricted to selection of transmission range. While for empty wing model, the transmission range selected is amenable to the effect of energy and throughput considerations, the internal structure of the realistic wing is a constraint and poses a reliability issue for the WSN. Therefore, 1m is selected as the transmission range for all the wing models.

From assumption 1, the different node densities are as follows:

<i>Range, m</i>	<i>Number of Nodes</i>
0.5	760
0.75	338
1	190
1.25	122
1.5	85
1.75	62
2	48

The impact of assumption 1 is that more nodes will have to be deployed, but the redundancy is a trade-off in view of the reliability and survivability of the WSN. The actual number of nodes on a square grid of 1 m can be easily found, since the area of the wing to be covered is calculated,

as previously, as 47.55m^2 . An area of 1 m^2 is covered by four nodes placed at the four vertices of the square. Hence, to cover an area of 47.55 m^2 , the number of nodes is less than $47.55 \times 4 = 190.2$. The number of nodes theoretically required is rounded to 200. Various scenarios where the number of nodes varies from 100 to over 240 are examined in simulations to find the shortest path (see Section 6.4).

In addition, ZigBee specifies a physical range of 10 to 20m, and effective communication therefore needs to be reliable, subject to the availability of enough power, because of the very low range. The optimal number of nodes, however, will be found in optimization problem using mTSP.

Thus, to summarize:

- Node deployment is homogenous;
- Node density is determined by optimization;
- CST simulations were used to infer communication range and path loss models for different wing models. Moreover, this communication range being equal for each node, it also forms the Euclidean distance between immediate neighbours on the square grid.

Coverage and connectivity are considered as the QoS for the sensor network. In the present case of different wing models, and according to *assumption 1*, coverage is achieved using a regular deployment method of ZigBee units loaded with suitable SHM sensors [163][164]. Therefore, connectivity issues can be detached from coverage and formulated as issues of available power for node operation at each node, power control, and available power at each node at different times during the operation of the WSN, which is known as power management. Furthermore, it is required to identify the power demands of connectivity-assuring routing protocols in the WSN. For example, an event near the wing tip region will trigger sensor activity, and the measured data has to travel back to nodes at the wing root so that it can further be transmitted to a control site in the cockpit. The connectivity issues ask the following questions:

- What power is available at those nodes where the event is triggered?
- Is this power above the threshold for transmission so that the implemented routing algorithm ensures successful reception at the wing root node? What are the chances of success if a multiple of such sensor or node activity events is triggered?
- What level of redundancy in the WSN is needed to address a given level of connectivity, for example 99%?

These concerns are addressed using a mTSP (multiple Travelling Salesman Problem), in which the goals set for optimization embody the above questions on connectivity. The mTSP formulates present thresholds for reliable connectivity and its management and then finds optimal deployment strategies. In all deployment strategies, connectivity is graph-based, and a communication edge is present for a particular node with each of its immediate neighbours.

- ***Effects of power management and control on connectivity issues considered***

Power control refers to the spatial distribution or demands of the power required at each node and its design. Power management, on the other hand, refers to temporal changes in power distribution, such as routing, transmitting, reception and other node activities triggered by sensing activities by sensors at different locations; in short, residual power at different nodes. Therefore, the tracking and budgeting of the spatial and temporal power requirements of WSN directly correlate with the connectivity measure of QoS [138], [165]–[169].

- ***Routing schemes that comply with the aforementioned connectivity designs***

The protocol stack has the third layer, called the network layer, the main function of which is routing. This affects the performance of the lower layers, namely the data and link layers. Therefore, incorporating the effects of lower layers and handling these effects is the objective of protocol design. For example, some features of the physical layer mean that the communication range of the devices/communicating nodes may be asymmetric. This means that if node A can send a message directly to node B, it is possible that node B cannot reply directly back to node A. These communication issues should be taken into account when designing or selecting a

routing protocol.

It is challenging to find routing protocols that fit all the prescribed criteria for the design. Therefore, salient criteria and constraints on the routing required in the wing model WSNs are explored below, so that relevant routing schemes can be identified or designed.

- The prime requirement is delivery of the data signal originating from any node to any of the FOUR nodes that sit at the wing root, through multi-hop paths [170]–[174].
- Therefore, finding multi-hop paths for almost all nodes and picking the ones with the least hops is the main objective in routing.
- Redundancy in multipath routing is allowed with increased power consumption for critical events, but the communication link fault is not tolerated within the given threshold.

The proposed routing scheme is as follows and reflects the higher level of connectivity:

- A table-based routing protocol [175]–[179] can be adapted to maintain routing information about all nodes and each node maintains four tables:
 - Distance table:
 - Routing table:
 - Link cost table:
 - Message retransmission table.
- The protocol will work on global information; every node can compute the shortest distance to destination for the data signal.
- The shortest path and alternatives to it, as computed from optimization problems, will be fed into the aforementioned tables.

The routing paths for each node in all three wing models are discussed in Chapter 4 and analysed in the context of energy optimization goals.

Trade-offs

The trade-offs are primarily in power control and optimal topology. To maintain higher qualitative levels of connectivity in the network, higher transmitting powers are expected. However, this in turn conflicts with the limited energy available from batteries. Energy harvesting is an option to supplement the energy from the environment and prolong the WSN's lifetime and efficiency. Power constraints and limited resources also affect the routing schemes and protocols used [160], [180]–[184]

The prime trade-offs between power management and control and reliable connectivity are as follows for the different wing models:

- Use of routing table and global WSN information for routing to achieve higher connectivity is in stark contrast with power control and management. Encourage the use of power-aware routing protocols.
- Such power-aware routing protocols can be evaluated only after assessment of power demands for higher connectivity through table-based routing paradigm.
- The sensor mobilization will be event-based, and hence there are opportunities for power saving by scheduling sleep-wake cycles for a different node. However, it is not clear what connectivity loss occurs in such settings [91,92,93].

6.3 mTSP Formulation for Wing Models

Connectivity and topology control of WSN is formulated as a multiple Travelling Salesman (mTSP) problem and subsequently solved using Ant Colony Optimization (ACO). The mTSP identifies sensor node positions as vertices and persistence connectivity between any i th and j th node as the edges between those vertices.

The features of the mTSP are:

- It is an *open tour* problem, since once the signal has left a sensor node it need not come back; instead, it is desired that it reaches one of the head nodes at the wing base.
- The distance between any two sensor nodes can be at the *max* communication range, and the threshold communication range is input from the user or inferred based on the CST simulations.
- As the selection of communication range, namely the optimal distance between two nodes that allows them to reliably communicate with each other, affects the number of nodes and the required energy for transmission, various other parameters can be tweaked using only communication range as the single most important parameter. For example:
 - The empty wing model is different from the realistic NACA64A410 inner structure wing model. However, the effect of reduced signal strength as a result of the presence of structural elements such as ribs and spars can be accounted for by reducing the communication range. The amount of reduction will be guided by the link parameter profiles from the CST simulations.
 - The communication range also presents correlation with the power required for transmission at a particular node. For example, if distances smaller than the communication range are used, then the power required is reduced and vice-versa. This also affects the number of nodes required.
 - Therefore, relations between power required at the node, the number of nodes required, and the effect of internal structure on communication can be evaluated or changed in the problem by changing the communication range, r .

- The goal of the optimization problem is to find various topologies that guarantee the connectivity of the WSN for most of the operational time of the aircraft. The steps followed to obtain a solution are:
 - Find communication range, r , for all the three wing models from CST simulations:
 - NACA64A410 model for the inner structure of the wing;
 - Empty NACA64A410 model for the wing;
 - Empty prismatic model of the wing.
 - Find all possible topologies consistent with selected r across the wing using the dimensions and geometry shown in Figure 75. In this wing model, the area that needs to be monitored for structural health ranges from 1.77 to 5.9m on the width and 12.4m on length. The total area is therefore around 47.55m².
 - Find all the paths that reach any of the head nodes from any m sensors near the wing tip.
 - Find overall power requirements for all these paths and rank the paths from the lowest to the highest power requirement.
 - Analyse the reliability of the connectivity of near-tip sensors with head nodes in different stochastic scenarios, i.e. assigning different probabilities of failure for each node.
 - Change the topology until a solution with a given level of reliability and connectivity is found.

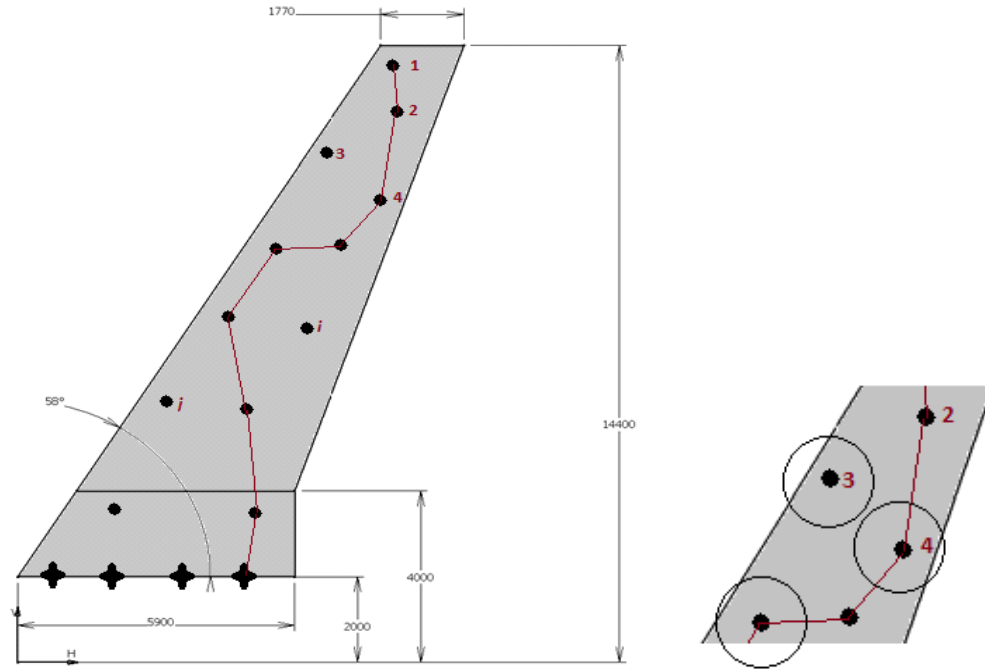


Figure 75: Wing geometry and dimensions for the sensor environment.

A shaded grey area is a region to be monitored by sensors for SHM. Dark circles are sensor nodes, whereas the head or principal nodes are spade-like symbols. Here, inputs are the geometry and CST simulations that identify the optimal number of nodes for initial deployment. The objective is to find the shortest and fastest travel path to the sink that will use the least power out of all the scenarios. The output is the shortest path that uses the least power.

Let:

N , the total number of sensor nodes on the aircraft wing;

V , set of N sensor nodes;

A , set of edges;

c_{ij} , cost with an edge, and the parameter from CST simulations for the various setting of topologies and wing settings;

d_{ij} , a distance of an edge; that is, the distance between i th and j th sensor node,

r , minimum communication range between the sensor node.

The open tour mTSP is formulated in two forms with different goals:

Goal 1– Minimize the total distance of travel for the signal from wing tip node to any one of the sink nodes at the wing base for various numbers of nodes that minimizes the transmission power required. The outcome of this is the shortest path to deliver the packet. The analysis of Assumption 1 shows 200 nodes as the most optimal for the realistic wing model. Assumption 1 is based on wing geometry, selected dimensions and CST simulations to assist in the identification of the number of nodes within a found communication range.

The objective function is:

$$\min \sum_i \sum_{j; i \neq j} d_{ij} x_{ij} \quad (9.1)$$

Subject to

$$\sum_{j \in V: (i,j) \in A} x_{ij} = k \quad \forall i = \{1, 2, \dots, m\} \quad (9.2)$$

where m is the number of nodes near the wing tip regions,

$$\sum_{j \in V: (i,l) \in A} x_{jl} = k \quad \forall l = \{N - 3, N - 2, N - 1, N\} \quad (9.3)$$

$$\sum_{i \in V: (i,j) \in A} x_{ij} = 1 \quad \forall j = \{m + 1, m + 2, \dots, N - 3, N - 2, N - 1, N\} \quad (9.4)$$

$$\sum_{j \in V: (i,j) \in A} x_{ij} = 1 \quad \forall i = \{m + 1, m + 2, \dots, N - 3, N - 2, N - 1, N\} \quad (9.5)$$

Goal 2 – maximize signal connectivity and strength using the link parameter obtained from simulations for various topologies, subject to the same constraints as in equations (9.2) to (9.5).

If, after enumerating, the solution set of topologies for Goal 1 and Goal 2 show any intersecting solutions, they will be the desired topologies; otherwise, the solutions that satisfy minimum

power required and maintain the given reliability will be selected.

- **Solution Prerequisites**

CST simulations were carried out to assess the link parameter between different topologies in different wing models. To map the scattering parameter across the length of the wing, one port was placed stationary at the wing base, while a second port was moved across the length at incremental distances of $\frac{1}{4}$ of the wing length. Based on the S parameter results obtained from the previous chapter, a summary of variations in the S parameter is presented in Tables 15 and 16.

Table 15: Summary of S parameter variation with distance for different materials, NACA64A410 model for the inner structure of the wing.

- **PEC**

Port Location 1	Port Location 2	Distance, m	Average S parameter, $S_{21,avg}$, dB	Frequency Range, GHz	Remarks
Wing root	$\frac{1}{4}$ wing length	3.1 m	-107.55	2.4 - 2.5	-
Wing root	$\frac{1}{2}$ wing length	6.2 m	-116.85	2.4 - 2.5	-
Wing root	$\frac{3}{4}$ wing length	9.3 m	-119.25	2.4 - 2.5	-
Wing root	Tip of wing length	12.4 m	-110.35	2.4 - 2.5	-

- Aluminium

Port 1 Location	Port 2 Location	Distance, m	Average S parameter, S _{21,avg} , dB	Frequency Range, GHz	Remarks
Wing root	¼ wing length	3.1 m	-113.29	2.4 - 2.5	-
Wing root	½ wing length	6.2 m	-115.33	2.4 - 2.5	-
Wing root	¾ wing length	9.3 m	-120.85	2.4 - 2.5	-
Wing root	Tip of wing length	12.4 m	-122.63	2.4 - 2.5	-

- CFC

Port 1 Location	Port 2 Location	Distance, m	Average S parameter, S _{21,avg} , dB	Frequency Range, GHz	Remarks
Wing root	¼ wing length	3.1 m	-105.32	2.4 - 2.5	-
Wing root	½ wing length	6.2 m	-115.45	2.4 - 2.5	-
Wing root	¾ wing length	9.3 m	-120.10	2.4 - 2.5	-
Wing root	Tip of wing length	12.4 m	-110.34	2.4 - 2.5	-

For the NACA64A410 model of the aircraft wing, considering the dimensions and shape of the inner structure, the composition was changed to aluminium, PEC and CFC. One antenna is fixed at the wing root, and the position of the other is changed. The summary of the results shown above indicates the variation in the S parameter based on both the antenna position and the wing composition material. By maintaining the same frequency level between 2.4 to 2.5 GHz, the comparison of S₂₁ values above reveals the ability of CFC and PEC materials to record a high link budget value compared to the wing models made of aluminium. This situation was found to be the same even when the position of the second antenna was changed, as shown in Table 15.

Table 16: Summary of S parameter variation with distance for different materials, empty prismatic wing model.

- **PEC**

Port 1 Location	Port 2 Location	Distance, m	Average S parameter, S _{21,avg} , dB	Frequency Range, GHz	Remarks
Wing root	¼ wing length	3.1 m	-61.9	2.4 - 2.5	
Wing root	½ wing length	6.2 m	-91.58	2.4 - 2.5	
Wing root	¾ wing length	9.3 m	-94.29	2.4 - 2.5	
Wing root	Tip of wing length	12.4 m	-88.66	2.4 - 2.5	

- Aluminium

Port 1 Location	Port 2 Location	Distance, m	Average S parameter, S _{21,avg} , dB	Frequency Range, GHz	Remarks
Wing root	¼ wing length	3.1 m	-100.22	2.4 - 2.5	-
Wing root	½ wing length	6.2 m	-105.44	2.4 - 2.5	-
Wing root	¾ wing length	9.3 m	-110.23	2.4 - 2.5	-
Wing root	Tip of wing length	12.4 m	-111.32	2.4 - 2.5	-

- CFC

Port 1 Location	Port 2 Location	Distance, m	Average S parameter, S _{21,avg} , dB	Frequency Range, GHz	Remarks
Wing root	¼ wing length	3.1 m	-87.34	2.4 - 2.5	-
Wing root	½ wing length	6.2 m	-98.34	2.4 - 2.5	-
Wing root	¾ wing length	9.3 m	-104.23	2.4 - 2.5	-
Wing root	Tip of wing length	12.4 m	-109.34	2.4 - 2.5	-

For the empty prismatic wing model of the aircraft wing, with regard to the dimensions and shape of the inner structure, the composition was changed to aluminium, PEC and CFC. One antenna was fixed at the wing root, and the position of other one was changed. The summary of the results shown above indicates the variation in S parameter based on both the antenna position and the wing composition material. By maintaining the same frequency level between 2.4 to 2.5GHz, the comparison of S21 values above reveals the ability of CFC and PEC materials to record a high link budget value compared to the wing models made of aluminium. This situation was found to be the same even when the position of the second antenna was changed, as shown in Table 16.

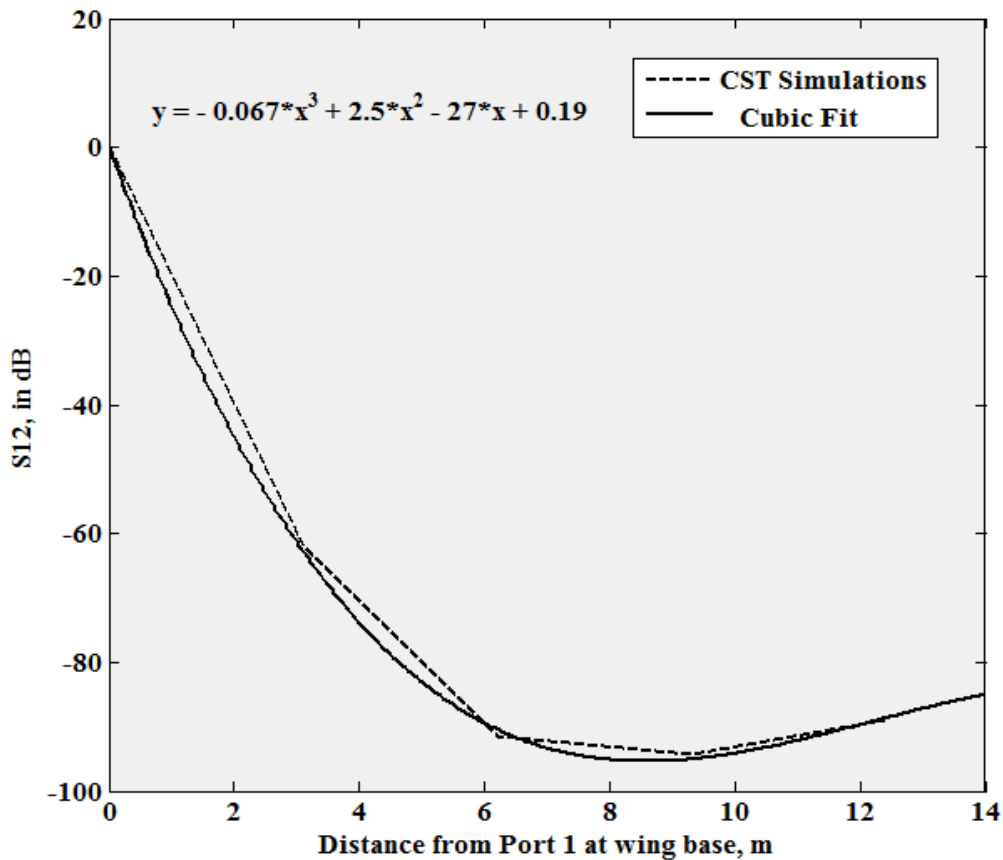


Figure 76: Empty prismatic model, signal attenuation with distance for PEC material.

To determine communication or transmission range, the results of simulations from CST are depicted in Figure 76 and Table 17 for the simple case of the prismatic wing model with PEC material. Figure 76 is the plot of data from Table 17 for PEC, using columns of distance, m and

average parameter, $S_{21,avg}$ dB. While $S_{21,avg}$ is measured in CST simulations only at discrete locations, such as 3.1m, a smooth fit cubic polynomial can be used for the interpolation of the $S_{21,avg}$ parameter for any intermediate distance. A cubic polynomial fit is used for interpolation since higher order polynomial fits might be oscillatory and not a good fit. However, piecewise linear interpolation would also suffice, since the $S_{21,avg}$ values did not change significantly for determining the transmission range. Furthermore, the transmission range was selected as a conservative 1 m, as discussed in later sections.

Table 17: Average S12 with distance from wing base (PEC prismatic model).

Distance from wing base, M	$S_{12,avg}$, dB
0.25	-6.4048
0.50	-12.6934
0.75	-18.6820
1.00	-24.3770
1.25	-29.7846
1.50	-34.9111
1.75	-39.7628
2.00	-44.3460

For example, a gain of around -20 dB indicates a transmission range of 75 cm to 1 m from Table 17 and suggests a mean range of 87.5 cm. Furthermore, if it is assumed that all nodes have to communicate with each other, then a square lattice or topology with inter-node spacing of around 80 cm is the first guess for optimal value. However, this inter-node spacing is for the empty wing model, and with the presence of inner structure, the signal strength decreases rapidly, suggesting the use of even smaller inter-node spacing. However, how close two nodes can be placed is dictated by the interference of the signals, noise and the power dissipated in

nearby structural elements.

Furthermore, in order to evaluate the reliability of connectivity and deployment of nodes for optimization goals, the following essential points need to be considered:

- The transmission range of transceivers at each node can be homogeneous, where all have the same transmission range, or node-based, where each node has its transmission range depending upon its location in the topology.
- Depending on the selection of transmission range, whether homogeneous or node-based, different topologies are possible for the deployment of nodes in WSN.
- The deployment of nodes can be regular or random, and in the case of the empty, prismatic and NACA64A410 models, a random deployment is possible. It is also feasible to test the optimal number of nodes for connectivity. However, in the NACA64A410 model for the inner structure in the wing, arbitrary placement of the nodes is not possible because the deployment will be constrained by the presence of spars, ribs, and other elements in the wing.

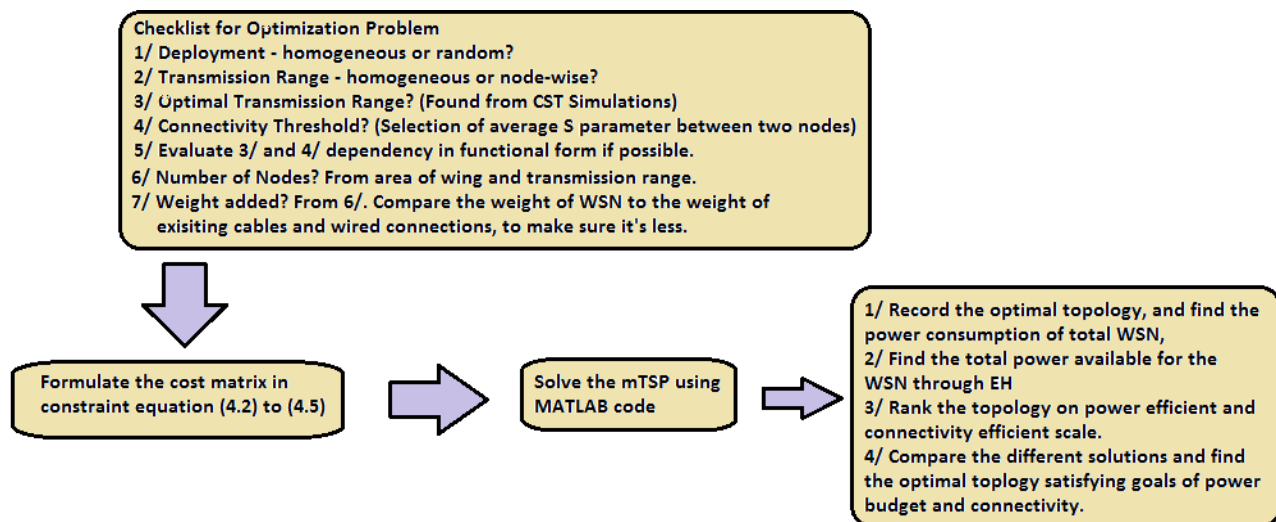


Figure 77: Flowchart for the optimization problem.

The flowchart in Figure 77 presents all the issues and questions to be systematically implemented in the optimization problem.

6.4 Implementation Results

The implementation of mTSP using ACO requires different functionalities. Modular code was developed and implemented in MATLAB. The different functions and code snippets are included and explained in Appendix A. Additional data processing MATLAB codes were also developed and included in the same Appendix with an explanation.

The resulting solutions of optimal topology that lie at the intersection of minimal power-demanding configurations of the WSN, and simultaneously in harmony with those representatives of reliable connectivity of the network, are of most importance. These solutions show varied behaviour within the empty prismatic model and empty NACA64A410 model compared with the NACA64A410 inner structure wing model. In the latter, only homogeneous topology yields reliable connectivity, and trade-offs between reliable connectivity and optimal power demands often do not negotiate in a beneficial manner.

The results include optimal paths for high reliable connectivity and power budget profiles in all three models of an aircraft wing:

- NACA64A410 model for inner structure of the wing
- Empty NACA64A410 model or empty prismatic model of the wing
- Empty wing models.

Regular node deployment of 52, 100, 160, 200 and 240 nodes was simulated to find the shortest distance for the signals originating at nodes near the wing tip. This test case was simple in that optimization of power was decoupled to obtain the shortest routes. Some iteration was required to calibrate the performance of mTSP using ACO. The figures show the shortest routes to increase the number of nodes. The power at each node is identical and assumed to be around 1mW, but it does not enter into computation as the optimization simplified aim is to find the shortest distance from all nodes. The figures indicate increasing minimum distances with an increasing number of nodes, which is anticipated. However, the routes reveal an identical pattern of edgewise signal routing; most of the time, the shortest path is along the nodes that fall in a

straight line between the source and destination nodes.

In addition, it can be seen that cross-talk between nodes mostly occurs when some nodes are small, such as 52 compared to more than 150 nodes. Thus, once the number of nodes exceeds 150, the best routes are along straight edges towards the destination node.

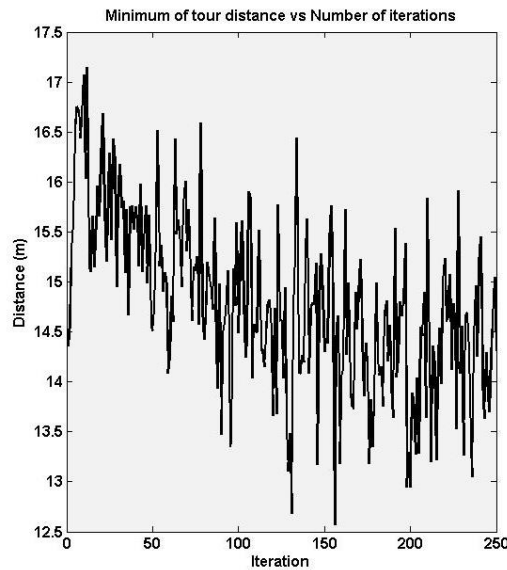


Figure 78: Minimum distance vs number of iterations

The calculation of the minimum tour distance concerning the number of iterations is given in Figure 78. Since the number of nodes is low, the minimum distance iterations show a rapid variation. Such a variation is expected because the number of back-and-forth travels between the nodes, as well the inter-node spacing, is large.

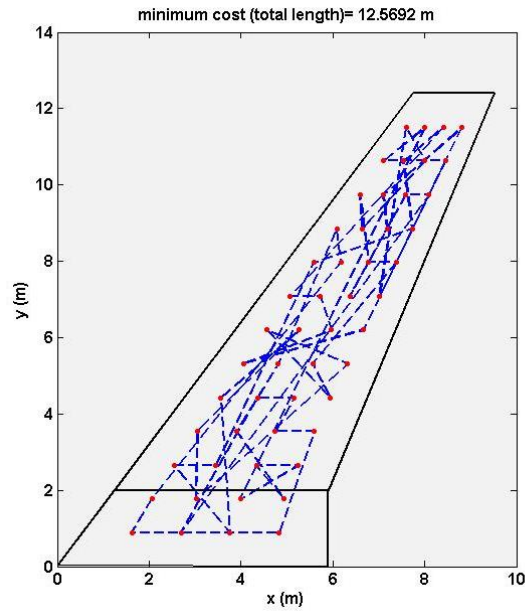


Figure 79: Shortest distance for 52 nodes in empty wing models.

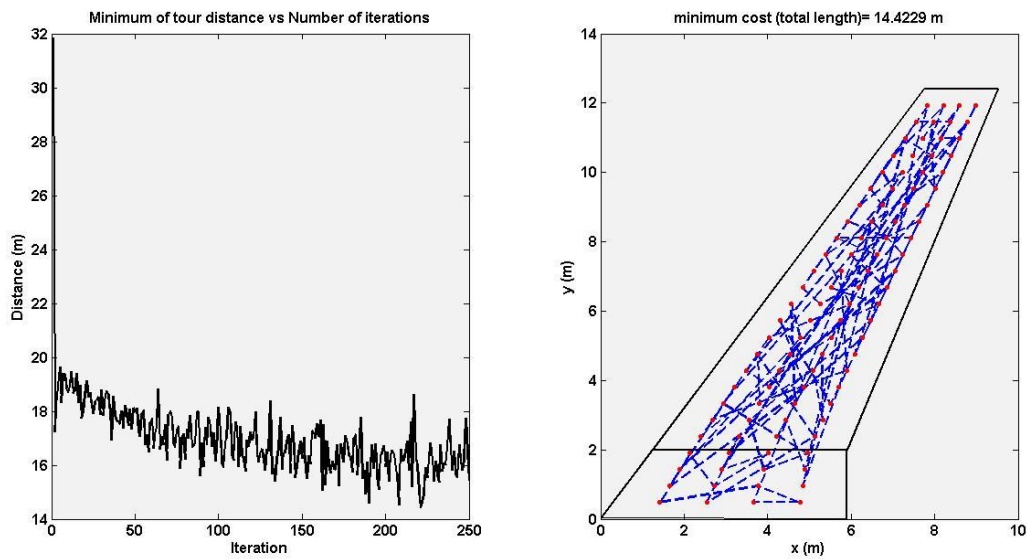


Figure 80: Shortest distance for 100 nodes in empty wing models.

When the number of nodes on empty wing models is increased to 100, the way in which the shortest distance is calculated is given in Figure 80 by applying the multiple travelling salesman problem. As the number of nodes is increased, the characteristics of the solutions change, and for each case set parameters of the simulations are presented in Table 18 below. For each case

of a given number of nodes, the open tour is taken by around 1000 Ants (Initial Setup). This means that 1000 independent probabilistic explorations start off from the four nodes near the wing tip. Since the last row near the wing tip has four nodes, 250 independent explorations start at each node and reach any of the sink nodes at the wing root. The best routes converge after around 150 iterations. This is expected because of initial setup uses a high number of ants. The probability to visit the j th node from the i th node depends as much on the scattering parameter assigned from CST simulations.

Table 18: Simulation summary for mTSP.

Number of nodes, sink nodes	Iteration for convergence	ACO parameters, same for all scenarios	Shortest total distance	Comments
52, 4	160	Maximum number of iterations set are 250, evaporation coefficient is set at 0.19, $\alpha = 0.5$, $\beta = 4$, the number of ants that set out is 1000	12.57	The shortest total distance is observed to increase with the addition of a number of nodes. The observation is expected because more nodes are densely packed and travel distance increases in the horizontal traverse.
100,4	220		14.42	
160,4	185		18.17	
200,4	245		20.38	
240,4	240		26.22	
78, 3			14.04	

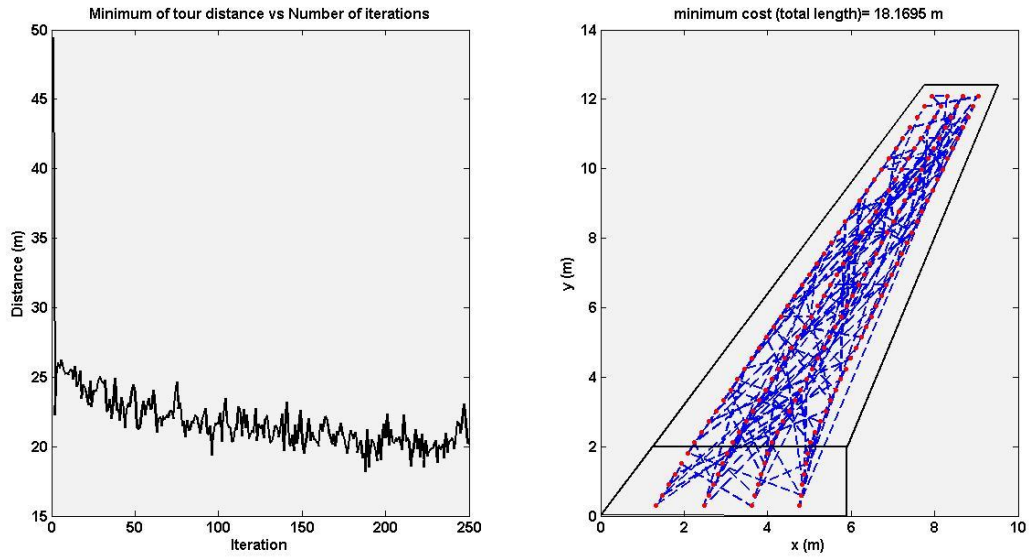


Figure 81: Shortest distance for 160 nodes in empty wing models.

The number of nodes on the aircraft wing was then increased to 160 nodes. Here again, the convergence of the ACO algorithm is smooth compared to the case of 52 nodes.

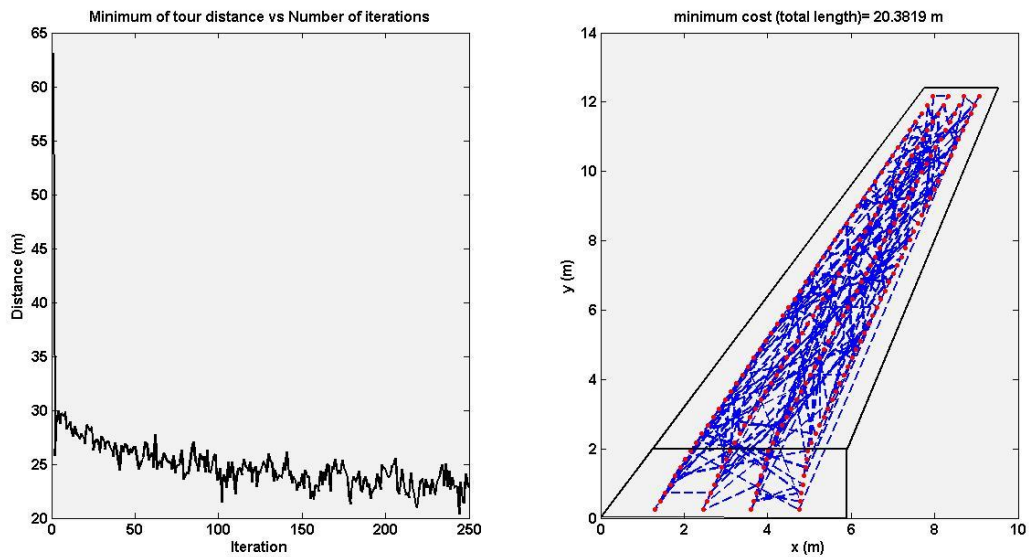


Figure 82: Shortest distance for 200 nodes in empty wing models.

The number of nodes on the aircraft wing was then increased to 200 nodes. This is also the case of final node deployment in all the wing models considering 1m as the transmission range.

Therefore, the convergence of the minimum total travel distance at the 245th iteration, as read

from Figure 82 on the left pane, reveals that convergence is preferably gradual. It is less oscillatory compared to the case of 52 nodes. The shortest distance of 20.38 m is also within the boundary. This distance will dictate the time delay in data aggregation if the data is pulled from the farthest nodes near the wing tip.

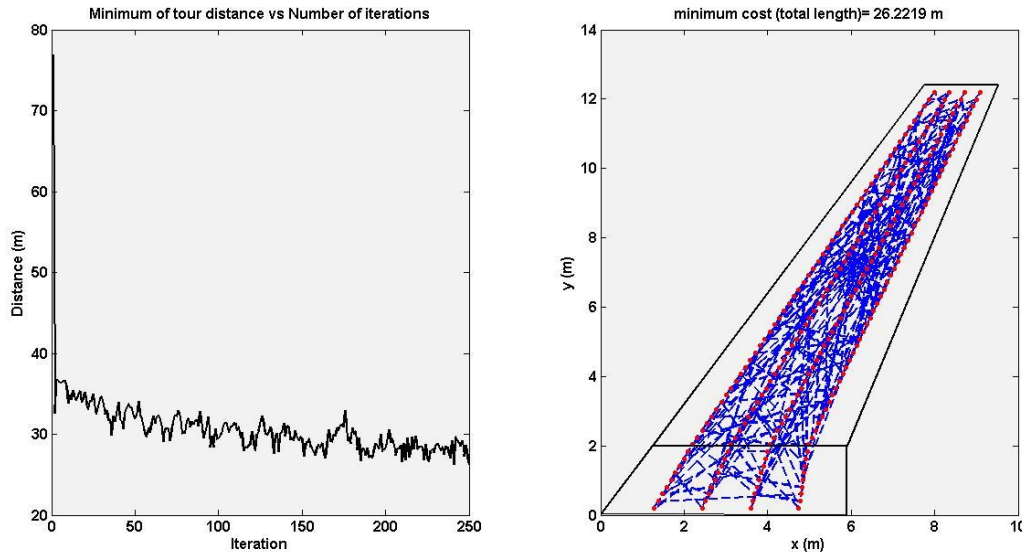


Figure 83: Shortest distance for 240 nodes in empty wing models.

With the final case of using 240 nodes, a trade-off can be executed. The shortest distance of around 26.22 m was found in the case of 240 nodes deployed in the empty wing (see Figure 83). A further increase in the shortest distance entails adverse delay times in data aggregation. In addition, since the inter-node spacing is reduced, it will add to more interference and congestion. Therefore, the case of 200 nodes is optimal.

The implications of studying shortest distance signal routing in empty wings are as follows:

- With the increased number of nodes (>150) the shortest route is along straight edges towards the destination node when four nodes are fixed at the wing root. Enumerated paths can be tested to find solutions quickly in the case of the realistic wing model.
- Given the presence of spars and ribs, the signal visibility between nodes is along the direction perpendicular to the ribs, through their circular holes. The best routes are anticipated to be similar to the routes in the empty wing model below the limit of higher

node density (total number of nodes > 500).

These claims are evaluated in the realistic wing model in the next section.

- **Realistic NACA64A410 model**

The realistic wing model has ribs and spars that significantly attenuate the signals. Signal propagation across spars is very weak, and it was not possible to chart out a reliable route to the destination. Figure 84 shows the anticipated routes for the signals towards destination nodes.

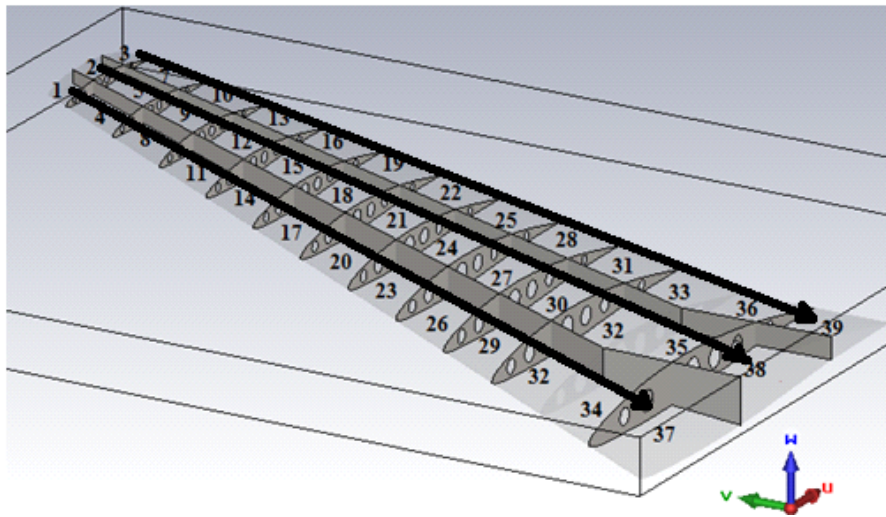


Figure 84: Signal routes towards destination and nodes in the realistic NACA64A410 model.

The nodes labelled with numbers in the positions and arrows show the preferred direction of signal routing. To illustrate this, consider node 1, which has 2, 3 and 4 as its immediate neighbours, but the links to nodes 2 and 3 would be weaker than to 4. Thus, the first preferred neighbouring node will be 4, and from 4 it will be 8, and so on. The first choice of the best path is hence along the arrows, as shown in Figure 84. Therefore, the optimization of node topology can be divided into nodes within shorter compartments created by the presence of ribs and spars. Moreover, the number of nodes within these compartments cannot exceed five or six. It is thus imperative to assess the different ZigBee nodes and their functionality.

The three types of ZigBee devices are based on these node types, as shown in Figure 85.

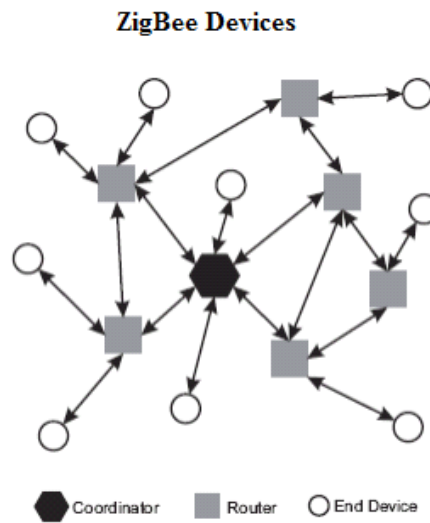


Figure 85: ZigBee Devices

Coordinators and routers are Fully Functional Devices (FFDs). These have higher energy requirements compared to End Devices, which are Reduced Functional Devices (RFDs). As the only function of RFDs is to transmit application data packets, they need less energy. The feasibility of a ZigBee WSN across the wing compartments, as shown in Figure 85, was assessed based on the following scenarios.

Scenario 1

Objective – To find an efficient communication placement of ZigBee nodes in the wing.

Compartment numbers were used to chart out the type of ZigBee node and its location. The holes in the ribs are the only line of sight paths for the signals; therefore, it is easy to see that sensors should be placed near the rib holes. In terms of what kind of device node should be placed, it should be clear that all nodes, as end devices, cannot be used as they cannot communicate with each other. Routers thus have to be used. Figure 86 presents a simple possible arrangement of end devices and routers at rib holes in each compartment. The wing region and compartments are drawn perfectly rectangularly for simplification.

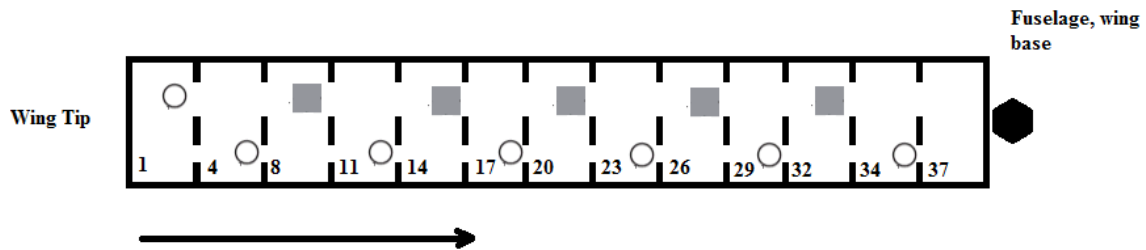


Figure 86: Optimal configuration: Config1.

The arrangement is shown only for compartments 1, 4, 8 - 37 and is identical for compartments 2, 5, 9 - 38 and 3, 7, 10 - 39. The ZigBee devices required are seven end devices, five routers, and one coordinator, i.e. a total of 13 for the wing compartments, as shown in Figure 87.

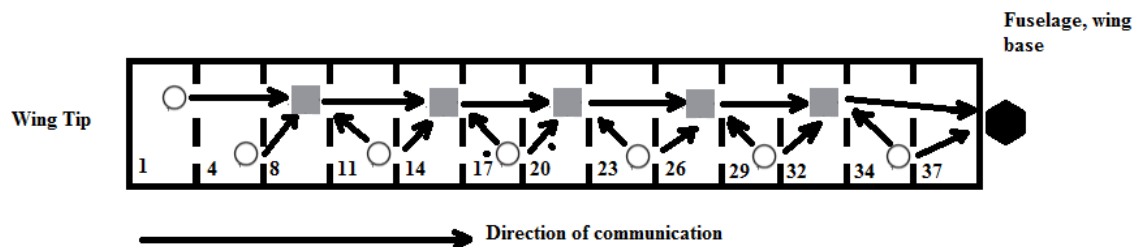


Figure 87: Communication across nodes.

For the complete wing, there will be $13 \times 3 = 39$ nodes. The communication will be as shown in Figure 87. The placement of at least one node in each compartment therefore gives the minimal baseline WSN, and reliability of communication is expected as the inter-compartmental distances are small. However, a more reliable scenario is little more redundant than 1 and is discussed next.

Scenario 2

Objective – To find a more communication efficient version of scenario 1.

Quality and efficiency can be improved by the placement of at least two nodes in each compartment. One of them should be a router, as this will guarantee two-way communication.

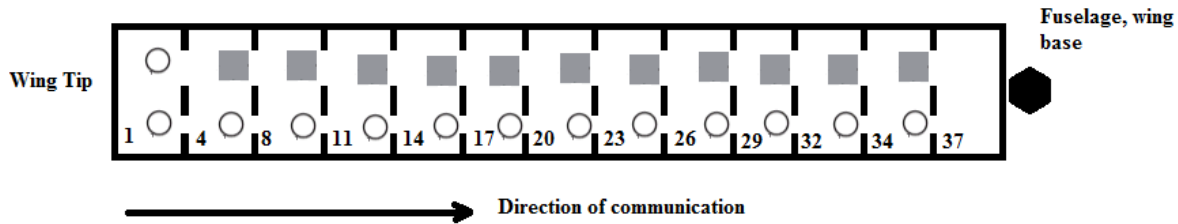


Figure 88: Reliable communication configuration: Config2.

