

# Chapter 1

## Introduction

The word *wireless* was first used in the 1890s while using the *wireless telegraphy* service as a transmitting and receiving technology. Later on, it was replaced by the new word *radio* which was afterwards revived to differentiate the devices that communicate without wires in the late 1980s from those that need wires. This word is commonly used in the telecommunication industry to refer to systems or devices that use radio waves for transmission and reception of information over long distances, which is practically impossible via wires or cables. Common examples of wireless equipment using radio waves include remote control devices, cordless phones, satellite television, cellular telephones, amateur radio service, air traffic control, Bluetooth and many more. The proliferation of these devices occurs with the improvements in the digital wireless networks, i.e., the paradigm shift from wired to wireless technology at the beginning of the 1990s. [1]. Wireless communication has witnessed many revolutionary advancements in recent decades, which have transformed the face of modern communications. The main component of this advancement is the paradigm shift from bipolar transistor (BJT) to MOSFET (metal-oxide semiconductor field effect transistor) in the late 1980s and its scaling, i.e., the number of transistors accommodated on a chip that has been doubling every 24 months [2]. This has led to the production of highly compact wireless devices

without compromising much on their QoS (quality of service) parameters [3]. Not only this, these compact wireless devices support two or more technologies. For example, a smart phone has a Bluetooth connection and a Wi-Fi (wireless fidelity) connection for data transfer and also has a provision for GPS for location updation [4]. Depending upon the size and frequency requirements of these wireless devices, several techniques have been proposed to design such antenna structures that must be compact enough to be easily accommodated within these devices and have the capability of supporting them in terms of multiple frequency band operation and other QoS parameters [5].

With growing data transmission demand, the present 4G-LTE network can not meet the expectations of massive device communications, high data rate and bandwidth, and low latency. As a result, new communication technologies must be designed. The fifth-generation mobile network, or 5G, is one of the most popular and efficient technologies in the wireless communication field. By operating at a much higher frequency, typically more than ten times higher than 4G technology, it can carry significantly more data, provide a wider bandwidth, and avoid the already crowded low-frequency band, since the majority of conventional wireless communication occurs between 300 MHz and 3GHz [6]. Frequency ranges in the 24.25–86 GHz range are highly suitable for 5G deployment, provided that propagation restrictions at such frequencies are adequately managed. Significant advancements in the design of existing wireless networks are desperately needed to adopt 5G technology. The International Telecommunication Union Radiocommunication Sector (ITU-R) categorises 5G applications into three broad categories: ultra-reliable low-latency communications (uRLLC) used for applications like autonomous vehicles, massive machine-type communications (mMTC) used for functioning of large-scale applications of IoT, and enhanced mobile broadband (eMBB) used for resource-intensive applications and wideband Internet access [7]. Fig. 1.1 provides a summary of the applications under these three categories.

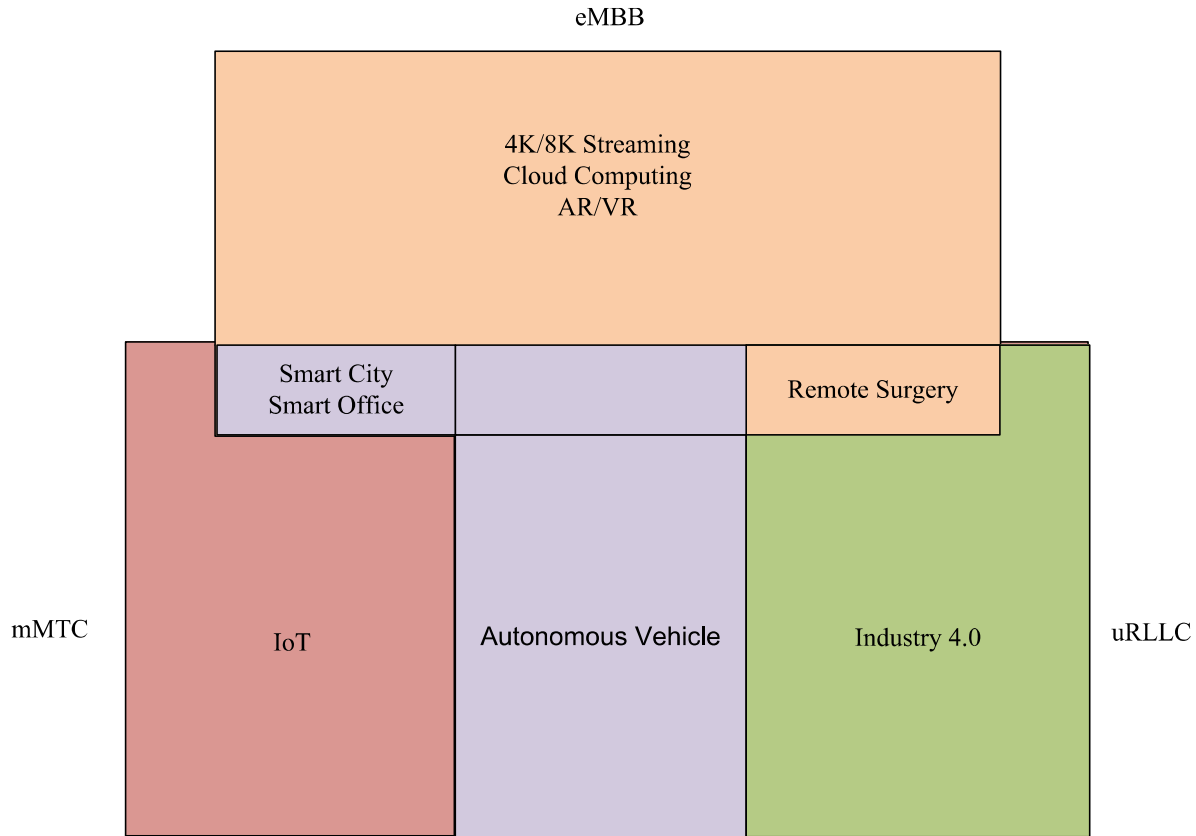
Here, an overview of the frequency bands that are predicted to be assigned to 5G

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communication systems, as well as a potential transition to a higher frequency band in the mmWave bandwidth, is summarized. For frequencies below 6 GHz, a maximum of 2.5 GHz of licenced bandwidth might be potentially assigned, with the largest part at 3.5 GHz. The Federal Communications Commission (FCC) [8] and the International Telecommunication Union-Radio (ITU-R) in World Radiocommunication Conferences (WRC) proceedings are responsible for spectrum management and allocation in the mmWave range in the United States [9]. For the 5G cellular network, many bands have been released at 28–30 GHz, 38–40 GHz, and the free-licensed band 57–64 GHz, which has been expanded to 71 GHz, with 14 GHz of continuous band, which is 15 times more than all of the Wi-Fi unlicensed spectrum [10]. Additionally, a 12.9 GHz band exists inside the E-band at 71–76 GHz, 81–86 GHz, and 92–95 GHz [11,12]. Ofcom [13] has announced the pioneer band centred at 26 GHz in the United Kingdom for future 5G usage between 24.25 and 27.5 GHz. China has considered 45 GHz frequency bands for licenced and unlicensed communications technologies and 5G. Moreover, licenced spectrum sharing might be applied in the 95–150 GHz region (LSA). This would allow mobile networks to utilise bandwidth that was initially provided for incumbent systems without affecting their operation. Considering that 1.177 MHz of the International Mobile Telecommunications (IMT) band is now in use, a 3 to 10x increase in allotted spectrum is anticipated by 2020 or later [14]. These bands may become available for 5G as a potential solution for increasing capacity over present LTE-A networks. Fig. 1.2 displays the potential 5G spectrum [15].

In recent years, there has been a significant rise in interest in wireless components and systems. Thus, present services utilise frequencies in the X-band and lower, making this area of the spectrum congested and exceeding its maximum capacity. The exponential increase in users and applications necessitates a shift to the Ku-band and above, where a large portion of the spectrum is accessible for new high-throughput applications. Commercial aircraft (Ku/Ka-band), satellite broadcasting reception in