The configuration is shown in Figure 88. A total of 25 nodes are required, including the coordinator, as shown in Figure 88. Hence, a total of 75 nodes are required. Since a router is present in almost every compartment, efficiency is higher, given there is no link failure between routers.

Scenario 3

Objective – To find a more reliable communication version of scenario 2.

Reliability can be improved by using routing devices in all locations except the near wing tip compartments, as shown in Figure 89. However, since more routers are used, energy requirements will be comparatively higher. An alternative is to use only one device per compartment, and for reliability, it is obvious that the device should be routed as shown in Figure 89.

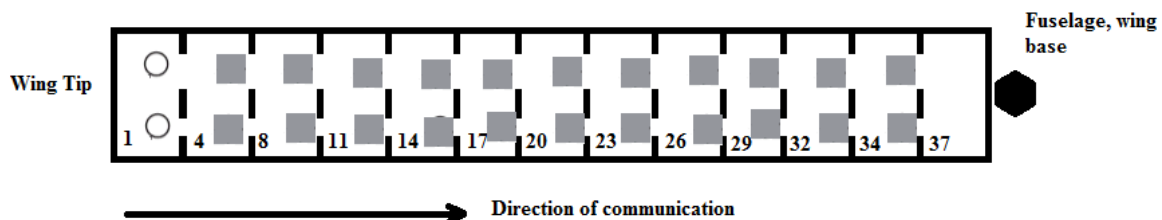


Figure 89: More reliable communication configuration: Config3.

The details of the configuration of the nodes on the aircraft wing are given in Figure 89. The clear details of the wing tip, base and the other nodes are given in Figure 89.

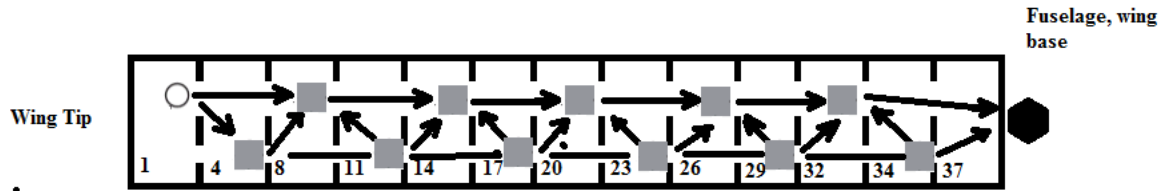


Figure 90: A better energy efficient and reliable configuration: Config4.

These different scenarios can be evaluated for different power-efficient routing protocols. The routing protocol will be table-based, and the shortest route tables will therefore be prepared using global information of nodes.

6.5 Routing Algorithm

The routing in the realistic wing model has different constraints compared to routing in the empty wing models, whether NACA64A410 or prismatic. It was, however, to the first approximation, warranted to investigate the possible paths of connectivity in empty wing models. A CST simulation was set up to determine the S parameter values for a set of 79 nodes in the empty prismatic wing. Each node communicates with every other node in the topology, as shown in Figure 91.

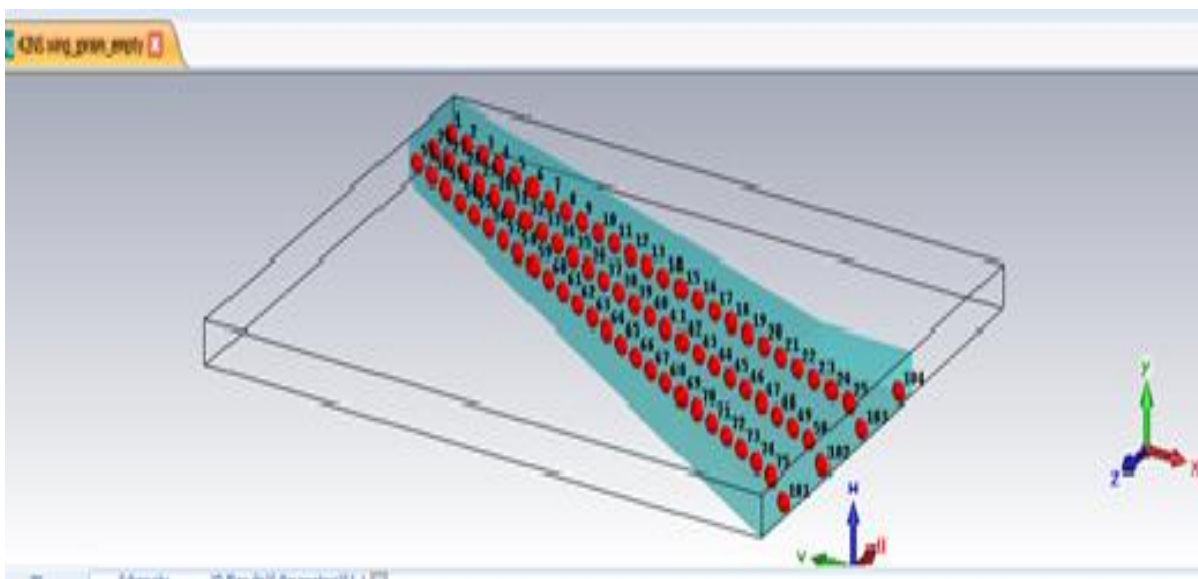


Figure 91: Non-centralized (distributed) scenario for 79 sensor nodes.

It forms a 79 x 79 matrix for S parameters. The S parameter values are averaged over the frequency range of 2.4 to 2.5 GHz, and then presented in the matrix from the MATLAB processing (refer to Appendix D for the S-matrix).

It is also easy to see the S parameter from a particular selected node to others. A plot of a row in the S parameter matrix is shown above. For example, the plot for a set of 3, 4, 5 nodes from near the wing tip to all others is shown in Appendix D.

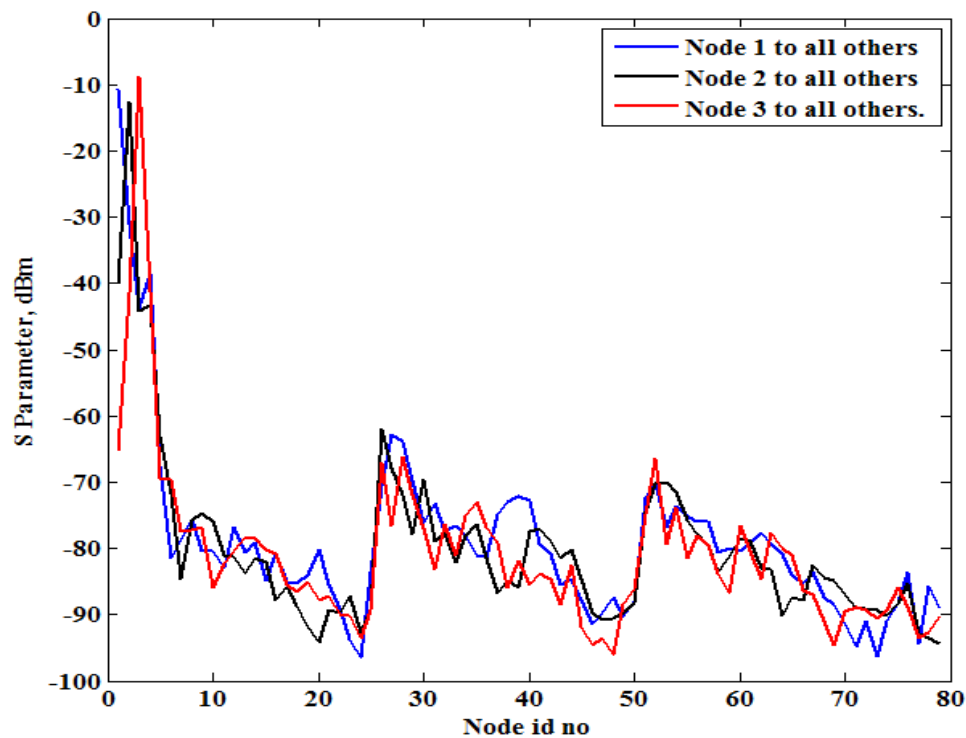


Figure 92: S parameter from the selected node to all other nodes in panels (A) (self-explanatory through legends).

The change in S parameter values for each node present in panel A when each node communicates with other nodes is shown in Figure 92 above.

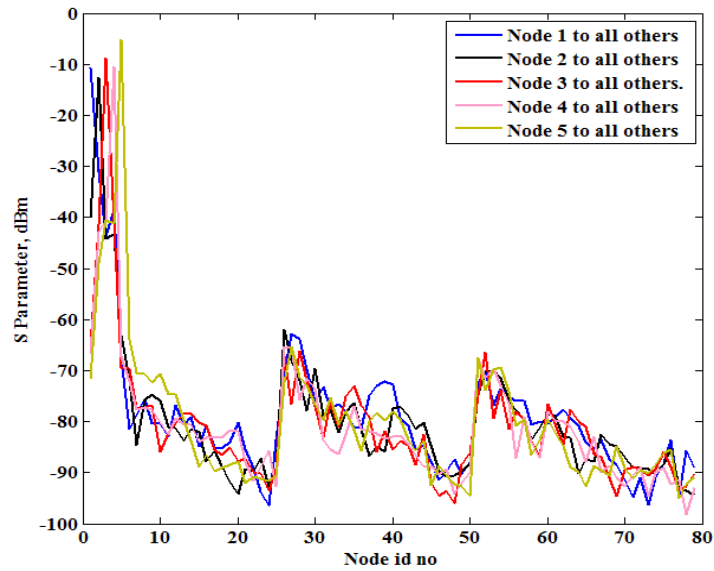


Figure 93: S parameter from the selected node to all other nodes in panels (A) (self-explanatory through legends).

The change in S parameter values for each node present in panel B when each node communicates with other nodes is shown in Figure 93 above.

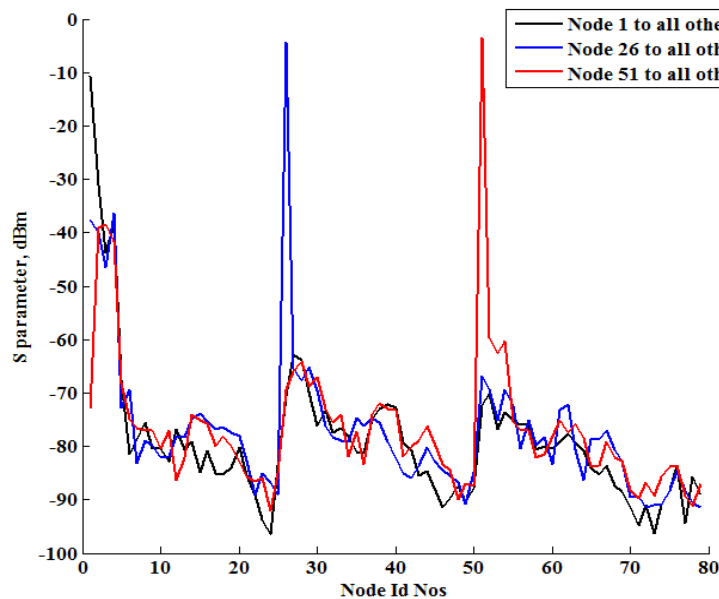


Figure 94: S parameter from the selected node to all other nodes in panels (C) (self-explanatory through legends).

The change in S parameter values for each node present in panel C when each node communicates with other nodes is shown in Figure 94 above.

Figure 94 clearly shows through different comparisons that each node is able to communicate effectively with a few neighbouring nodes, typically 4-5, above S parameter values of -50dBm. Compared to the sensitivity of ZigBee units, which is typically around -90dBm or less in few cases, higher chances of assured connectivity exist between neighbouring 4-5 nodes. Hence the suggested topology is 4 or 5-connected. In other words, each node should transmit its data signal to around four nodes which are adjacent neighbours, and which should not overlap. The S parameter results were also found to match with mTSP analysis of the shortest distance for the signal from the figure below.

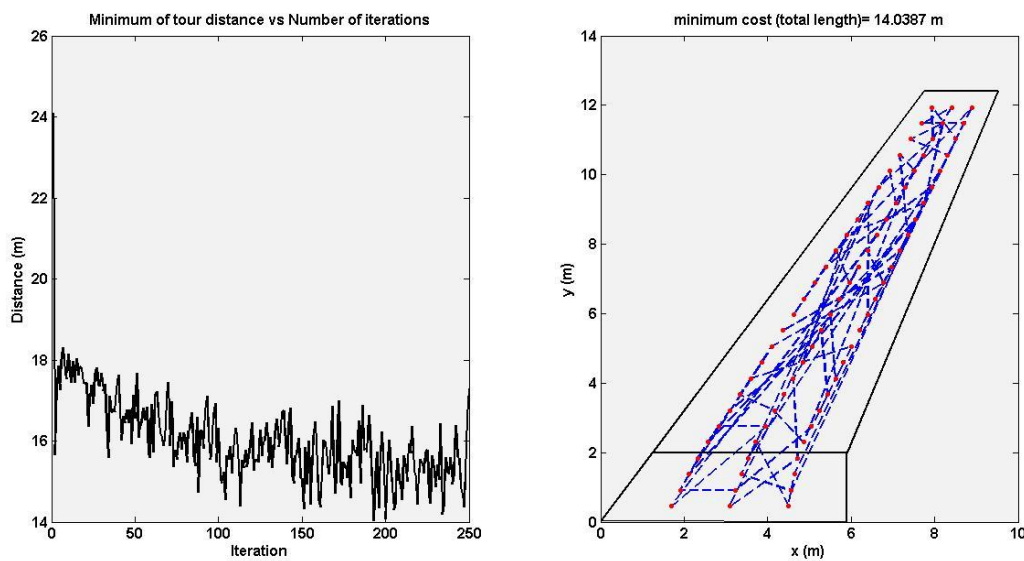


Figure 95: mTSP result for 78 nodes in the empty wing.

The mTSP results in Figure 95 also indicate that each node should be connected to at least four neighbouring nodes. Routing from the farthest node in the 4-connected topology can efficiently route the signal to the nodes at the wing root. When this scenario was compared independently, the S parameter and shortest distance constraints on the identification of k-connected topology were found to be 4-connected.

The constraints of power at each node and its effect on routing will be considered in future work.

6.6 Summary and Conclusions

Important WSN design considerations, such as node deployment, energy consumption, and performance metrics, were assessed in this chapter. The output of the models, namely MatLab and CST simulations, were consolidated to assess the performance metrics of the final WSN.

To summarize node deployment, the findings from the empty wing model and realistic wing model were analysed systematically. Node deployment is decided by the wing structural elements, as these prompt a path loss model. CST simulations provide the S parameters at various distances along wing length. Using the S parameter profile at 2.4-2.5GHz at various distances along the wing length, a correlation between the number of nodes and transmission range and levels of interference was obtained. A transmission range of 1 m was obtained using the minima of the profile. Based on a regular square grid arrangement of nodes in all wing models, the outputs of this chapter are as follows:

1. Around 200 nodes were deployed with a 1m^2 transmission range, and the shortest distance was found to be 20.38 m. The throughput of this WSN was around 50Kbps, but it decreases as the transmission range is increased from 1m onwards. The energy consumption of the network was 1.34J.
2. The data rate from the farthest nodes affects the overall data rate. Since the transmission range is 1m, the data aggregation from the farthest nodes, viz. those near the wing tip, accounts for a substantial portion of the data rate. Therefore, the effective data rate will decrease as the farthest nodes transmit all of their data to sink nodes.

The WSN is affected by issues relating to the power constraints of the sensor nodes, which affects the network lifetime. This is investigated in the next chapter, which analyses the power transfer characteristics of the aircraft wing in which the wireless sensor network is deployed.

7.1 Overview

The effective utilization of wireless sensor networks for aircraft SHM applications requires some critical design challenges to be addressed. Among several of the design challenges associated with the wireless sensor network, and indicated in [159], the power constraints of sensor nodes affecting the network's lifetime is a key challenge to be addressed. This chapter intends to address the power constraint challenges of sensor nodes, by analysing the power transfer characteristics of aircraft wings, as this is where wireless sensor networks are deployed.

This analysis of the power transfer characteristics of aircraft wings helps us achieve the aims and objectives of this thesis; as it will clarify the feasibility of using ZigBee communications on aircraft wings for SHM applications. Details of simulation setups, and simulation results obtained from CST and Mat lab are set out in this chapter. Towards the end of the chapter, a comparative analysis of NC37 and NC38 simulations regarding S-Parameters, and the minimum power consumed by each node is presented. This approach to analysing power transfer features using CST simulations helps identify how to minimise the power consumption of each sensor node in accordance with the direction of communication.

7.2 Simulation Setup

In the simulation, discrete ports in CST were used to model node antennas, as given in Figure 96. In this process, the 50Ω normalized S-parameter, obtained through a transient solver is used. Through the application of a Gaussian excitation signal of 70 ns, the mesh setting of WSN was very fine. The Integral Solver was optimized, and 48 multi threads used for five equidistant samples across a range of 2.4 to 2.5 GHz frequency. The 1D results tapped out were,

- S-parameters normalized with 50Ω
- Currents and voltages at discrete ports

- Y and Z matrices of the ports
- Convergence
- Voltage Standing Wave Ratio

The steps used to set up the simulation are detailed in the figures below. Using the discrete port setup in CST, as shown in Figure 96, the Excitation signal is as shown in Figure 96. Figure 97 shows the fine mesh of the WSN prepared using the integral resolver, and the screen used for the solver setup is shown in Figures 97 and 98.

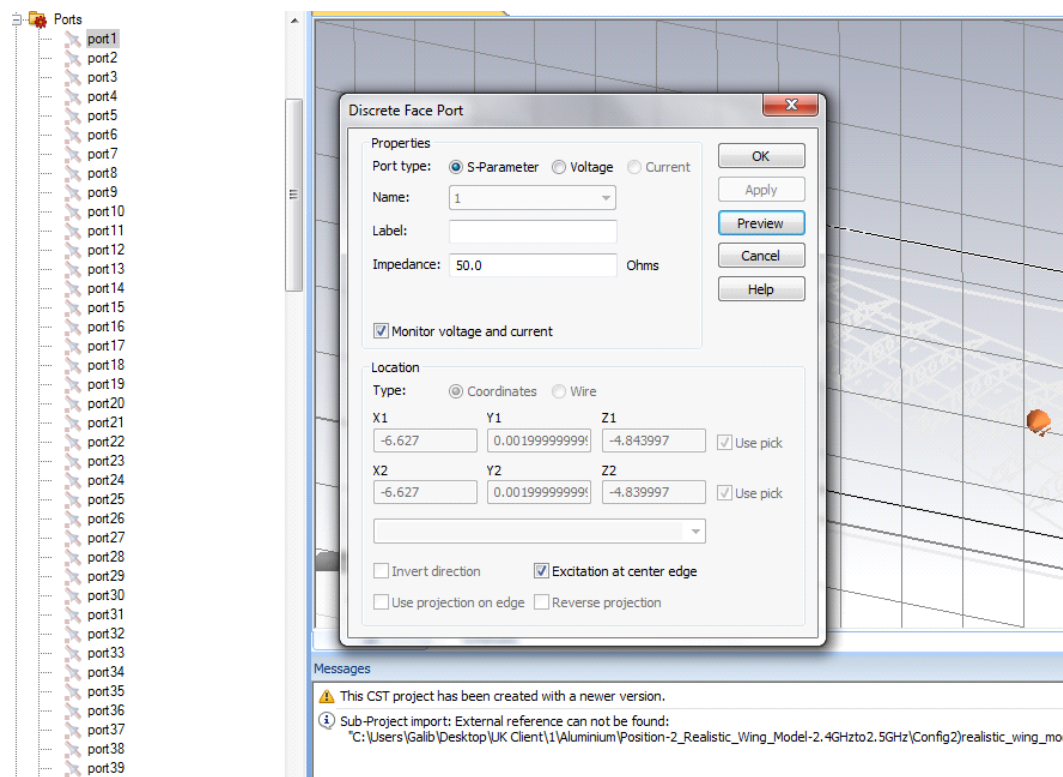


Figure 96: Discrete port set up

The details for the discrete port set up are given in figure 96, wherein the discrete ports in CST were used to model node antennas. In this set up, a 50Ω normalized S-parameter, obtained through a transient solver is used.

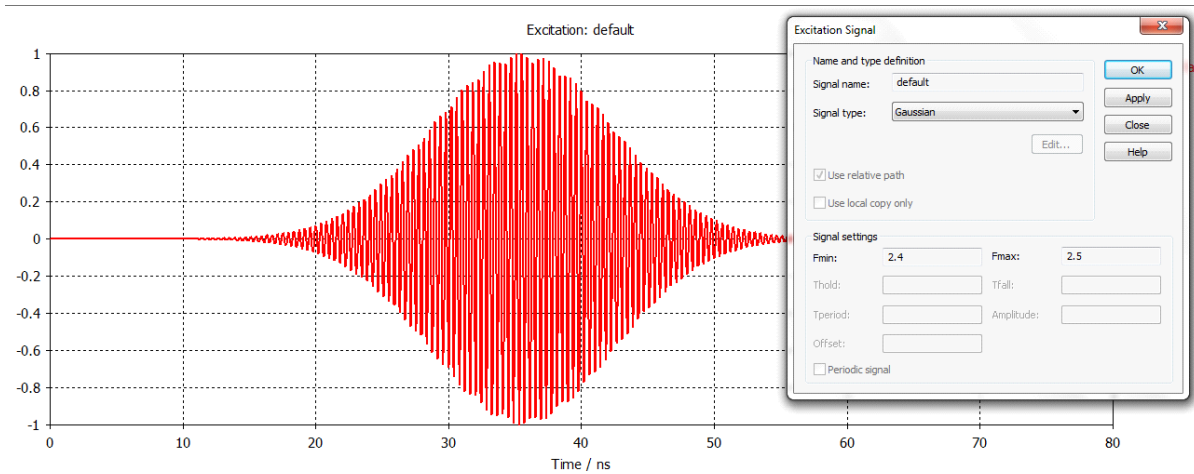


Figure 97: Excitation signal setup

An excitation signal setup is one of the setups used during the simulation process, as shown in figure 97.

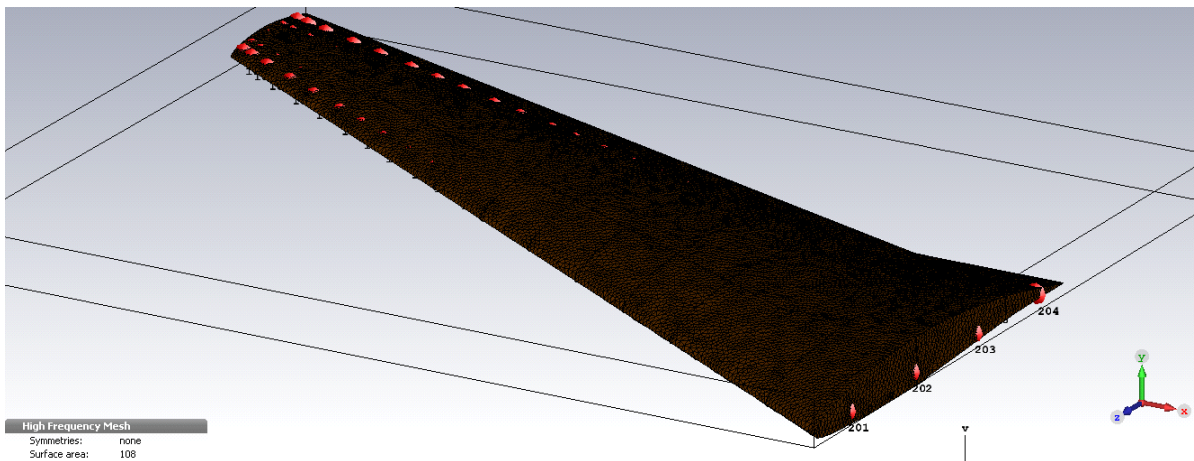


Figure 98: Fine mesh for integral solver

The fine mesh obtained after the excitation signal setup is given in figure 98. Here the details of some of the nodes are given in a red colour.

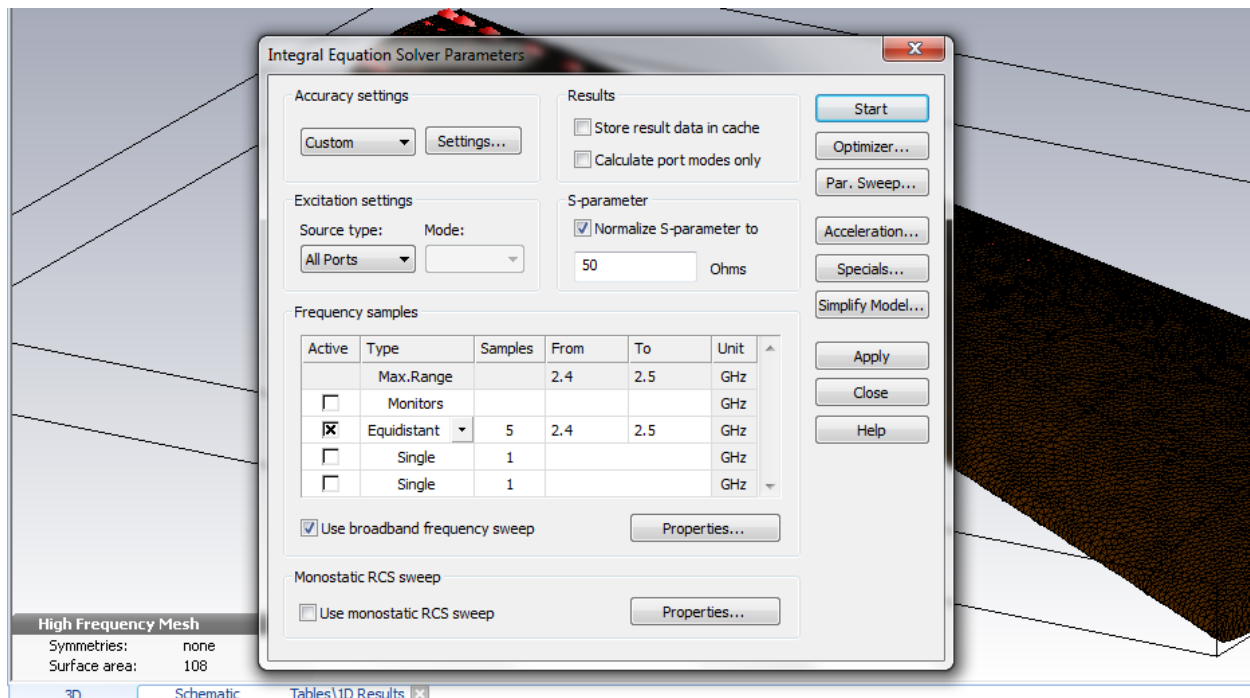


Figure 99: Solver setup

The solver setup is another approach to setup used for the simulation process. The details of this solver setup are included in figure 99.

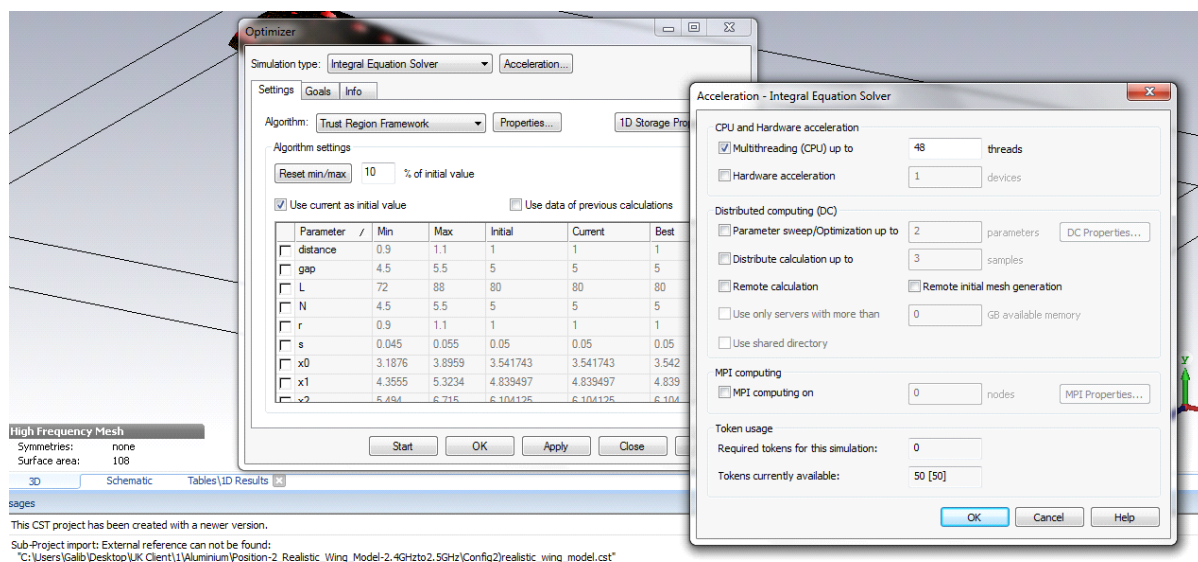


Figure 100: Solver setup – acceleration

As part of the solver setup, acceleration is undertaken to promote a quick simulation process. The details of this acceleration are given in figure 100. All the above figures reveal how each

CST simulation was carried out, and the different parameters defined in order to analyse the power transfer characteristics of the sensor nodes deployed on the aircraft wing.

7.3 CST Results

The outputs obtained from the CST simulation are grouped into five categories: S-parameters, balanced S-parameters, discrete port currents, discrete port voltages, and Convergence of transient integral solver (as indicated in the figures below obtained from the NC37 CST simulation).

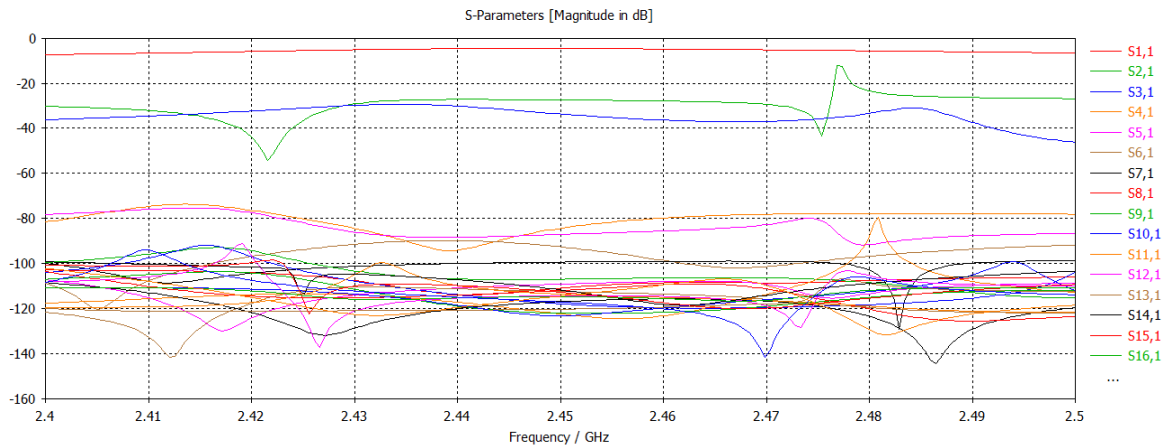


Figure 101: S-parameters CST results

Figure 101 above specifies the S-parameters for the CST results, between the 2.4 and 2.5 GHz frequency range.

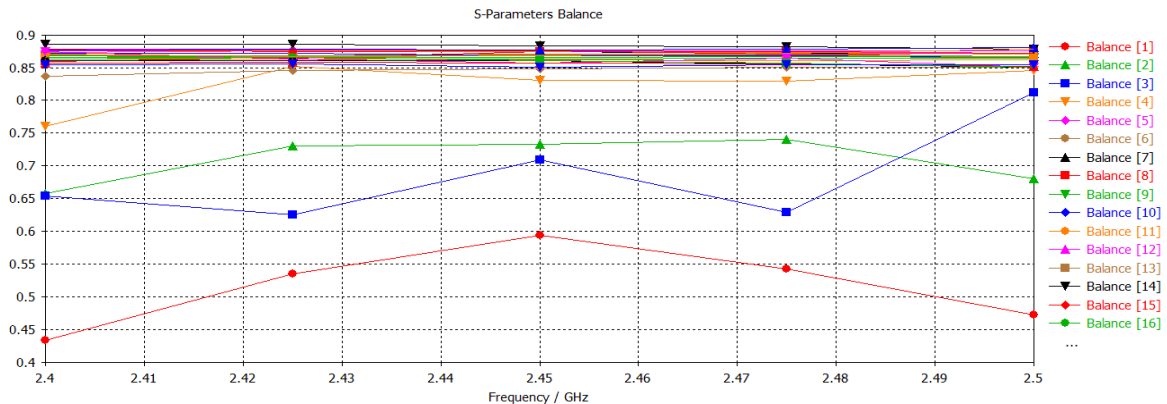


Figure 102: Reduced S-parameter results

Figure 102 above specifies the reduced S-parameters values for the CST results between the 2.4 and 2.5 GHz frequency range.

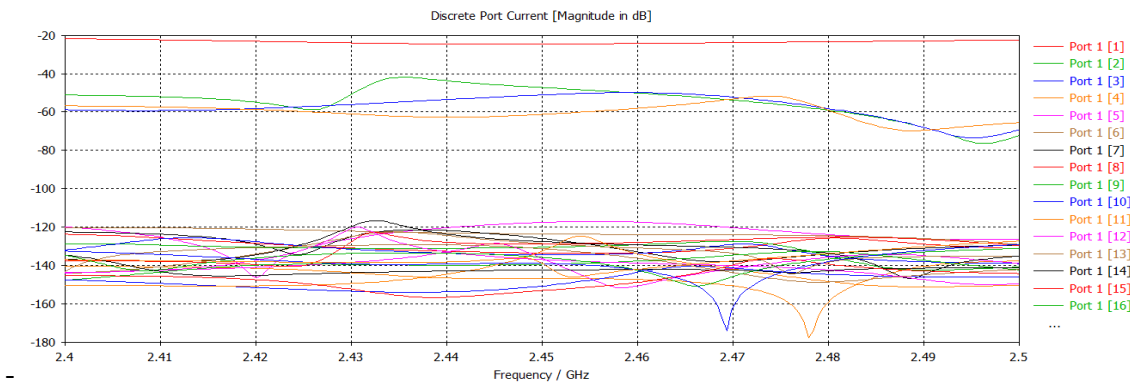


Figure 103: Discrete port currents

Figure 103 above specifies the discrete port currents for the CST results between the 2.4 and 2.5 GHz frequency range.

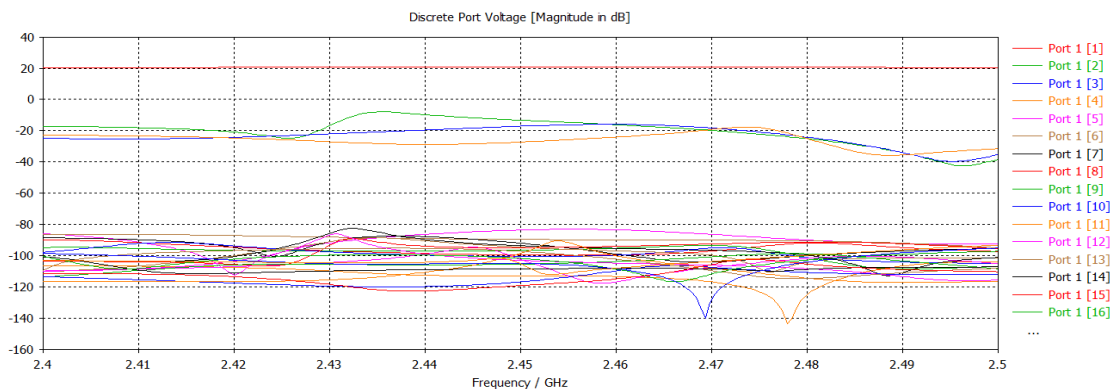


Figure 104: Discrete port voltages - Convergence of the solver

Figure 104 above specifies the discrete port voltages for the CST results between the 2.4 and 2.5 GHz frequency range.

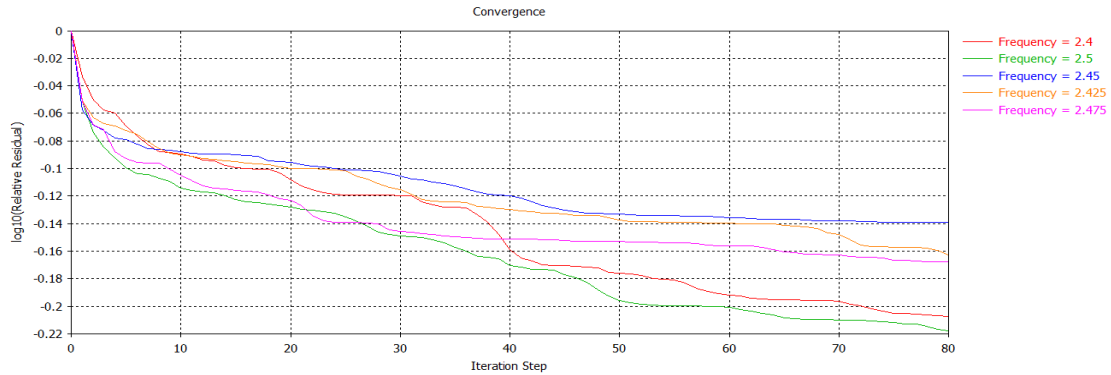


Figure 105: Convergence of transient integral solver

Figure 105 above specifies the convergence of the transient integral solver of the CST results between the 2.4 and 2.5 GHz frequency range.

7.3.1 Explanation

The NC37 and NC38 CST simulations have been of considerable benefit in identifying the variations in S-Parameters, balanced S-parameters, discrete port currents, discrete port voltages and the Convergence of transient integral solvers. With respect to the S-parameter, $S_{1,1}$ recorded a higher value than the other parameter values within a frequency range of 2.4 to 2.5 GHz. This implies the existence of a higher link budget value effecting the first antenna, rather than the other antenna levels. Similarly, the variation in the reduced S-parameter value, between the range frequency of 2.4 and 2.5 GHz showed possibility for balance [1], recording a better level of balance than the other options. The value of the reduced S-parameter results, which are represented as balance, started to increase later, and then fluctuated with an increase in the frequency level between 2.4 and 2.5GHz. In the simulation process, the use of discrete port currents took place, and the variation level could then be clarified. From an analysis of this level of variation, it can be implied that as port number increased, the port current value declined. From this graphical result, it can be implied that an increase in port number, results in a corresponding increase in the value of the current level supplied. This clearly shows the capacity of initial ports to support a discrete level of port current to a greater extent than the other ports. The same situation is identified to be true in the case of discrete port voltages, as the initial ports were provided with higher voltages than the others. The main reason behind this appears to be

that the initial ports supply a higher level of discrete current, and thereby have higher discrete voltage levels than those obtained from the graphs. The transient integral solver value was found to decline with an increase in the number of iterations. When compared with one another, the values for the transient integral solver for the frequency level 2.45 GHz tended to be higher when compared to other frequency levels, such as 2.4 GHz, 2.5 GHz, 2.425 GHz and 2.475 GHz. This clearly shows the increase in the power transfer characteristics of sensor nodes parallels an increase in frequency level, where the optimum level for frequency remained 2.45 GHz. This finding correlates with the findings reported in the literature regarding the power transfer characteristics of wireless sensor networks.

7.3.2 CST Results in Mat Lab

In addition to visualizing these CST results, a thorough analysis is required, and therefore findings need to be imported into MATLAB. After importing the data, Plot Wing, can be used to plot wing layout in MATLAB. The code used to plot the aircraft wing, as illustrated in Figure 106, is included in Appendix A.

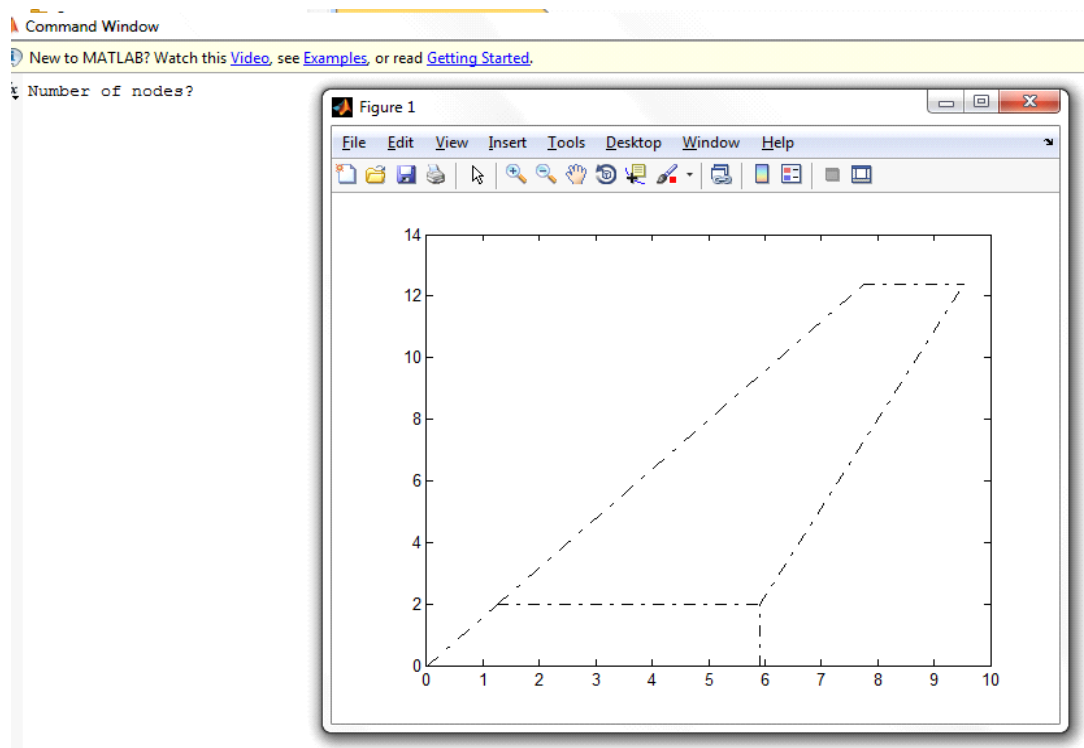


Figure 106: Wing layout plot in MATLAB. See Appendix A.1 for the code.

Figure 106 displays the simulated aircraft wing mode as it appears in Mat lab. For this simulated wing, the details of the wing structure place less emphasis on the number of nodes on the wing.

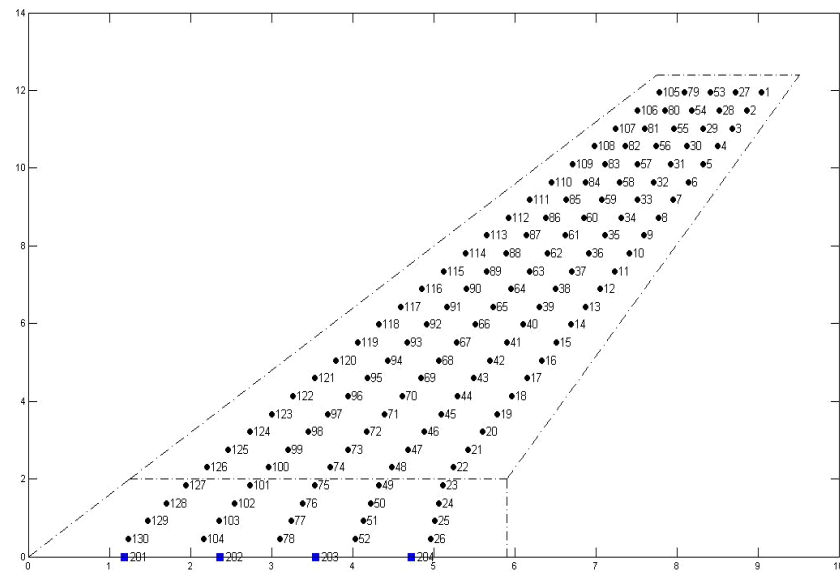


Figure 107: Node numbering and positions for NC37 and NC38

Figure 107 displays the simulated aircraft wing mode, with all 13 nodes deployed and labelled. The MATLAB code for the proposed routing protocol explained in the next chapter performs the function of displaying the S-parameter of the selected node at 2.4.

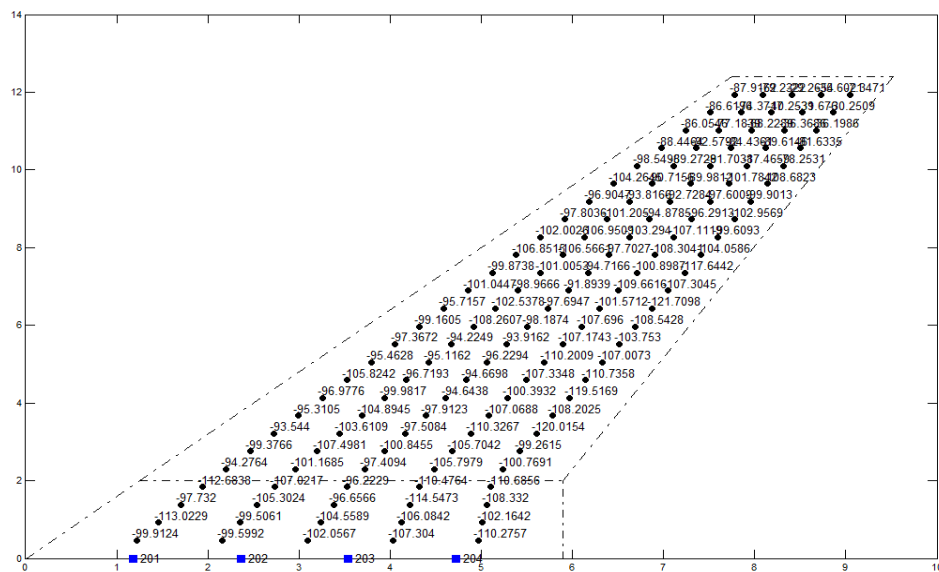


Figure 108: S-parameters from Node 1 to all others for 2.4 GHz

As part of the proposed routing protocol, S-parameters can be used to rank the best neighbouring nodes, to thereby identify the best routes for multi-hop transmission. Figure 108 above shows routes for transmission from ports near the wing tip.

7.4 Critical Analysis

The results obtained are in the form of an S-parameter between different nodes, as they communicate with all other nodes. An Excel program is used to help visualize the behaviour of S-parameters from a select node in the WSN to all other nodes, using NC 37 and NC 38 simulations. This Excel file was assembled using an exploratory tool to assist in the comparison of the S-parameters for the NC37 and NC38 simulation, as shown in Figure 109.