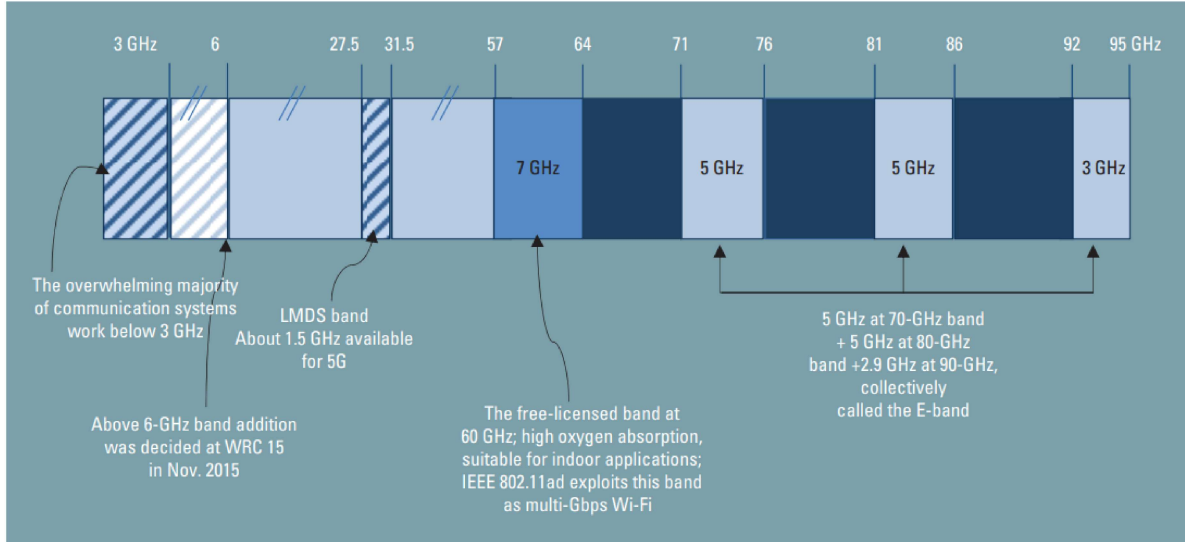
automobiles (Ku/Ka-band), high-rate interior communications (V band), automotive radars, and the new generation of wireless mobile networks are all examples of services that will soon be available in these higher frequency bands (ongoing research from Ka- to V-band). However, the introduction of these services is fraught with difficulties.



**Figure 1.1:** Three Major Cases of 5G Applications.

Wireless communications at high frequencies suffer not only from significant propagation losses but also material losses, which substantially degrade system performance. Because the copper thickness in printed circuits approaches the dimensions of the skin depth, conductor loss grows considerably. The use of hollow metallic waveguides, which offer unrivalled efficiency and high power handling capabilities, is a classic and well-mastered way of overcoming this difficulty. Nonetheless, they are heavy, large, and expensive to make. This is especially true at higher frequencies, when tolerances in the machining and assembly processes become rigid, necessitating the use of extra tuning

mechanisms to tune the performance after the manufacturing process. Metallic waveguide components are not good for general-purpose solutions because they are expensive and hard to make. Instead, they are mostly used in high-performance systems, which are often used in space or military applications.



**Figure 1.2:** mmWave candidate bandwidth for 5G.

At lower frequencies, antennas and microwave components often employ planar designs, which are typically realised using the Printed Circuit Board (PCB) fabrication technique. This developed technology leads to not only low-cost designs, but they can also be simply integrated with standard electrical components. However, because of the nature of these planar designs, they are not completely shielded, which makes them susceptible to radiation, cross-talk, and packaging difficulties. These disadvantages, along with the possibility of substantial conductor losses, make this technology unsuitable for implementing high-frequency complex structures such as massive feeding networks. As a result, a large performance gap exists between components based on metallic waveguides and those based on PCBs.

The Substrate Integrated Waveguide (SIW) technology, or, more broadly, the Substrate Integrated Circuit (SIC) architecture, is a very promising candidate for filling

this gap and providing widespread commercial solutions. This technology enables the fabrication of high-performance, low-cost, and reliable waveguide-like components by the use of planar processing methods such as PCB or Low-Temperature Co-fired Ceramic (LTCC). When using SIW technology, the top and bottom metallizations of the substrate are used to form the horizontal walls of the waveguide, while vias are drilled through the substrate and metallized to form the vertical walls. SIW technology may be used to implement many different types of antennas and other microwave devices that are generally made with metallic waveguides. Importantly, they retain the majority of the benefits of traditional waveguides (e.g., low conductor losses, minimal cross-talk, medium-high power handling capabilities) while retaining the benefits of planar technology (e.g., low-cost, light weight, easy integration).