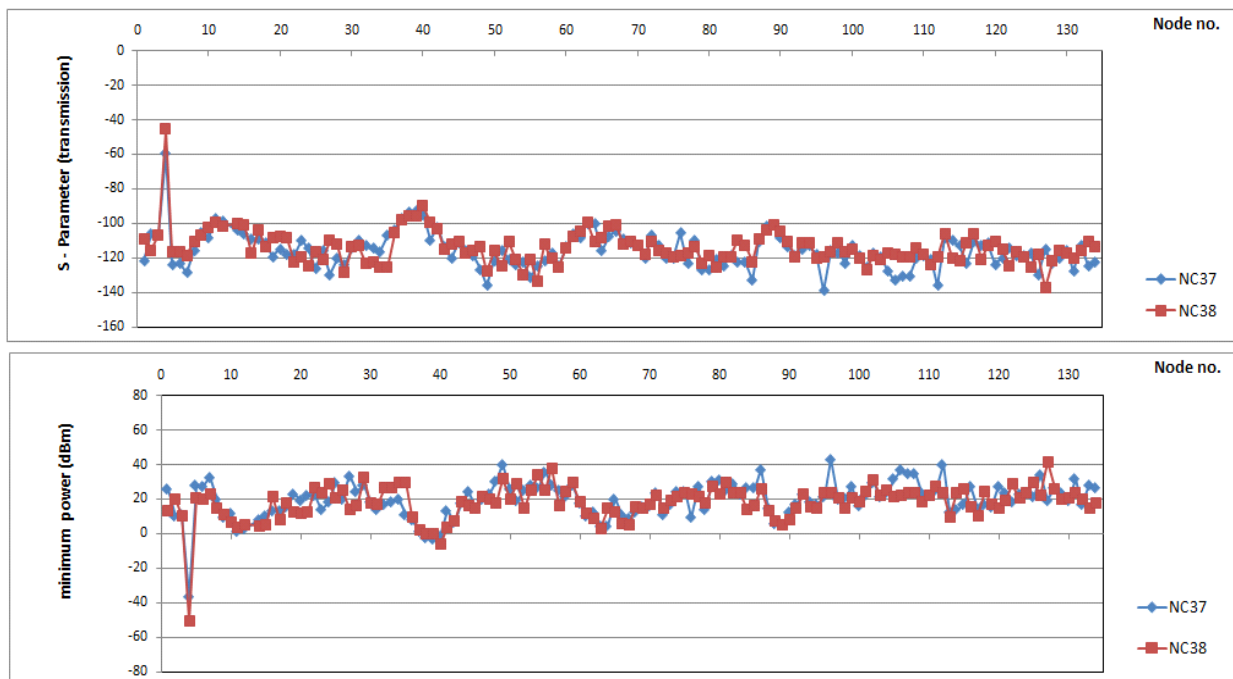


Figure 109: Comparative behaviour of S-parameter from Node 13 to all other nodes.

Comparison data for the S-parameter values from the node 13 to the other nodes present in aircraft wings, are given in figure 109.

Table 19: S-Parameter (transmission, link budget for NC 37 Node 26)

Neighbour node	-2	-1	1	2
x direction	-100	-92.2	0	0
y direction	-100	-87.8	0	0
45° direction	-105	-98.2	0	0
- 45° direction	0	0	0	0

The link budget values for node 26 are present in NC37 wing structures, as tabulated in table 19.

Table 20: Minimum Power needed for communication, NC37 node 26

Sensitivity of the node (dBm): -96				
Neighbour node	-2	-1	1	2
x direction	4.112			
	9	-3.794	n.c.	n.c.
y direction	4.464			
	9	-8.244	n.c.	n.c.
45° direction	8.592	2.226		
	5	1	n.c.	n.c.
- 45° direction	n.c.	n.c.	n.c.	n.c.

Table 20 gives the details for the minimum power needed to support communication by node 26 in the NC37 wing.

Table 21: Minimum Power needed for communication in mW, NC37, Node 26

Neighbour node	-2	-1	1	2
x direction	2.58	0.42	n.c.	n.c.
y direction	2.80	0.15	n.c.	n.c.
45° direction	7.23	1.67	n.c.	n.c.
- 45° direction	n.c.	n.c.	n.c.	n.c.

The details for minimum power required (in mW) to support communication by node 26 in NC37 wing are given in table 21.

Table 22: Minimum needed Power for communication in uW, NC37, and Node 26

Neighbour node	-2	-1	1	2
x direction	2578.036	417.416	n.c.	n.c.
y direction	2795.683	149.832	n.c.	n.c.
45° direction	7231.910	1669.573	n.c.	n.c.
- 45° direction	n.c.	n.c.	n.c.	n.c.

The details for minimum power in uW required to support communication by node 26 in NC37 wing are given in table 22.

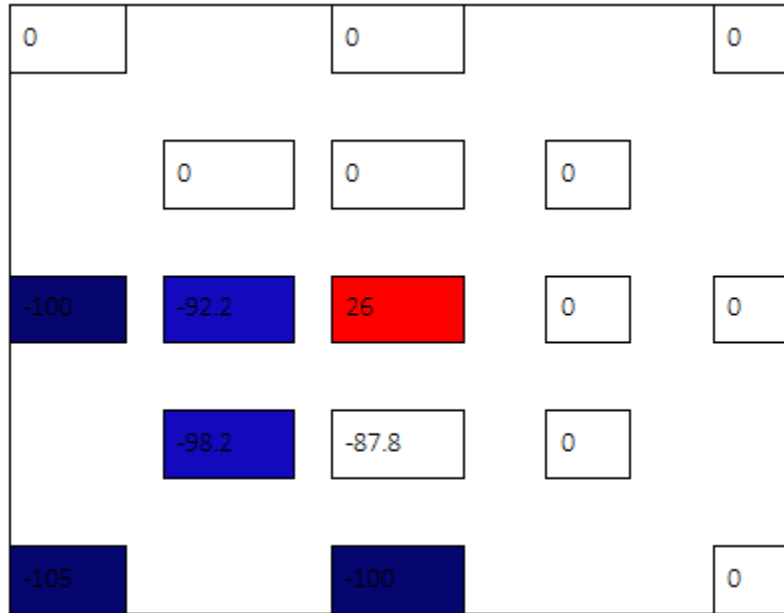


Figure 110: Link budget (S-Parameter), NC 37, Node 26

The details of S-Parameters, specifying the link budget value for node 26 in wing NC37 is given in figure 110.

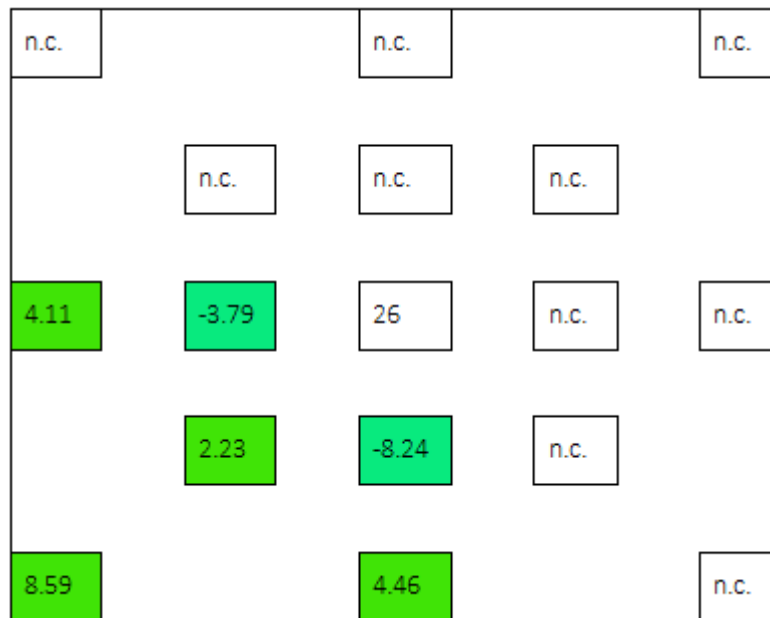


Figure 111: Minimum power to communicate with neighbouring nodes (dBm), NC37, node 26

The details of the minimum power needed for communication with neighbouring nodes in the form of decibels for node 26 of the NC37 wing structure is given in figure 111.

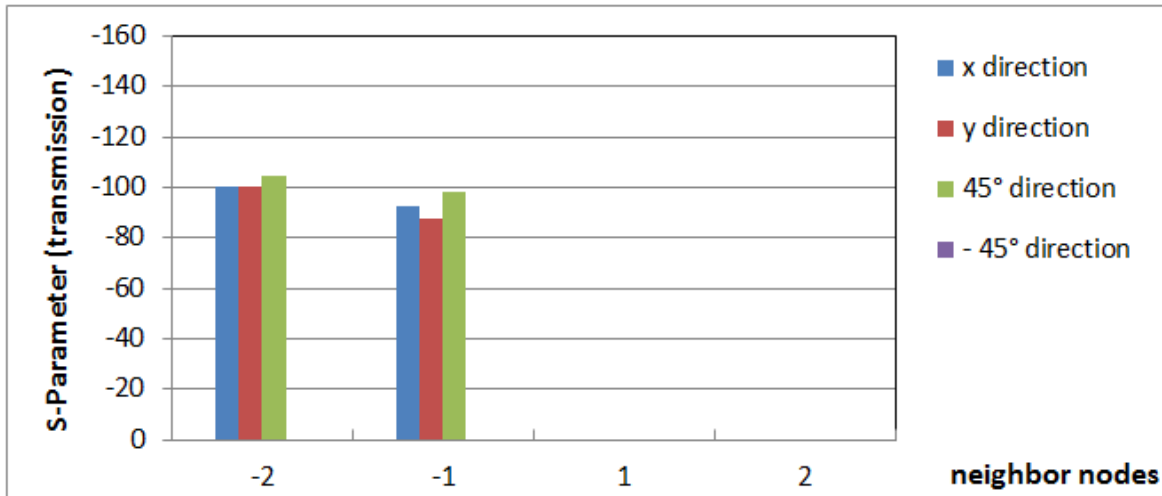


Figure 112: S-parameter of node 26, NC37

The details of the S-parameter for node 26 on the NC37 wing structure is given in figure 112.

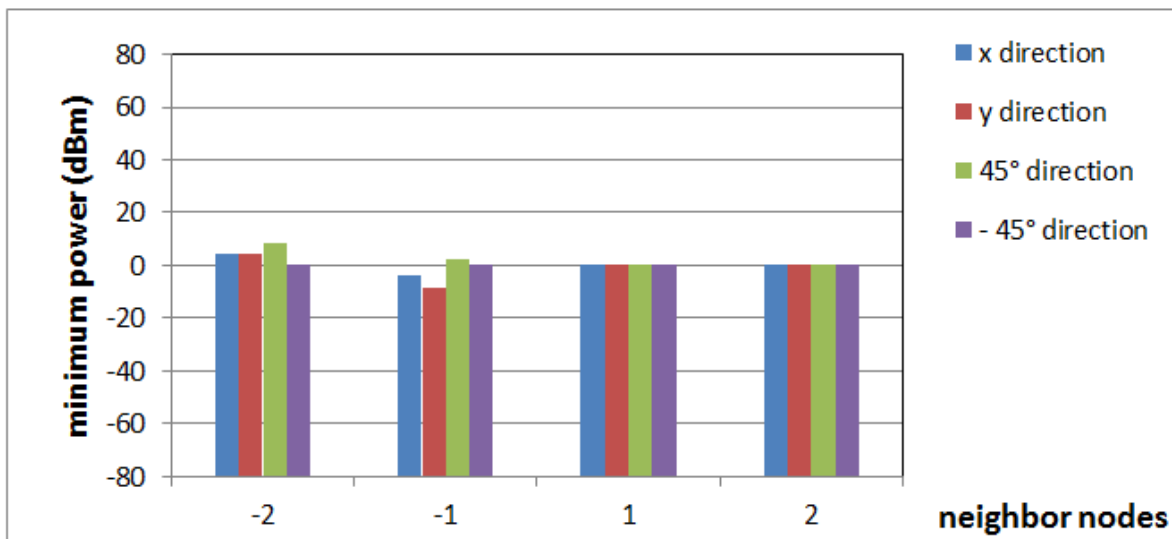


Figure 113: Minimum power of node 26, NC37

Analyses of the simulation results, in the form of S-Parameters for node 26 in the NC37 simulation are tabulated in Tables, and graphically presented in Figures. The minimum amount of power-consumed in node 26 in the NC37 simulation is tabulated in Tables, and graphically presented in the Figures.

7.3.3 Reasoning for Critical analysis

The critical analysis of the CST simulation results identified the number of nearest neighbours required for reliable, optimal routes, as three in almost all cases. The actual neighbour is of greatest significance, but the neighbours that facilitate communication to the base nodes with minimal distance in hops are also important. Considering variations in the S-parameter value, the discrete value of current input and the voltage levels, node 13 was considered to be the most efficient to transmit data to all the other sensor nodes in the network. Analysing the S-parameter value and the reduced S-parameter value assisted greatly in the selection of node 26 in the wireless sensor network when analysing the power transfer characteristics. When node 26 is considered, the distance in terms of hops is a maximum of 26 and a minimum of 1, while sensitivity level is estimated to be -96 dBm. Critical analysis of the simulation results obtained also showed the transmission power for each port or node is one mW, and that this power can be changed from 1.5 to two mW, assuming the channel characteristic does not change with a scaling-up of transmission power. Altogether, these values have assisted greatly in analysing the power transfer characteristics of the wireless sensor nodes deployed on an aircraft wing. Critically analysing all the obtained values has shown that the amount of power being consumed by each sensor node in the network varies based on the location of the sensor node, with respect to other nodes in the network, and also based on the direction of the communication. This dependence on the amount of power consumed within the communication direction of the sensor node as identified in this research is consistent with the works reported in the literature. Therefore, when designing a sensor network for use for aircraft wings in SHM applications, it is important to consider the direction of communication to minimise power consumption and thereby increase the lifetime of the wireless sensor network.

7.4 Summary and Conclusions

In this chapter, assessing the feasibility of using ZigBee communications on aircraft wings for SHM applications, and the power transfer characteristics of aircraft wings are studied in detail. A Comparative analysis of NC37 and NC38 simulations in terms of S-Parameters and the minimum power consumed by node 26 has been carried out. This critical analysis shows the change in

power requirements, based on the direction of communication indicated in the literature (ref). Considering these findings can greatly help when designing a sensor network effectively, such that the power constraints can be addressed and network lifetime can thereby be increased. By taking the simulation results obtained when analysing the power transfer characteristics, the need to design a power efficient routing method for communication in aircraft wings is highlighted in the following chapter.

8.1 Overview

In the process of assessing the feasibility of using ZigBee communications on aircraft wings for SHM applications; the influence of wing shape, wing structure, and wing composition on radio wave propagation was identified. As part of this process, the design challenges to be considered when designing an effective wireless sensor network for aircraft wing SHM applications were identified. Among the several design challenges WSN identified in the literature [185]–[187] the need to minimise the power consumption of the sensor nodes was identified as a key challenge to be addressed by the researcher. By taking the simulation results obtained when analysing the power transfer characteristics, the need to design a power efficient routing method for communication in aircraft wings was identified. Based on this necessity, this chapter presents the complete details for the hybrid routing protocol proposed herein for aircraft SHM applications. The effectiveness of the proposed algorithms is specified in terms of mathematical models and simulation studies, carried out in a MATLAB and Network simulator.

8.2 Research Question

The result when mapping S-parameters and radio propagation inside an aircraft wing is to assist the design of an application-specific energy efficient routing protocol. The sensor node deployment in the aircraft wing is regular, controlled and deterministic. As, the node positions, the radiation pattern, and because S-parameters are deterministic, the following question is considered as the primary research question posed in this study.

Given the knowledge of node deployment and power transfer characteristics, can we design a new energy efficient routing protocol?

Tentatively we can respond, yes to the above research question, as S-parameters offer to map the shortest routes from the source to the destination. Despite the availability of different types

of routing protocols in the literature, these do not solve routing issue in all cases. Application specific routing protocols need to adapt, optimizing tuning to the requirements as well as the data available for the deployed nodes [49].

The analysis of the inner structure of an aircraft wing as given in the above Figures, revealed the existence of connected compartments in this aircraft wings like holes in ribs. This environment provides a need to deploy sensor nodes in an ad hoc manner on an aircraft wing. As indicated in [188], the ad hoc deployment of sensor nodes requires sensor nodes with an identifiable position initially, with information concerning other sensor nodes' locations and a capacity to route the information accordingly. All the activities the sensor node needs to perform require the consumption of more energy than is normally possible [44], [189]. Therefore, even in the case of the random deployment of the sensor nodes on the aircraft wing in ad hoc manner, there is a need for a dedicated power efficient routing protocol. This power efficient routing protocol has to be designed based on the determined node positions, their radiation pattern and S-parameters as identified in previous chapters.

8.3 Proposal of a New Routing Protocol

To develop an energy efficient protocol, the following ideas are considered,

- All the nodes transmit the packets towards the base node, which is located at the wing root. Therefore, the packet flow is mostly unidirectional: from the aircraft wing towards the wing root. The algorithm maintains the routing direction all the times, so that the nodes can spare the need to maintain an ID or routing table, which is called the Minimum Cost Forwarding Algorithm (MCFA) [190]. However, the nodes have to keep broadcasting messages to their neighbours, until chosen by a least cost-neighbouring node during rebroadcasting [53].
- To avoid broadcasting, Energy Aware Routing [21] can be adopted. This routing method maintains a set of pathways based on certain probabilities in place on one of the single optimal pathways. The value of this probability depends on the achieved energy consumption of each path. By choosing paths at different times, the energy of any single path will be unlikely to deplete quickly [20]. This can help to achieve a longer network

lifetime as energy can be dissipated more equally among the nodes. Network survival is the main metric of this protocol. Based on neighbour node ranking conducted by node residual energy, link strength and the S-parameter between the nodes, at least three paths can be traced for each node until the packets reach the base station located at the wing root.

- The residual energy can be taken into consideration by applying an energy harvesting scenario in the region of node deployment. The cost at node, based on residual energy can be accounted for by the Energy-Opportunistic Weighted Minimum Energy (EOWEME) introduced by Lin et al. [91].
- The cost at each sensor node is calculated according to the views of Lin et al [91]. According to Lin et al. [191], the cost of each sensor node is calculated based on available energy, capacitor capacity, harvesting power rate, reception and transmission energies. Clear details and proper explanations for all these factors are given below:
 - The available energy at each sensor node is expressed in Joules.
 - Battery capacity or the equivalent capacity of a capacitor is assumed to be 4 Volts [191].
 - **Harvesting power rate:** The rate of energy harvesting is different in different regions of the aircraft wing. Table 20 provides complete details for changes in harvesting power rate, based on the aircraft's wing region.
 - **Reception and transmission energies:** This is the energy required to receive a packet from the i th node and transmit it to j th node. This research assumes the existence of 2 mW for each sensor node; where 1 mW is for the transmission of energy and another 1 mW for the reception energy. This assumption about allocating 2mW is based on work carried out by Wan et al. (2014) [192], which showed the different factors to be considered when calculating the cost of each sensor node.

The algorithm that incorporates these points is presented in Figure 114.

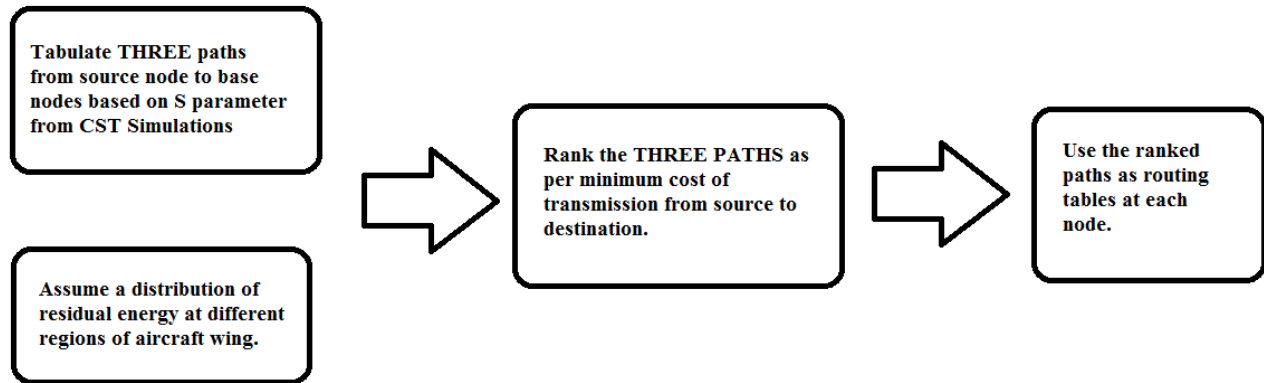


Figure 114: Proposed routing protocol

The MATLAB code that aims to import and execute the search across nodes for a set of best S-parameters, and to find a path from the source node to the destination is as specified in the appendix. The output for the farthest node near the wing tip is shown in Figure 115. The direct line of sight path shows a lesser amount of scattering than the other paths.

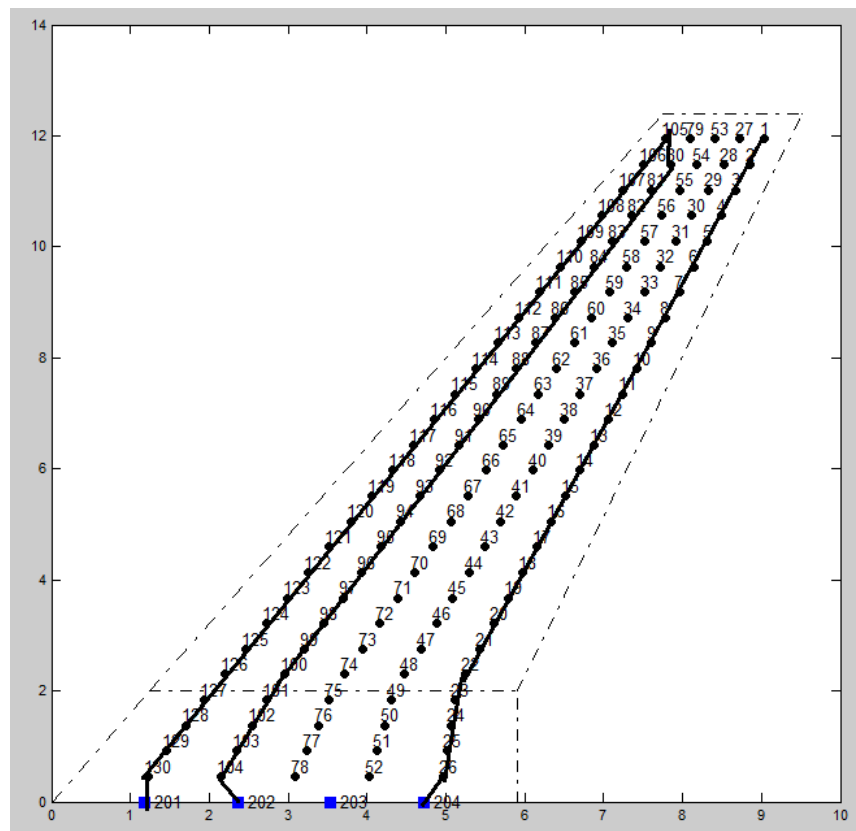


Figure 115: Direct line of sight paths from CST simulations

After identifying the paths for each sensor node, the next step is to assign a cost for each distance from the source node to the base node. The parameters for determining the cost of transmission from the i th to the j th sensor node need to be considered based on the selected region of the aircraft wing, as shown in Table 23.

Table 23: Parameters for transmission and reception costs between two nodes [119]

Region	p_i	ε	μ	$E_{cap,i}$ V	$e_{i,j}$ mW,
R1	7-9	1.2	2.09	4	1,2
R2	3-5	1.3	4.28	4	1,2
R3	3-5	1.25	5.43	4	1,2

All the values of the different parameters given in Table 20 were obtained based on CST simulations that were conducted and given in Figure 115. As indicated in the CST simulations, a direct line of sight has been established among the different sensor nodes across the different regions. Line of sight paths and cost-effective paths were merged to use the multiple pathways between a given node and its base station in this wireless sensor network [119].

8.4 Model of WSN System

The following assumptions were made concerning the sensor nodes in aircraft deployment.

- The links are symmetric, despite the preferred and utilized links being located towards the wing root.
- The network is homogeneous and static. In other words, the sensor and other components of the node, such as the microcontroller, are identical, and their position/coordinates are fixed, and mostly determined by the rib holes in the wing layout.

- The sensor nodes are capable of computing residual energy, and the energy harvesting circuits of commercial projects serve as a prototype. For example, the features of project ADVICE with the VDCu boards are taken into account as part of the simulation.

The network model is deterministic and regular. It comprises 130 nodes deployed near the rib holes, and 4 sink nodes at the wing root, and their location information (x_i, y_i) is known. Timeout Media Access Control (TMAC) supports communication between the sensors. The power supply, as well as the computational capabilities of the sink nodes at the wing root are unlimited, and they contain the coordinates and identifiers of each sensor node, as per the deployment in the wing layout, see Figure 115. The four sink nodes coordinate the sensor node in their purview or direct line of sight. Any of the four sink nodes can request data from a particular sensor node by selecting the *best-ranked path* between the selected node and itself. The threshold energy describes the minimal residual energy, below which the node will not only perform a sensing activity but not transmit or receive until the energy is restored. The residual energy is calculated by each sensor node using equation (4.1), and the parameters are as recommended in Table 20.

The well informed and pre-determined deployment of WSN was facilitated in simple energy calculations. Let $E_{Ti}(k, d)$ and $E_{Ri}(k)$ denote the transmission energy for k bits over distance d , and reception energy for k bits at given node i . Then the energy equation is,

$$E_{Ti}(k, d) = E_{elec} * k + \xi_{amp} * k * d^2$$

$$E_{Ri}(k) = E_{elec} * k \quad (4.1)$$

Where, E_{elec} is the energy required in the circuit to transmit or receive one bit. ξ_{amp} is the energy required for the amplifier, which is the path loss exponent, and taken as two because of the shorter distance between the sensor nodes, and t is the time.

8.5 Working of routing protocol

The working of the proposed hybrid protocol can be explained according to four stages. The algorithms to explain each of the four stages of the hybrid protocol are given in this section.

Stage 1: Initiation and neighbour selection: This stage consists of ranking neighbours based on residual energies and S-parameters. After ranking neighbours, the data packet is sent to the selected node.

Table 24: Algorithm for stage 1: Initiation and neighbour selection

Neighbour Information (Neighbour discovery)
<i>Data structure</i> 9
<i>Algorithm: transmission of data packet</i> Select a node j, k and l from NbrTab (i). If ErTab(i, j)>ErTab(i, k) If ErTab(i, j)>ErTab(i, l) TranNode:=j if ErTab(i, k) >ErTab(i, l) TranNode:=k Else TranNode:=l End if End if End if If SparTab(TanNode)==min(SparTab(i)) FTanNode = l Send data packet to neighbour with id l. End if

The algorithm above involves the initiation and neighbour selection stages of the hybrid routing protocol. Here, the NbrTab() function stores all the details of the nodes present in the network, and the ErTab() represents the energy level of each sensor node present. The different steps comparing the energy levels of each node, as detailed in the above algorithm, help with the selection of the transmission node, which is indicated as **TranNode**.

Stage 2: Multipath construction: Multipath construction is repeatedly executed after stage 1 until the neighbouring node becomes one of four sink nodes.

Table 25: Algorithm for stage 2: Multipath construction

Multipath construction
<i>Data structure.</i> 10 id_i = id of ith node. See figure for node number/ids. 11 NodeB=[26,52,78,104,130] 12 PrimaryPath[] 13 SecondaryPath[] 14 TertiaryPath[] <i>Algorithm, selection of path.</i> For a given node i. For j=1:5 If $id_i < \text{NodeB}(j)$ PrimaryPath:=[i i+1 i+2 26] SecondaryPath:=[i i+27 i+2852] TertiaryPath:=[[i i+53 i+54104]] Break; Else

```

;
End if
End for.

```

The algorithm above concerns the multipath construction stages of the hybrid routing protocol. Here, PrimaryPath [], SecondaryPath [] and TertiaryPath [] are the three arrays created to store the multiple paths that are created through this algorithm. The different steps present in the above algorithm help when forming the multiple paths from source to destination, depending on the selection of nodal positions.

Stage 3: Route repair and maintenance: If any of the three routes found have failed, then a substitute is made using a SecondaryPath and then a TertiaryPath.

Table 26: Algorithm for route repair

Route repair

Data structure.

15 id_i = id of i th node which is the source node. See figure for node number/ids.

16 Id_k = id of k th node which is the fail node in PrimaryPath or SecondaryPath.

17 NodeB=[26,52,78,104,130]

18 PrimaryPath []:=assigned path, see multipath construction algorithm.

19 SecondaryPath []:=assigned path, see multipath construction algorithm.

20 TertiaryPath []:=assigned path, see multipath construction algorithm.

Algorithm, selection of path.

For a given node $k > i$.

If response $k == \text{FALSE}$

For $j=2:5$

```

If k<NodeB(j)
PrimaryPath:=[k+26 k+27 ....{52,104,130}]
Break;
Else;
End if
End for.

```

The algorithm above involves implementing the route repair and the maintenance stage of the hybrid routing protocol. Here, PrimaryPath [], SecondaryPath [] and TertiaryPath [] are the three arrays created to store the multiple paths that are created through this algorithm. Using SecondaryPath [] and TertiaryPath [], route repair and maintenance will be carried out in this algorithm as part of the third stage.

8.6 Simulation in MATLAB

The proposed and designed hybrid protocol is simulated in MATLAB, and the various functions used in this implementation are set out with a short description in table 27.

Table 27: Functions used in MATLAB simulation

Function	Purpose
wingLayout()	Prints the layout of the wing with a distributed given number of nodes and a set number of rows.
Scatparameters()	Imports the scattering parameter data from Excel or the text file that printed from CST.
pathScat()	Finds paths for each node based on scattering parameters

pathEnergyResidual()	Finds paths for each node based on energy residual and costs incurred in transmission.
AODVSim()	Simulates the AODV routing protocol.
PropProtocol() Dependent functions are, InitNode() MultiPath() RouteRepair() ComputeEnergy()	Simulates the proposed protocol using the dependent functions at every stage of protocol.
printResults()	Prints the histogram and other results for the simulation

8.7 Simulation Results

The goal of the simulations was to evaluate the performance of the proposed protocol, for comparison with the AODV routing protocol. The sensor node parameters selected are given in Table 28, and the MICAz, which was developed by Crossbow Technology Inc is also used in the simulation.

Table 28: MATLAB simulation parameters

Simulation Parameter	Value
Network deployment area	Aircraft wing model, around 12 m in length.
Number of sensor nodes	130
Size of data packet	512 bytes
Size of control packet	32 bytes

Initial energy	1 J
Simulation time	600 sec
Threshold energy	0.2 nJ/sec
MAC protocol	TMAC
Transmission power	1 mW
Node power variance	0.25 mW
Data rate	128 Kbits/sec

The simulation requires input from the user concerning node deployment and data rate information before it executes. Additionally, either the proposed or AODV protocol have to be selected as shown in the screenshot for the program output below.

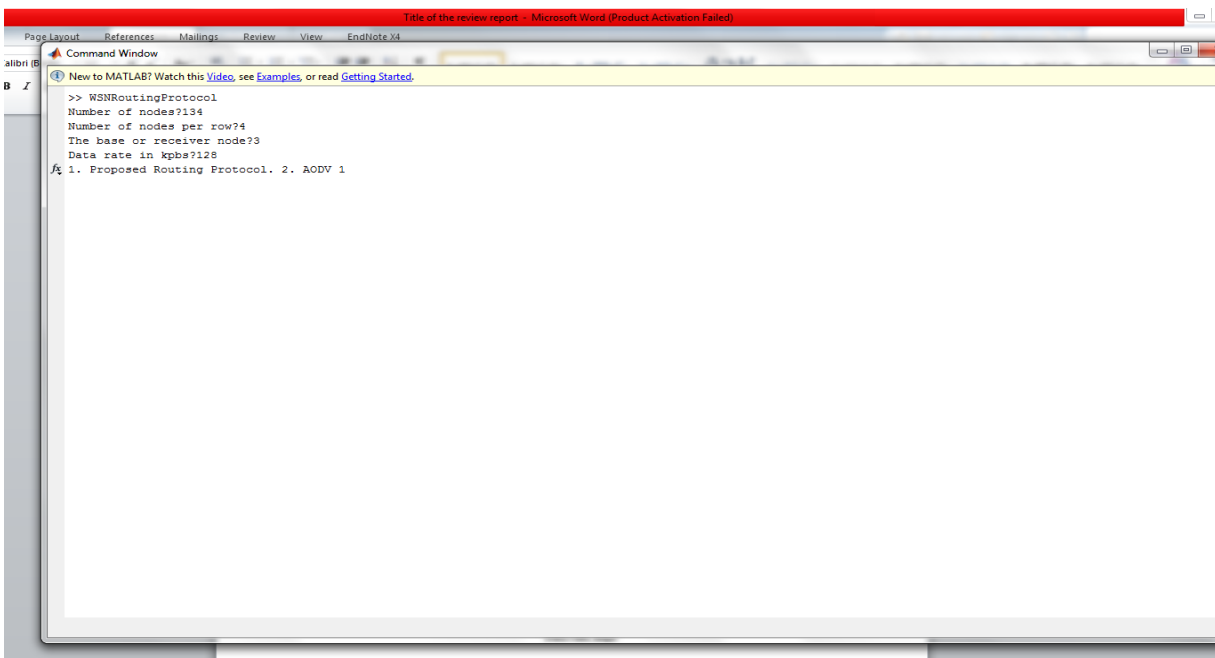


Figure 116: Screenshot of the MATLAB simulator prompting input of its different parameters.

After inputting the required parameters in the form of the node deployment, data rate, and applicable routing protocol, the actual transmission and receipt of the packets is carried out in

the simulated WSN for aircraft SHM. Figure 116 reveals how packets are transmitted and received by the nodes in the form of red markers.

The packets received, and the number of packets traversed from each node are indicated in the statistics using the histograms in Figures 117 and 118. The histogram indicates the selection of node 2 as a base node. The packets originating from all the other nodes were successfully received at node 2. A 97% level of reliability was observed when simulating a 79-node scenario, which is also known as NC38 for CST simulations. The simulator code was developed to incorporate AODV, and to facilitate a comparative analysis between the proposed routing protocol and the AODV routing protocol. The efficiency of the packets received at the base nodes functioned at different rates in the case of the NC37 simulation and the NC38 simulation, as given.

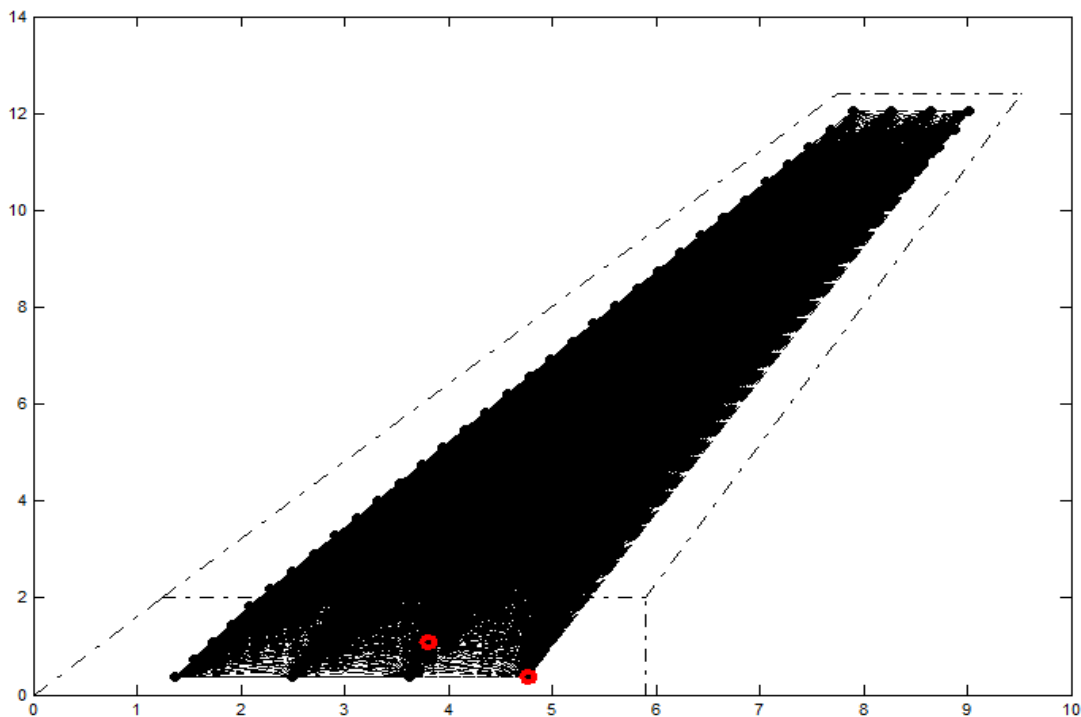


Figure 117: The nodes are highlighted with red markers on the aircraft wing

The results of the Matlab simulation are given in Figure 117, in which the send nodes are indicated to show how data processing is carried out.

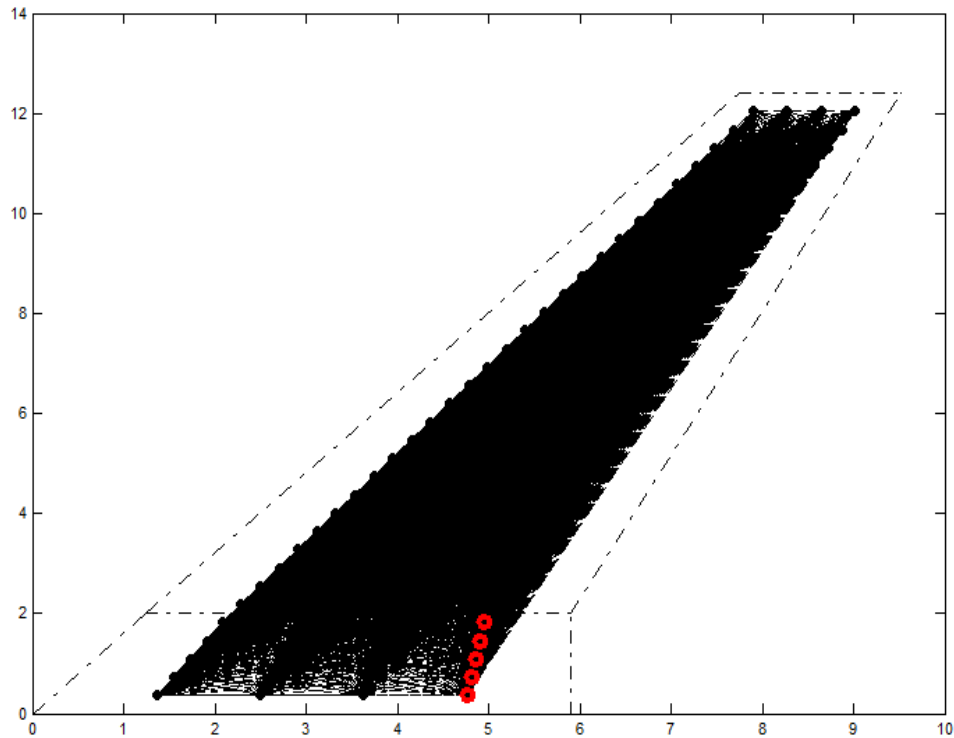


Figure 118: The nodes transmitting and receiving packets are highlighted with red markers to mark the path of the packet flow visually

The flow of the data from one node to another is shown by the red markers in Figure 118 above.

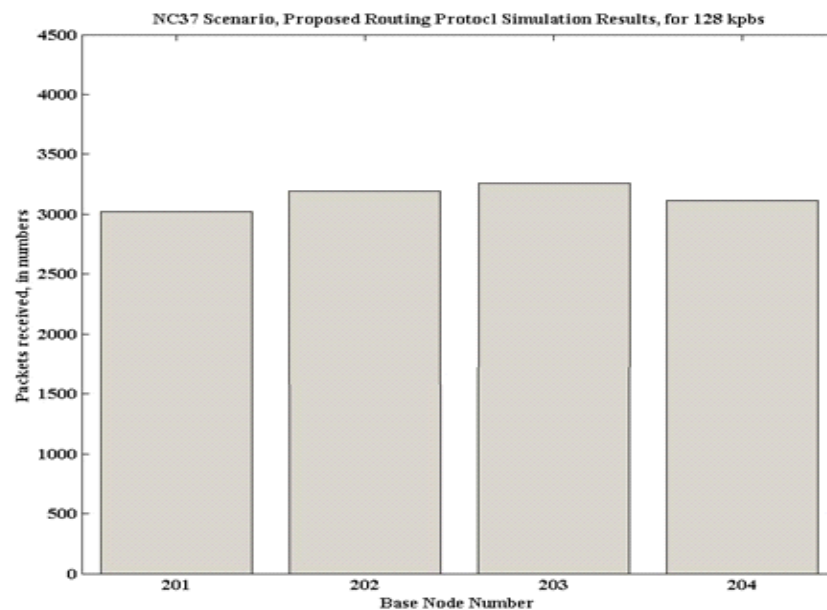


Figure 119: Number of packets received, at base nodes at 128 kbps and 1 mW power at transmission, NC37

In figure 119, the results of the MATLAB simulation are shown in the form of the number of packets received at the base nodes during the transmission over an NC37 wing structure.

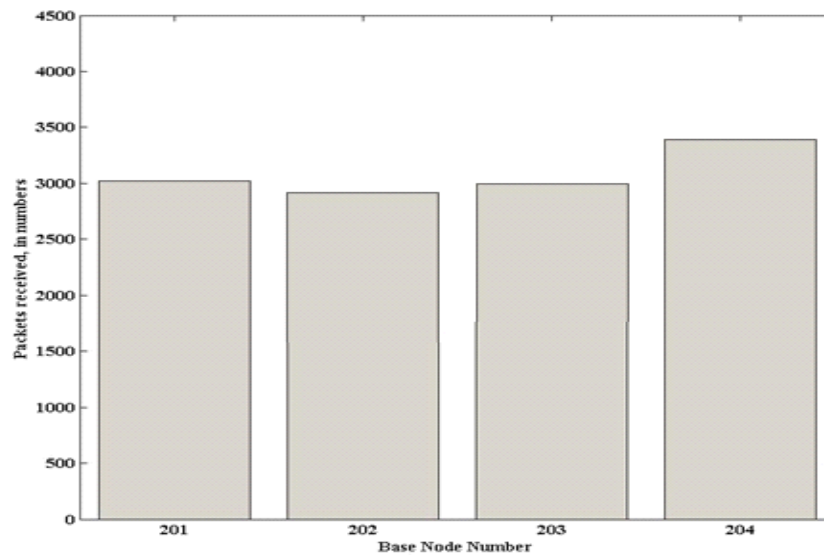


Figure 120: Number of packets received at base nodes at 128 kbps and one mW power at transmission, NC38

Figure 120 gives the details of the packets received from the base nodes present in aircraft wing NC38 at the power of one mW of transmission.

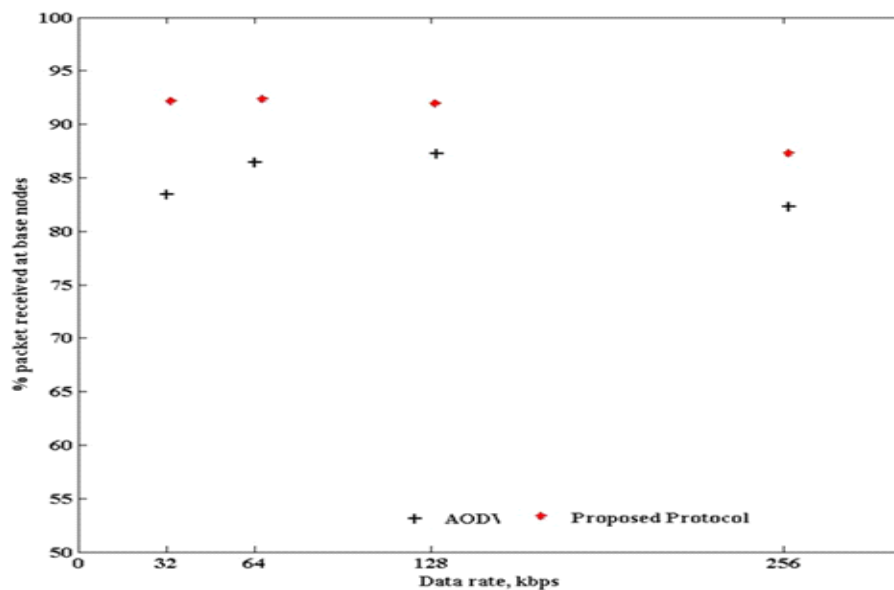


Figure 121: Efficiency of the packet reception at different data rates, NC37

The efficiency levels of packet reception for the NC37 wing in the case of different data rates is shown in Figure 121.

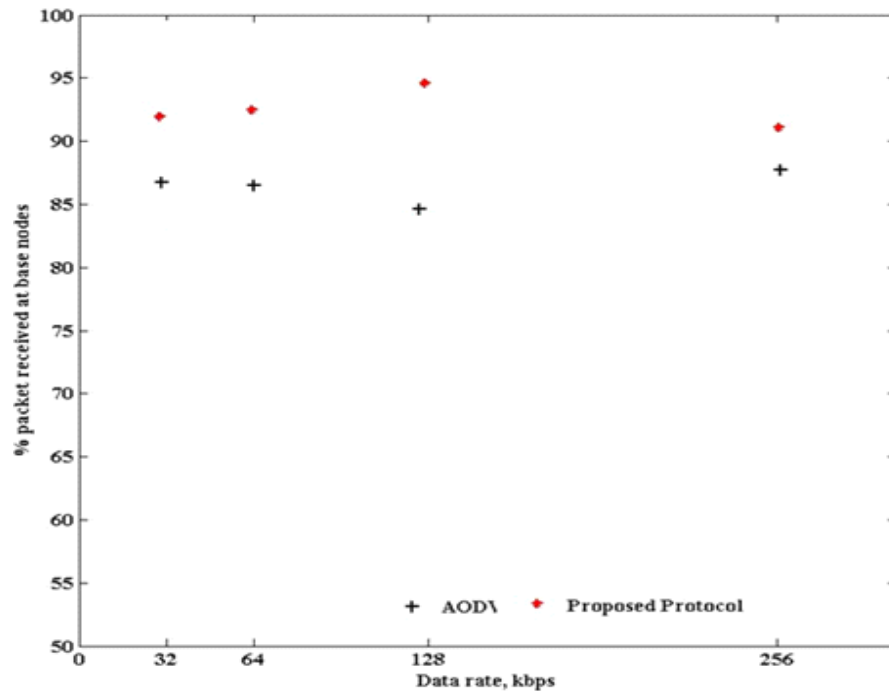


Figure 122: Efficiency of packet reception at different data rates, NC38

The efficiency levels of the packet reception for the NC38 wing in case of different data rates are shown in Figure 122.