## **1.1 Motivation of the Research Work**

An antenna is an important and necessary microwave component. It is the terminal component of any wireless communication system that works as a bridge between guided and unguided media by transmitting and receiving electromagnetic waves. Different types of antennas have been utilised in military, space applications, and daily life for decades, but technological improvements have changed their structure from basic wire-based radiating elements to current microstrip or SIW technology-based complex planar designs.

SIW technology is now being utilised as an alternative to microstrip-based planar microwave components. By embedding two rows of metallic posts through a dielectric substrate, SIW structures are created. These conducting posts connect the top and bottom metallic plates. SIW can be viewed as a bridge between traditional metallic waveguide structures and planar microstrip structures, as it possesses characteristics of both of these well-established technologies. SIW technology is also a strong contender for making low-profile cavity-backed planar antennas on low-cost substrates.

These antennas offer better radiation and power handling capacities than their microstrip counterparts [16]. Within the SIW cavity, apart from conventional modes, different hybrid modes can be excited by judiciously introducing various kinds of slots or shorting pins [14, 17]. It is very hard to excite multiple radiating modes at the right frequencies, because not all of the excited modes are necessarily radiating modes. The SIW cavity-backed slot antenna and the SIW self-diplexing antenna can replace the bulky, non-planar metallic cavity and waveguide-based antennas in several microwave and millimeterwave applications. The use of thin SIW cavity-backed slot antenna helps to implement high frequency microwave systems to be realised on a planar substrate, which may find application in automotive radar, sensor, and satellite communication applications as well as in 5G wireless communication applications.

With the fast advancement of modern wireless communication, there is a growing demand for high-speed communication systems with broad bandwidth performance. Researchers are focusing on making microwave and millimetre wave circuits so they can meet the needs of these high-performance communication systems.

In a traditional dual-band transceiver system, the received mixed signals are separated by a diplexer comprised of two filters with differing frequency characteristics. However, a self-diplexing antenna can split incoming signals due to its inherent isolation feature. Therefore, a self-diplexing antenna can eliminate the need for diplexers, which are not only difficult to build but also occupy a large amount of space [18]. Consequently, the deployment of self-diplexing antennas reduces the number of RF front-end system components. The most difficult aspect of constructing a successful self-diplexing antenna is designing it to provide consistent and strong isolation across the frequency spectrum while maintaining a low frequency ratio. Even though most microstrip-based self-diplexing antennas have multiple substrate layers and are therefore bulky, SIW technology has shown a way to make small self-diplexing antennas with a single resonator and a single substrate layer.

In the next several years, the data transmission rate must be multiplied numerous times due to the fast development in the number of users of cellular networks. On the other hand, the frequency bandwidth for commercial wireless communication is limited. Therefore, researchers are shifting towards multiple-input-multiple-output (MIMO) technology for the next generation of wireless communication since this technology enables a significant increase in data transfer rate while maintaining the same bandwidth and power level. However, one of the most difficult aspects of building a multiband MIMO antenna is maintaining the isolation between the antenna components, which must be below a particular threshold value concurrently throughout all the working bands. In general, the isolation mechanism for one operating band may not be applicable to the other working bands. Therefore, designing the appropriate decoupling networks for each of the communication frequency bands is a difficult issue. There are also other criteria for performance, like the envelope correlation coefficient, that must be below a certain threshold value.

## **1.2 Scope of Work**

From the motivation section, following scopes of designs are found.

- (i) Wideband SIW cavity-backed slot antennas.
- (ii) SIW based self duplexing / self triplexing antennas at multiple different frequency bands.
- (iii) MIMO antennas for higher data rate communication for satellite and 5G systems.