8.8 Comparison of NC37 and NC38 Simulations

A summary of the performance comparison between the simulation of AODV and the proposed energy-opportunistic routing protocol are presented in Tables 29 and 30.

Table 29: Comparison of different protocols NC37

Item	Energy-Opportunistic	AODV
Packet sent	1500	1450
Packet received	3323	3227
Packet ratio	4.94	3.23
Delivery rate	92%	87%

End to end delay	52.3 ms	59.5 ms
Average hop count	15	17
Route Setup time	12 sec	21 sec

Based on the analysis of the performance comparisons, the results for NC37 as presented in Table 29, provide evidence that the packet delivery ratio and delivery rate of the proposed routing protocol are high as it is one among the 3 best-ranked routes, with lower hop count and route setup times comparative to the AODV routing protocol.

Table 30: Comparison of different protocols NC38

Item	Energy-Opportunistic	AODV
Packet sent	1040	2347
Packet received	3554	3672
Packet ratio	2.67	4.3
Delivery rate	90%	85%
End to end delay	50.2 ms	42 ms
Average hop count	14	17
Route Setup time	10 sec	24 sec

Based on the analysis of the performance comparisons results for NC38 presented in Table 30, it is evident that the packet delivery ratio and the delivery rate of the proposed routing protocol are high, as it is one among the 3 best-ranked routes, with a lower hop count and route setup times comparative to the AODV routing protocol.

8.9 Improving EOWEME Protocol

The Energy-Opportunistic Weighted Minimum Energy (EOWEME) protocol currently adopts two metrics to select the routing path from source to destination. One metric describes the energy of the neighbouring node, and the other metric describes the cost of each routing pathway (C_i). Linear routing paths are identified via this routing protocol, which requires the higher energy of the sensor nodes to transmit the data to the sink nodes [11], [193]. Additional factors that necessitate improvements to the EOWEME protocol are as follows:

- Linear transmission of the sensed information requires greater energy consumption than achievable through cluster heads [193], [194]. For example, the aeroplane wing shown in Figure 24 has 130 sensor nodes and 4 sink nodes; thus, if node 1 needs to transmit sensed information to the nearest sink node, 204, then it either uses the routing path [1, 2, 3, 4, ... 25, 25, 2014] or the routing path [1, 27, 28, 29, ..., 51, 52, 204]. In this process, all the sensor nodes along the routing path are required to use their energy resources to forward the data.
- Despite the adoption of linear routing paths, there is a high probability of packet loss due to the energy depletion of intermediate sensor nodes. The successful delivery of information sensed by sensor node 1 is highly dependent on the energy of all the sensor nodes present in the routing paths: [1, 2, 3, 4, .25, 26, and 2014] and [1, 27, 28, 29, 51, 52, 204]. Energy depletion of any of these intermediate nodes, 2 to 27 (or) 27 to 52, then requires routing path reconstruction must take place, which places significant demand for energy consumption on the sensor node.
- In the current EOWEME protocol, it is assumed there will be 4 sink nodes with extensive energy resources to benefit 130 nodes. However, this approach to using 4 sink nodes is unfeasible in all applications, as the deployment of 4 sink nodes demands considerable energy resources.
- The current EOWEME protocol has not addressed how the sink nodes communicate with one another in order to carry out data aggregation, which is considered one of the key steps in a data analysis designed to avoid data redundancy.

- Conversely, the EOWEME protocol is a single-layer protocol as it is based on only the properties of the network layer. Cross-layer approaches are more effective than single layer approaches as they emphasize cross-layer communications between the two layers during the working process [193].

8.10 Proposed Changes to EOWEME

Based on the limitations present in the current EOWEME protocol, the following changes to this routing protocol are proposed.

- Cluster-based routing is incorporated into the proposed EOWEME routing protocol. In this approach, the given network area of sensor nodes on the aeroplane wing is as given in Figure 24, and is divided into several regions called clusters. Each cluster is characterized as having a Cluster Head (CH) node and a non-cluster head (non-CH) node. The cluster node is responsible for collecting the information sensed from all non-CH nodes, for transmission to the sink node.
- Instead of the four sink nodes, it is assumed the aeroplane wing comprises two sink nodes placed in the middle of the network to transmit aggregated information.
- The current EOWEME routing protocol is a single layer approach based on only the network layer. A cross-layer approach is proposed for adoption by combining the properties of both the MAC layer and the network layer.

8.11 Network Model

We consider a wireless sensor network with $N = 132$ number of static sensor nodes and 2 sink nodes deployed in the aircraft wing. The structure of the aircraft wing is given in Figure 123. Each static sensor node can collect information about the structural health of the aircraft wing independently. Each of these sensor nodes is also equipped with an energy harvesting unit, which helps the nodes collect energy from ambient environments.

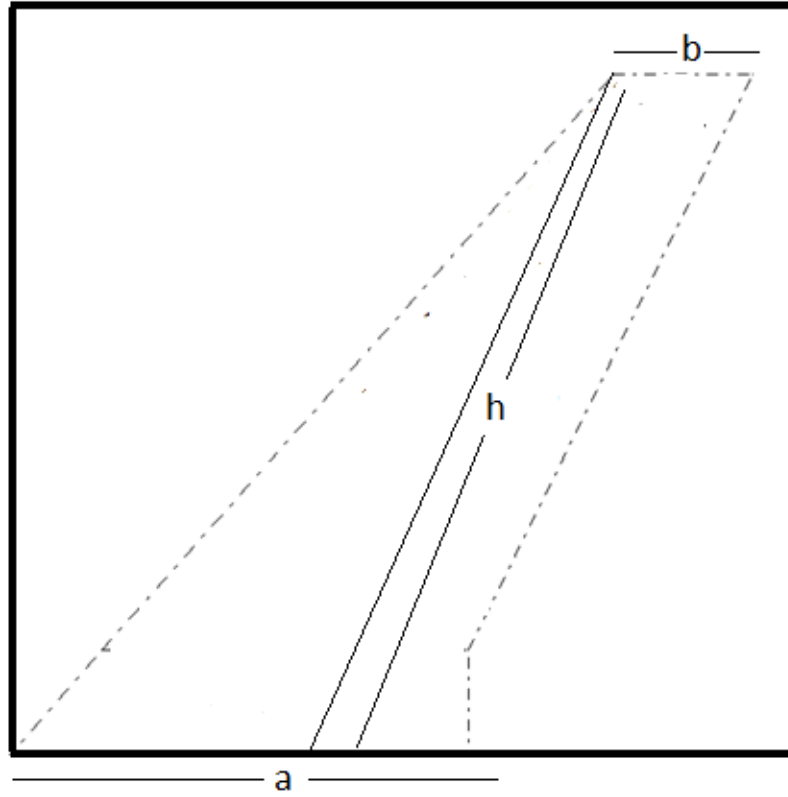


Figure 123: Network model

From figure 123, it is apparent that sensor nodes are deployed in a trapezium with an area of $\frac{1}{2} l (a + b) \text{ m}^2$. In this network, let (x_1, y_1) and (x_c, y_c) be the positions of the arbitrary node and cluster head respectively; then the distance between these two nodes d_{1c} is calculated as, $d_{1c} = \sqrt{(x_c - x_1)^2 + (y_c - y_1)^2}$. Similarly, the distance between the cluster head node at (x_c, y_c) and sink node at (x_s, y_s) is calculated as:

$$d_{cs} = \sqrt{(x_s - x_c)^2 + (y_s - y_c)^2}$$

8.12 Channel Contention and Allocation

The proposed improvements to the EOWEME routing protocol would permit a cross-layer approach between the MAC layer and the network layer. In other words, the packet routing in the network layer of the sensor network is performed based on the channel access contention carried out in the MAC layer. As the routing of the information is carried out in an error-prone

and contention-based common wireless channel, the MAC layer information helps the network routing to route the information effectively according to channel availability, and based on traffic priority levels.

In the MAC layer, the sensor nodes use a Distributed Coordinated Function (DCF) to sense the wireless channel, and to establish whether the channel is busy or empty. If the channel is found to be idle for the time period of the Distributed Inter Frame Space (DIFS), then the sensor node can access the channel to transmit the sensed information. If acknowledgements are enabled then the receiver sends those acknowledgements using the same channel after Short Inter-Frame Space (SIFS) time period. If the channel appears busy, it waits until the end of the current transmission, and if there is no collision it waits for DIFS time duration and then accesses the channel. In cases where a collision is detected collision, the node defers the transmission over a period of extended timing, called AIFS (Arbitrary Inter Frame Spacing), setting off a back-off timer based on the contention window. By the end of the back-off timer, the medium is idle, and then ready to be accessed by the node for data transmission. The complete sequence of data transmission is shown in Figure 124.

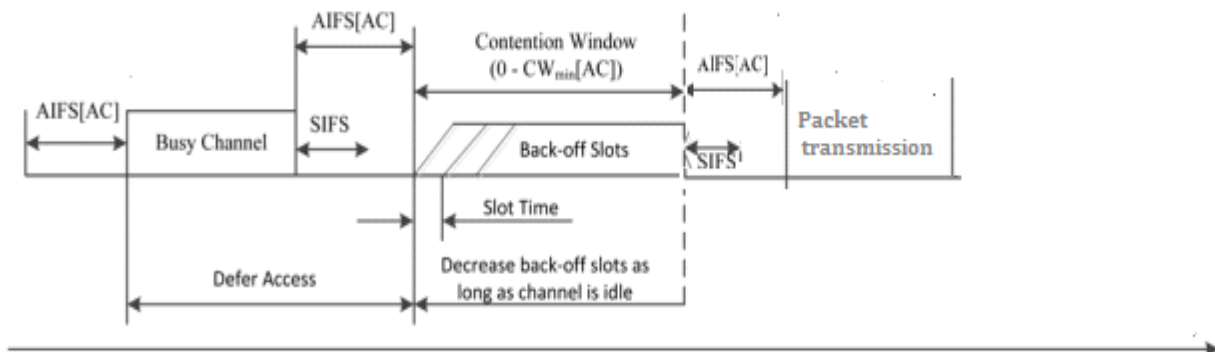


Figure 124: Data transmission sequence

Based on this channel contention information, the success probabilities of packet transmission, packet collisions can be identified. This information from the MAC layer enables the improved EOWEME protocol, present in the network layer, to route the information effectively.

Lemma: The success probability of a CH node, collecting the information sensed from all the non-CH nodes in the cluster with N_c non-CH nodes given.

Proof:

A cluster is formed with a CH node and other non-CH nodes. The CH node is responsible for collecting the information sensed from the non-CH nodes, and then transmitting it to the sink node. Let, $P_{cluster}$ be the success probability of the CH node collecting sensed information from the non-CH nodes and then returning it to the sink node.

Then, the $P_{cluster}$ is given as,

$$P_{cluster} = \alpha + \beta \quad (1)$$

Where, α = Sum of the success probabilities of each non-CH nodes sending sensed information

$$\alpha = \sum_{i=1}^{N_c} P_{st}(i) \quad (2)$$

β = Success probability of CH node transmitting to sink node

In equation (2), $P_{st}(i)$ refers to the success probability of a non-CH node i transmitting the sensed information, and N_c represents the number of the non-CH nodes in a cluster. This probability can be expressed thus,

$$P_{st}(i) = 1 - [P_{nst}(i) + P_{col}(i)] \quad (3)$$

where, $P_{nst}(i)$ is the probability of unsuccessful data transmission by a non-CH node, and $P_{col}(i)$ is the probability of packets colliding during transmission.

A non-CH node will be unsuccessful at transmitting the sensed information if all its transmission energy is used to transmit the sensed information. Hence,

$$P_{nst}(i) = \lim_{t \rightarrow \infty} \left[\frac{1}{N_p} \sum_{i=1}^{N_p} (1 - E_{tx}(i)) \right] \quad (4)$$

In equation (4), N_p refers to the number of packets transmitted by each non-CH node; and $E_{tx}(i)$ refers to the probability of a non-CH node i having sufficient transmission energy.

The probability of sensed data being transmitted by a non-CH node undergoing collision occurs when the wireless is busy during Clear Channel Assessment (CCA1 and CCA2), and while a non-CH node transmits the sensed data via the wireless channel. Now,

$$P_{col}(i) = (1 - \partial)(1 - \epsilon) \lim_{t \rightarrow \infty} \left[\frac{1}{N_p} \sum_{i=1}^{N_p} (E_{tx}(i)) \right] \quad (5)$$

In equation (5), ∂, ϵ represents the probability that the wireless channel is not busy during the CCA1 and CCA2 periods respectively.

The results when substituting equation (4) and equation (5) in equation (3) are as follows,

$$P_{st}(i) = 1 - \left[\lim_{t \rightarrow \infty} \left[\frac{1}{N_p} \sum_{i=1}^{N_p} (1 - E_{tx}(i)) \right] + \left\{ (1 - \partial)(1 - \epsilon) \lim_{t \rightarrow \infty} \left[\frac{1}{N_p} \sum_{i=1}^{N_p} (E_{tx}(i)) \right] \right\} \right] \quad (6)$$

β = (1- probability of the CH node not having enough energy to send data to the sink node)

$$\beta = 1 - \lim_{t \rightarrow \infty} \left[\frac{1}{\left(\sum_{i=1}^{N_{cp}} (E_{ctx}(i)) \right) N_{cp}} \sum_{i=1}^{N_{cp}} (1 - E_{ctx}(i)) \right] \quad (7)$$

In equation (7), $E_{ctx}(i)$ refers to the probability of the CH node having sufficient transmission energy, and N_{cp} refers to the number of packets transmitted by the CH node.

Substituting equation (7) and (6) in equation (1):

$$P_{cluster} = \sum_{i=1}^{N_c} \left\{ 1 - \left[\lim_{t \rightarrow \infty} \left[\frac{1}{N_p} \sum_{i=1}^{N_p} (1 - E_{tx}(i)) \right] + \left\{ (1 - \partial)(1 - \epsilon) \lim_{t \rightarrow \infty} \left[\frac{1}{N_p} \sum_{i=1}^{N_p} (E_{tx}(i)) \right] \right\} \right] \right\} + \left\{ 1 - \lim_{t \rightarrow \infty} \left[\frac{1}{\left(\sum_{j=1}^{N_{cp}} (E_{ctx}(j)) \right) N_p} \sum_{j=1}^{N_{cp}} (1 - E_{ctx}(j)) \right] \right\} \quad (8)$$

8.13 Energy Consumption Model

The improved EOWEME routing protocol works in accordance with two main steps: Network initialisation and data routing.

Network initialisation: This step involves initializing the network and choosing the CH node for each cluster.

Data routing: This step involves routing the sensed information from the non-CH nodes to the CH nodes, and then from CH nodes to the sink node.

In the network initialisation stage, each sensor node broadcasts energy levels E_{node} to the neighbouring nodes and then based on the energy information obtained from the neighbouring sensor nodes, each node then calculates the residual energy $E_{residue}$ using equation (9).

$$E_{residue} = \frac{E_{node} - E_{min}}{E_{max} - E_{min}} \quad (9)$$

where, E_{node} = Energy of each node, which is a sum of the transmission power, receiving power, idle power, sleep power and state transition power.

$$E_{node} = E_{tx} + E_{rx} + E_{idle} + E_{sleep} + E_{txpower} \quad (10)$$

E_{min} , E_{max} refer to the minimum and maximum energy levels of all neighbouring nodes respectively.

$$E_{min} = \text{Min} (E_1, E_2, E_3, \dots, E_{NR}) \quad (11)$$

$$E_{max} = \text{Max} (E_1, E_2, E_3, \dots, E_{NR}) \quad (12)$$

In equations (11) and (12), E_1 refers to the energy of the first neighbouring node, E_2 refers to the energy of the second neighbouring node, and NR refers to the number of the neighbouring nodes. $\text{Min} ()$ is a function specifying the minimum of all the values, and $\text{Max} ()$ is the function specifying the maximum of all values.

Now the $E_{residue}$ of each sensor node can be compared with its neighbouring nodes to choose the node with highest $E_{residue}$ value as the CH node using the algorithm. This completes the process in this initialisation stage, which consumes certain levels of energy, given as E_{init} in equation (13).

$$E_{init} = \sum_{i=1}^N \sum_{j=1}^{NR} (E_p(i(t_s + t_p))j) \quad (13)$$

In equation (13), N represents the total number of sensor nodes present in the network

N_R specifies the number of neighbouring nodes,

E_p represents the energy required to broadcast one packet,

t_s specifies the time stamp for the network initialisation

t_p specifies the time required to transmit and receive P number of packets

8.14 Simulation of Improved EOWEME

The proposed improved EOWEME routing protocol, designed to support energy efficient routing in a sensor network used for aeronautical applications, is simulated with the help of Network simulator 2.33 (NS2.33). The extensive use of network simulator software for academic projects when networking and considering the NS2.33 simulator as a real-time simulator have resulted in selecting this software to simulate an improved EOWEME routing protocol. The NS2.33 network simulator is capable of simulating local area networks, ad-hoc networks and ZigBee networks, which have also become a reason for selecting the NS2.33 simulation tool for this research. Taking the properties of ZigBee standard, in terms of the presence of wireless communications, low powered sensor nodes, the design of a ZigBee network is considered suitable for the structural health monitoring of aircraft wings. This ZigBee network is simulated with a total of 130 nodes, whereby each node has the properties of a sensor node, such that it can collect the information from its surroundings and then return it to the base station. Despite current research focusing on aircraft wing applications, sensor nodes are arranged according to the wing structures, such that each node will be able to monitor the structural health of the wing and then present that information to the nearest base station. The communication from one ZigBee node to the other in the simulated network is carried out using wireless links. The physical layer, Mac layer and the network layer parameters of all the nodes are configured in line with IEEE802.15.4 specifications, which resemble the ZigBee network. This summarizes the various simulation parameters used for simulating the ZigBee network for an aircraft wing.

8.15 Analysis of Simulation Results

A number of simulations were carried out in NS2.33 to show the effectiveness of the proposed improved EOWEME routing protocol for ZigBee networks for use in aircrafts' structural health monitoring applications. The simulation time varied from 50 seconds to 500 seconds, increasing 50 seconds each time. In each case, the number of packets is sent by the source, and the number of packets received at the receiver, as well as the number of packets lost during data transmission were obtained from trace files. In network simulator 2.33 software, the trace files are the system files generated each time the simulation is made to run. Using the information gathered from trace files, the packet delivery rate for the simulated routing method is calculated. This calculation of the packet delivery rate is done for the improved EOWEME routing protocol, the original EOWEME routing protocol and the existing AODV routing protocol. The results of the simulation are presented in the graph shown in figure 125 below.

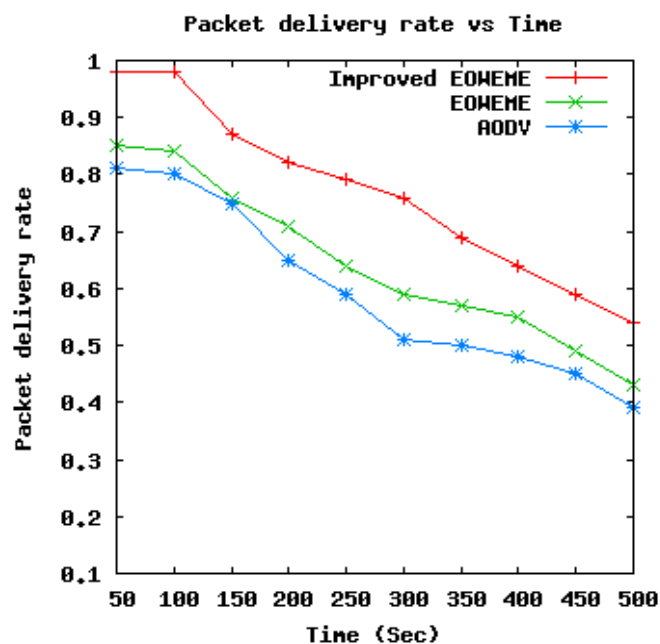


Figure 125: Packet delivery rate vs. time

A critical analysis of above graph indicates that an increase in simulation time from 50 seconds to 500 seconds results in a decline in the packet delivery rate. For all three routing methods considered, the packet delivery rate declines with an increase in simulation time. The principal reason for this is that there is an increase in network load, because as the simulation time

increases the network load increases the wireless channel contention, resulting in a high probability of packet collision and packet loss. Any kind of wireless network communication that takes place over wireless channels encounters this problem. However, a comparative analysis of the improved EOWEME routing protocol with the original protocol EOWEME routing protocol, and AODV, indicates the ability of the improved version to have a lower packet delivery rate when compared to EOWEME routing protocol and AODV. The main reason behind this can be explained by the fact that improved versions of the EOWEME routing protocol use the clustering method when the cluster nodes are collecting and aggregating information to reduce the problem of channel contention in the ZigBee network.

Figure 126 shows the average throughput of the ZigBee network when the routing protocols are simulated, in order to route the information from the source to the destination. This graph is plotted against network load and the average throughput value, where average throughput is defined by the number of packets sent per second by each node present in the network.

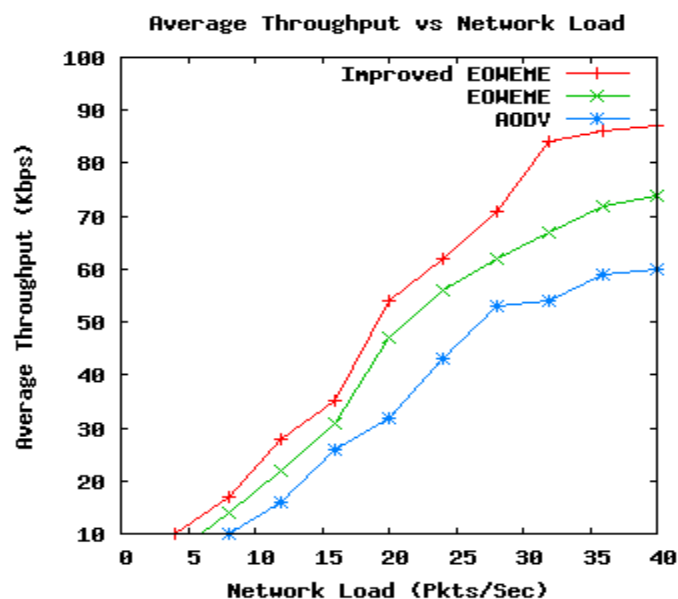


Figure 126: Average throughput vs. network load

A critical analysis of the above graph indicates that increases in network load enhance the average throughput value for all three routing protocols simulated in the ZigBee network. However, a comparative analysis reveals that an improved EOWEME routing protocol delivers a

higher value of average throughput when compared to the EOWEME routing protocol and the AODV routing protocol. This capability of the improved EOWEME routing protocol to record a higher value of average throughput arises from the ability of sensor nodes to route information sensed from the surroundings continuously, despite increasing network load. One factor causing this can be explained by the presence of cluster nodes that are highly energy efficient at collecting information from normal nodes to be sent to the base station.

Figure 127 presents the graph showing the probability of cluster head nodes transmitting data from non-cluster head nodes to the base station. Comparisons of mathematical models, and simulation studies of improved EOWEME routing protocols are performed with original EOWEME routing protocols.

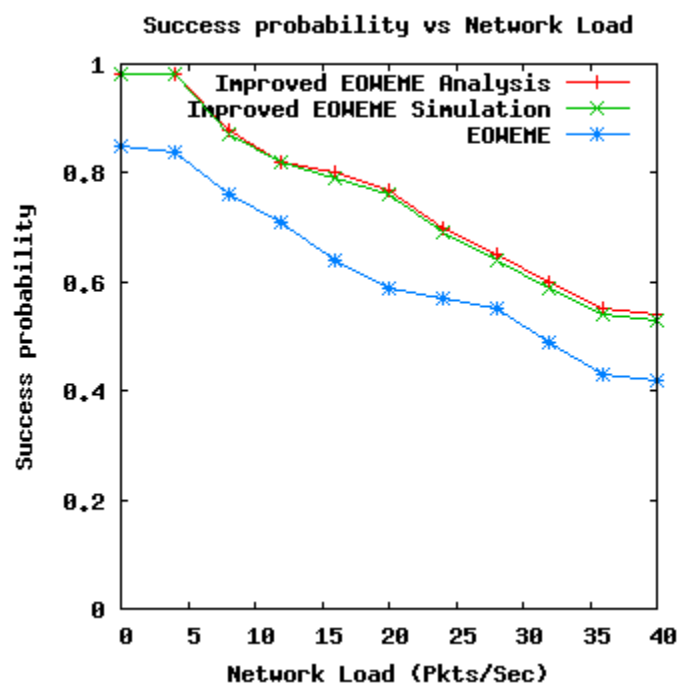


Figure 127: Success probability vs. network load

Comparative analysis reveals an improved version of the EOWEME routing protocol has a greater probability to ensure that cluster head nodes collect the necessary information from non-cluster head nodes to be sent to the base station. In the above graph, the values of analytical modelling and simulation studies for improved EOWEME routing protocols are identified as the same. However, these results are comparatively higher than for the original EOWEME routing protocol,

because of the ability of clustering concepts to be used in the improved version to route the information from non-cluster head nodes to the base station through cluster head nodes. Despite the increase in the network load on the ZigBee network, the improved version of the EOWEME routing protocol is capable of achieving greater probability relative to the original EOWEME routing protocol.

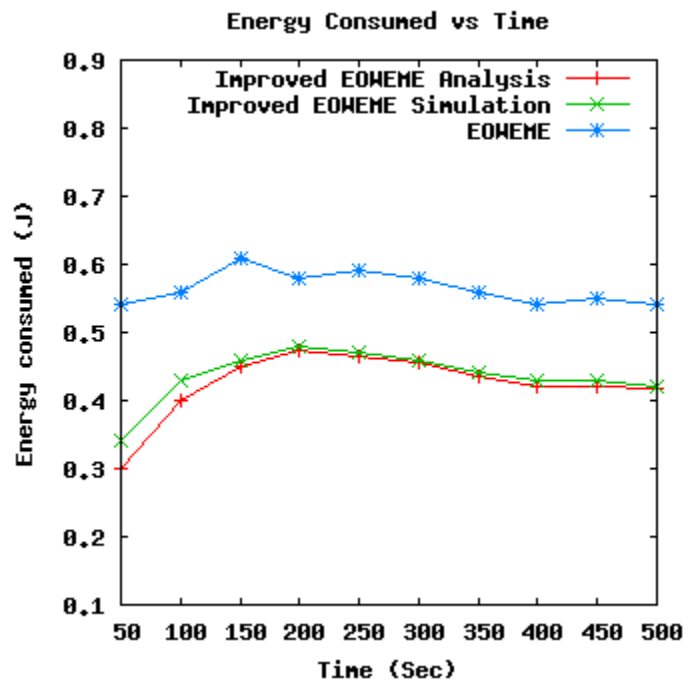


Figure 128: Energy consumed vs. time

Figure 128 details the amount of energy consumed by each of the routing protocols when used in ZigBee network for aircraft wing structural monitoring applications. A critical analysis of the graphical results shows the fluctuations in the quantity of energy consumed by each node in the ZigBee network when routing the required information.

A Comparative Analysis of energy consumption indicates that an improved EOWEME routing protocol consumes less energy during the simulation process, compared to an EOWEME routing protocol. Although the amount of energy calculated as consumed by each node in the ZigBee network is approximately the same according to mathematical analysis and simulation studies, it is less when compared with the original EOWEME routing protocol. The primary reason for this reduction in energy consumption is that the use of the clustering concept helps in allocating the

responsibility of data collection and data aggregation only to the cluster head nodes that consist of a high extent of energy resources comparative to other nodes in the network.

8.16 Summary and Conclusions

The original EOWEME protocol was demonstrably energy efficient, but the design has since been improved to be even more efficient. The use of non-linear routing, based on calculating (a) cost of the communication, (b) communication strength, and (c) residual energy resulted in an optimum route. This improved EOWEME protocol determines the optimum location for hub nodes and was proven to be more energy efficient through an iterative design, as well as more energy efficient than the AODV protocol.

For wing models, it was found that with an increasing number of nodes and fixed nodes restricted to 4 at the wing root, cross-links were reduced, and reportedly suitable for the realistic wing model. The recommendation for node deployment is that it shall be regular, and that the transmission range from the CST simulation is decisive in formulating node positions and some nodes. Transmission and sensing range is *assumed* to be identical, and that is also the Euclidean distance between the nodes or the grid spacing. Routing protocol recommendations are table based and use global information to maintain higher connectivity throughout the network for the majority of the WSN's operation time.

9.1 Conclusion

This project work described in this thesis analysed the feasibility of using the ZigBee standard based sensor network in an aircraft environment to support SHM applications. In the process of assessing feasibility, this researcher filled the literature gap by developing a novel technique to address the key challenges faced by WSN as used for SHM applications. In this research, three wing modes were considered and designed to fit the aircraft environment. Each of these wing models consists of different levels of complexity and various features, which has resulted in a different level of influence over radio wave propagation. The design and simulation of the three wing models using the CST tool have helped to identify the wing structure, wing shape, aircraft wing materials and wing antenna positions on the signal propagation of those WSNs used in structural health monitoring applications. Two range frequency ranges were used for simulations where one is 100 MHz to 5GHz and the other is 2.4GHz to 2.48GHz. The simulation result analysis specified a coupling difference between antennas; effecting the different antenna positions and mapping of wing interiors for radio propagation. A computational electromagnetic approach was implemented to find the S-parameters between the deployed nodes in an aircraft wing. The best positions for the nodes were inferred from the presence of rib holes that permit a direct line of sight propagation. Critical analysis of S21 results identified that the ISM band relates to ZigBee standard in the frequency range between 100 MHz and 5GHz, revealing the existence of weak coupling differences across a frequency band of 2.4 GHz. A further analysis has shown the presence of less coupling than the minimum level of the expected ZigBee SNR value. This finding revealed that the ZigBee wireless sensor network is not applicable for reverberant environments such as the wing cavity.

To satisfy the aims when assessing the feasibility of using ZigBee communications in aircraft SHM applications, the influence of wing shape, wing material composition and wing interior on connectivity control and connectivity quality between the two antennas present in the aircraft

wing has been identified. According to the review of wing composition, aluminium, CFC and PEC were the three materials considered to have an identifiable influence on the S21 parameter. Two transceivers: one fixed at the wing root and the other movable and positioned at the $1/4^{\text{th}}$, $1/2^{\text{nd}}$ and $3/4^{\text{th}}$ incremental length of the wing was simulated for three different materials used in the construction of wing models. These simulations were carried out on all three wing models, indicating that CFC exhibits a higher value of S21 compared to other wing structure materials, and is highly effective at improving the connectivity between antennas in ZigBee communications.

The importance of identifying optimal network topology for sensor networks, and the various connectivity issues reported in the literature pertaining to sensor networks have resulted in the formulation of multiple Travel salesman problems. Node deployment was regular, and inferences about the number of nodes, and shortest paths for signals were found using multiple Travelling Salesman Problem (mTSP) formulations. Different goals were formulated coupling the shortest Euclidian distance with power usage and fault tolerance for connectivity. The simplest goal for shortest distance for a signal to travel from source to a destination nodes was found for the empty wing models, using CST simulation data for the communication range. The Ant Colony Optimization paradigm was used to solve formulated mTSP. After analysing the results, feasible scenarios for node deployment, subject to structural constraints in the realistic wing model were proposed, given the results from an empty wing model. From this data analysis, a Table based routing protocol was suggested for higher levels of connectivity in WSN, wherein global information about nodes will be stored with each node and executed from the control site.

Based on the analysis of the results obtained; the node positions, their radiation pattern and S-parameters are highly deterministic. Considering the need to propose a suitable routing protocol for supporting ZigBee communications on an aircraft wing, an opportunistic and energy efficient routing method was proposed in this thesis. In the routing method, three equivalent optimal routes with some hops were identified using the three nearest neighbours. The back off rate is based on the highest strength signal for transmission among the available paths. The proposed Self-Healing and opportunistic routing protocol use optimal shortest power-based paths, ranked

according to their power consumption and S-parameters from CST simulations. Reliability of around 97% was observed in the simulation for NC38, with 134 nodes. The proposed protocol indicates a higher number of packets were received at the base nodes; although, a comparison with AODV and other protocols is still required. However, considering the energy constraints of wireless sensor nodes, an opportunistic routing protocol was proposed to improve the EOWEME protocol. Mathematical analysis and simulation studies were carried out in this project, to show the effectiveness of the improved EOWEME protocol. Based on a critical analysis of simulation studies, it is evident that the proposed improved EOWEME protocol uses 20% less energy compared to the EOWEME protocol. The main reason behind this was the use of the clustering method to route the information, as the cluster head nodes were only responsible for collecting and carrying out data collection and data aggregation activities. Therefore, combining all the different findings of this thesis highlights the ability of this project to propose a complete package to support ZigBee communications to reduce their cabling costs, and support structural health monitoring applications in aircraft.

9.2 Future work

This research study proposed a complete package to support ZigBee communications over wireless sensor networks deployed on aircraft wings. This package is mainly intended to minimise cabling costs, and at the same time to support the structural health monitoring of aircraft applications. However, sensor networks which serve as one of the main sources when implementing structural health applications suffer from a number of limitations in terms of energy content and lifetimes. Therefore, this research study can be extended across two main areas in the future.

One area into which to extend this research would be to investigate the lifetimes of those wireless sensor networks used for structural health monitoring on aircraft applications, besides using the proposed energy efficient routing protocol. This area of future work involves identifying node replacement strategies to replace sensor nodes that are running out of battery power in a cost-effective manner. Sensor node replacement policies involve completely replacing sensor nodes, while sensor node recovery policies involve recovering those sensor nodes that are about

to die. As part of any future work, approaches to recharging can be designed to recover sensor nodes with very low energy levels, thereby resulting in a decline in sensors' network lifetime. As part of future work, comparisons of replacement and recharging policies can be carried out to identify recovery options for sensor nodes, as this would extend the lifetime of wireless sensor networks.

The second area into which this research could be extended concerns the security level offered for those wireless sensor nodes present in the wireless sensor networks. Security is a key aspect to address as a means to protect any data collected and stored by those sensor nodes present in the network. As part of future work, different means to secure information sensed by the sensor node during storage, and also communication of that information can be identified. Appraisal of cryptographic methods can be carried out as part of future work. By considering the resource constraints of sensor nodes, future work can be involved in proposing an effective and suitable security method for sensor nodes in a wireless sensor network.

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Appendix A

MATLAB codes for multiple Travelling Salesman Problem and Ant Colony Optimization.

How node deployment decided and plotted?

The first step is to decide a number of nodes, and how many of them should be put in a row. These two variables are given by the user. Therefore, any number of nodes can be deployed in the wing model. The MATLAB file *wingLayout.m* does this job.

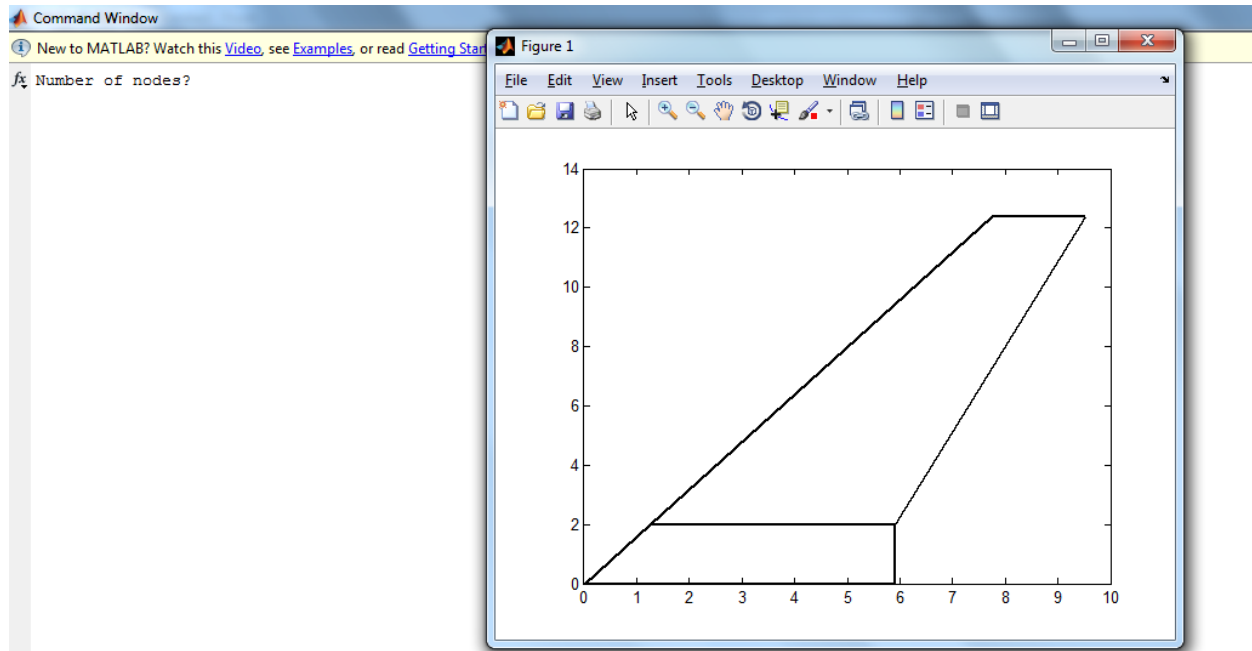


```
1 - clear all;
2 - close all;
3 - clc;
4 - figure('color',[1 1 1]);
5 - plot([0 5.9],[0 0],'k','Linewidth',2);
6 - hold on;
7 - plot([5.9 5.9],[0 2],'k','Linewidth',2);
8 - hold on;
9 - plot([0 2*cosd(58)/sind(58)],[0 2],'k','Linewidth',2);
10 - hold on;
11 - plot([2*cosd(58)/sind(58) 5.9],[2 2],'k','Linewidth',2);
12 - hold on;
13 - plot([2*cosd(58)/sind(58) 12.4*cosd(58)/sind(58)],[2 12.4],'k','Linewidth',2);
14 - hold on;
15 - plot([12.4*cosd(58)/sind(58) 12.4*cosd(58)/sind(58)+1.77],[12.4 12.4],'k','Linewidth',2);
16 - hold on;
17 - plot([5.9 12.4*cosd(58)/sind(58)+1.77],[2 12.4],'k','Linewidth',2);
18 - hold on;
19
20 - nNodes=input('Number of nodes?');
21 - nR=input('Number of nodes per row?');
22 - y=0;
23 - coNodes=zeros(nNodes,2);
24 - ii=0;
25 - for i=1:nNodes/nR
26 -     y=y+(12.4/(nNodes/nR +1));
27 -     if y<=2
```

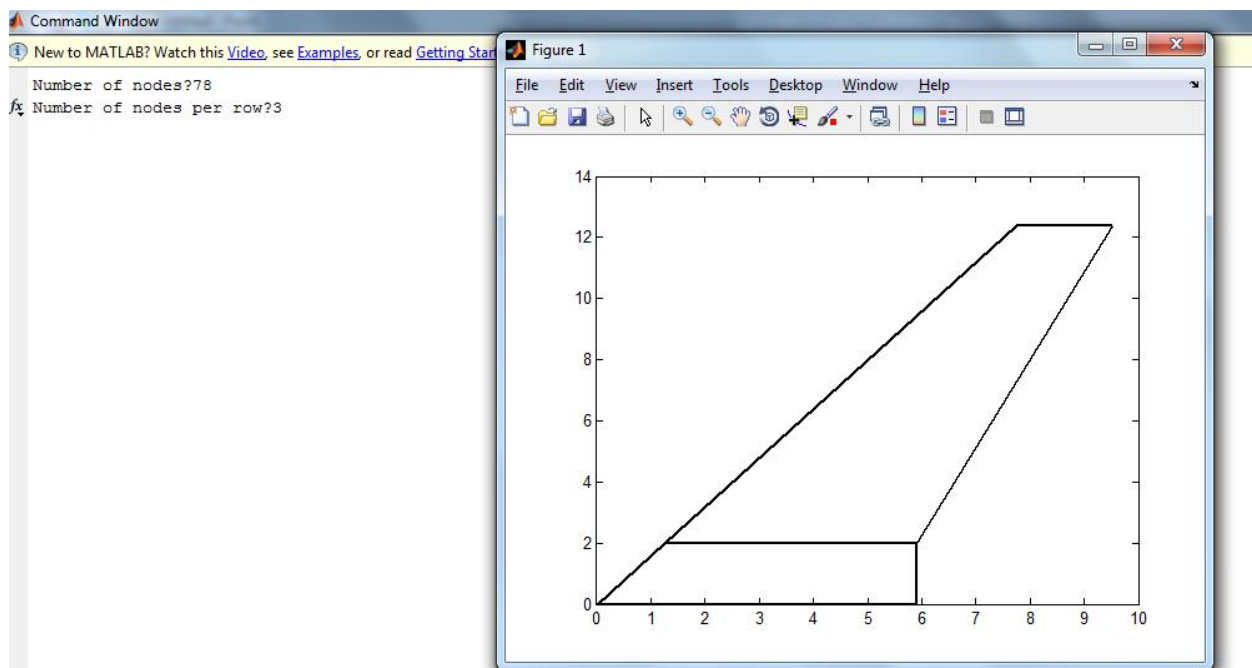
← This part plots the wing geometry

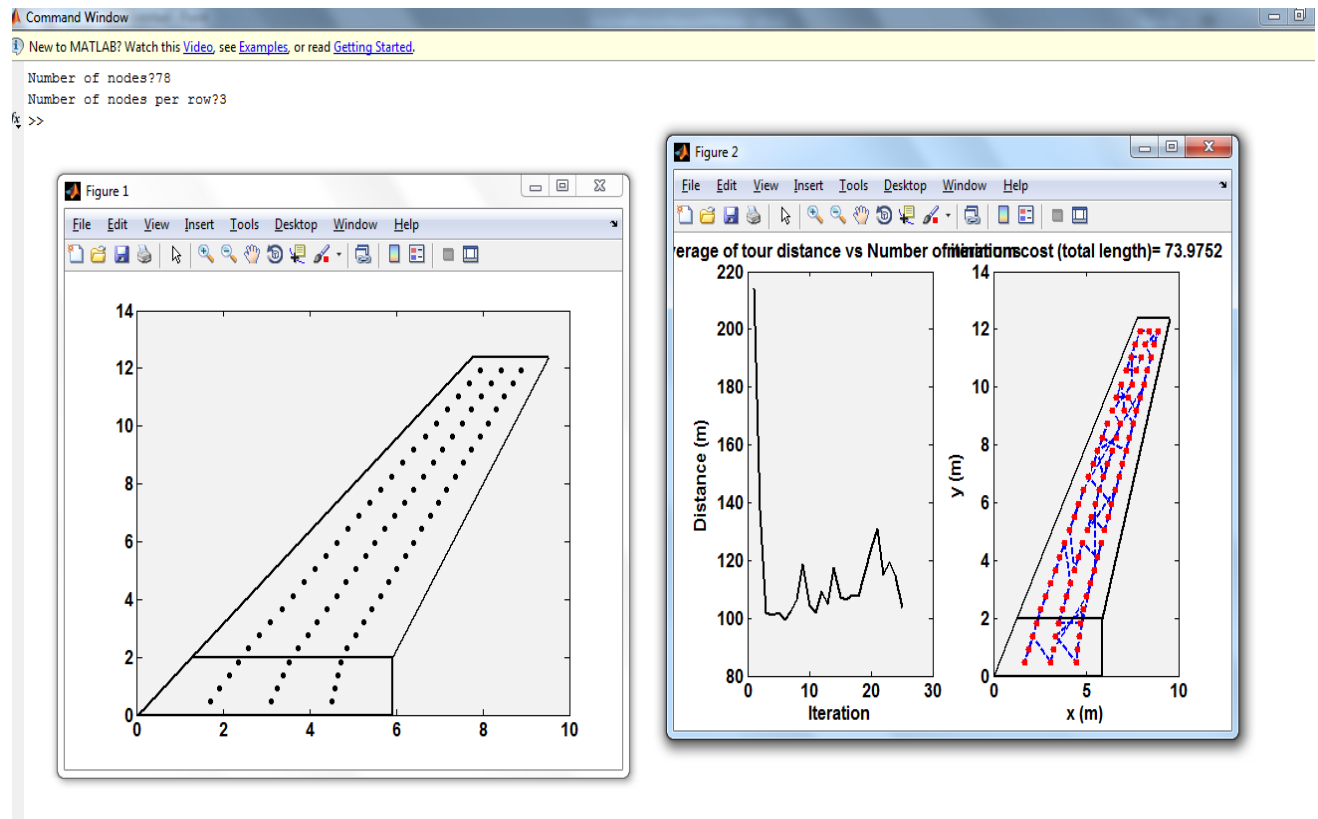
← Node deployment is prompted here

If we run the *wingLayout.m*, the command prompt output looks like,



Once we enter the number of nodes and number of nodes per row, the nodes are uniformly distributed over the wing, and relevant ACO functions are initialized and called. After the successful execution, the shortest path connecting all the nodes is displayed with the number of iterations. See screenshots below. The functions for ACO are described next.





Let's return to the functionality in the *wingLayout.m*

After the nodes are uniformly distributed on the wing, Ant Colony Optimization parameters are initialized, as shown and explained in screenshot below,

```

54 - end
55 - end
56 -
57 - for i=1:nNodes
58 -     for j=1:nNodes
59 -         d(i,j)=sqrt((coNodes(i,1)-coNodes(j,1))^2+(coNodes(i,2)-coNodes(j,2))^2);
60 -     end
61 - end
62 -
63 - for i=1:nNodes
64 -     for j=1:nNodes
65 -         if d(i,j)==0
66 -             h(i,j)=0;
67 -         else
68 -             h(i,j)=1/d(i,j);
69 -         end
70 -     end
71 - end
72 -
73 - miter=25;
74 - m=nNodes;
75 - n=nNodes;
76 - e=.15;           % evaporation coefficient.
77 - alpha=1;        % effect of ants' sight.
78 - beta=4;         % trace's effect.
79 - t=0.0001*ones(n); % primary tracing.
80 - el=.97;         % common cost elimination.

```

↑ Finds distance between each nodes

← Uses the inverse of the distance as the visibility of node

← ACO parameters like number of iterations, alpha, beta are initialized here, using the standard values.