## **1.3 Objectives**

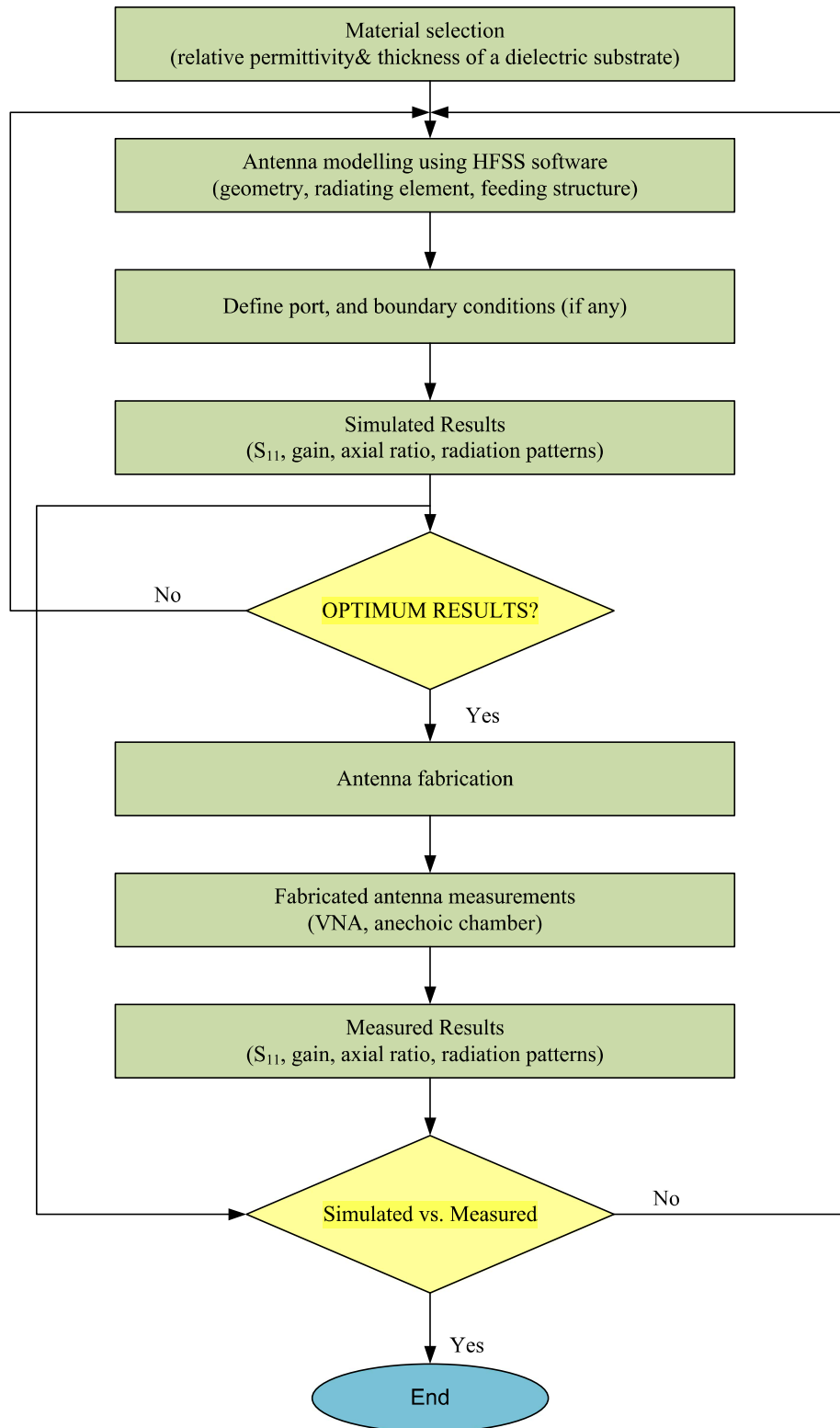
The major goal of this research work is to design a SIW based wideband antennas, self-multiplexing antennas and its corresponding MIMO prototype for supporting modern wireless applications supporting multiple frequency ranges and high data rates. This

has to be compact to get easily placed inside the compact wireless devices and good level of gain/efficiency within the operating frequency range. The major objectives of the current research work are as follows:

- (i) Design of substrate integrated waveguide cavity-backed wideband antenna with enhanced performance for 5G applications.
- (ii) Design and analysis of SIW cavity-backed self-diplexing (SDA) and self-triplexing slot antenna (STA) to reduce the bulky filter network.
- (iii) Design and development of a multiple-input-multiple-output (MIMO) antenna with an asymmetric cross-slot to obtain dual-band dual-circularly polarized operation for 5G applications.

## 1.4 Design Methodology

The process of designing an antenna comprises choosing an appropriate dielectric substrate to fabricate SIW structures. This step is part of the antenna design approach. When it comes to the design of an antenna, the thickness of the substrate and its relative permittivity are both extremely important factors. During the modelling process of an antenna with the help of a unit of commercial software such as high frequency simulation software (HFSS) ver. 19.0, the port and boundary conditions are specified. High Frequency Structure Simulator (HFSS) is a 3D electromagnetic (EM) simulation tool used to design a broad range of high frequency products such as antennas, filters, and IC packages. The numerical technique used in HFSS<sup>TM</sup> is the Finite Element Method (FEM). In this method a structure is subdivided into many small subsections called finite elements. In HFSS these finite elements are in the form of tetrahedra. The entire collection of tetrahedra constitutes the finite element mesh. A solution is found for the fields within these tetrahedra. These fields are interrelated so that Maxwell's Equations are satisfied across inter-element boundaries yielding a field solution for the entire original structure. Once the field solution is found, the generalized S-matrix



**Figure 1.3:** Flowchart of antenna design methodology.

solution is determined [19]. The methodology which is to be followed is as follows:

- (i) The design procedure starts with the design of a simple microstrip antenna. The simulation software that we use for the simulation is ANSYS Electronics Desktop ver. 19.0.
- (ii) Apply the wideband techniques to the antenna geometry (either on the radiating or ground plane or on both) to meet the frequency and size requirements.
- (iii) Examine the antenna characteristics such as  $S_{11}$ , input impedance, radiation patterns and gain/efficiency. For MIMO counterparts, parameters such as envelope correlation coefficient (ECC), diversity gain (DG), mean effective gain (MEG) and total adaptive reflection coefficient (TARC) are also studied.
- (iv) Study several techniques for obtaining multiband/wideband response in SIW for supporting modern wireless applications.
- (v) Lastly, in order to check the validity of the simulated design, antennas are fabricated. A comparison between the results of simulated and fabricated antennas is also performed.
- (vi) To show the applicability to common technology, the antennas must be intently designed for working at useful frequency bands. In addition to this, the radiation properties of the proposed antenna structures must be similar to those of common antenna systems.