At line number 83 in *winglayout.m*, the ACO code starts, and following steps are taken,

- ✓ Select randomly the number of nodes to start travel with. In other words, randomly nodes are selected where the signal originates or transmitted, to travel to other nodes.
- ✓ The function *ant_tour.m* constructs the probabilistic route.
- ✓ The function *calculate_cost.m* computes the cost of each route; the cost is the total distance to be travelled.
- ✓ The function *tour.m* finds the best tour among the computed tours and presents as a solution on the wing model with nodes.

These steps are shown in the code with following screenshots.

```

81 % -----
82
83 for i=1:miter
84 % Step 1: Forward ants and solution construction
85
86 % Generate places for each ant
87 for j=1:m
88     start_places(j,1)=fix(1+rand*(n-1));
89 end
90 % Step 2:probabilistic solution construction
91 [tour]=ant_tour(start_places,m,n,h,t,alpha,beta);
92 tour=horzcat(tour,tour(:,1));
93
94 % Step 3: Calculate the cost --> total distace
95 [cost,f]=calculate_cost(m,n,d,tour,e1);
96 [t]=update_the_trace(m,n,t,tour,f,e);
97 average_cost(i)=mean(cost);
98
99 % Step 4: Determine the best route
100 [min_cost(i),best_index]=min(cost);
101 besttour(i,:)=tour(best_index,:);
102 iteration(i)=i;
103 end
104 % -----
105 set(gca,'Color',[0.95,0.95,0.95]);
106 set(gca,'Fontweight','bold');
107 set(gca,'Fontname','Timesnewroman');

```

Initialize random starting nodes for the signal transmission

Construct an ant tour

Calculate the cost of the tour

Find the best tour, with least cost of travel

Plot the solution on the wing model

script Ln 82

How the different results are generated?

Figures 4.4 to 4.10 were generated using a different number of nodes in the wing model, and no other data. The default parameters were the same, for ACO initialization, such as evaporation coefficient, ant's sight, trace effect etc. The S parameter values were not used, as it is not possible to do all CST simulations in short time. So only distances among the nodes were used as a criterion for optimization of total travel distance. Therefore, all the simulations find the shortest distance of travel.

How the S parameter results are generated using CST simulation for anon-central prismatic model with 79 nodes?

The S parameter values were obtained in a text file of size around 70 MB, and those were imported in MATLAB using import tool.

The S parameters were then processed to remove any string or text and stored in the .mat file.

The .mat file was accessed and loaded using MATLAB code as shown in the screenshot below,

```
1 - clear all;
2 - close all;
3 - clc;
4 - hold on;
5 - load('NSPrismatic.mat');
6 - tmpS=SNew;
7 - for i=1:79*79
8 -     SS(i)=mean(tmpS(1+(i-1)*200:i*200));
9 - end
10 - SSmat=reshape(SS,79,79);
11 - for j=[1 26 51]
12 -     plot(SSmat(j,:));
13 -     hold on;
14 - end
15 -
16 -
17 -
18 -
```

Load the S parameter data

Find the average of S parameters over the frequency range of 2.4 GHz to 2.5 GHz

Plot the results from a particular node, as shown in figure

The file is *sparPlotter.m*

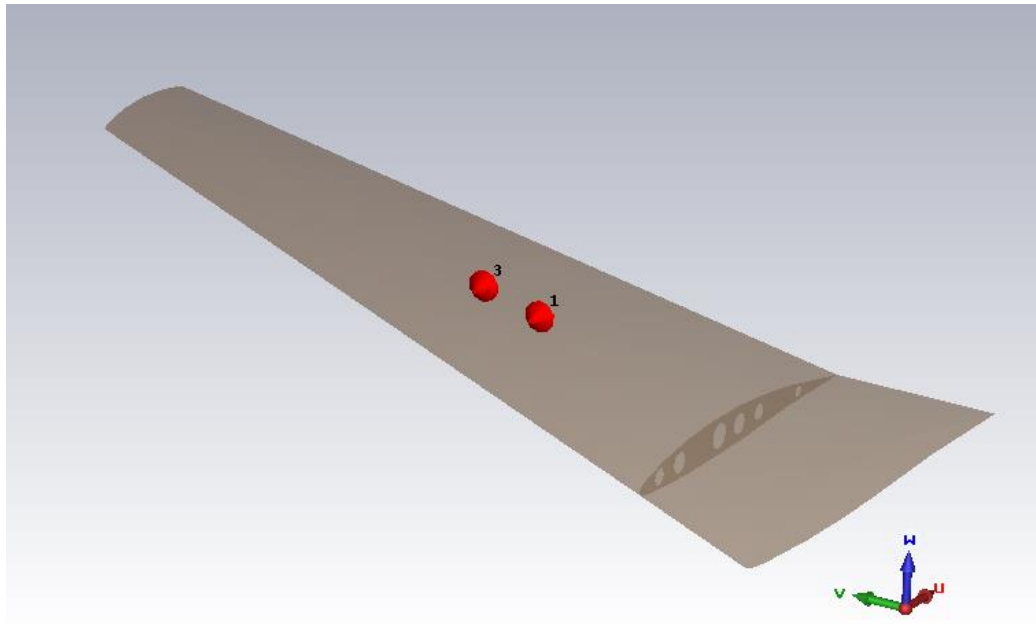
Appendix B

Mesh Analysis

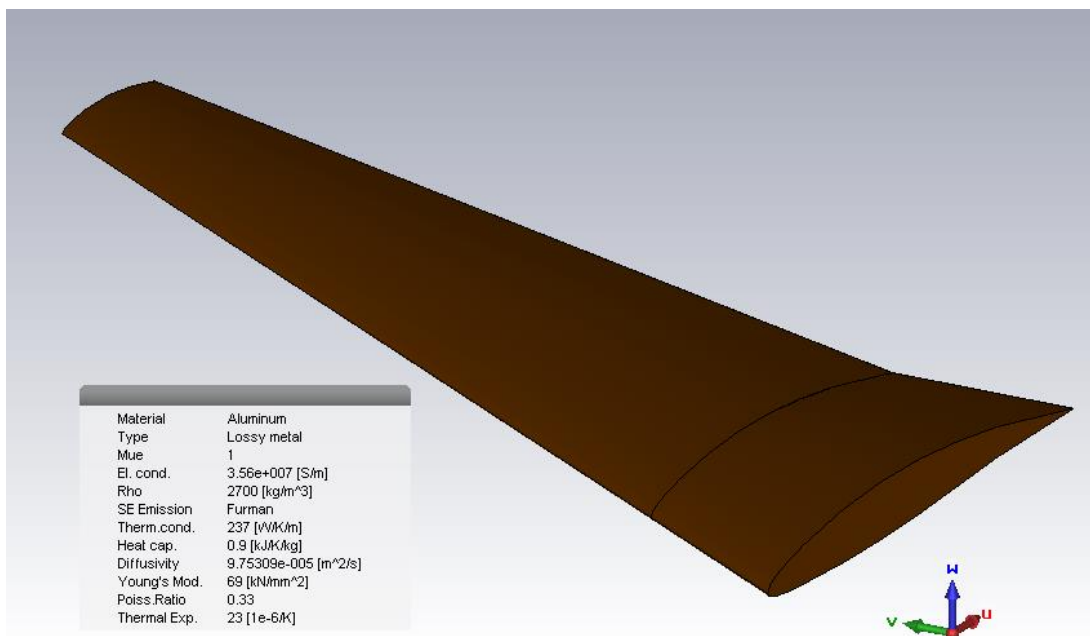
This section of the thesis is aimed in analyzing the mesh of the aeroplane wings before conducting the actual simulation part. Mesh is defined as very small cells that are obtained by dividing the target structure using simulation tool. In this work, the simulation tool CST divides the aeroplane wing into several small cells where each cell is being referred to as the mesh. As the accuracy of the simulation along with the time of simulation directly depends on the mesh dimensions, this section aims in identifying the exact compromise between the simulation accuracy and that of the simulation time. To identify this exact balance between the simulation time and simulation accuracy, one wing structure is only considered an investigation of different mesh options is carried out.

Empty Wing Simulation

The structure of the wing which is considered in this simulation is an empty wing with two sensor antennas on it that communicates with each other. The main reason for choosing this empty wing model for this mesh analyses is the wide application of this wing model in major passenger aeroplanes such as McDonnell Douglas, Airbus 320, DC-9-80 and Boeing 737-200. The simulation of this empty air wing model in CST simulation software with two sensor antennas is given in the below screenshot.



As this work intends in verifying the effect of the air wing surface materials used, this empty aeroplane wing that is simulated in CST is simulated with the material configuration of aluminium. The next picture shows, the aluminium material configuration of the empty wing in CST.

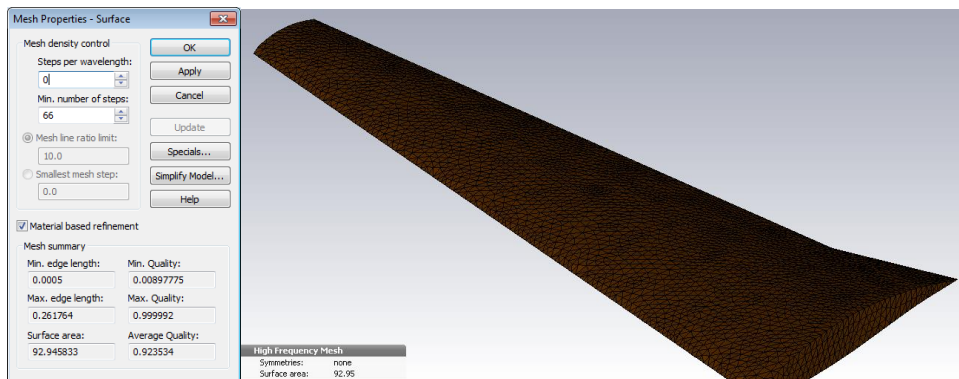


Three Mesh Options

For the aluminium empty wing model simulated in CST, three different mesh sizes are created, and the investigation is carried out to identify the suitable mesh size that can effectively balance the simulation time and the simulation accuracy. The three mesh sizes which are created include:

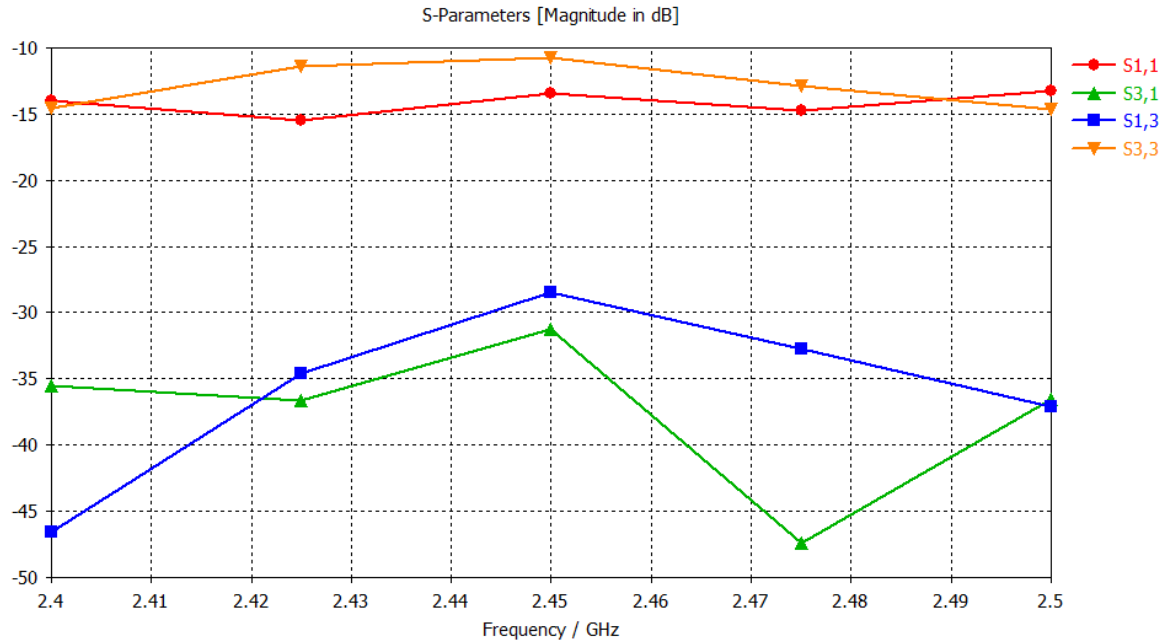
1. Mesh Size 1: 10,000 cells
2. Mesh Size 2: 30,000 cells
3. Mesh Size 3: 60,000 cells

1. Mesh Size 1: 10,000 cells



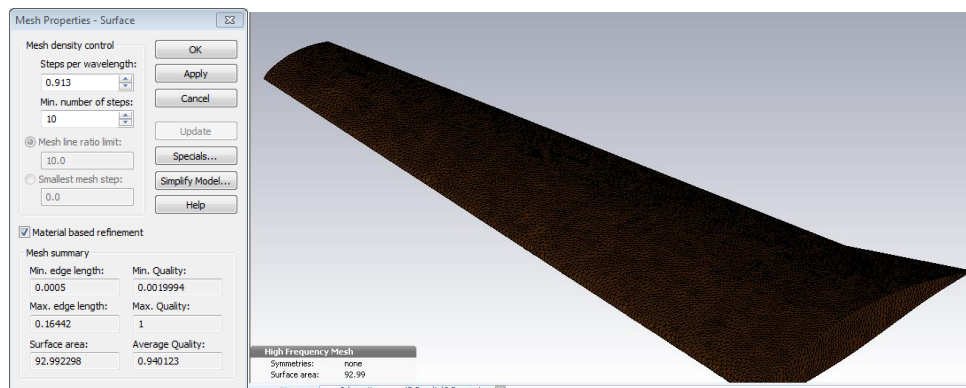
The first mesh option that is planned to be investigated is mesh size 1, which is obtained by dividing the empty aeroplane wing model into 10,000 very small cells. This creation of the mesh option mesh size 1 is done in CST simulation using the Mesh Properties option for the empty aeroplane wing surface. The resultant mesh size 1 that is created in CST is shown below.

Simulation results for mesh with 10,000 cells



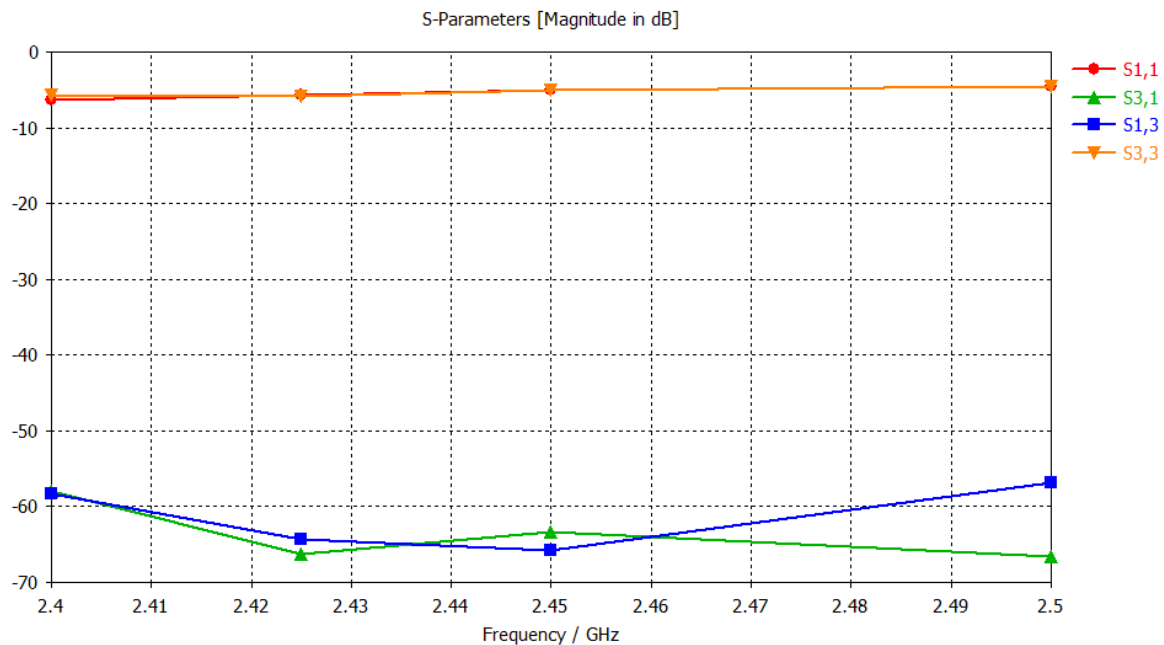
The above graph shows the simulation results of the first mesh option *mesh size 1* of aluminium-based empty aeroplane wing model with 10,000 cells. Analyses of the S13 and S31 parameters of the above graph indicate the existence of significant differences between them. Evaluation of these results based on the theory of free field propagation for EM waves indicates that the transmission coefficient between the two antennas is varying as the *link budget* has not remained constant. On the other hand, the two scattering parameters S13 and S31 have not matched each other (which must be matched according to the theory of free field propagation).

2. Mesh Size 2: 30,000 cells



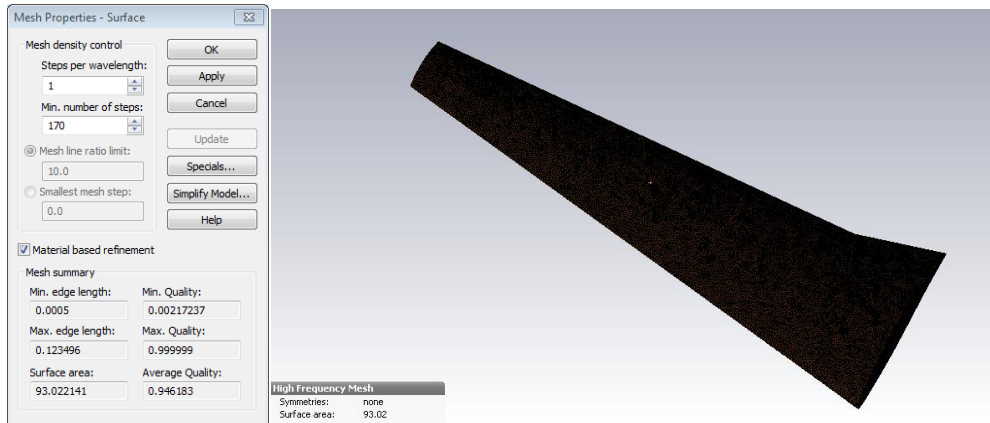
The second mesh option that is planned to be investigated is mesh size 2, which is obtained by dividing the empty aeroplane wing model into 30,000 very small cells. This creation of the mesh option *mesh size 2* is done in CST simulation using the *Mesh Properties* option for the empty aeroplane wing surface. The resultant *mesh size 2* that is created in CST is shown above.

Simulation results for mesh with 30,000 cells



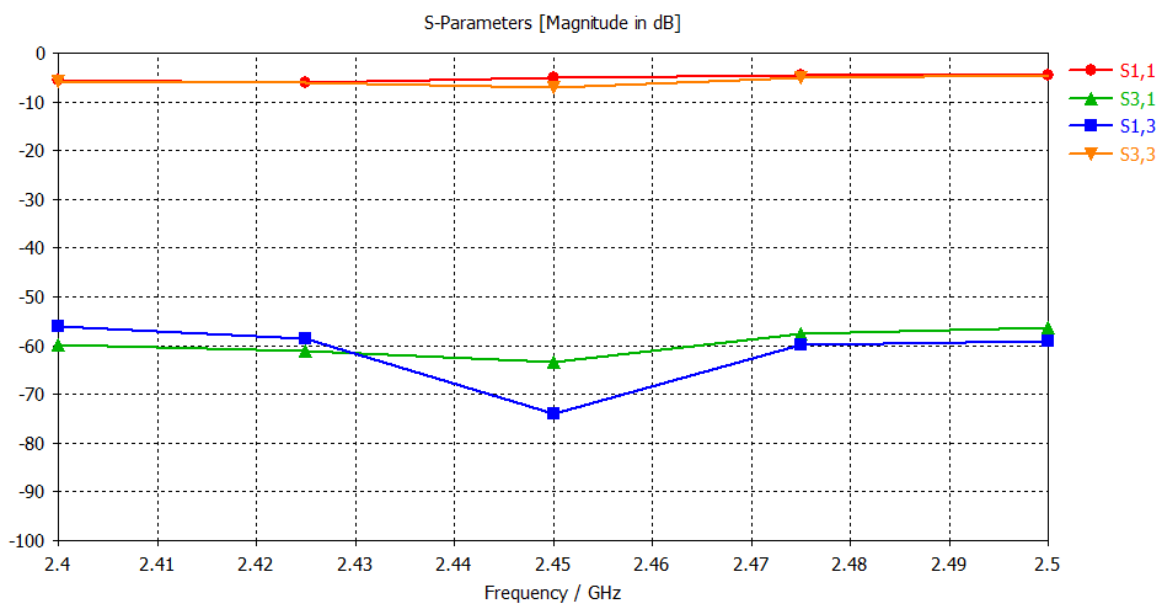
The above graph shows the comparative analysis of the scattering parameters of second mesh option *mesh size 2* with 30,000 cells on the aluminium-based empty wing model. Analyses of these scattering parameters indicate that there exists only a slight difference between the parameters S31 and S13. Evaluation of these results based on the theory of free field propagation of EM waves indicates that transmission coefficient of the two antennas is almost the same which made *link budget* to remain constant. On the other hand, the scattering parameters S13 and S31 are almost matched with each other and are also according to the theory.

3. Mesh Size 3: 60,000 cells



The third mesh option that is planned to be investigated in this mesh analyses is mesh size 3, which is obtained by dividing the aluminium material empty aeroplane wing model into 60,000 very small cells. This creation of the mesh option *mesh size 3* is done in CST simulation using the *Mesh Properties* option for the aluminium empty aeroplane wing surface. The resultant *mesh size 1* that is created in CST is shown above.

Simulation results for mesh with 60,000 cells



The above graph shows the comparative analysis of the scattering parameters of third mesh option mesh size 3 with 60,000 cells on the aluminium based empty wing model. Analyses of these scattering parameters indicate that there exists no difference between the parameters S31 and S13. Evaluation of these results based on the theory of free field propagation of EM waves indicates that transmission coefficient of the two antennas is almost the same which made link budget to remain constant. On the other hand, the scattering parameters S13 and S31 are almost matched with each other and are also according to the theory. These results are similar to that of mesh size 2 with 30,000 cells but include higher complexity than the mesh with 30,000 cells.

From the mesh analyses results, it is evident that the value of *link budget* remains constant and results look logical and realistic for mesh size 2 cases with 30,000 cells. To summarize, the second mesh option *mesh size 2* is considered for simulations in this work, as it is realistic and logical in balancing simulation time and simulation accuracy.

Appendix C

Comparative Analysis

Introduction

This chapter is mainly intended in comparing the link budget values of the two sensor antennas that are simulated for the different wing models that are considered in this simulation. Two groups of simulation studies are carried out of which the first group investigates the impact of the wing model on the *link budget* value, the second group, on the other hand, investigates the impact of the material used for the wing on the *link budget* value.

Comparison parameters

In the process of comparing the simulations two main groups are created in this work. These two groups of comparative analysis are mainly aimed in performing the following aspects:

1. Identification of the impact of different antenna position and different wing model on the value of link budget.
2. Investigating the impact of different aeroplane wing material on the link budget value of the two antennas placed on the wings.

The number of the simulations that is carried out is slowly increased to suit different wing models and different positions of the antenna. In each of these simulations, different antenna positions will be used on aircraft wing for identifying the better antenna position that can improve the performance of ZigBee communications. In the same way, different materials are used for air wings to identify the impact of the air wing material on the link budget value. As the test cases that were performed before, in the frequency range between 0 and 5 GHz identified that no significant coupling differences exists between the nodes in the frequency range between 2.40 GHz and 2.50 GHz, all the simulations carried out in the work are carried out in this frequency range itself in order to identify the better position of the antenna in this frequency range.

In all these 36 simulations that are carried out, some assumptions are considered of which the most important one is assuming the presence of free space for EM wave propagation despite of the existence of different types of medium such as air, lubricants and the fuel in which the EM propagation can be done. By considering free space medium for EM propagation in this work, the impact of the medium in EM wave propagation is minimized in this work.

Simulated wing models

As part of these 36 simulations, three different wing models are being investigated which are given below,

1. Realistic wing model
2. Empty wing model
3. Prismatic wing model

Wing Surface material

Unlike the previous simulations that are carried out as in the frequency range of 0 to 5 GHz; this work does not make any assumptions regarding the type of material used for air wing surface. But in this work, three different types of air wing surface materials are used to identify the impact of these materials on link budget value. These three different materials used for this work are:

1. Aluminum
2. Carbon fibre
3. Perfect Electric (PE) conductor

Antenna Positioning

For the simulations, two sensor antennas are considered. These two sensor antennas are placed at different positions that are distant apart. One antenna is always fixed at one position on the wing that is at the one end of the wing (near to the fuselage). The other antenna varied at 4 different positions:

1. **Small distance:** In this position, the first antenna is fixed at one position near the fuselage and the second antenna is placed at the $1/4^{\text{th}}$ position of the wing length.
2. **Second distance:** In this position, the first antenna is fixed at one position near the fuselage and the second antenna is placed at $1/2^{\text{nd}}$ position of the wing length
3. **Third distance:** In this position, the first antenna is fixed at one position near the fuselage and the second antenna is placed at $3/4^{\text{th}}$ position of the wing length
4. **Highest distance:** In this position, the first antenna is fixed at one position near the fuselage and the second antenna is placed at tip of the wing

Each of the 36 simulations that are carried out in this work uses two antennas. Summary of the steps detailing the simulations process that intends in identifying the effect of antenna position, different wing model and wing surface material on the value of link budget is given below.

1. Chosen the surface material of air wing as aluminium
2. Select wing realistic model of the air wing
3. Place the first antenna near the fuselage of the air wing and place the second antenna at $1/4^{\text{th}}$ of wing length (small distance). Run simulations.
4. Change the second antenna position to $1/2^{\text{nd}}$ of wing length (second distance) and run simulation
5. Change the second antenna position to $3/4^{\text{th}}$ of wing length (third distance) and run simulation
6. Change the second antenna position to tip of wing (highest distance) and run simulation
7. Repeat step 3 to 6 for empty wing model and prismatic wing model
8. Now choose the surface material of air wing as carbon fibre and repeat from step 2 to step 7
9. Now choose the surface material of air wing as PEC and repeat from step 2 to step 7

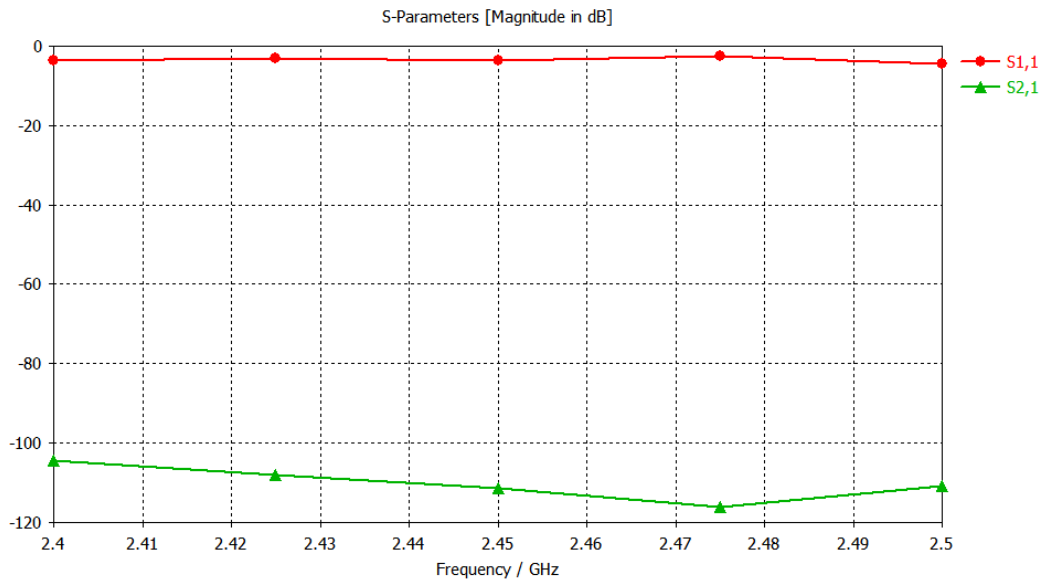
Results of 36 Simulations

Details of each of 36 simulations along with their characteristics is given in the below table.

Altogether 36 simulation results are used for this comparison.

wing material	model no	wing realisitc	wing empty	wing prismatic empty	small distance	second distance	third distance	highest distance
Aluminum	1	x			x			
	2	x				x		
	3	x					x	
	4	x						x
	5		x		x			
	6		x			x		
	7		x				x	
	8		x					x
	9			x	x			
	10			x		x		
	11			x			x	
	12			x				x
Carbon fiber	13	x			x			
	14	x				x		
	15	x					x	
	16	x						x
	17		x		x			
	18		x			x		
	19		x				x	
	20		x					x
	21			x	x			
	22			x		x		
	23			x			x	
	24			x				x
PEC	25	x			x			
	26	x				x		
	27	x					x	
	28	x						x
	29		x		x			
	30		x			x		
	31		x				x	
	32		x					x
	33			x	x			
	34			x		x		
	35			x			x	
	36			x				x

Simulation Model 1

Result	S-Parameters [Magnitude in dB] <table><thead><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr></thead><tbody><tr><td>2.4</td><td>0</td><td>-105</td></tr><tr><td>2.425</td><td>0</td><td>-108</td></tr><tr><td>2.450</td><td>0</td><td>-112</td></tr><tr><td>2.475</td><td>0</td><td>-115</td></tr><tr><td>2.5</td><td>0</td><td>-110</td></tr></tbody></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	0	-105	2.425	0	-108	2.450	0	-112	2.475	0	-115	2.5	0	-110
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.4	0	-105																	
2.425	0	-108																	
2.450	0	-112																	
2.475	0	-115																	
2.5	0	-110																	
Description	This is the simulation result for the wing realistic model that is made of aluminium material and where the second antenna is placed at 1/4th wing length. Here the reflection coefficient (S1, 1) is close to zero indicating the reflection of all the power from the first antenna. The amount of power transmitted from antenna 1 to antenna 2 is specified by transmission coefficient (S2, 1). At 2.475 GHz frequency, the transmitted power has declined and further increased.																		

Simulation Model 2

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>0</td><td>-115</td></tr><tr><td>2.41</td><td>0</td><td>-116</td></tr><tr><td>2.42</td><td>0</td><td>-117</td></tr><tr><td>2.425</td><td>0</td><td>-118</td></tr><tr><td>2.43</td><td>0</td><td>-117</td></tr><tr><td>2.44</td><td>0</td><td>-116</td></tr><tr><td>2.45</td><td>0</td><td>-112</td></tr><tr><td>2.46</td><td>0</td><td>-114</td></tr><tr><td>2.47</td><td>0</td><td>-116</td></tr><tr><td>2.475</td><td>0</td><td>-118</td></tr><tr><td>2.48</td><td>0</td><td>-118</td></tr><tr><td>2.49</td><td>0</td><td>-118</td></tr><tr><td>2.5</td><td>0</td><td>-118</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	0	-115	2.41	0	-116	2.42	0	-117	2.425	0	-118	2.43	0	-117	2.44	0	-116	2.45	0	-112	2.46	0	-114	2.47	0	-116	2.475	0	-118	2.48	0	-118	2.49	0	-118	2.5	0	-118
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																									
2.4	0	-115																																									
2.41	0	-116																																									
2.42	0	-117																																									
2.425	0	-118																																									
2.43	0	-117																																									
2.44	0	-116																																									
2.45	0	-112																																									
2.46	0	-114																																									
2.47	0	-116																																									
2.475	0	-118																																									
2.48	0	-118																																									
2.49	0	-118																																									
2.5	0	-118																																									
Description	This is the simulation result for the wing realistic model that is made of aluminium material and where the second antenna is placed at $\frac{1}{2}$ of wing length. With the increase in the distance between the first and second antenna, the reflection coefficient ($S_{1,1}$) has more closely approximated to zero than the previous case. Even the transmission coefficient ($S_{2,1}$) is reduced, and only at 2.45 GHz frequency, the transmitted power from antenna 2 to antenna 1 has increased and further declined.																																										

Simulation Model 3

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>0</td><td>-110</td></tr><tr><td>2.425</td><td>0</td><td>-125</td></tr><tr><td>2.45</td><td>0</td><td>-115</td></tr><tr><td>2.475</td><td>0</td><td>-100</td></tr><tr><td>2.5</td><td>0</td><td>-125</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	0	-110	2.425	0	-125	2.45	0	-115	2.475	0	-100	2.5	0	-125
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.4	0	-110																	
2.425	0	-125																	
2.45	0	-115																	
2.475	0	-100																	
2.5	0	-125																	
Description	This is the simulation result for the wing realistic model that is made of aluminium material and where the second antenna is placed at 3/4th wing length. With the increase in distance between antenna 1 and antenna 2, the reflection coefficient (S1, 1) is equal to zero, indicating the reflection of all the power from the first antenna. Surprisingly, at this distance, the transmission coefficient (S2, 1) reached a high value of -100 dB at 2.475 GHz frequency and reached a low value of -130 dB at 2.425 frequencies.																		

Simulation Model 4

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.40</td><td>-5</td><td>-98</td></tr><tr><td>2.41</td><td>-5</td><td>-102</td></tr><tr><td>2.42</td><td>-5</td><td>-108</td></tr><tr><td>2.43</td><td>-5</td><td>-105</td></tr><tr><td>2.44</td><td>-5</td><td>-102</td></tr><tr><td>2.45</td><td>-5</td><td>-99</td></tr><tr><td>2.46</td><td>-5</td><td>-101</td></tr><tr><td>2.47</td><td>-5</td><td>-103</td></tr><tr><td>2.48</td><td>-5</td><td>-102</td></tr><tr><td>2.49</td><td>-5</td><td>-100</td></tr><tr><td>2.50</td><td>-5</td><td>-97</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.40	-5	-98	2.41	-5	-102	2.42	-5	-108	2.43	-5	-105	2.44	-5	-102	2.45	-5	-99	2.46	-5	-101	2.47	-5	-103	2.48	-5	-102	2.49	-5	-100	2.50	-5	-97
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																			
2.40	-5	-98																																			
2.41	-5	-102																																			
2.42	-5	-108																																			
2.43	-5	-105																																			
2.44	-5	-102																																			
2.45	-5	-99																																			
2.46	-5	-101																																			
2.47	-5	-103																																			
2.48	-5	-102																																			
2.49	-5	-100																																			
2.50	-5	-97																																			
Description	This is the simulation result for the wing realistic model that is made of aluminium material and where the second antenna is placed at the tip of the wing. Here the distance between the first and second antenna is very large, and the reflection coefficient ($S_{1,1}$) reached -5dB value from 2.40 to 2.43 GHz. Hence the antenna1 radiates best in this range. The transmission coefficient ($S_{2,1}$) at this position of the second antenna remained between -100 and -110 db.																																				

Simulation Model 5

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>-10</td><td>-100</td></tr><tr><td>2.425</td><td>-10</td><td>-93</td></tr><tr><td>2.45</td><td>-10</td><td>-98</td></tr><tr><td>2.475</td><td>-11</td><td>-108</td></tr><tr><td>2.5</td><td>-9</td><td>-95</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	-10	-100	2.425	-10	-93	2.45	-10	-98	2.475	-11	-108	2.5	-9	-95
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.4	-10	-100																	
2.425	-10	-93																	
2.45	-10	-98																	
2.475	-11	-108																	
2.5	-9	-95																	
Description	This is the simulation result for the wing empty model that is made of aluminium material and where the second antenna is placed at 1/4th wing length. The reflection coefficient (S1, 1) value of empty wing model is better than the wing realistic model. Throughout the frequency range between 2.4 GHz and 2.5 Hz, the first antenna in this empty wing model will radiates best as the value of S11 is -10dB. The transmission coefficient (S2, 1) is between the range -90 dB and -110 dB which are found to be better when compared to wing realistic model with the same antenna position.																		

Simulation Model 6

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.40</td><td>-10</td><td>-110</td></tr><tr><td>2.425</td><td>-10</td><td>-112</td></tr><tr><td>2.45</td><td>-10</td><td>-110</td></tr><tr><td>2.475</td><td>-10</td><td>-108</td></tr><tr><td>2.50</td><td>-10</td><td>-105</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.40	-10	-110	2.425	-10	-112	2.45	-10	-110	2.475	-10	-108	2.50	-10	-105
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.40	-10	-110																	
2.425	-10	-112																	
2.45	-10	-110																	
2.475	-10	-108																	
2.50	-10	-105																	
Description	This is the simulation result for the empty wing model that is made of aluminium material and where the second antenna is placed at the $\frac{1}{2}$ position of wing length. With the increase in the distance between antennas, the reflection coefficient ($S_{1,1}$) has declined less than -10 dB which indicates comparatively less radiation of the first antenna. The increase in the distance between the two antennas also decreased the transmission coefficient value $S_{2,1}$ as shown above.																		

Simulation Model 7

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.40</td><td>0</td><td>-100</td></tr><tr><td>2.425</td><td>-2</td><td>-130</td></tr><tr><td>2.45</td><td>-5</td><td>-105</td></tr><tr><td>2.475</td><td>-8</td><td>-100</td></tr><tr><td>2.50</td><td>-10</td><td>-115</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.40	0	-100	2.425	-2	-130	2.45	-5	-105	2.475	-8	-100	2.50	-10	-115
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.40	0	-100																	
2.425	-2	-130																	
2.45	-5	-105																	
2.475	-8	-100																	
2.50	-10	-115																	
Description	This is the simulation result for the empty wing model that is made of aluminium material and where the second antenna is placed at 3/4th wing length. The reflection coefficient (S1, 1) is close to zero initially but then slowly reached -10 dB indicating the improvement in first antenna radiation. The transmission coefficient (S2,1) remained less than -100 dB between the frequency range 2.4 GHz and 2.5 GHz.																		

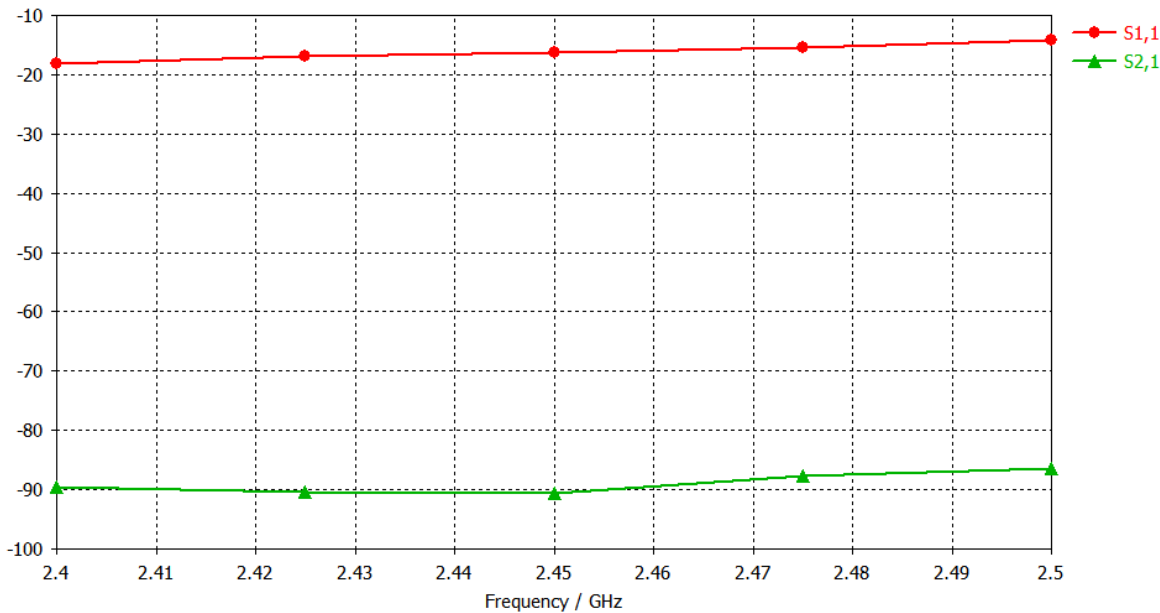
Simulation Model 8

Result	S-Parameters [Magnitude in dB] The graph displays two S-parameters over a frequency range from 2.4 GHz to 2.5 GHz. The y-axis represents magnitude in dB, ranging from -120 to 0. The red line with circular markers represents S1,1, which remains consistently near 0 dB. The green line with triangular markers represents S2,1, which is mostly flat at -100 dB but shows a significant dip to -115 dB at 2.475 GHz. <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.400</td><td>-5</td><td>-102</td></tr><tr><td>2.425</td><td>-7</td><td>-103</td></tr><tr><td>2.450</td><td>-5</td><td>-102</td></tr><tr><td>2.475</td><td>-7</td><td>-115</td></tr><tr><td>2.500</td><td>-5</td><td>-103</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.400	-5	-102	2.425	-7	-103	2.450	-5	-102	2.475	-7	-115	2.500	-5	-103
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.400	-5	-102																	
2.425	-7	-103																	
2.450	-5	-102																	
2.475	-7	-115																	
2.500	-5	-103																	
Description	This is the simulation result for the empty wing model that is made of aluminium material and where the second antenna is placed at the tip of the wing. Here the reflection coefficient ($S_{1,1}$) has become close to zero with the increase in antenna distance showing a high reflection of the power with poor radiation levels. The transmission coefficient ($S_{2,1}$) is recorded low at 2.475 GHz frequency as -115dB as shown above.																		

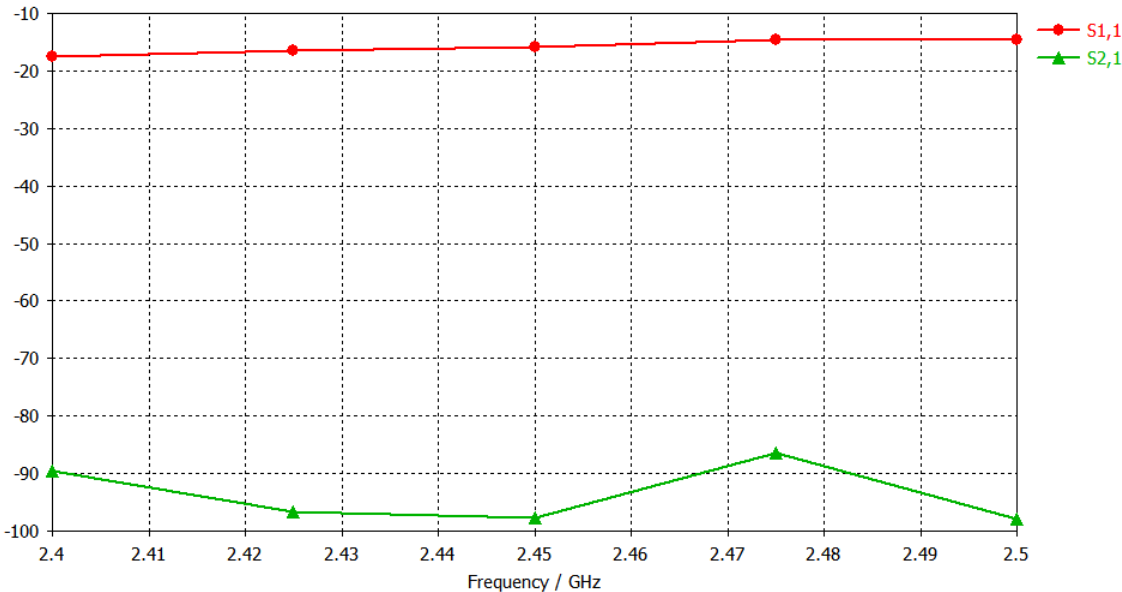
Simulation Model 9

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.400</td><td>-15.5</td><td>-85.0</td></tr><tr><td>2.425</td><td>-16.0</td><td>-88.0</td></tr><tr><td>2.450</td><td>-16.0</td><td>-92.0</td></tr><tr><td>2.475</td><td>-15.5</td><td>-98.0</td></tr><tr><td>2.500</td><td>-15.0</td><td>-88.0</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.400	-15.5	-85.0	2.425	-16.0	-88.0	2.450	-16.0	-92.0	2.475	-15.5	-98.0	2.500	-15.0	-88.0
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.400	-15.5	-85.0																	
2.425	-16.0	-88.0																	
2.450	-16.0	-92.0																	
2.475	-15.5	-98.0																	
2.500	-15.0	-88.0																	
Description	This is the simulation result for the wing prismatic model that is made of aluminium material and where the second antenna is placed at 1/4th wing length. When compared to other two wing model, the reflection coefficient (S1, 1) of this wing model is better at this position of the second antenna. In the similar way, the transmission coefficient (S2,1) of this wing prismatic wing model is better as it is above -100 dB indicating better transmission of the power from antenna 1 to antenna 2.																		

Simulation Model 10

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.40</td><td>-18</td><td>-90</td></tr><tr><td>2.41</td><td>-18</td><td>-90</td></tr><tr><td>2.42</td><td>-18</td><td>-90</td></tr><tr><td>2.43</td><td>-18</td><td>-90</td></tr><tr><td>2.44</td><td>-18</td><td>-90</td></tr><tr><td>2.45</td><td>-18</td><td>-90</td></tr><tr><td>2.46</td><td>-18</td><td>-90</td></tr><tr><td>2.47</td><td>-18</td><td>-90</td></tr><tr><td>2.48</td><td>-18</td><td>-90</td></tr><tr><td>2.49</td><td>-18</td><td>-90</td></tr><tr><td>2.50</td><td>-10</td><td>-85</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.40	-18	-90	2.41	-18	-90	2.42	-18	-90	2.43	-18	-90	2.44	-18	-90	2.45	-18	-90	2.46	-18	-90	2.47	-18	-90	2.48	-18	-90	2.49	-18	-90	2.50	-10	-85
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																			
2.40	-18	-90																																			
2.41	-18	-90																																			
2.42	-18	-90																																			
2.43	-18	-90																																			
2.44	-18	-90																																			
2.45	-18	-90																																			
2.46	-18	-90																																			
2.47	-18	-90																																			
2.48	-18	-90																																			
2.49	-18	-90																																			
2.50	-10	-85																																			
Description	This is the simulation result for the wing prismatic model that is made of aluminium material and where the second antenna is placed at the $1/2^{\text{nd}}$ position of wing length. The increase in the distance between the antennas has also affected the S1, 1 and S2, 1 parameters. The reflection coefficient (S1, 1) is close to -20 dB initially and reached -10 dB by the end of a simulation. The amount of power reflected by antenna has declined with the increase in the second antenna distance. Similarly, the power transmitted by antenna1 to antenna 2 is better as transmission coefficient (S2, 1) remained at -90 dB.																																				

Simulation Model 11

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.40</td><td>-17.5</td><td>-90</td></tr><tr><td>2.425</td><td>-17.5</td><td>-97</td></tr><tr><td>2.45</td><td>-17.5</td><td>-98</td></tr><tr><td>2.475</td><td>-17.5</td><td>-87</td></tr><tr><td>2.50</td><td>-17.5</td><td>-99</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.40	-17.5	-90	2.425	-17.5	-97	2.45	-17.5	-98	2.475	-17.5	-87	2.50	-17.5	-99
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.40	-17.5	-90																	
2.425	-17.5	-97																	
2.45	-17.5	-98																	
2.475	-17.5	-87																	
2.50	-17.5	-99																	
Description	This is the simulation result for the wing prismatic model that is made of aluminium material and where the second antenna is placed at the 3/4th position of the wing. The reflection coefficient (S1, 1) is same as before simulation while the transmission coefficient (S2, 1) declined from -90 dB to -100 dB with the increase in distance between the two antennas.																		

Simulation Model 12

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.400</td><td>-12.0</td><td>-92.0</td></tr><tr><td>2.425</td><td>-12.0</td><td>-95.0</td></tr><tr><td>2.450</td><td>-12.0</td><td>-91.0</td></tr><tr><td>2.475</td><td>-12.0</td><td>-90.0</td></tr><tr><td>2.500</td><td>-12.0</td><td>-85.0</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.400	-12.0	-92.0	2.425	-12.0	-95.0	2.450	-12.0	-91.0	2.475	-12.0	-90.0	2.500	-12.0	-85.0
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.400	-12.0	-92.0																	
2.425	-12.0	-95.0																	
2.450	-12.0	-91.0																	
2.475	-12.0	-90.0																	
2.500	-12.0	-85.0																	
Description	This is the simulation result for the prismatic wing model that is made of aluminium material and where the second antenna is placed at the tip of the wing. Here the reflection coefficient ($S_{1,1}$) value indicates the poor radiation of antenna 1 when compared to the previous simulation. This increase in the distance between antennas had minimal impact on the transmission coefficient ($S_{2,1}$) as indicated above.																		

Simulation Model 13

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.40</td><td>-5</td><td>-95</td></tr><tr><td>2.425</td><td>-5</td><td>-108</td></tr><tr><td>2.45</td><td>-5</td><td>-102</td></tr><tr><td>2.475</td><td>-5</td><td>-102</td></tr><tr><td>2.50</td><td>-5</td><td>-108</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.40	-5	-95	2.425	-5	-108	2.45	-5	-102	2.475	-5	-102	2.50	-5	-108
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.40	-5	-95																	
2.425	-5	-108																	
2.45	-5	-102																	
2.475	-5	-102																	
2.50	-5	-108																	
Description	This is the simulation result for the wing realistic model that is made of carbon fibre material and where the second antenna is placed at 1/4th wing length. Based on the reflection coefficient (S1, 1) values, it is evident that the first antenna radiates best at 2.45 GHz and is comparatively better than aluminium material based air wing. The transmission coefficient (S2,1) has shown approximately the same values as that of the aluminium-based air wing at second antenna at 1/4th position of wing length																		

Simulation Model 14

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>0</td><td>-105</td></tr><tr><td>2.425</td><td>0</td><td>-118</td></tr><tr><td>2.45</td><td>0</td><td>-110</td></tr><tr><td>2.475</td><td>0</td><td>-115</td></tr><tr><td>2.5</td><td>0</td><td>-112</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	0	-105	2.425	0	-118	2.45	0	-110	2.475	0	-115	2.5	0	-112
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.4	0	-105																	
2.425	0	-118																	
2.45	0	-110																	
2.475	0	-115																	
2.5	0	-112																	
Description	This is the simulation result for the wing realistic model that is made of carbon fibre material and where the second antenna is placed at $\frac{1}{2}$ of wing length. The reflection coefficient (S1, 1) of first antennas has not been significantly affected by the increase in the distance between the two antennas. However, the increase in the distance between the antennas has further declined the transmission coefficient (S2, 1) and thereby the amount of power transmitted from antenna 1 to antenna 2.																		

Simulation Model 15

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>0</td><td>-118</td></tr><tr><td>2.41</td><td>0</td><td>-120</td></tr><tr><td>2.42</td><td>0</td><td>-120</td></tr><tr><td>2.43</td><td>0</td><td>-120</td></tr><tr><td>2.44</td><td>0</td><td>-120</td></tr><tr><td>2.45</td><td>0</td><td>-120</td></tr><tr><td>2.46</td><td>0</td><td>-118</td></tr><tr><td>2.47</td><td>0</td><td>-115</td></tr><tr><td>2.48</td><td>0</td><td>-115</td></tr><tr><td>2.49</td><td>0</td><td>-115</td></tr><tr><td>2.5</td><td>0</td><td>-115</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	0	-118	2.41	0	-120	2.42	0	-120	2.43	0	-120	2.44	0	-120	2.45	0	-120	2.46	0	-118	2.47	0	-115	2.48	0	-115	2.49	0	-115	2.5	0	-115
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																			
2.4	0	-118																																			
2.41	0	-120																																			
2.42	0	-120																																			
2.43	0	-120																																			
2.44	0	-120																																			
2.45	0	-120																																			
2.46	0	-118																																			
2.47	0	-115																																			
2.48	0	-115																																			
2.49	0	-115																																			
2.5	0	-115																																			
Description	This is the simulation result for the wing realistic model that is made of carbon fibre and where the second antenna is placed at 1/4th wing length. Here the reflection coefficient (S1, 1) is close to zero indicating the reflection of all the power from the first antenna. The transmission coefficient (S2, 1) is also relatively less showing the transmission of relatively less power by antenna 1 to antenna 2 when compared to the previous model.																																				

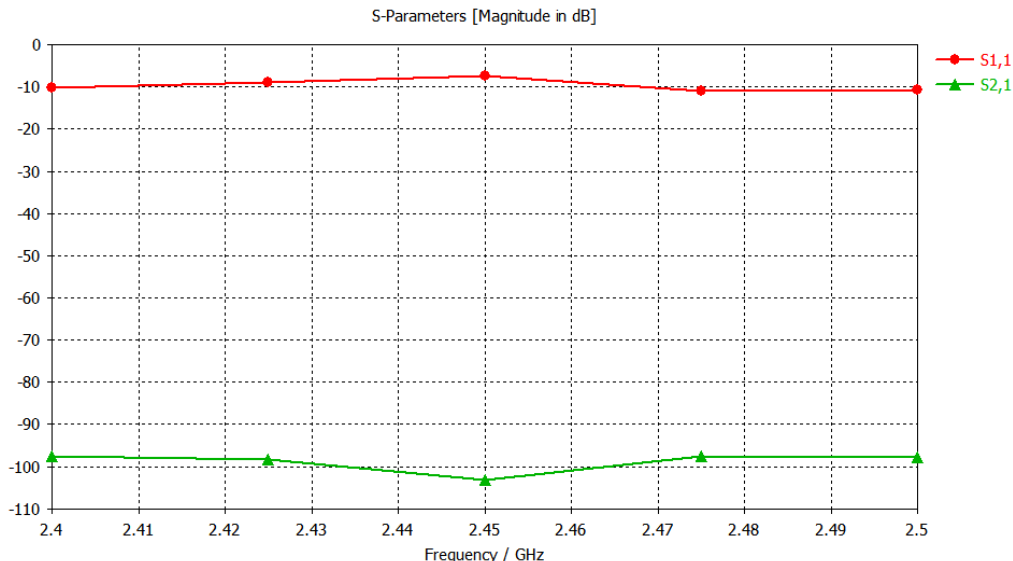
Simulation Model 16

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>-7</td><td>-98</td></tr><tr><td>2.41</td><td>-6</td><td>-100</td></tr><tr><td>2.42</td><td>-5</td><td>-102</td></tr><tr><td>2.43</td><td>-4</td><td>-103</td></tr><tr><td>2.44</td><td>-3</td><td>-103</td></tr><tr><td>2.45</td><td>-2</td><td>-103</td></tr><tr><td>2.46</td><td>-3</td><td>-105</td></tr><tr><td>2.47</td><td>-4</td><td>-108</td></tr><tr><td>2.48</td><td>-5</td><td>-105</td></tr><tr><td>2.49</td><td>-6</td><td>-100</td></tr><tr><td>2.5</td><td>-7</td><td>-98</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	-7	-98	2.41	-6	-100	2.42	-5	-102	2.43	-4	-103	2.44	-3	-103	2.45	-2	-103	2.46	-3	-105	2.47	-4	-108	2.48	-5	-105	2.49	-6	-100	2.5	-7	-98
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																			
2.4	-7	-98																																			
2.41	-6	-100																																			
2.42	-5	-102																																			
2.43	-4	-103																																			
2.44	-3	-103																																			
2.45	-2	-103																																			
2.46	-3	-105																																			
2.47	-4	-108																																			
2.48	-5	-105																																			
2.49	-6	-100																																			
2.5	-7	-98																																			
Description	This is the simulation result for the wing realistic model that is made of aluminium material and where the second antenna is placed at the tip of the wing. At 2.54 GHz frequency, the reflection coefficient ($S_{1, 1}$) is almost equal to zero, and hence all the power input for antenna1 is reflected and not radiated. The change in the position of the second antenna has no significant impact on the transmission coefficient ($S_{2, 1}$) with the least power transmission from antenna 1 to antenna 2 at 2.475 GHz frequency.																																				

Simulation Model 17

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>-15</td><td>-82</td></tr><tr><td>2.425</td><td>-15</td><td>-90</td></tr><tr><td>2.45</td><td>-15</td><td>-90</td></tr><tr><td>2.475</td><td>-15</td><td>-90</td></tr><tr><td>2.5</td><td>-15</td><td>-88</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	-15	-82	2.425	-15	-90	2.45	-15	-90	2.475	-15	-90	2.5	-15	-88
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.4	-15	-82																	
2.425	-15	-90																	
2.45	-15	-90																	
2.475	-15	-90																	
2.5	-15	-88																	
Description	This is the simulation result for the empty wing model that is made of carbon fibre and where the second antenna is placed at 1/4th wing length. Here the reflection coefficient (S1, 1) is better when compared to the realistic wing model made of carbon fibre. The transmission coefficient (S2, 1) is also relatively better for carbon fibre wing when compared to the aluminium wing at this wing position as the value is recorded at above -90 dB shown above.																		

Simulation Model 18

Result	S-Parameters [Magnitude in dB] <table border="1"><thead><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr></thead><tbody><tr><td>2.40</td><td>-10.0</td><td>-98.0</td></tr><tr><td>2.425</td><td>-9.5</td><td>-98.5</td></tr><tr><td>2.45</td><td>-8.5</td><td>-102.0</td></tr><tr><td>2.475</td><td>-10.5</td><td>-97.5</td></tr><tr><td>2.50</td><td>-10.5</td><td>-98.0</td></tr></tbody></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.40	-10.0	-98.0	2.425	-9.5	-98.5	2.45	-8.5	-102.0	2.475	-10.5	-97.5	2.50	-10.5	-98.0
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.40	-10.0	-98.0																	
2.425	-9.5	-98.5																	
2.45	-8.5	-102.0																	
2.475	-10.5	-97.5																	
2.50	-10.5	-98.0																	
Description	This is the simulation result for the empty wing model that is made of carbon fibre and where the second antenna is placed at the $1/2^{\text{nd}}$ position of wing length. Here the reflection coefficient ($S_{1,1}$) is at -10 dB. With the increase in the distance between antennas the amount of power radiated by antenna 1 has declined close to zero indicating the reflection of all the power from the first antenna. In the same way, the increase in the antenna distance also declined transmission coefficient ($S_{2,1}$) when compared to previous simulation result.																		

Simulation Model 19

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>-10</td><td>-100</td></tr><tr><td>2.41</td><td>-10</td><td>-102</td></tr><tr><td>2.42</td><td>-10</td><td>-104</td></tr><tr><td>2.43</td><td>-10</td><td>-105</td></tr><tr><td>2.44</td><td>-10</td><td>-104</td></tr><tr><td>2.45</td><td>-10</td><td>-103</td></tr><tr><td>2.46</td><td>-10</td><td>-102</td></tr><tr><td>2.47</td><td>-10</td><td>-102</td></tr><tr><td>2.48</td><td>-10</td><td>-102</td></tr><tr><td>2.49</td><td>-10</td><td>-102</td></tr><tr><td>2.5</td><td>-10</td><td>-102</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	-10	-100	2.41	-10	-102	2.42	-10	-104	2.43	-10	-105	2.44	-10	-104	2.45	-10	-103	2.46	-10	-102	2.47	-10	-102	2.48	-10	-102	2.49	-10	-102	2.5	-10	-102
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																			
2.4	-10	-100																																			
2.41	-10	-102																																			
2.42	-10	-104																																			
2.43	-10	-105																																			
2.44	-10	-104																																			
2.45	-10	-103																																			
2.46	-10	-102																																			
2.47	-10	-102																																			
2.48	-10	-102																																			
2.49	-10	-102																																			
2.5	-10	-102																																			
Description	This is the simulation result for the empty wing model that is made of carbon fibre and where the second antenna is placed at $3/4^{\text{th}}$ wing length. Here the reflection coefficient (S1, 1) is constant at -10 dB. The transmission coefficient (S2, 1) is also relatively less showing the transmission of relatively less power by antenna 1 to antenna 2 with the increase in the distance between antennas.																																				

Simulation Model 20

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.40</td><td>-5</td><td>-95</td></tr><tr><td>2.425</td><td>-5</td><td>-105</td></tr><tr><td>2.45</td><td>-5</td><td>-102</td></tr><tr><td>2.475</td><td>-5</td><td>-115</td></tr><tr><td>2.50</td><td>-5</td><td>-110</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.40	-5	-95	2.425	-5	-105	2.45	-5	-102	2.475	-5	-115	2.50	-5	-110
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.40	-5	-95																	
2.425	-5	-105																	
2.45	-5	-102																	
2.475	-5	-115																	
2.50	-5	-110																	
Description	This is the simulation result for the empty wing model that is made of carbon fibre and where the second antenna is placed at the tip of the wing. Here the reflection coefficient (S1, 1) remained the same and the transmission coefficient (S2, 1) gradually declined from 2.4 GHz to 2.5 GHz as shown above.																		

Simulation Model 21

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.40</td><td>-17.0</td><td>-88.0</td></tr><tr><td>2.41</td><td>-17.0</td><td>-89.0</td></tr><tr><td>2.42</td><td>-17.0</td><td>-90.0</td></tr><tr><td>2.425</td><td>-17.0</td><td>-91.0</td></tr><tr><td>2.43</td><td>-17.0</td><td>-90.0</td></tr><tr><td>2.44</td><td>-17.0</td><td>-87.0</td></tr><tr><td>2.45</td><td>-17.0</td><td>-85.0</td></tr><tr><td>2.46</td><td>-17.0</td><td>-85.0</td></tr><tr><td>2.47</td><td>-17.0</td><td>-85.0</td></tr><tr><td>2.475</td><td>-17.0</td><td>-85.0</td></tr><tr><td>2.48</td><td>-17.0</td><td>-87.0</td></tr><tr><td>2.49</td><td>-17.0</td><td>-89.0</td></tr><tr><td>2.50</td><td>-16.0</td><td>-91.0</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.40	-17.0	-88.0	2.41	-17.0	-89.0	2.42	-17.0	-90.0	2.425	-17.0	-91.0	2.43	-17.0	-90.0	2.44	-17.0	-87.0	2.45	-17.0	-85.0	2.46	-17.0	-85.0	2.47	-17.0	-85.0	2.475	-17.0	-85.0	2.48	-17.0	-87.0	2.49	-17.0	-89.0	2.50	-16.0	-91.0
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																									
2.40	-17.0	-88.0																																									
2.41	-17.0	-89.0																																									
2.42	-17.0	-90.0																																									
2.425	-17.0	-91.0																																									
2.43	-17.0	-90.0																																									
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2.46	-17.0	-85.0																																									
2.47	-17.0	-85.0																																									
2.475	-17.0	-85.0																																									
2.48	-17.0	-87.0																																									
2.49	-17.0	-89.0																																									
2.50	-16.0	-91.0																																									
Description	This is the simulation result for the prismatic empty wing model that is made of carbon fibre and where the second antenna is placed at 1/4th of wing length. The reflection coefficient (S1, 1) is better than other two wing models showing effective radiation of power supplied to antenna1. The transmission coefficient (S2, 1) is also relatively better ranging between -80 dB and -90 dB showing the transmission of relatively high power by antenna 1 to antenna 2 when compared to other two wing models.																																										

Simulation Model 22

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.400</td><td>-18.0</td><td>-85.0</td></tr><tr><td>2.425</td><td>-17.5</td><td>-85.0</td></tr><tr><td>2.450</td><td>-17.0</td><td>-87.0</td></tr><tr><td>2.475</td><td>-16.5</td><td>-97.0</td></tr><tr><td>2.500</td><td>-15.0</td><td>-83.0</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.400	-18.0	-85.0	2.425	-17.5	-85.0	2.450	-17.0	-87.0	2.475	-16.5	-97.0	2.500	-15.0	-83.0
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.400	-18.0	-85.0																	
2.425	-17.5	-85.0																	
2.450	-17.0	-87.0																	
2.475	-16.5	-97.0																	
2.500	-15.0	-83.0																	
Description	This is the simulation result for the prismatic wing model that is made of carbon fibre and where the second antenna is placed at 1/2 of wing length. As the distance between two antennas increased, the reflection coefficient (S1, 1) moved from -20 dB to -10 dB showing the decline in the amount of radiated power by antenna 1. The transmission coefficient (S2, 1) has declined after frequent range of 2.45 GHz to less than -90 dB as shown above.																		

Simulation Model 23

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>-17.0</td><td>-100.0</td></tr><tr><td>2.41</td><td>-17.0</td><td>-95.0</td></tr><tr><td>2.42</td><td>-17.0</td><td>-90.0</td></tr><tr><td>2.43</td><td>-17.0</td><td>-90.0</td></tr><tr><td>2.44</td><td>-17.0</td><td>-90.0</td></tr><tr><td>2.45</td><td>-17.0</td><td>-90.0</td></tr><tr><td>2.46</td><td>-17.0</td><td>-90.0</td></tr><tr><td>2.47</td><td>-17.0</td><td>-90.0</td></tr><tr><td>2.48</td><td>-17.0</td><td>-90.0</td></tr><tr><td>2.49</td><td>-17.0</td><td>-90.0</td></tr><tr><td>2.5</td><td>-17.0</td><td>-90.0</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	-17.0	-100.0	2.41	-17.0	-95.0	2.42	-17.0	-90.0	2.43	-17.0	-90.0	2.44	-17.0	-90.0	2.45	-17.0	-90.0	2.46	-17.0	-90.0	2.47	-17.0	-90.0	2.48	-17.0	-90.0	2.49	-17.0	-90.0	2.5	-17.0	-90.0
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																			
2.4	-17.0	-100.0																																			
2.41	-17.0	-95.0																																			
2.42	-17.0	-90.0																																			
2.43	-17.0	-90.0																																			
2.44	-17.0	-90.0																																			
2.45	-17.0	-90.0																																			
2.46	-17.0	-90.0																																			
2.47	-17.0	-90.0																																			
2.48	-17.0	-90.0																																			
2.49	-17.0	-90.0																																			
2.5	-17.0	-90.0																																			
Description	This is the simulation result for the prismatic wing model that is made of carbon fibre and where the second antenna is placed at 3/4th of wing length. The reflection coefficient (S1, 1) is same as that of before simulation when the second antenna is at the 1/2nd position of wing length. The amount of power transmitted by antenna 1 to antenna 2 has increased to -90 dB and remained at this state till 2.5 GHz.																																				

Simulation Model 24

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.400</td><td>-10.0</td><td>-90.0</td></tr><tr><td>2.410</td><td>-10.5</td><td>-85.0</td></tr><tr><td>2.420</td><td>-11.0</td><td>-80.0</td></tr><tr><td>2.430</td><td>-11.5</td><td>-81.0</td></tr><tr><td>2.440</td><td>-12.0</td><td>-82.0</td></tr><tr><td>2.450</td><td>-12.5</td><td>-83.0</td></tr><tr><td>2.460</td><td>-13.0</td><td>-88.0</td></tr><tr><td>2.470</td><td>-13.5</td><td>-95.0</td></tr><tr><td>2.480</td><td>-14.0</td><td>-94.0</td></tr><tr><td>2.490</td><td>-14.5</td><td>-93.0</td></tr><tr><td>2.500</td><td>-15.0</td><td>-92.0</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.400	-10.0	-90.0	2.410	-10.5	-85.0	2.420	-11.0	-80.0	2.430	-11.5	-81.0	2.440	-12.0	-82.0	2.450	-12.5	-83.0	2.460	-13.0	-88.0	2.470	-13.5	-95.0	2.480	-14.0	-94.0	2.490	-14.5	-93.0	2.500	-15.0	-92.0
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																			
2.400	-10.0	-90.0																																			
2.410	-10.5	-85.0																																			
2.420	-11.0	-80.0																																			
2.430	-11.5	-81.0																																			
2.440	-12.0	-82.0																																			
2.450	-12.5	-83.0																																			
2.460	-13.0	-88.0																																			
2.470	-13.5	-95.0																																			
2.480	-14.0	-94.0																																			
2.490	-14.5	-93.0																																			
2.500	-15.0	-92.0																																			
Description	This is the simulation result for the prismatic wing model that is made of carbon fibre and where the second antenna is placed at the tip of wing length. Here the reflection coefficient ($S_{1,1}$) is less and better radiation of antenna 1 power is done at 2.45 GHz. Till this frequency range, the transmission coefficient ($S_{2,1}$) is between -80 dB and -90 dB as shown above.																																				

Simulation Model 25

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>-2</td><td>-100</td></tr><tr><td>2.41</td><td>-2</td><td>-100</td></tr><tr><td>2.42</td><td>-2</td><td>-101</td></tr><tr><td>2.43</td><td>-2</td><td>-103</td></tr><tr><td>2.44</td><td>-2</td><td>-108</td></tr><tr><td>2.45</td><td>-2</td><td>-115</td></tr><tr><td>2.46</td><td>-2</td><td>-110</td></tr><tr><td>2.47</td><td>-2</td><td>-105</td></tr><tr><td>2.48</td><td>-3</td><td>-105</td></tr><tr><td>2.49</td><td>-3</td><td>-106</td></tr><tr><td>2.5</td><td>-4</td><td>-107</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	-2	-100	2.41	-2	-100	2.42	-2	-101	2.43	-2	-103	2.44	-2	-108	2.45	-2	-115	2.46	-2	-110	2.47	-2	-105	2.48	-3	-105	2.49	-3	-106	2.5	-4	-107
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																			
2.4	-2	-100																																			
2.41	-2	-100																																			
2.42	-2	-101																																			
2.43	-2	-103																																			
2.44	-2	-108																																			
2.45	-2	-115																																			
2.46	-2	-110																																			
2.47	-2	-105																																			
2.48	-3	-105																																			
2.49	-3	-106																																			
2.5	-4	-107																																			
Description	This is the simulation result for the wing realistic model that is made of PEC materials and where the second antenna is placed at 1/4th of wing length. The reflection coefficient (S1, 1) is close to zero indicating the reflection of all the power from the first antenna. The amount of power transmitted by antenna 1 to antenna 2 ranged between -100 dB and -120 dB and reached lowest at 2.45 GHz frequency.																																				

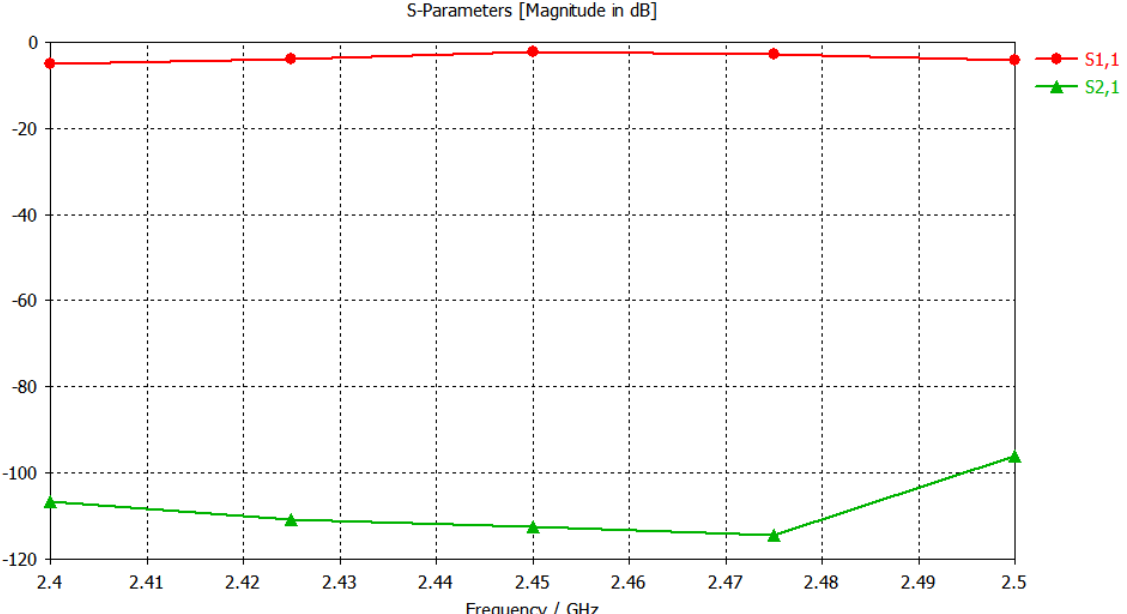
Simulation Model 26

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.400</td><td>0</td><td>-110</td></tr><tr><td>2.425</td><td>0</td><td>-120</td></tr><tr><td>2.450</td><td>0</td><td>-120</td></tr><tr><td>2.475</td><td>0</td><td>-120</td></tr><tr><td>2.500</td><td>0</td><td>-110</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.400	0	-110	2.425	0	-120	2.450	0	-120	2.475	0	-120	2.500	0	-110
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.400	0	-110																	
2.425	0	-120																	
2.450	0	-120																	
2.475	0	-120																	
2.500	0	-110																	
Description	This is the simulation result for the wing realistic model that is made of PEC material and where the second antenna is placed at $\frac{1}{2}$ of wing length. With the increase in the distance between the two antennas, the reflection coefficient ($S_{1,1}$) has more approximated to zero, and the transmission coefficient ($S_{2,1}$) declined to -120 dB as indicated above.																		

Simulation Model 27

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.400</td><td>0</td><td>-110</td></tr><tr><td>2.425</td><td>0</td><td>-125</td></tr><tr><td>2.450</td><td>0</td><td>-120</td></tr><tr><td>2.475</td><td>0</td><td>-122</td></tr><tr><td>2.500</td><td>0</td><td>-115</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.400	0	-110	2.425	0	-125	2.450	0	-120	2.475	0	-122	2.500	0	-115
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.400	0	-110																	
2.425	0	-125																	
2.450	0	-120																	
2.475	0	-122																	
2.500	0	-115																	
Description	This is the simulation result for the wing realistic model that is made of PEC material and where the second antenna is placed at 3/4th of wing length. The increase in the distance between antennas has not affected the reflection coefficient (S1, 1) and the transmission coefficient (S2, 1) as the values of S1, 1 and S2, 1 are same as that of the previous simulation.																		

Simulation Model 28

Result	S-Parameters [Magnitude in dB] <table border="1"><thead><tr><th>Frequency / GHz</th><th>S_{1,1} [dB]</th><th>S_{2,1} [dB]</th></tr></thead><tbody><tr><td>2.40</td><td>-2</td><td>-105</td></tr><tr><td>2.425</td><td>-3</td><td>-110</td></tr><tr><td>2.45</td><td>-2</td><td>-112</td></tr><tr><td>2.475</td><td>-3</td><td>-115</td></tr><tr><td>2.50</td><td>-4</td><td>-95</td></tr></tbody></table>	Frequency / GHz	S _{1,1} [dB]	S _{2,1} [dB]	2.40	-2	-105	2.425	-3	-110	2.45	-2	-112	2.475	-3	-115	2.50	-4	-95
Frequency / GHz	S _{1,1} [dB]	S _{2,1} [dB]																	
2.40	-2	-105																	
2.425	-3	-110																	
2.45	-2	-112																	
2.475	-3	-115																	
2.50	-4	-95																	
Description	This is the simulation result for the wing realistic model that is made of PEC material and where the second antenna is placed at the tip of the wing. The reflection coefficient (S1, 1) is better at 2.4 GHz which has later become closer to zero at 2.45 GHz. The transmission coefficient (S2, 1) is relatively better when compared to the previous simulation showing the transmission of relatively high power by antenna 1 to antenna 2 when compared to the previous simulation.																		

Simulation Model 29

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.400</td><td>-10.0</td><td>-105.0</td></tr><tr><td>2.410</td><td>-10.0</td><td>-100.0</td></tr><tr><td>2.420</td><td>-10.0</td><td>-95.0</td></tr><tr><td>2.425</td><td>-10.0</td><td>-92.0</td></tr><tr><td>2.430</td><td>-10.0</td><td>-95.0</td></tr><tr><td>2.440</td><td>-10.0</td><td>-100.0</td></tr><tr><td>2.450</td><td>-10.0</td><td>-102.0</td></tr><tr><td>2.460</td><td>-10.0</td><td>-100.0</td></tr><tr><td>2.470</td><td>-10.0</td><td>-98.0</td></tr><tr><td>2.480</td><td>-10.0</td><td>-96.0</td></tr><tr><td>2.490</td><td>-10.0</td><td>-95.0</td></tr><tr><td>2.500</td><td>-10.0</td><td>-93.0</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.400	-10.0	-105.0	2.410	-10.0	-100.0	2.420	-10.0	-95.0	2.425	-10.0	-92.0	2.430	-10.0	-95.0	2.440	-10.0	-100.0	2.450	-10.0	-102.0	2.460	-10.0	-100.0	2.470	-10.0	-98.0	2.480	-10.0	-96.0	2.490	-10.0	-95.0	2.500	-10.0	-93.0
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																						
2.400	-10.0	-105.0																																						
2.410	-10.0	-100.0																																						
2.420	-10.0	-95.0																																						
2.425	-10.0	-92.0																																						
2.430	-10.0	-95.0																																						
2.440	-10.0	-100.0																																						
2.450	-10.0	-102.0																																						
2.460	-10.0	-100.0																																						
2.470	-10.0	-98.0																																						
2.480	-10.0	-96.0																																						
2.490	-10.0	-95.0																																						
2.500	-10.0	-93.0																																						
Description	This is the simulation result for the empty wing model that is made of PEC material and where the second antenna is placed at 1/4th wing length. The reflection coefficient (S1, 1) is better for this wing model than realistic wing model as it reached -10 dB as shown above. For this wing model, the transmission coefficient (S2, 1) is also relatively better and reached high at 2.425 GHz frequency.																																							

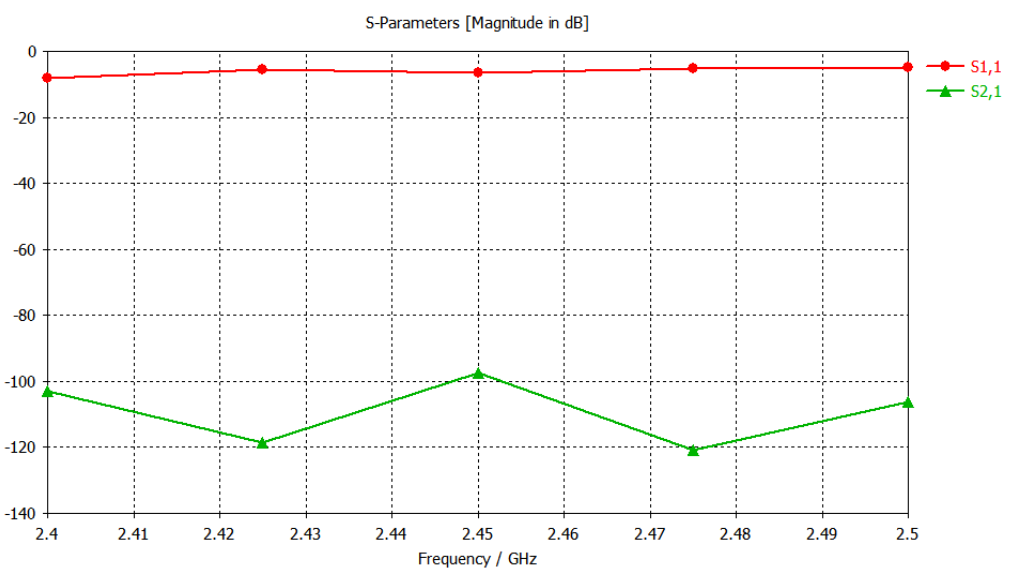
Simulation Model 30

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>-7</td><td>-105</td></tr><tr><td>2.425</td><td>-5</td><td>-112</td></tr><tr><td>2.45</td><td>-3</td><td>-103</td></tr><tr><td>2.475</td><td>-5</td><td>-122</td></tr><tr><td>2.5</td><td>-7</td><td>-112</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	-7	-105	2.425	-5	-112	2.45	-3	-103	2.475	-5	-122	2.5	-7	-112
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.4	-7	-105																	
2.425	-5	-112																	
2.45	-3	-103																	
2.475	-5	-122																	
2.5	-7	-112																	
Description	This is the simulation result for the empty wing model that is made of PEC material and where the second antenna is placed at $\frac{1}{2}$ of wing length. The increase in distance between antennas declined the amount of power radiated by antenna 1 which is evident from the reflection coefficient ($S_{1,1}$). The transmission coefficient ($S_{2,1}$) is also relatively less showing the transmission of relatively less power by antenna 1 to antenna 2 when compared to the previous simulation in which the second antenna is placed at the $\frac{1}{4}$th position of wing length.																		

Simulation Model 31

Result	S-Parameters [Magnitude in dB] <table border="1"><thead><tr><th>Frequency / GHz</th><th>S_{1,1} [dB]</th><th>S_{2,1} [dB]</th></tr></thead><tbody><tr><td>2.4</td><td>-5</td><td>-105</td></tr><tr><td>2.425</td><td>-5</td><td>-125</td></tr><tr><td>2.45</td><td>-5</td><td>-110</td></tr><tr><td>2.475</td><td>-5</td><td>-100</td></tr><tr><td>2.5</td><td>-5</td><td>-110</td></tr></tbody></table>	Frequency / GHz	S _{1,1} [dB]	S _{2,1} [dB]	2.4	-5	-105	2.425	-5	-125	2.45	-5	-110	2.475	-5	-100	2.5	-5	-110
Frequency / GHz	S _{1,1} [dB]	S _{2,1} [dB]																	
2.4	-5	-105																	
2.425	-5	-125																	
2.45	-5	-110																	
2.475	-5	-100																	
2.5	-5	-110																	
Description	This is the simulation result for the empty wing model that is made of PEC material and where the second antenna is placed at $\frac{3}{4}$ the of wing length. Improvement in the value of reflection coefficient (S1, 1) value, when compared to the previous simulation, is observed at frequency range of 2.45 GHz. Similarly, at the frequency range of 2.475 GHz, the transmission coefficient (S2, 1) is relatively better than previous simulation result.																		

Simulation Model 32

Result	S-Parameters [Magnitude in dB] <table border="1"><thead><tr><th>Frequency / GHz</th><th>S_{1,1} [dB]</th><th>S_{2,1} [dB]</th></tr></thead><tbody><tr><td>2.4</td><td>-2</td><td>-105</td></tr><tr><td>2.425</td><td>-2</td><td>-120</td></tr><tr><td>2.45</td><td>-2</td><td>-100</td></tr><tr><td>2.475</td><td>-2</td><td>-120</td></tr><tr><td>2.5</td><td>-2</td><td>-105</td></tr></tbody></table>	Frequency / GHz	S _{1,1} [dB]	S _{2,1} [dB]	2.4	-2	-105	2.425	-2	-120	2.45	-2	-100	2.475	-2	-120	2.5	-2	-105
Frequency / GHz	S _{1,1} [dB]	S _{2,1} [dB]																	
2.4	-2	-105																	
2.425	-2	-120																	
2.45	-2	-100																	
2.475	-2	-120																	
2.5	-2	-105																	
Description	This is the simulation result for the empty wing model that is made of PEC material and where the second antenna is placed at the tip of the wing. There is no significant in the reflection coefficient ($S_{1,1}$) value with the further increase in the distance between the antennas. But at this position of the second antenna, the transmission coefficient ($S_{2,1}$) reached high of -100 dB at 2.45 GHz showing relatively better transmission of the power from antenna 1 to antenna 2.																		

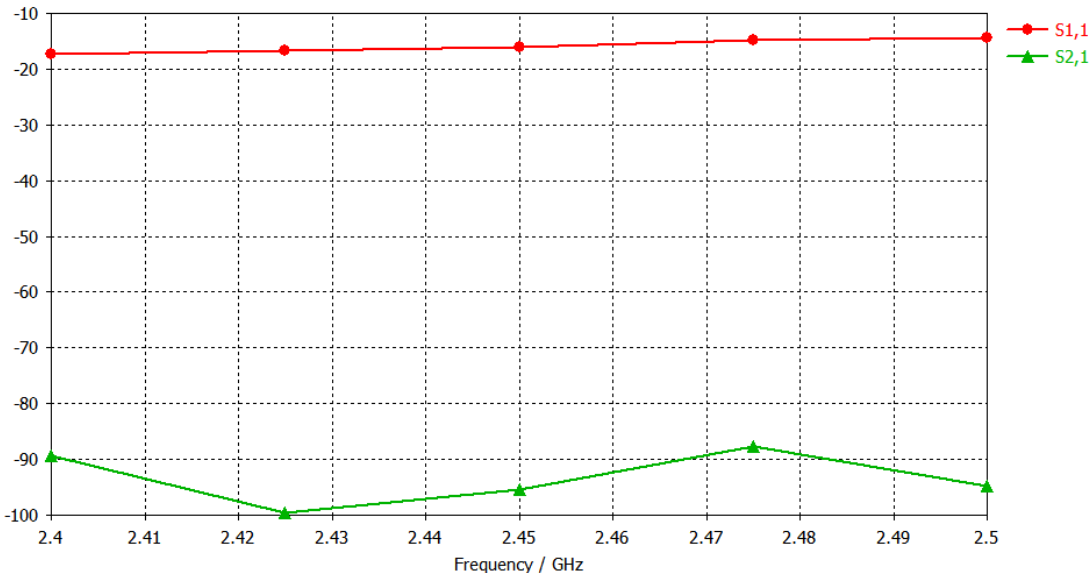
Simulation Model 33

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.4</td><td>-15.5</td><td>-84.0</td></tr><tr><td>2.41</td><td>-15.5</td><td>-85.0</td></tr><tr><td>2.42</td><td>-15.5</td><td>-86.0</td></tr><tr><td>2.43</td><td>-15.5</td><td>-86.5</td></tr><tr><td>2.44</td><td>-15.5</td><td>-87.0</td></tr><tr><td>2.45</td><td>-15.5</td><td>-87.5</td></tr><tr><td>2.46</td><td>-15.5</td><td>-88.0</td></tr><tr><td>2.47</td><td>-15.5</td><td>-88.5</td></tr><tr><td>2.48</td><td>-15.5</td><td>-88.0</td></tr><tr><td>2.49</td><td>-15.5</td><td>-87.0</td></tr><tr><td>2.5</td><td>-15.5</td><td>-85.0</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.4	-15.5	-84.0	2.41	-15.5	-85.0	2.42	-15.5	-86.0	2.43	-15.5	-86.5	2.44	-15.5	-87.0	2.45	-15.5	-87.5	2.46	-15.5	-88.0	2.47	-15.5	-88.5	2.48	-15.5	-88.0	2.49	-15.5	-87.0	2.5	-15.5	-85.0
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																																			
2.4	-15.5	-84.0																																			
2.41	-15.5	-85.0																																			
2.42	-15.5	-86.0																																			
2.43	-15.5	-86.5																																			
2.44	-15.5	-87.0																																			
2.45	-15.5	-87.5																																			
2.46	-15.5	-88.0																																			
2.47	-15.5	-88.5																																			
2.48	-15.5	-88.0																																			
2.49	-15.5	-87.0																																			
2.5	-15.5	-85.0																																			
Description	This is the simulation result for the prismatic wing model that is made of PEC material and where the second antenna is placed at 1/4th wing length. The reflection coefficient (S1, 1) for this wing model has further increased showing better radiation of the power by antenna 1. For this wing model, the transmission coefficient (S2, 1) is also relatively better ranging between -80 dB and -90 dB as indicated in the above graph.																																				

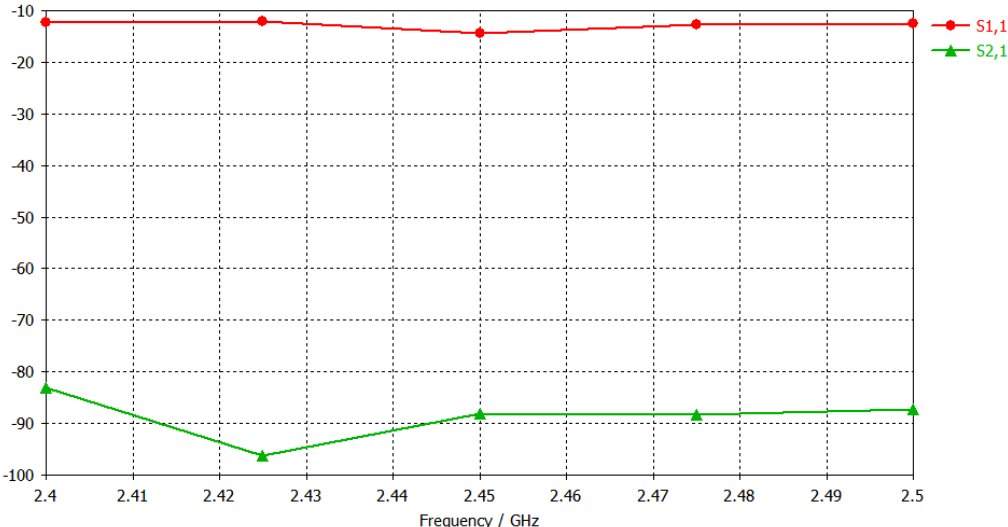
Simulation Model 34

Result	S-Parameters [Magnitude in dB] <table><tr><th>Frequency / GHz</th><th>S1,1 [dB]</th><th>S2,1 [dB]</th></tr><tr><td>2.40</td><td>-20</td><td>-80</td></tr><tr><td>2.425</td><td>-18</td><td>-90</td></tr><tr><td>2.45</td><td>-15</td><td>-105</td></tr><tr><td>2.475</td><td>-14</td><td>-88</td></tr><tr><td>2.50</td><td>-12</td><td>-85</td></tr></table>	Frequency / GHz	S1,1 [dB]	S2,1 [dB]	2.40	-20	-80	2.425	-18	-90	2.45	-15	-105	2.475	-14	-88	2.50	-12	-85
Frequency / GHz	S1,1 [dB]	S2,1 [dB]																	
2.40	-20	-80																	
2.425	-18	-90																	
2.45	-15	-105																	
2.475	-14	-88																	
2.50	-12	-85																	
Description	This is the simulation result for the prismatic wing model that is made of PEC material and where the second antenna is placed at $1/2^{\text{nd}}$ of wing length. The reflection coefficient ($S1, 1$) for this wing model is initially at -20 dB and this value increased to -10 dB and thereby declining the amount of power radiated by antenna1. With the increase in the distance between the antennas, the transmission coefficient ($S2, 1$) has declined from -80 dB to less than -100 dB as shown above.																		

Simulation Model 35

Result	S-Parameters [Magnitude in dB] <table border="1"><thead><tr><th>Frequency / GHz</th><th>S_{1,1} [dB]</th><th>S_{2,1} [dB]</th></tr></thead><tbody><tr><td>2.4</td><td>-18</td><td>-90</td></tr><tr><td>2.425</td><td>-17</td><td>-100</td></tr><tr><td>2.45</td><td>-16</td><td>-95</td></tr><tr><td>2.475</td><td>-15</td><td>-88</td></tr><tr><td>2.5</td><td>-14</td><td>-95</td></tr></tbody></table>	Frequency / GHz	S _{1,1} [dB]	S _{2,1} [dB]	2.4	-18	-90	2.425	-17	-100	2.45	-16	-95	2.475	-15	-88	2.5	-14	-95
Frequency / GHz	S _{1,1} [dB]	S _{2,1} [dB]																	
2.4	-18	-90																	
2.425	-17	-100																	
2.45	-16	-95																	
2.475	-15	-88																	
2.5	-14	-95																	
Description	This is the simulation result for the prismatic wing model that is made of PEC material and where the second antenna is placed at $3/4^{\text{th}}$ of wing length. The reflection coefficient ($S_{1,1}$) is almost the same value as that of the previous simulation for this wing model despite of increasing the size between antennas. For this wing model, the transmission coefficient ($S_{2,1}$) is also same as that of the previous simulation except with a slight improvement at 2.45GHz and also at 2.475 GHz.																		

Simulation Model 36

Result	S-Parameters [Magnitude in dB] <table border="1"><thead><tr><th>Frequency / GHz</th><th>S_{1,1} [dB]</th><th>S_{2,1} [dB]</th></tr></thead><tbody><tr><td>2.40</td><td>-12.0</td><td>-83.0</td></tr><tr><td>2.425</td><td>-12.0</td><td>-97.0</td></tr><tr><td>2.45</td><td>-13.0</td><td>-88.0</td></tr><tr><td>2.475</td><td>-12.0</td><td>-88.0</td></tr><tr><td>2.50</td><td>-12.0</td><td>-88.0</td></tr></tbody></table>	Frequency / GHz	S _{1,1} [dB]	S _{2,1} [dB]	2.40	-12.0	-83.0	2.425	-12.0	-97.0	2.45	-13.0	-88.0	2.475	-12.0	-88.0	2.50	-12.0	-88.0
Frequency / GHz	S _{1,1} [dB]	S _{2,1} [dB]																	
2.40	-12.0	-83.0																	
2.425	-12.0	-97.0																	
2.45	-13.0	-88.0																	
2.475	-12.0	-88.0																	
2.50	-12.0	-88.0																	
Description	This is the simulation result for the prismatic wing model that is made of PEC material and where the second antenna is placed at the tip of the wing. The reflection coefficient (S_{1,1}) is relatively less than the previous simulation with better radiation at the frequency range of 2.45 GHz. In case of the transmission coefficient (S_{2,1}), its value is improved when compared to the previous simulation showing the bitterness in the power transmitted from antenna 1 to antenna 2 as given above.																		

Method of Comparison

The results of all the 36 simulations are considered for the comparative analysis that is mainly aimed in investigating two main characteristics. The first characteristic is the effect of wing surface materials on the *link budget* by keeping the wing model constant. Graph group1 with all the 12 diagrams in it are obtained to show the result of this effect. The table below gives a detailed description of all the 12 graphs that are grouped under “graph group1” section.

graph group 1	description
1	different materials; realistic wing; small distance
2	different materials; realistic wing; second distance
3	different materials; realistic wing; third distance
4	different materials; realistic wing; highest distance
5	different materials; empty wing; small distance
6	different materials; empty wing; second distance
7	different materials; empty wing; third distance
8	different materials; empty wing; highest distance
9	different materials; prismatic wing; small distance
10	different materials; prismatic wing; second distance
11	different materials; prismatic wing; third distance
12	different materials; prismatic wing; highest distance

The second characteristic that is investigated through the comparative analysis that is carried out in this study is the effect of antenna positions on the *link budget* by keeping the wing model constant. All the 9 graphs that are obtained from simulations and used to show the impact of antenna positions on the *link budget* are grouped under “graph group 2”. The table below gives a detailed description of all the 9 graphs that are grouped under “graph group 2” section.

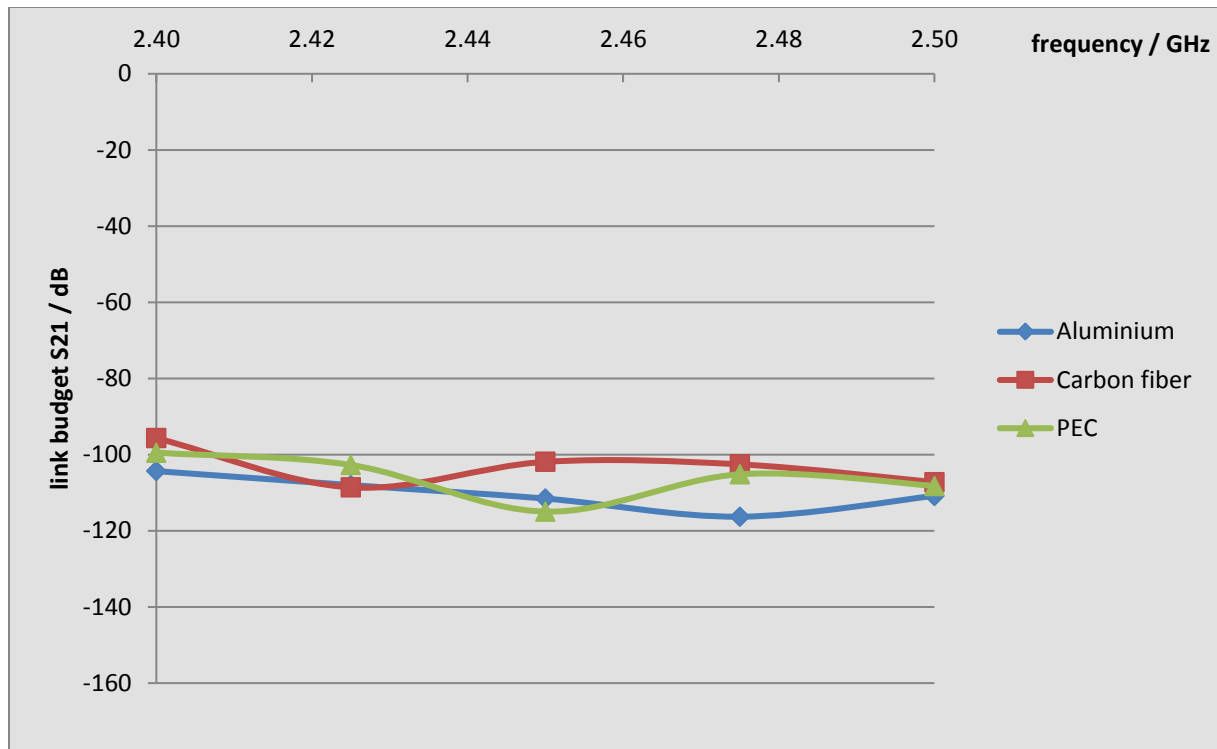
graph group 2	description
<u>1</u>	aluminium; realistic wing; different distances
<u>2</u>	aluminium; empty wing; different distances
<u>3</u>	aluminium; prismatic wing; different distances
<u>4</u>	carbon fibre realistic wing; different distances
<u>5</u>	carbon fibre; empty wing; different distances
<u>6</u>	carbon fibre; prismatic wing; different distances
<u>7</u>	PEC; realistic wing; different distances
<u>8</u>	PEC; empty wing; different distances
<u>9</u>	PEC; prismatic wing; different distances

Graph group 1: Different wing surface material

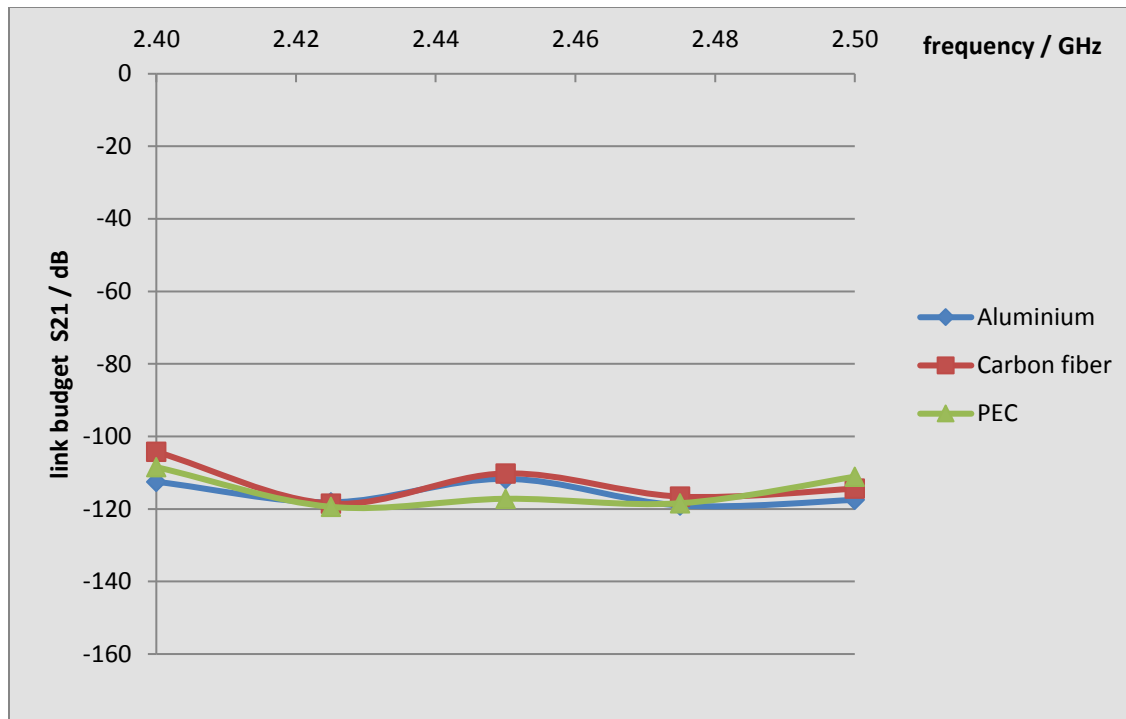
The graphs in this section are used to analyze the effect of air wing surface material on the *link budget* value where the model of the air wing is kept constant. For each of the air wing model, the variations in the link budget value for three different materials as used for the air wing surface are compared in this group.

Realistic wing model

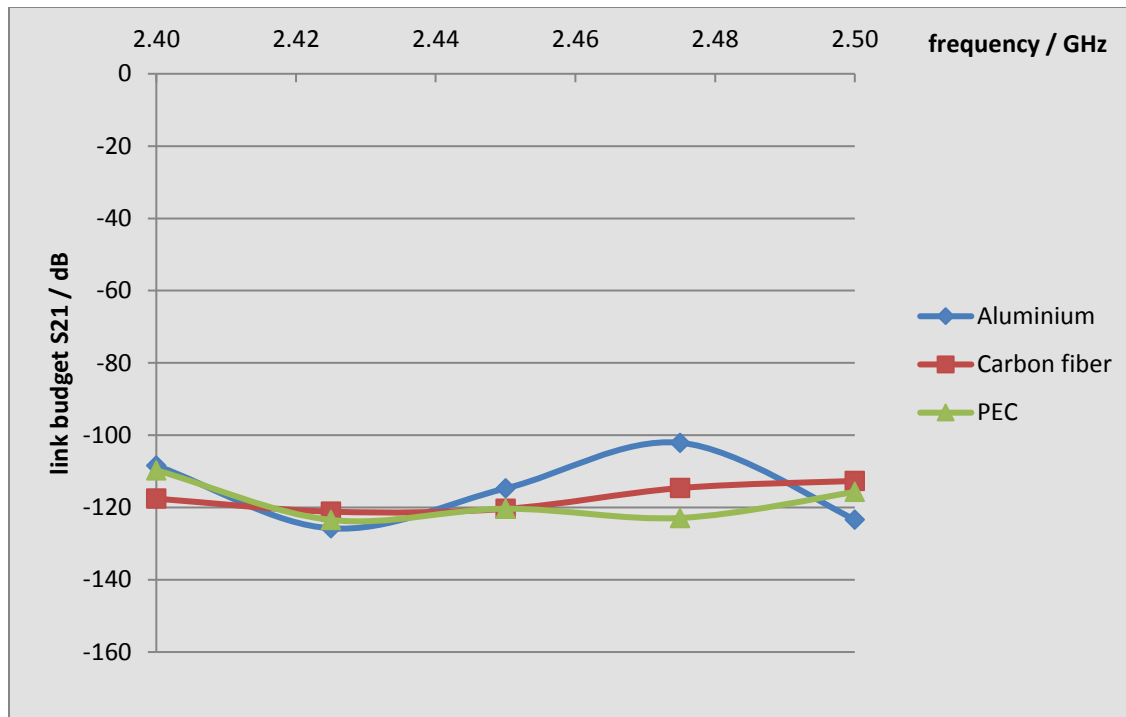
For the realistic model, 4 different positions of the antennas are investigated. All these investigations have targeted the frequency between 2.4 GHz and 2.5 GHz and identified the effect of the wing surface material used on the value of link budget.



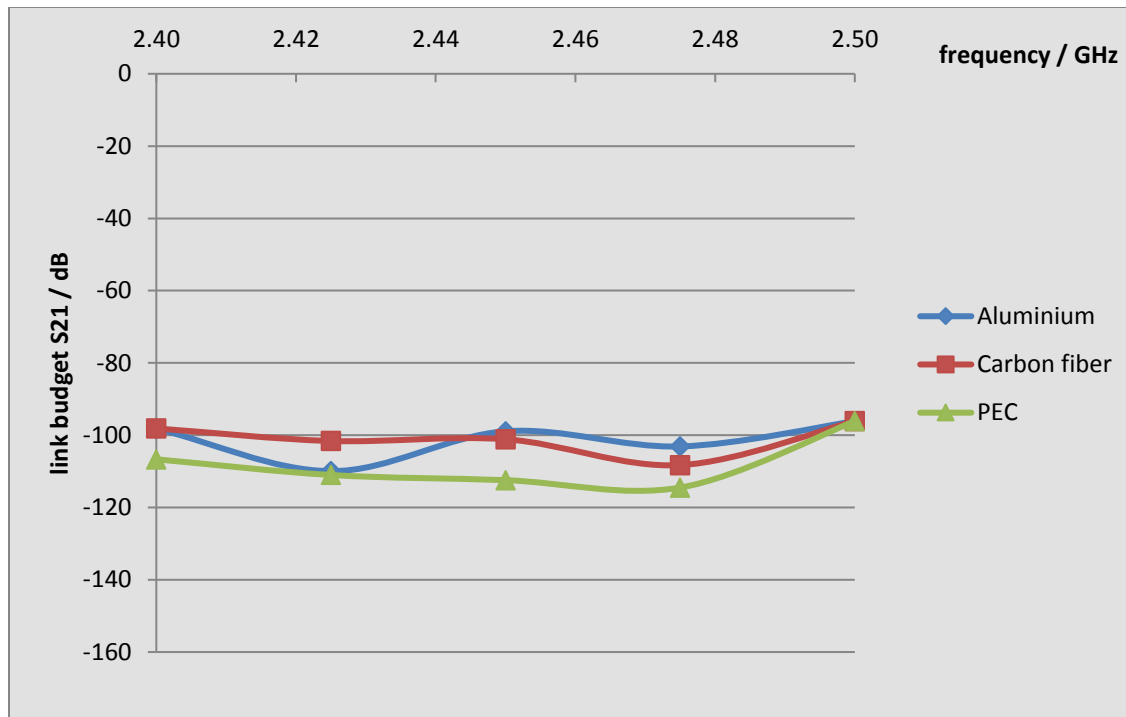
For realistic wing model, when the second antenna is placed at the $1/4^{\text{th}}$ position of the wing length, the link budget value of carbon fibre material is higher than the other material surfaces such as aluminium and PEC. However, at 2.42 GHz frequency, the transmission coefficient of PEC material surfaced air wing is slightly higher than the other two materials aluminium and carbon fibre. The transmission coefficient value of carbon fibre surfaced wing which is -95 dB at 2.40 GHz has slightly varied to -110 dB when the frequency increased to 2.5 GHz.



For the realistic wing model, when the second antenna is placed at the $\frac{1}{2}$ position of the wing length, no significant differences exist among the three different materials that are considered for the air wings. However, the highest value of the link budget is recorded at 2.4 GHz for carbon fibre aeroplane wing as -105 dB and almost reached to the same value by the end of the simulation.

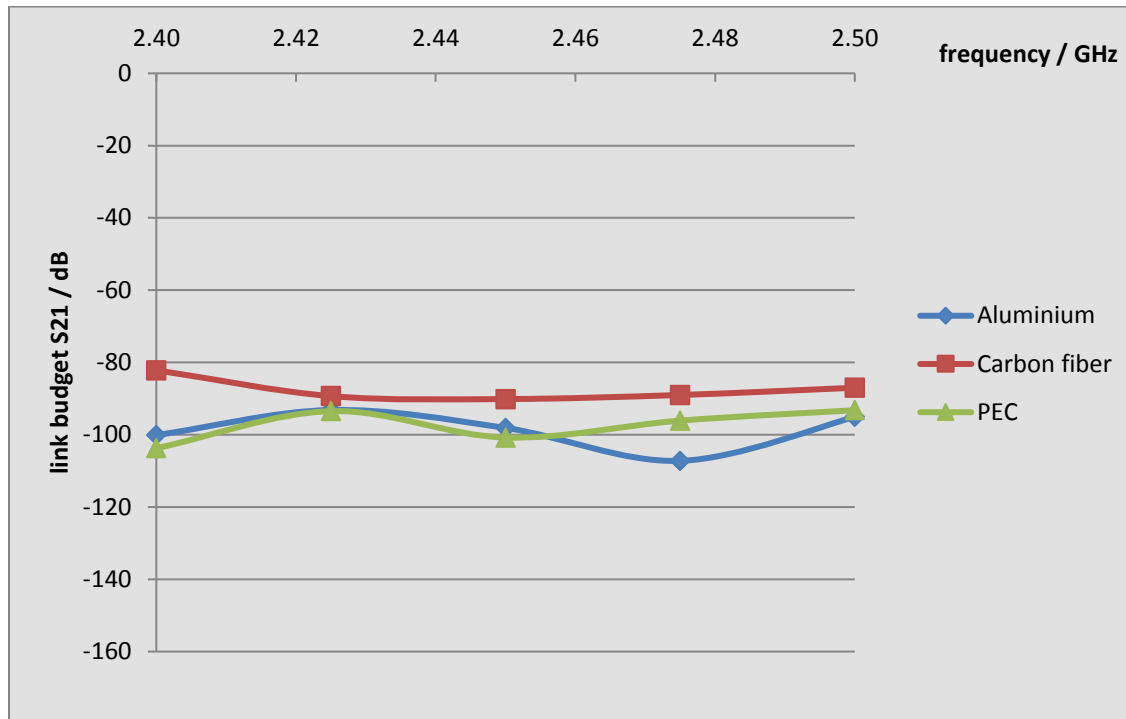


The above graph shows the variations in the link budget value for the realistic wing model when the second antenna is placed at a third distance which is the $3/4^{\text{th}}$ length of the wing. In this case, the link budget value of all the three materials of the wing surface remained the same except at 2.48 GHz. At the frequency of 2.4 GHz, the link budget value has rose to -100 dB and further changed to -120 dB.

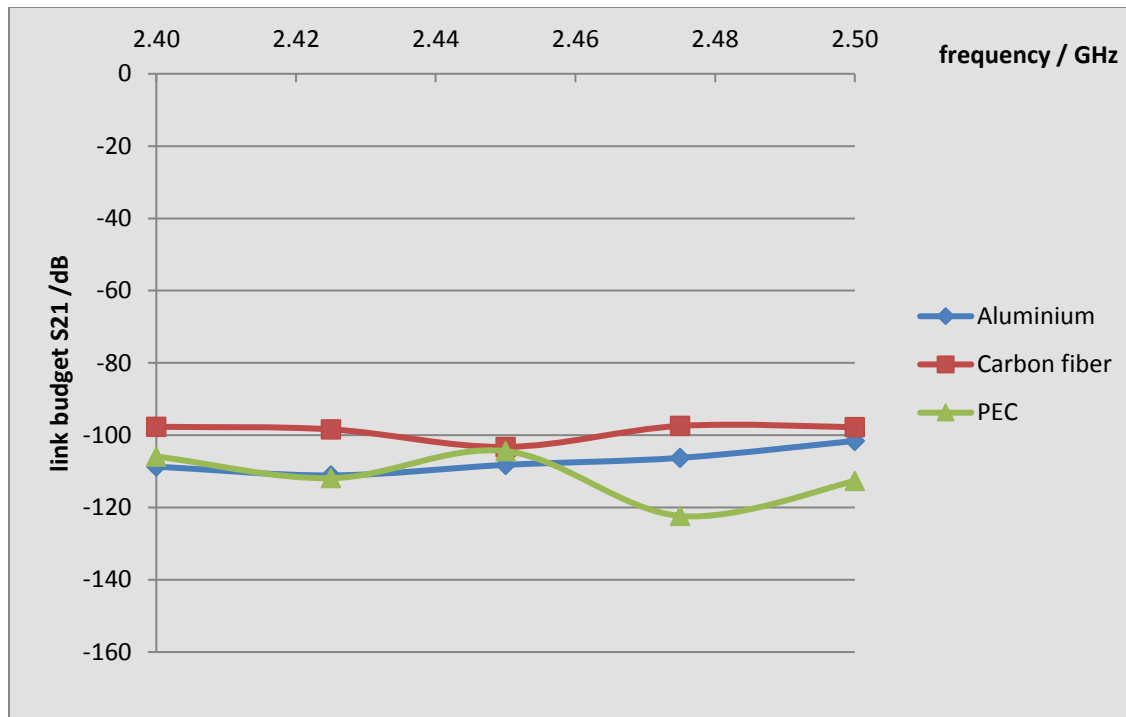


The variations in the link budget value of the aeroplane wings that are made with different materials and are of the same realistic sing model is given in the above graph. Comparative analysis showed that wing made of PEC showed comparatively less value of the link budget when compared to the other materials aluminium and carbon fibre. Among all the four case simulations on the realistic wing model, when the second transceiver is place at the tip of the wing, all the three type of material based wings have showed a slight increase in its link budget value.

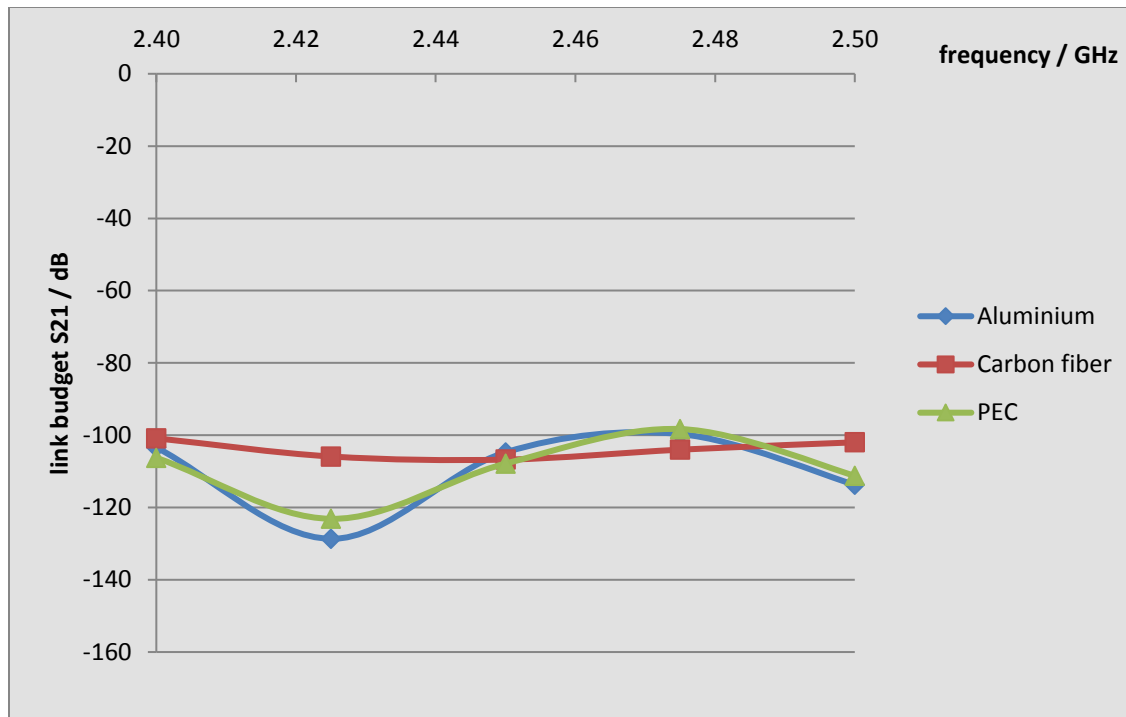
Empty wing model



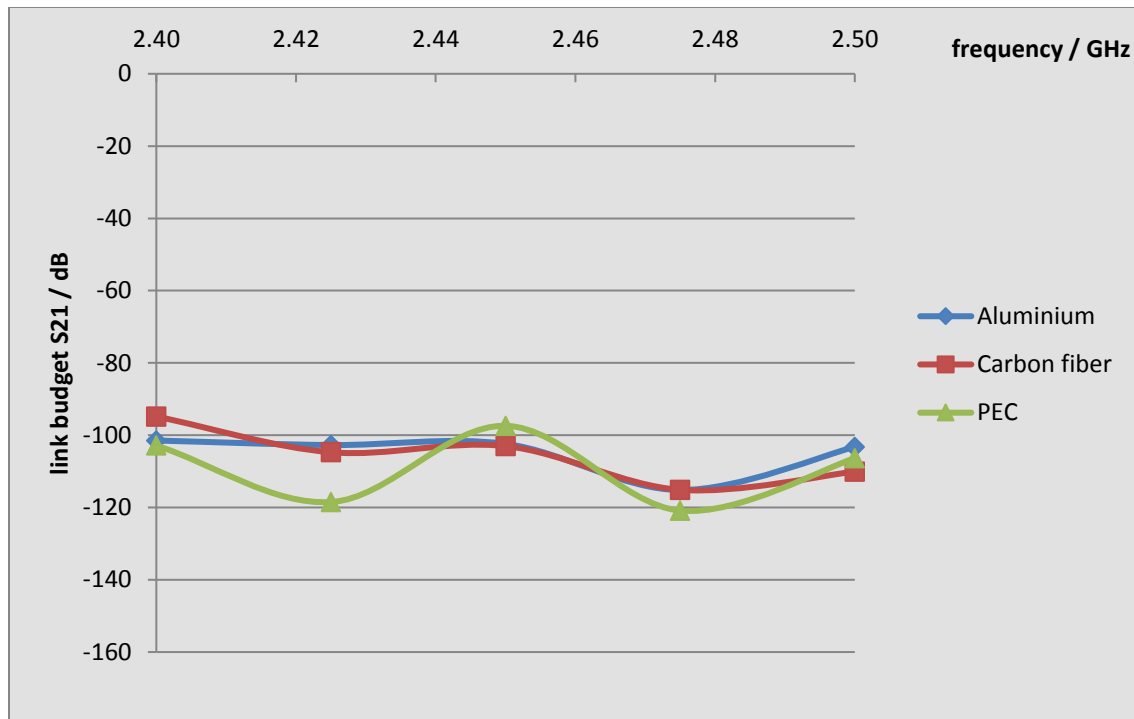
For the empty wing model when the second antenna is placed at a small distance to the first antenna (that is at the $1/4^{\text{th}}$ position of the wing), the variations in the link budget value for three different surface materials of the aeroplane wings is shown above. Between 2.4 GHz and 2.5 GHz frequency value, the aeroplane wing that is made of carbon fibre showed the high value of link budget when compared to the aeroplane wings that are made of other materials like aluminium and PEC. However, at 2.48 GHz, carbon fibre based aeroplane wing showed the highest and aeroplane wing made of aluminium showed the least value of link budget.



For the empty wing model when the second antenna is placed at a second distance to the first antenna (that is at the $1/2^{\text{nd}}$ position of the wing length), the variations in the link budget value for three different surface materials of the aeroplane wings is shown above. Major differences in link budget value among the three material based aeroplane wings exists at 2.48 GHz with carbon fibre based wing model showing the high value of link budget all through the frequency between 2.4 to 2.5 GHz.

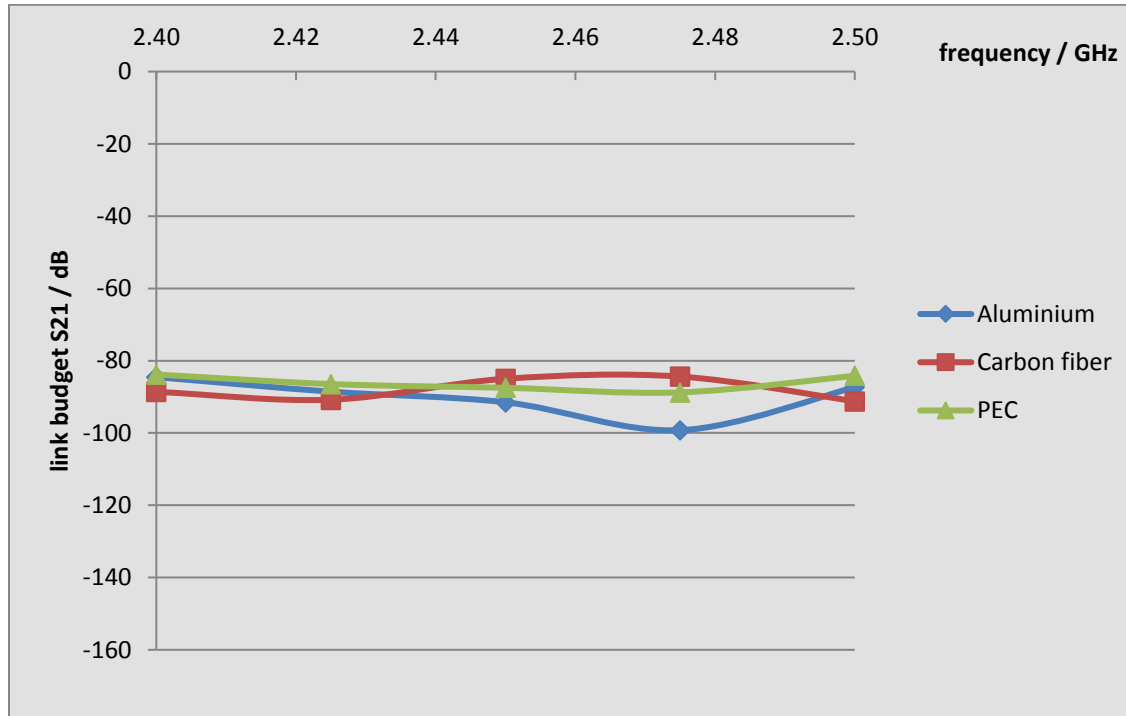


For the empty wing model when the second antenna is placed at a third distance to the first antenna (that is at the $3/4^{\text{th}}$ position of the wing length), the variations in the link budget value for three different surface materials of the aeroplane wings is shown above. Surprisingly major differences among the three material based aeroplane wings exist at 2.42 GHz, where carbon fibre based wing has higher link budget value and the aeroplane wings with the other two materials aluminium and PEC showed very less link budget of -130 dB at 2.42 GHz.

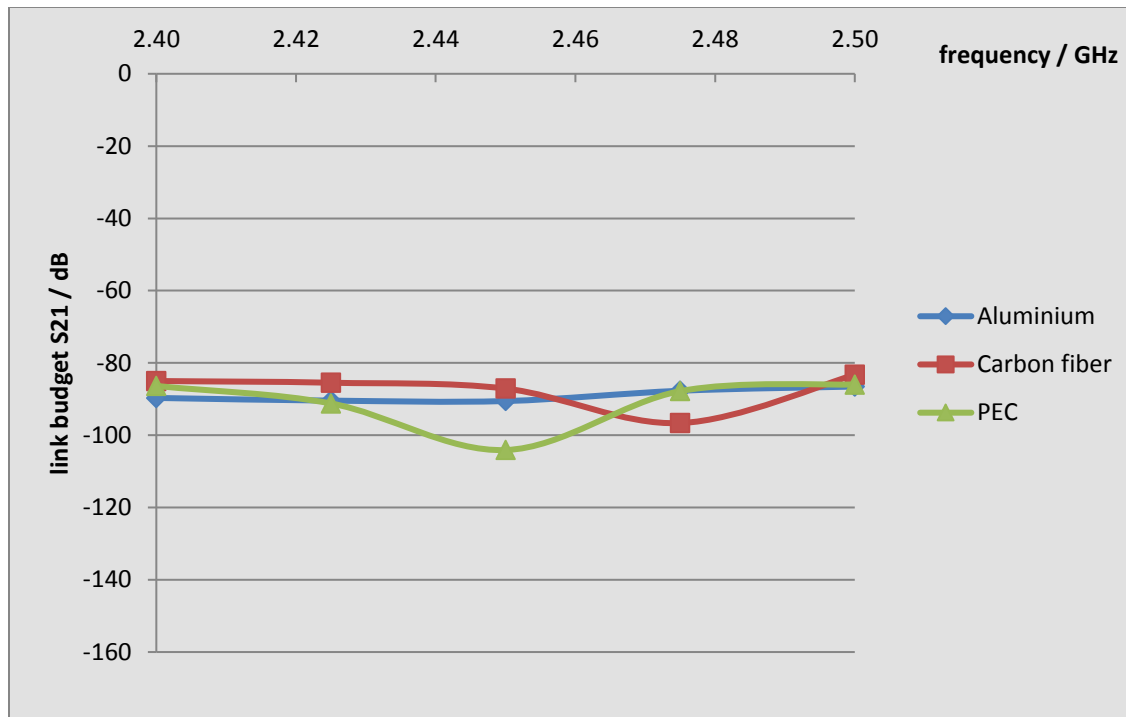


For the empty wing model when the second antenna is placed at a highest distance to the first antenna (that is at the tip of the wing), the variations in the link budget value for three different surface materials of the aeroplane wings is shown above. Aeroplane wing surfaces made of aluminium and carbon fibre exhibited the same value of the link budget while the aeroplane wing made of PEC has fluctuated greatly between the chosen frequency range of 2.4 GHz and 2.5 GHz.

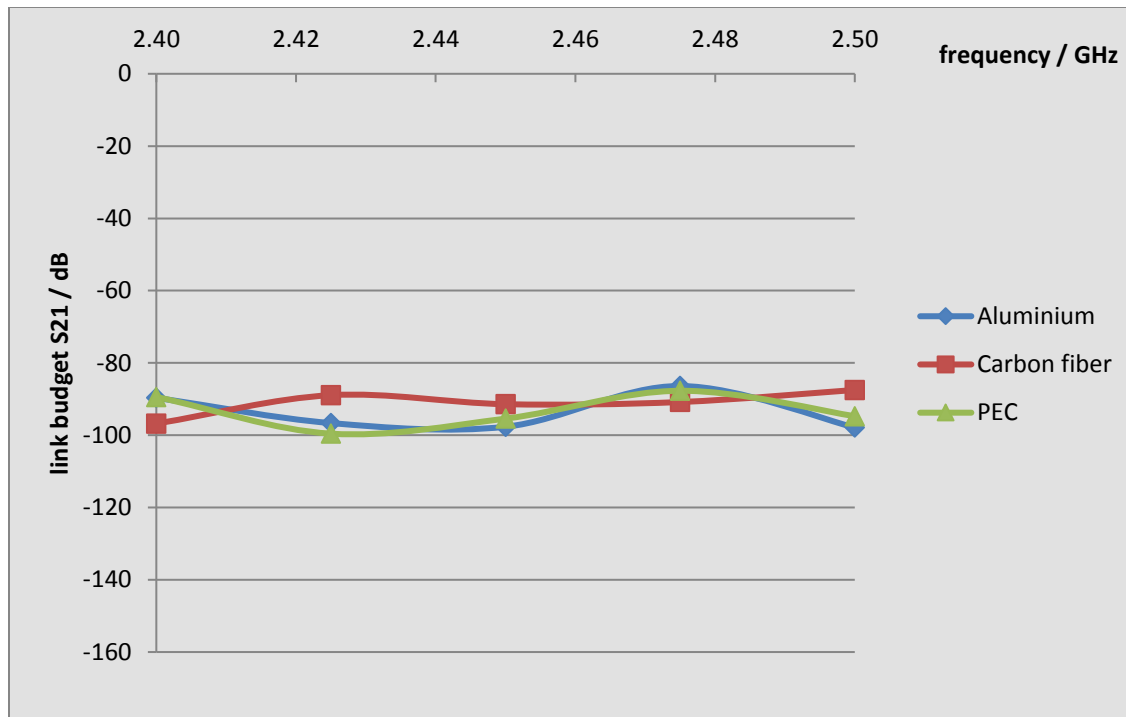
Prismatic wing model



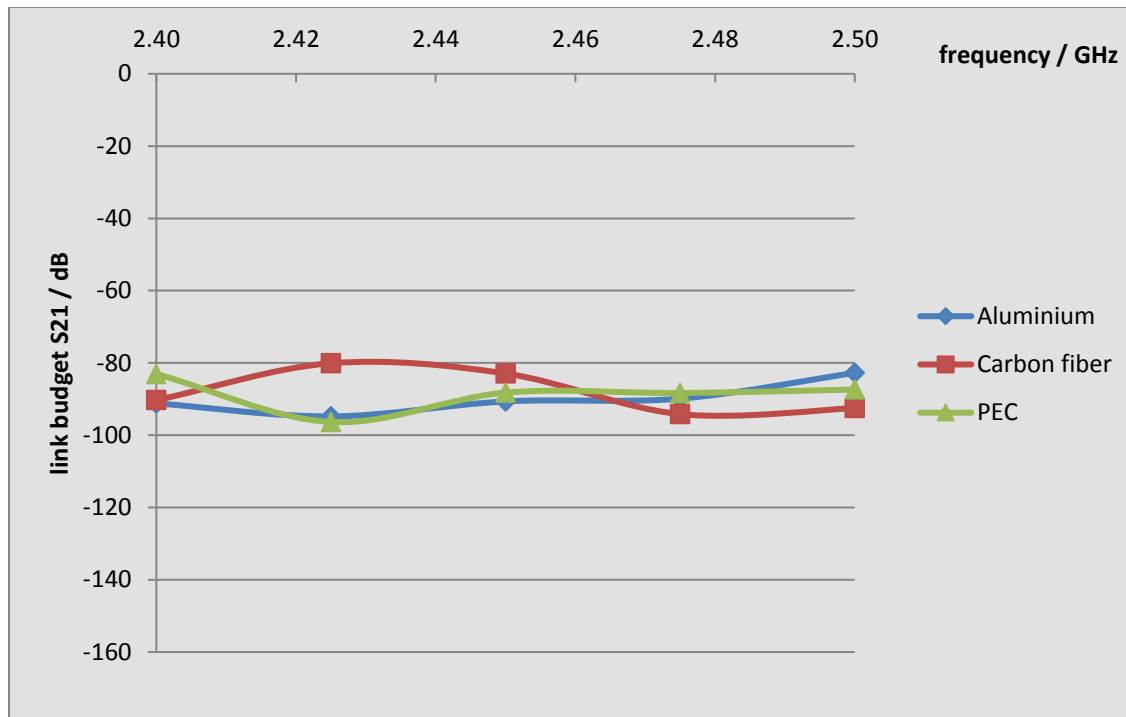
For the prismatic wing model when the second antenna is placed at a small distance to the first antenna (that is at the $1/4^{\text{th}}$ position of the wing length), the variations in the link budget value for three different surface materials of the aeroplane wings is shown above. No major differences in link budget value are found among the three materials based aeroplane wings except at 2.48 GHz. At the frequency of 2.48 GHz, aeroplane wing made of aluminium touched -100 dB while for aluminium and carbon fibre-based materials, the link budget remained -90 dB.



For the prismatic wing model when the second antenna is placed at a second distance to the first antenna (that is at the $1/2^{\text{nd}}$ position of the wing length), the variations in the link budget value for three different surface materials of the aeroplane wings is shown above. Only at 2.45 GHz frequency, a significant difference in the link budget value is identified as the aeroplane wing that is made of the PEC material showed -105 dB while wings surfaced with aluminium and carbon fibre materials exhibited link budget value of -90 dB.



For the prismatic wing model when the second antenna is placed at a third distance to the first antenna (that is at the $3/4^{\text{th}}$ position of the wing length), the variations in the link budget value for three different surface materials of the aeroplane wings is shown above. The aeroplane wings made of all three materials exhibited a similar level of the link budget value ranging between -80 dB and -100 dB.



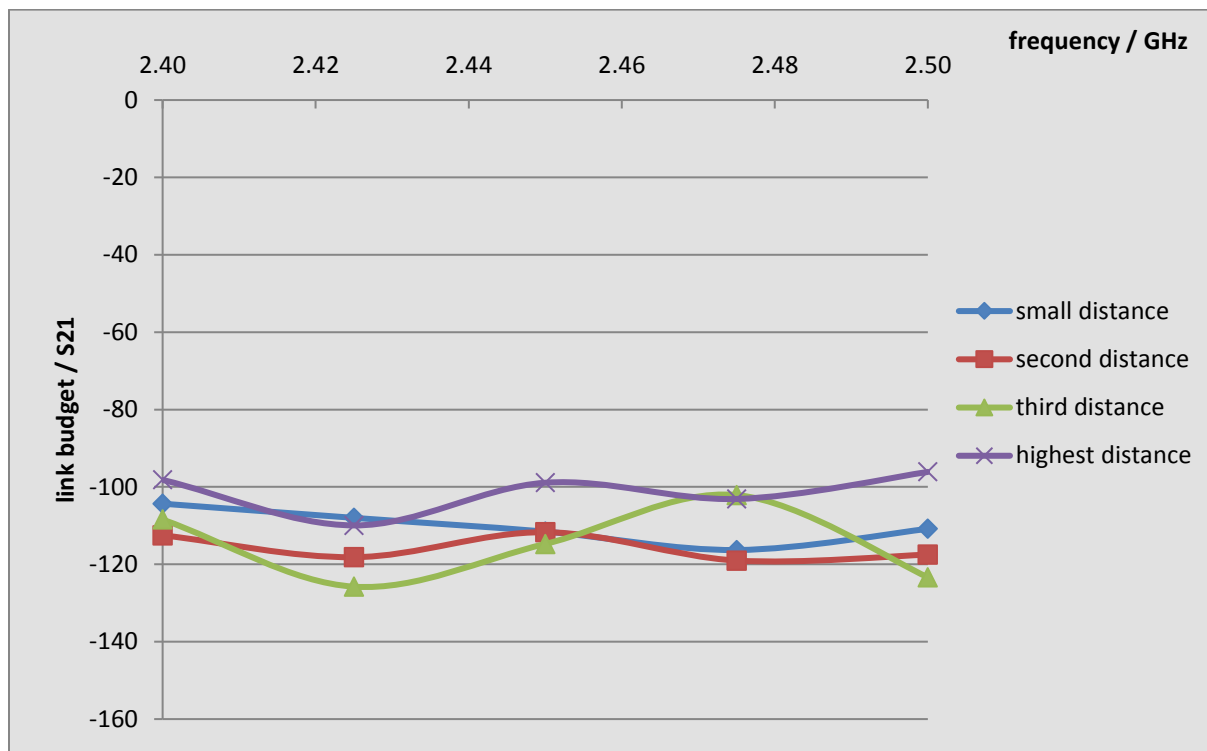
For the prismatic wing model when the second antenna is placed at a highest distance to the first antenna (that is at the $3/4^{\text{th}}$ position of the wing length), the variations in the link budget value for three different surface materials of the aeroplane wings is shown above. Except at 2.42 GHz, there exist no significant differences between the link budget values of the aeroplane wings that are made of the three different materials. At the frequency of 2.42 GHz, aeroplane wing surfaced with carbon fibre exhibited link budget of -80 dB higher than the aeroplane wings made of the other two materials.

Graph group 2: different distances

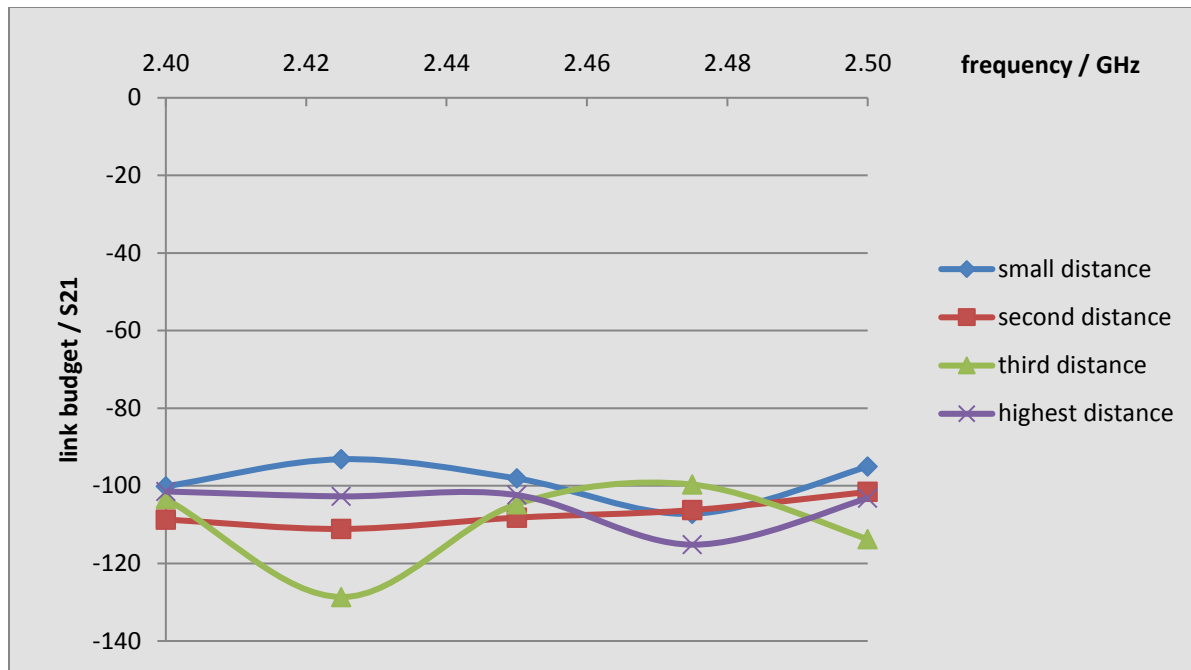
This group of graphs is mainly intended in changing the different positions of the antenna on the aeroplane wing by keeping the surface material of the aeroplane wing as constant. All the nine

graphs that are grouped under “group 2” are used to analyze the impact of this changing antenna position on the link budget value.

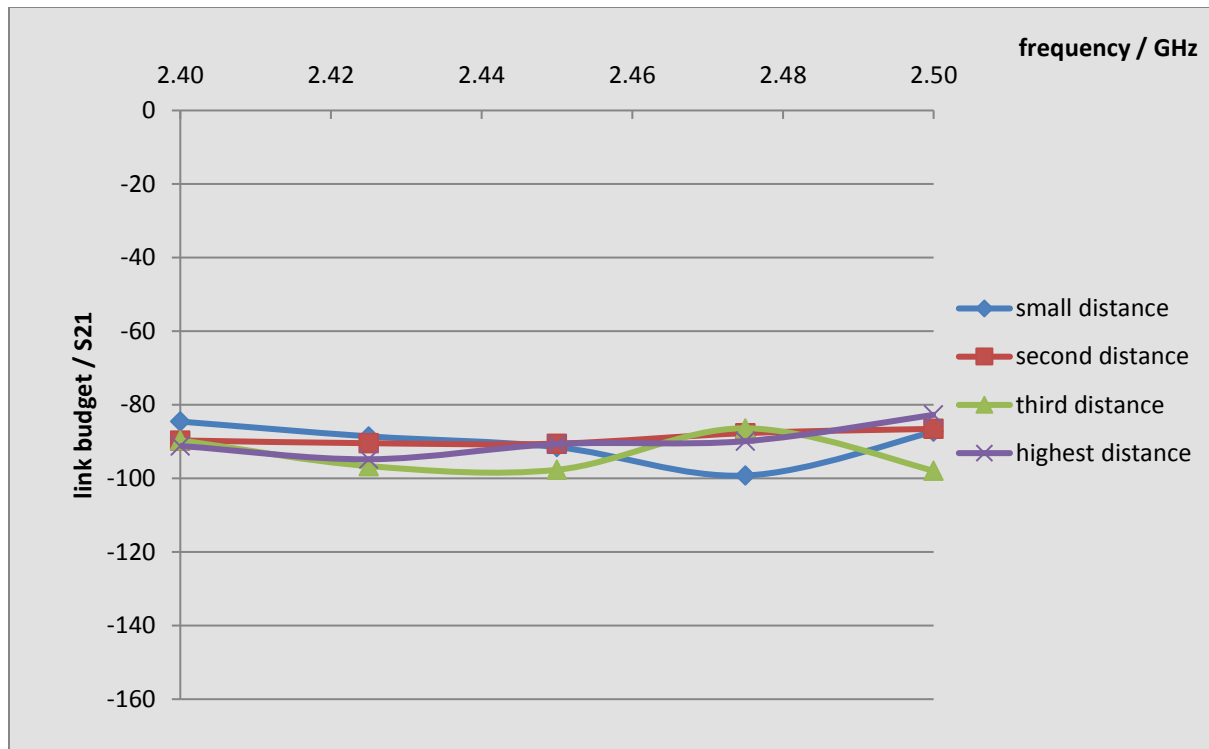
Aluminum wing material



For the aeroplane wing that is surfaced with the aluminium material, the position of the second antenna is varied, and its impact on the value of link budget is presented in the above graph. Comparative analysis of all the four distances of antenna positions indicated that when the second antenna is placed at the highest distance (tip of the wing); the link budget value has exhibited relatively high value when compared to the other three positions of the antenna on the aeroplane wing.

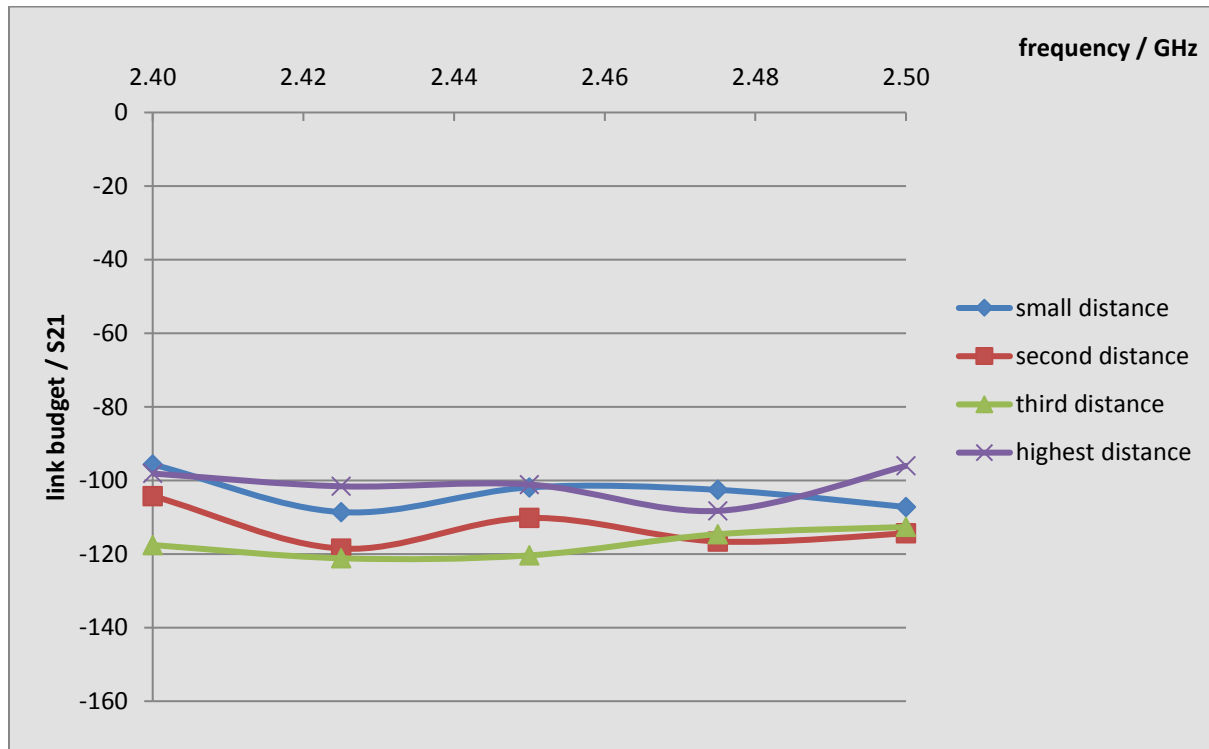


The empty wing model made of aluminium material is considered, and the impact of the different antenna positions on the link budget value is shown in the above graph. Only at the frequency of 2.42 GHz, significant differences exist among the different distances of the aeroplane wing. For a small distance and highest distance of the second antenna, the link budget values remained high, and for the other two distances, the link budget values have decreased to -130 dB especially when the second antenna is placed at the 3/4th position of the wing length.

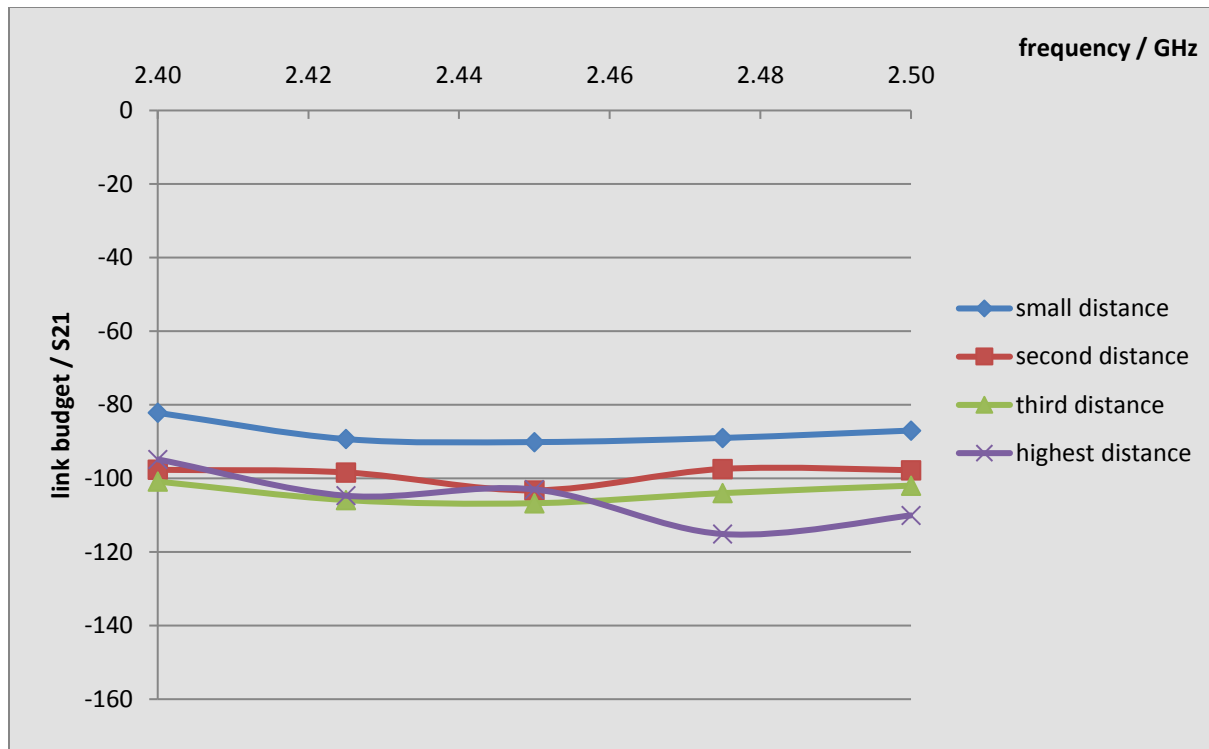


For prismatic wing model when the wing is surfaced with aluminium material, the variations in the link budget value with the changes in the positions of the second antenna. Throughout the considered frequency range of 2.4 GHz and 2.5 GHz, the link budget value of the aeroplane wings have remained between -80 dB and -100 dB without any major differences among the different antenna positions on the aeroplane wing.

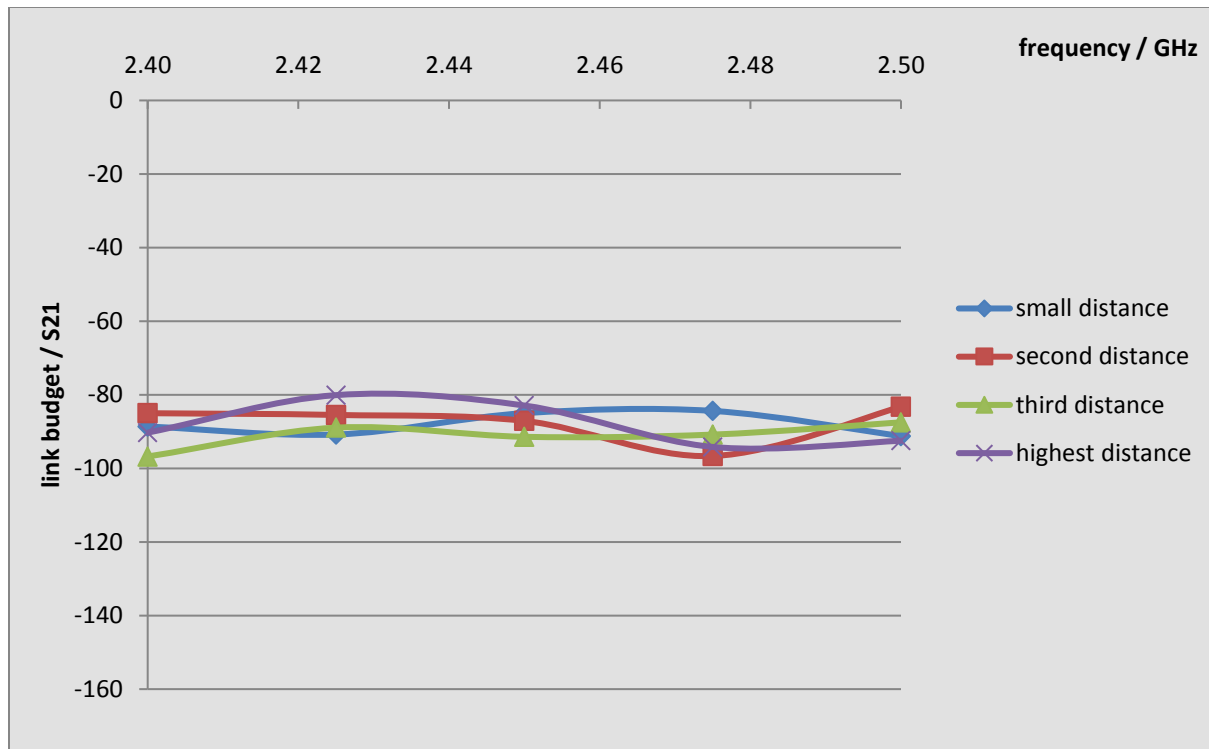
Carbon fibre wing material



For a realistic wing model when the surface of the aeroplane wing is chosen with carbon fibre material, the variations in the value of link budget with the changes in the positions of the second antenna on the wing is shown above. At the two distance positions of the second antenna that is at the small and the highest distance, the value of the link budget remained high when compared to the other two distance positions (second and the third distance) of the second antenna on the aeroplane wing.

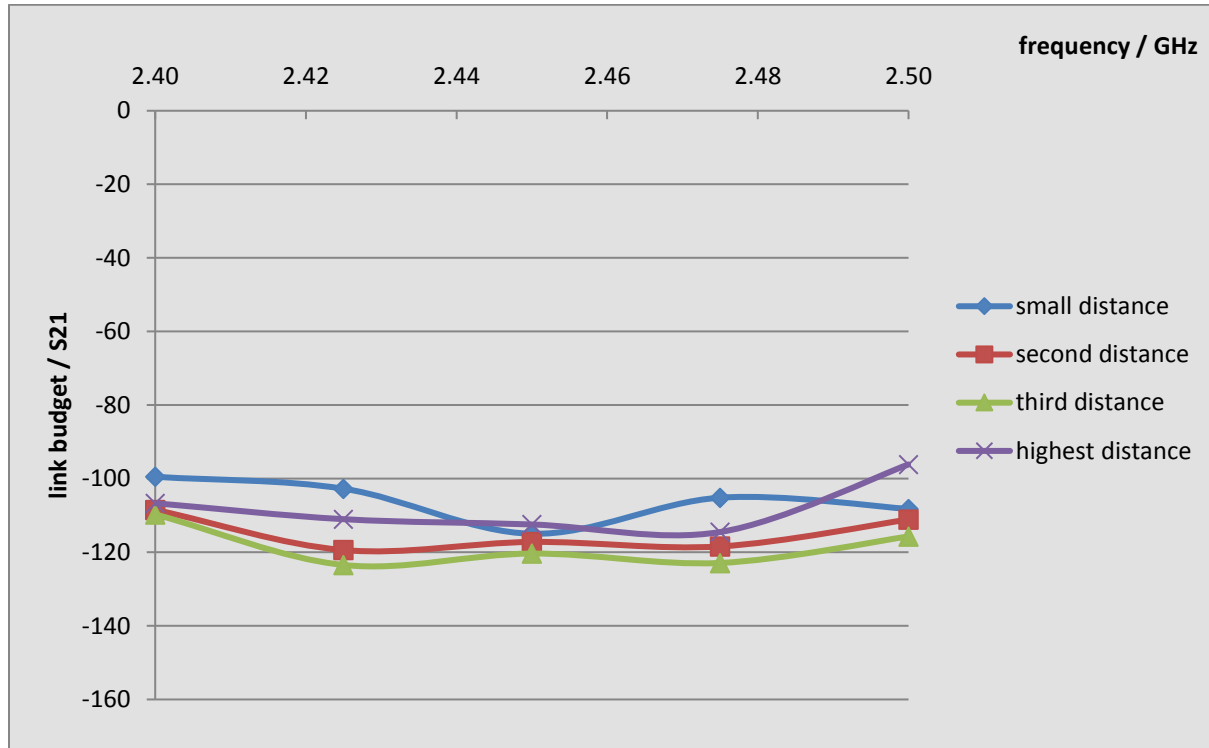


In case of the empty wing model, when the aeroplane wing is surfaced with carbon fibre material, the variation in the link budget value with the variations in the position of the second antenna is shown in the above graph. Interestingly, when the second antenna is placed at a short distance that is at the $1/4^{\text{th}}$ position of the wing length, the link budget value reached high ranging between -80 dB and -90 dB values.

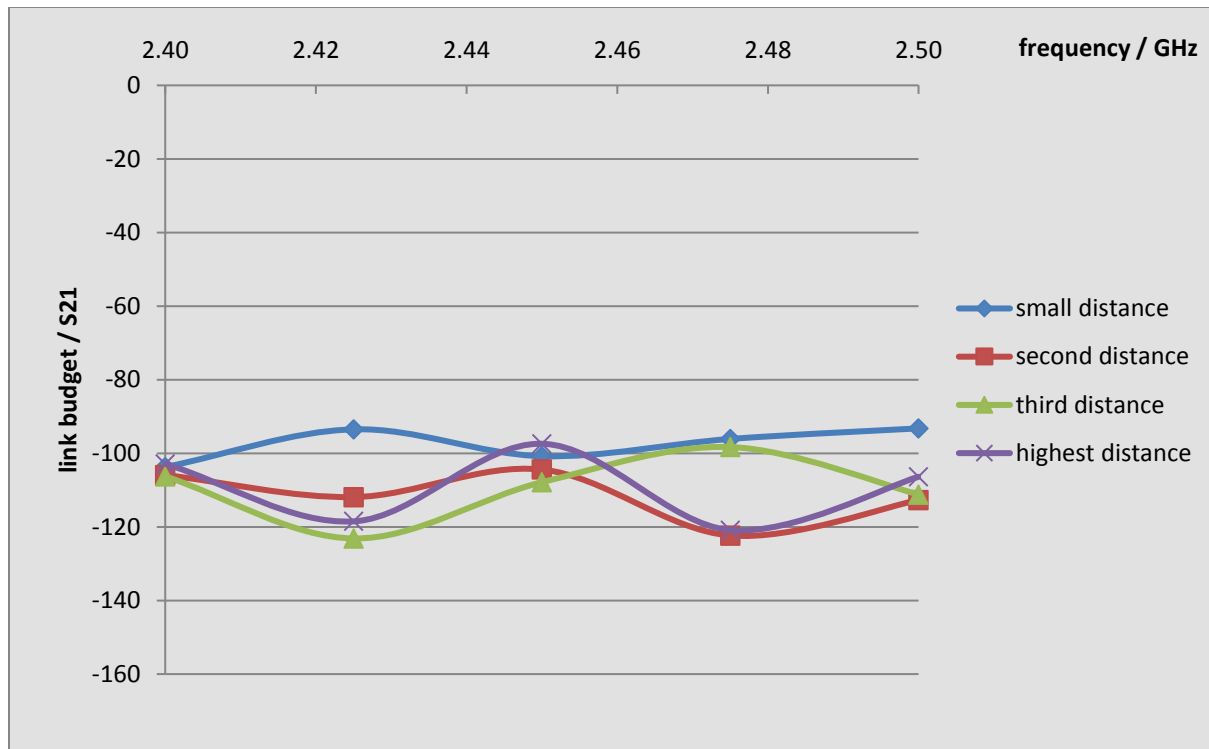


In case of the prismatic wing model, when the wing is surfaced with the carbon fibre material the impact of the changing antenna position on the link budget value is shown in the above graph. Between the frequency range of 2.40 GHz and 2.50 GHz, despite of changing the antenna position, the link budget value remained within the range of -80 dB and -100 dB as shown above.

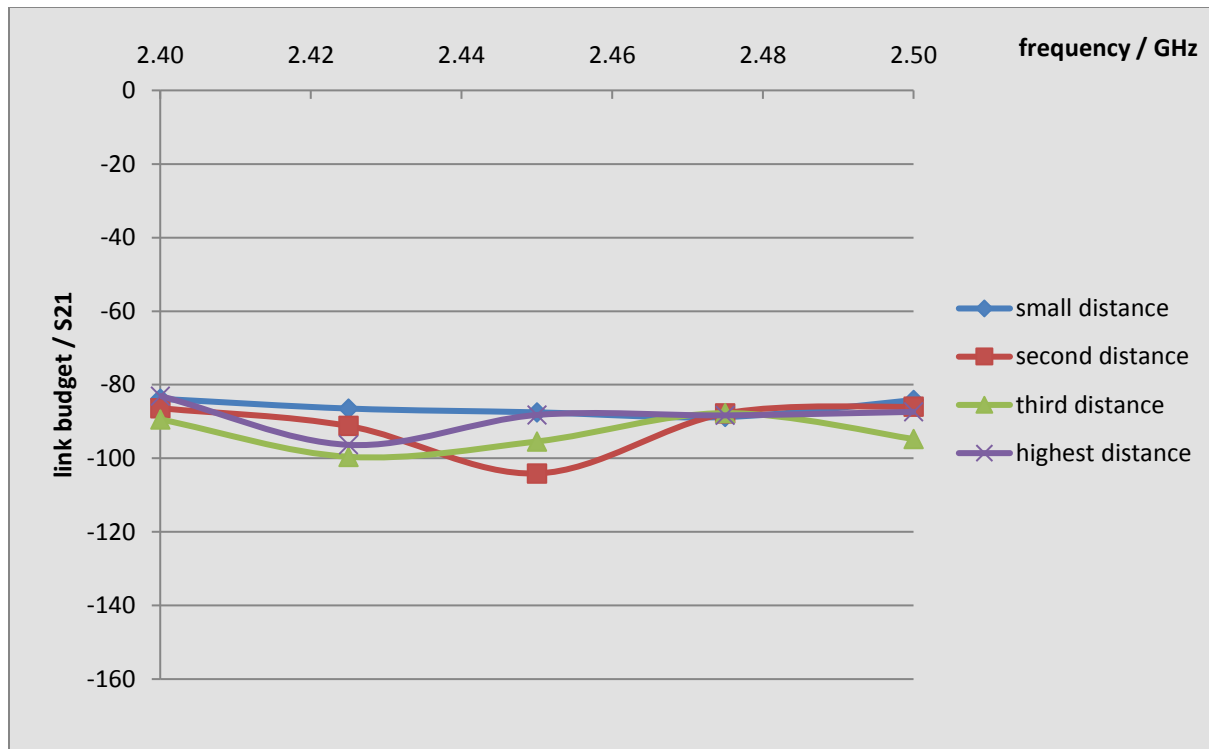
PEC wing material



In case of the realistic wing model, when the air wing is surfaced with PEC material, the variations in the link budget value with the changes in the second antenna positions is given in the above graph. When the second antenna is placed at small and highest distance with respect to the first antenna, the value of link budget exhibited high value when compared to the other two distances of the second antenna. However, when compared to highest distance, at a small distance of second antenna itself, the aeroplane wing experienced the high value of link budget of -100 dB at 2.42 GHz.



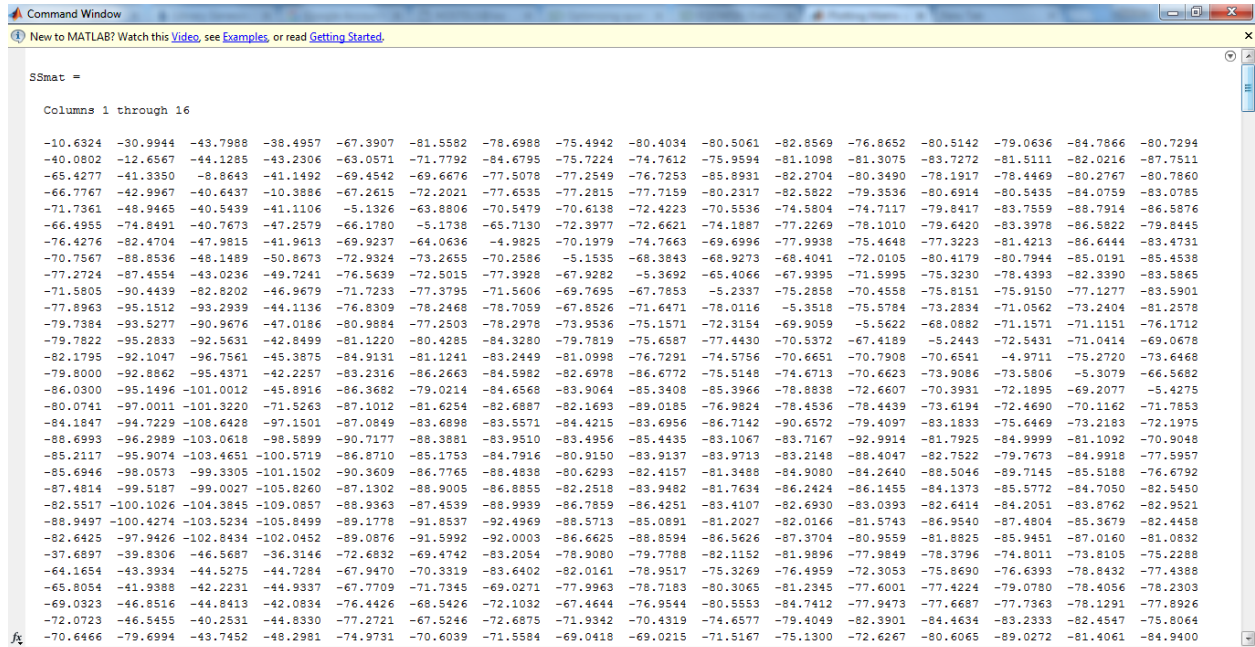
In case of the empty wing model, when the wing is surfaced with the PEC material the impact of the changing antenna position on the link budget value is shown in the above graph. High fluctuations in the link budget values are exhibited at the frequency range of 2.42 GHz and 2.48 GHz. Altogether, when the second antenna is placed at the small distance (at the $1/4^{\text{th}}$ position of wing length), the link budget value of the PEC surfaced aeroplane wing remained highest.



In case of the prismatic wing model, when the wing is surfaced with the PEC material the impact of the changing antenna position on the link budget value is shown in the above graph. At the frequency range of 2.47 GHz, all the different position of the second antenna exhibited the same value of the link budget as -90 dB. However, throughout the considered frequency range of 2.40 GHz and 2.50 GHz, the link budget value remained between -80 and -100 dB values with a slight decline at 2.45 GHz when the antenna is placed at a second distance.

Appendix D

The details of S matrix obtained from Matlab is given in below screens



Command Window

New to MATLAB? Watch this [Video](#), see [Examples](#), or read [Getting Started](#).

Smat =

Columns 1 through 16

-10.6324	-30.9944	-43.7988	-38.4957	-67.3907	-81.5582	-78.6988	-75.4942	-80.4034	-80.5061	-82.8569	-76.8652	-80.5142	-79.0636	-84.7866	-80.7294
-40.0802	-12.6567	-44.1285	-43.2306	-63.0571	-71.7792	-84.6795	-75.7224	-74.7612	-75.9594	-81.1098	-81.3075	-83.7272	-81.5111	-82.0216	-87.7511
-65.4277	-41.3350	-8.8643	-41.1492	-69.4542	-69.6676	-77.5078	-77.2549	-76.7253	-85.8931	-82.2704	-80.3490	-78.1917	-78.4469	-80.2767	-80.7860
-66.7767	-42.9967	-40.6437	-10.3886	-67.2615	-72.2021	-77.6535	-77.2815	-77.7159	-80.2317	-82.5822	-79.3536	-80.6914	-80.5435	-84.0759	-83.0785
-71.7361	-48.9465	-40.5439	-41.1106	-5.1326	-63.8906	-70.5479	-70.6138	-72.4223	-70.5536	-74.5804	-74.7117	-79.8417	-83.7559	-88.7914	-86.5876
-66.4955	-74.8491	-40.7673	-47.2579	-66.1780	-5.1738	-65.7130	-72.3977	-72.6621	-74.1887	-77.2269	-78.1010	-79.6420	-83.3978	-86.5822	-79.8445
-76.4276	-82.4704	-47.9815	-41.9613	-69.9237	-64.0636	-4.9825	-70.1979	-74.7663	-69.6996	-77.9938	-75.4648	-77.3223	-81.4213	-86.6444	-83.4791
-70.7567	-88.8536	-48.1489	-50.8673	-72.9324	-73.2655	-70.2586	-5.1535	-68.3843	-68.9273	-68.4041	-72.0105	-80.4179	-80.7944	-85.0191	-85.4538
-77.2724	-87.4554	-43.0236	-49.7241	-76.5639	-72.5015	-77.3928	-67.9282	-5.3692	-65.4066	-67.9395	-71.5995	-75.3230	-78.4393	-82.3390	-83.5865
-71.5805	-90.4439	-82.8202	-46.9679	-71.7233	-77.3795	-71.5606	-69.7695	-67.7853	-5.2337	-75.2858	-70.4558	-75.8151	-75.9150	-77.1277	-83.5901
-77.8963	-95.1512	-93.2939	-44.1136	-76.8309	-78.2468	-78.7059	-67.8526	-71.6471	-78.0116	-5.3518	-75.5784	-73.2834	-71.0562	-73.2404	-81.2578
-79.7384	-93.5277	-90.9676	-47.0186	-80.9884	-77.2503	-78.2978	-73.9536	-75.1571	-72.3154	-69.9059	-5.5622	-68.0882	-71.1571	-71.1151	-76.1712
-79.7822	-95.2833	-92.5631	-42.8499	-81.1220	-80.4285	-84.3280	-79.7819	-75.6587	-77.4430	-70.5372	-67.4189	-5.2443	-72.5431	-71.0414	-69.0678
-82.1795	-92.1047	-96.7561	-45.3875	-84.9131	-81.1241	-83.2449	-81.0998	-76.7291	-74.5756	-70.6651	-70.7908	-70.6541	-4.9711	-75.2720	-73.6468
-79.8000	-92.8862	-95.4371	-42.2257	-83.2316	-86.2663	-84.5982	-82.6978	-86.6772	-75.5148	-74.6713	-70.6623	-73.9086	-73.5806	-5.3079	-66.5682
-86.0300	-95.1496	-101.0012	-45.8916	-86.3682	-79.0214	-84.6568	-83.9064	-85.3408	-85.3966	-78.8838	-72.6607	-70.3931	-72.1895	-69.2077	-5.4275
-80.0741	-97.0011	-101.3220	-71.5263	-87.1012	-81.6254	-82.6887	-82.1693	-89.0185	-76.9824	-78.4536	-78.4439	-73.6194	-72.4690	-70.1162	-71.7853
-84.1847	-94.7229	-108.6428	-97.1501	-87.0849	-83.6898	-83.5571	-84.4215	-83.6956	-86.7142	-90.6572	-79.4097	-83.1833	-75.6469	-73.2183	-72.1975
-88.6993	-96.2989	-103.0618	-98.5899	-90.7177	-88.3881	-83.9510	-83.4956	-85.4435	-83.1067	-83.7167	-92.9914	-81.7925	-84.9999	-81.1092	-70.9048
-85.2117	-95.9074	-103.4651	-100.5719	-86.8710	-85.1753	-84.7916	-80.9150	-83.9137	-83.9713	-83.2148	-88.4047	-82.7522	-79.7673	-84.9918	-77.5957
-85.6946	-98.0573	-99.3305	-101.1502	-90.3609	-86.7765	-88.4838	-80.6293	-82.4157	-81.3488	-84.9080	-84.2640	-88.5046	-89.7145	-85.5188	-76.6792
-87.4814	-99.5187	-99.0027	-105.8260	-87.1302	-88.9005	-86.8855	-82.2518	-83.9482	-81.7634	-86.2424	-86.1455	-84.1373	-85.5772	-84.7050	-82.5450
-82.5517	-100.1026	-104.3845	-109.0857	-88.9363	-87.4539	-88.9939	-86.7859	-86.4251	-83.4107	-82.6930	-83.0393	-82.6414	-84.2051	-83.8762	-82.9521
-88.9497	-100.4274	-103.5234	-105.9499	-89.1778	-91.8537	-92.4969	-88.5713	-85.0891	-81.2027	-82.0166	-81.5743	-86.9540	-87.4804	-85.3679	-82.4458
-82.6425	-97.9426	-102.8434	-102.0452	-89.0876	-91.5992	-92.0003	-86.6625	-88.8594	-86.5626	-87.3704	-80.9559	-81.8825	-85.9451	-87.0160	-81.0832
-37.6897	-39.8306	-46.5687	-36.3146	-72.6832	-69.4742	-83.2054	-78.9080	-79.7788	-82.1152	-81.9896	-77.9849	-78.3796	-74.8011	-73.8105	-75.2288
-64.1654	-43.3934	-44.5275	-44.7284	-67.9470	-70.3319	-83.6402	-82.0161	-78.9517	-75.3269	-76.4959	-72.3053	-75.8690	-76.6393	-78.8432	-77.4388
-65.8054	-41.9388	-42.2231	-44.9337	-67.7709	-71.7345	-69.0271	-77.9963	-78.7183	-80.3065	-81.2345	-77.6001	-77.4224	-79.0780	-78.4056	-78.2303
-69.0323	-46.8516	-44.8413	-42.0834	-76.4426	-68.5426	-72.1032	-67.4644	-76.9544	-80.5553	-84.7412	-77.9473	-77.6687	-77.7363	-78.1291	-77.8926
-72.0723	-46.5455	-40.2531	-44.8330	-77.2721	-67.5246	-72.6875	-71.9342	-70.4319	-74.6577	-79.4049	-82.3901	-84.4634	-83.2333	-82.4547	-75.8064
-70.6466	-79.6994	-43.7452	-48.2981	-74.9731	-70.6039	-71.5584	-69.0418	-69.0215	-71.5167	-75.1300	-72.6267	-80.6065	-89.0272	-81.4061	-84.9400

S matrix for 79 nodes between columns 1 to 16

Command Window

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-82.8030	-96.9967	-106.3215	-99.7468	-85.1219	-92.4806	-90.3153	-82.4990	-84.9294	-82.9062	-85.5075	-83.3144	-84.4519	-87.3773	-82.2719	-88.7748
-83.2563	-99.3748	-103.5261	-98.5155	-91.8425	-90.5186	-84.8162	-86.6977	-86.3754	-83.5865	-84.7283	-83.9987	-83.8966	-86.3199	-84.2477	-81.3457
-87.9216	-95.5842	-108.2845	-101.6375	-85.8598	-89.2904	-88.7636	-86.0118	-86.0675	-82.3501	-87.1536	-85.0706	-84.2941	-85.4154	-81.3196	-83.9692
-88.5988	-98.0230	-106.4447	-101.4590	-87.1111	-88.5172	-87.5405	-86.0430	-88.6212	-81.6592	-84.5429	-80.8091	-81.6777	-85.7575	-80.5725	-82.2532
-86.0862	-93.1845	-104.6537	-104.1246	-91.7076	-92.7217	-88.4684	-85.7267	-86.2344	-84.7153	-90.2191	-87.2603	-82.1798	-83.9889	-86.4839	-87.0345
-86.2156	-100.1615	-108.6297	-105.0490	-88.2089	-90.5369	-92.8239	-85.5584	-85.6156	-88.0841	-85.3635	-87.7800	-80.7887	-88.0120	-82.6925	-89.2749
-88.2980	-101.4751	-108.1360	-107.7773	-90.0356	-94.6483	-93.8749	-87.2211	-92.6859	-92.8872	-83.8699	-84.9727	-83.5170	-80.9628	-85.4481	-84.3797
-90.2170	-101.9317	-108.3308	-114.1955	-88.4102	-95.2297	-90.5952	-84.6510	-93.0518	-86.4825	-83.9292	-84.2211	-92.0055	-82.7512	-86.5846	-81.0340
-90.6203	-97.7305	-100.0422	-104.1811	-89.4866	-92.1968	-90.0605	-88.7132	-90.7155	-90.4072	-86.4643	-84.8059	-88.6241	-90.1943	-89.4951	-79.7890
-89.3001	-97.7396	-108.0430	-105.4735	-94.2618	-87.8159	-92.7376	-89.5767	-94.7099	-88.3310	-86.9883	-81.4147	-89.3632	-83.6441	-80.3810	-84.5047
-90.2336	-101.6186	-108.1036	-104.3549	-94.8435	-89.1583	-94.6669	-86.6815	-95.6586	-89.4285	-89.8057	-86.0447	-86.4957	-82.7459	-86.1501	-90.0462
-96.3354	-100.4895	-110.2637	-100.0405	-93.8576	-92.9251	-98.9710	-90.7889	-93.2989	-87.5853	-90.6865	-88.2950	-85.4460	-86.9121	-85.6632	-83.7044

Columns 17 through 32

-85.1281	-85.3582	-84.0599	-80.2120	-85.5363	-89.0864	-93.7128	-96.4516	-83.5803	-70.6172	-62.7497	-63.7712	-69.9030	-76.2438	-73.2838	-77.4410
-85.6015	-88.7105	-91.9193	-94.1994	-89.2441	-89.7903	-87.2474	-92.6687	-89.3943	-62.0669	-67.8517	-71.9627	-77.9652	-69.6173	-78.9640	-77.5899
-85.4981	-86.5636	-85.0256	-87.7872	-87.2448	-90.0021	-90.2504	-93.4904	-89.3171	-67.0918	-76.6891	-66.2807	-71.9916	-76.9874	-83.0687	-76.4754
-82.9686	-83.1149	-81.6455	-81.9057	-87.8708	-91.6260	-88.8165	-85.6116	-92.7285	-65.3691	-65.6550	-75.7530	-71.4983	-73.5898	-83.5778	-85.5813
-89.7845	-89.1935	-88.4761	-87.8945	-92.0590	-90.7809	-91.1481	-91.6827	-90.4818	-72.3414	-65.4127	-71.2585	-73.0506	-76.6713	-79.8544	-75.2508
-85.2067	-86.4809	-87.5810	-87.1929	-89.2901	-89.6552	-90.7262	-90.2341	-90.3282	-69.8875	-67.5438	-65.8549	-67.4761	-68.4674	-69.9563	-73.0358
-83.3764	-80.7983	-83.4121	-83.9434	-88.1384	-88.6880	-87.7055	-92.4194	-87.9927	-80.7870	-81.7093	-67.4180	-70.5389	-68.7646	-70.5132	-68.2066
-86.7679	-83.4141	-84.0974	-81.6494	-84.2889	-85.9014	-84.9462	-87.7162	-95.5096	-80.6051	-77.9295	-72.8725	-65.7348	-70.4641	-74.3456	-68.5218
-87.3148	-85.3416	-85.5491	-82.2245	-82.7732	-84.6701	-88.0548	-86.1444	-89.5035	-79.4618	-78.1695	-76.5760	-75.4560	-66.2940	-71.5672	-73.9608
-83.5289	-85.1578	-85.4607	-81.9520	-80.0668	-82.1443	-82.0124	-83.1964	-83.5715	-82.9450	-73.7626	-81.2921	-79.4423	-73.3056	-71.5671	-68.0334
-83.5833	-87.7393	-84.3957	-87.0239	-85.5274	-85.1103	-82.1103	-82.5787	-87.0517	-83.2740	-75.5461	-80.2211	-81.1190	-78.1284	-76.9428	-69.2486
-81.8616	-84.1392	-84.8393	-84.3395	-84.2023	-83.9442	-81.5888	-82.5224	-80.2714	-81.9846	-74.2354	-74.3878	-80.3930	-82.0547	-74.5406	-70.9207
-74.8338	-82.3030	-80.5422	-80.9556	-85.5120	-88.6512	-86.0413	-84.0442	-80.7096	-82.3662	-76.2305	-78.5803	-78.5115	-82.0370	-78.8593	-77.3517
-75.3924	-74.9755	-80.4143	-77.6465	-83.6998	-87.3366	-86.5866	-83.5357	-84.1799	-76.7123	-77.1179	-75.7787	-77.3549	-79.8720	-84.5219	-84.2330
-68.7803	-78.1489	-77.0507	-82.6082	-84.2747	-80.1663	-86.3544	-81.9471	-89.8147	-74.1772	-77.7468	-82.0931	-77.7578	-85.3447	-83.4469	-83.2849
-71.2029	-70.3668	-70.3625	-78.3752	-76.5323	-83.8784	-80.1708	-82.3803	-80.1605	-75.8708	-77.8061	-79.8383	-79.2801	-75.4257	-84.2586	-78.4291
-5.1534	-63.7802	-71.7930	-70.3371	-72.6736	-79.3929	-81.8134	-80.1497	-79.8658	-74.8232	-81.7629	-82.4006	-83.9479	-74.6948	-80.9140	-81.0009
-65.8694	-5.3787	-71.5218	-69.1548	-72.3104	-75.6089	-78.0066	-78.7142	-79.7776	-77.2017	-87.8812	-84.0504	-82.9557	-75.0136	-79.8132	-91.0871
-74.8134	-71.6205	-5.4634	-64.9226	-72.4980	-76.9722	-74.0307	-81.4365	-80.2815	-78.2198	-86.8660	-84.3429	-82.1028	-79.3335	-86.1238	-85.1850
-78.8522	-71.2108	-63.5790	-5.5272	-77.2260	-80.2007	-73.0681	-78.4247	-78.4135	-82.9874	-87.9175	-83.2786	-84.8893	-81.9191	-79.6189	-81.9193
-75.1548	-73.1304	-71.1917	-71.3238	-5.2952	-73.5326	-73.1778	-73.3557	-78.6802	-87.4733	-85.9127	-85.8340	-90.8342	-80.8757	-80.5238	-82.0949

Command Window

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-85.6154	-80.9350	-90.5865	-90.7889	-90.7658	-85.0506	-85.9392	-87.3020	-86.9062	-89.1198	-83.6088	-83.5340	-75.2262	-75.8299	-72.7166	-70.7555
-85.0140	-77.6223	-86.2636	-87.9629	-86.4633	-82.3323	-88.3263	-83.4236	-83.8389	-91.3923	-86.0771	-82.0996	-84.8760	-79.6703	-73.2702	-71.7593
-76.1453	-76.4886	-88.0951	-89.5490	-90.1096	-86.3109	-87.0051	-89.8383	-82.9233	-90.4473	-84.2123	-84.0945	-83.1476	-82.8052	-76.3769	-83.6413
-78.4528	-81.3924	-84.5463	-90.8858	-92.7749	-90.0962	-88.9827	-88.2049	-88.2553	-89.0521	-83.4935	-84.6456	-85.5023	-85.9537	-75.9746	-82.2362
-70.7158	-76.4754	-87.0616	-90.1795	-91.0344	-88.1576	-89.7740	-95.3018	-87.5718	-93.0864	-87.8652	-84.2168	-82.8514	-81.4486	-81.3670	-83.5979
-76.5678	-70.9617	-88.5634	-93.6933	-90.1590	-87.8853	-86.8746	-94.2812	-89.2510	-84.3329	-88.3293	-84.2631	-83.0684	-85.7816	-83.8675	-83.3397
-81.0544	-74.7529	-89.5009	-94.3950	-89.1596	-89.6981	-90.7822	-90.0165	-90.3909	-86.1570	-92.4476	-93.8645	-87.8991	-87.5890	-80.9487	-85.1445
-82.2486	-73.7851	-88.6688	-89.0677	-95.7545	-96.1721	-96.3295	-97.0189	-90.4542	-87.6702	-92.2086	-84.4177	-89.0171	-83.7309	-80.9669	-84.3566
-83.0160	-77.7776	-87.8544	-90.7384	-96.2949	-95.1679	-95.3088	-90.9895	-90.5289	-92.0275	-88.7774	-86.0101	-86.9158	-85.5146	-83.1706	-80.7578
-79.6121	-80.8132	-87.5355	-93.4017	-101.3540	-91.9656	-93.0346	-94.5831	-91.3506	-85.5553	-93.0141	-91.6242	-95.1462	-93.1373	-84.7066	-82.8209
-86.5806	-83.6090	-90.9272	-92.8831	-95.3097	-88.3795	-95.6472	-90.9827	-96.4905	-97.4208	-94.0914	-91.8171	-91.7001	-92.5779	-89.8218	-89.6091
-80.9586	-84.0683	-87.0382	-88.4855	-88.6963	-100.1358	-91.4914	-90.5730	-90.5763	-87.4958	-92.3751	-84.4132	-90.3650	-85.4213	-83.8006	-82.3820
-69.5988	-71.6113	-93.7612	-90.0685	-95.1835	-91.8172	-92.2276	-86.6937	-88.9596	-87.0497	-84.2206	-88.5782	-85.7398	-83.0537	-85.8835	-86.7699
-76.6190	-81.2417	-91.3422	-93.3217	-84.2160	-93.9067	-90.9381	-92.4120	-92.4138	-89.3758	-86.9686	-86.3768	-84.5727	-80.1938	-83.7380	-84.0035
Columns 65 through 79															
-83.9393	-85.3524	-83.6222	-87.4628	-88.5485	-91.3991	-94.7372	-91.0042	-96.3492	-91.0681	-88.2619	-83.4913	-94.3716	-85.6009	-89.0858	
-87.3727	-87.7868	-82.4805	-84.4480	-84.8539	-86.9713	-89.0412	-88.9989	-89.3465	-90.2216	-88.1483	-85.2049	-92.8789	-93.5812	-94.4109	
-81.0682	-86.3150	-86.9809	-90.9687	-94.6450	-89.4254	-88.8133	-89.2782	-90.6580	-89.2341	-85.8386	-88.9459	-93.5946	-92.6503	-90.2132	
-87.7831	-82.9644	-89.8331	-88.6168	-90.9037	-92.7750	-90.6742	-88.9690	-94.5669	-89.9324	-89.0913	-92.2998	-91.3532	-98.1480	-92.9956	
-92.6045	-88.6574	-89.4149	-90.5110	-84.8189	-89.0791	-91.1959	-89.4844	-90.2127	-88.5169	-86.0540	-85.4408	-94.9562	-92.2545	-90.8128	
-83.4992	-82.4733	-83.2210	-87.9981	-88.9612	-94.4305	-92.1113	-90.9685	-91.0315	-95.0629	-89.6069	-87.3417	-96.0124	-94.6882	-92.3739	
-87.5135	-92.3974	-89.7207	-84.3040	-83.5906	-87.5199	-90.8519	-94.6547	-95.5112	-88.5642	-92.7826	-89.1795	-99.7441	-93.0596	-93.0721	
-88.1492	-82.1843	-83.2452	-83.8861	-86.9095	-91.4631	-92.6615	-88.0647	-90.8880	-88.7182	-90.0272	-86.9724	-93.3566	-91.6038	-91.1204	
-85.0736	-83.0073	-83.4726	-88.6530	-84.7112	-93.4706	-88.1624	-93.4051	-95.4491	-92.0772	-88.9625	-86.8392	-94.2407	-94.3215	-87.2634	
-80.4509	-91.2734	-87.3432	-87.5854	-94.5397	-87.1627	-85.4575	-88.6600	-93.1516	-94.7389	-87.1442	-89.8177	-94.0122	-92.0479	-92.6511	
-83.6503	-83.7190	-82.5355	-86.3407	-85.4021	-90.1997	-88.5426	-88.9584	-88.1894	-91.4651	-89.4045	-85.4894	-94.2833	-98.5207	-87.6804	
-85.2490	-86.4952	-84.8983	-87.2499	-88.8211	-92.5664	-88.0606	-88.7906	-93.6483	-86.3897	-89.4465	-80.7413	-87.1751	-92.4608	-86.5004	
-80.0625	-87.1193	-84.1919	-84.9715	-86.0363	-87.3370	-90.3051	-90.8087	-86.7796	-86.5450	-92.7519	-86.4771	-92.1846	-90.4430	-84.5524	
-82.1758	-85.0929	-85.5475	-88.7286	-84.4458	-87.4445	-87.3925	-87.8153	-89.3323	-87.8171	-83.3997	-83.3844	-89.4426	-86.6055	-84.2526	
-88.8707	-83.7366	-82.8427	-86.5882	-87.3926	-85.9762	-88.6323	-88.8386	-87.8657	-95.1156	-88.5738	-85.5052	-85.0449	-87.0127	-84.4833	
-79.5497	-85.3501	-81.4255	-87.2770	-85.7653	-85.0826	-86.0352	-92.6141	-95.8821	-92.1971	-87.4346	-80.7439	-87.1669	-85.8320	-81.4815	
-79.0917	-84.5088	-82.0077	-81.9280	-85.8111	-83.9629	-95.5838	-90.0715	-89.7956	-89.0621	-82.6320	-86.6082	-90.4353	-86.2864	-87.3737	
-77.2570	-83.2343	-84.5246	-85.2266	-82.1473	-89.9066	-86.7564	-85.1682	-87.2267	-88.7811	-84.5901	-82.5794	-89.8877	-83.2389	-78.5374	
-84.4774	-79.7178	-85.7921	-82.2529	-86.6276	-84.2264	-88.1754	-88.5635	-87.4309	-85.6351	-89.6678	-84.8357	-89.1241	-89.2898	-80.9779	
-79.7698	-81.8342	-84.7990	-82.4814	-84.6542	-82.8858	-88.0155	-87.7523	-86.8045	-86.8086	-85.0104	-81.8001	-82.6395	-84.6884	-77.8265	

S matrix for 79 nodes between columns 32 to 79