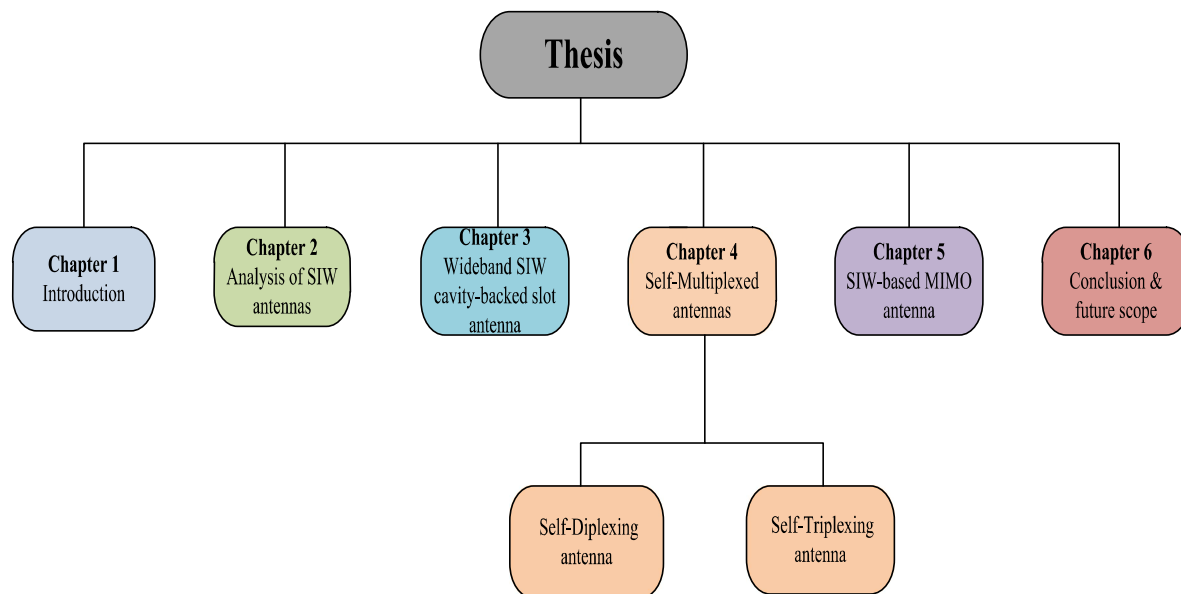
## 1.5 Organization of the Thesis

The thesis is divided into six chapters with **Chapter-1** as introduction, where the objective of the thesis is discussed. The motivation and organisation of the thesis have also been presented in this chapter. The rest of the thesis is organized as follows:

**Chapter 2:** This chapter provides a detailed discussion of designing SIW-based systems. The design rules to choose the dimension of the SIW are discussed. Next, the detailed literature review related to the research work is presented. The shortcomings

of the previously reported works, as well as the potential for further progress in those fields, are also discussed.

**Chapter 3:** The use of the high quality factor (Q) of the SIW cavity limits the bandwidth performance of the SIW cavity-backed slot antennas (CBSA). In this thesis, research to improve the band-width performance of the SIW CBSA is also extensively studied. This chapter deals with the design of the Substrate Integrated Waveguide Cavity-Backed Wideband Slot Antenna for 5G Applications. A SIW cavity-backed slot antenna with a U-shaped slot is proposed for bandwidth enhancement. An equivalent circuit model has also been developed to explain the working principle of the proposed antenna. Besides this, the proposed antenna can be an alternative for 5G and other wireless applications (including 27.50–28.28 GHz in Japan, 26.50–29.50 GHz in Korea, and 27.50–28.35 GHz in the USA).



**Figure 1.4:** A tree diagram of thesis.

**Chapter 4:** In this chapter, an interesting application of the SIW cavity-backed slot antenna is demonstrated. The proposed designs implement self-diplexing and self-triplexing slot antennas using SIW cavities, which can be directly connected to the RF front end system without using any bulky filter network. First, a dual-band dual-sense

circularly polarized self-diplexing SIW cavity-backed antenna with an elliptical slot for millimeter wave 5G applications has been developed. The generation of the perturbed cavity modes is also explained with the help of equivalent circuit analysis. Then, a self-triplexing SIW cavity-backed antenna with a non-linear replicated hybrid slot for C and X-band applications is proposed. The proposed SIW-based STA is the first of its kind in the literature where the concept of non-linear replication (NLR) is utilised for obtaining self-triplexed operation. The design is well explained with the help of an equivalent circuit diagram.

**Chapter 5:** To improve the overall throughput and increase the data rate, multiple-input multiple-output (MIMO) antennas are discussed as fifth part of the Thesis. A simple cavity-backed SIW based  $2 \times 1$  MIMO antenna with an asymmetric cross-slot (AXS) to obtain dual-band dual-circularly polarized operation is proposed. The unequal arm lengths of AXS and their angle of inclination are responsible for generating orthogonal modes and hence, CP with different sense of polarization in both operating frequency bands. Moreover, the isolation between the excitation ports is effectively adjusted by widening the center of AXS. Later, the proposed antenna structure is validated by the fabricated prototype shows a reasonable agreement between the simulated and measured results. The diversity performance of the proposed antenna is also studied and calculated using S-parameters and far-field results.

**Chapter 6:** Finally, this chapter concludes the thesis and also discusses future scope of the thesis to extend this work further in future.

This chapter begins with an overview of the developments and paradigm shifts in wireless technology. Afterwards, several wireless applications along with their frequency of operation are discussed. This explains the evolution and necessity of SIW-based wideband, multiplexing, and MIMO antennas, as well as the challenges that are driving current research. Further, problems with modern wireless devices and their possible solutions are discussed. There is a brief emphasis on the objectives and design method-

ology of the research work. In short, this chapter presents a comprehensive outline of the thesis. The fundamentals of SIW technology and a brief historical review based on SIW cavity-backed wideband slot antennas (SIW-CBWSA), SIW-based multiplexers, and SIW-based Multiple-Input Multiple-Output (MIMO) antennas are carried out in the next chapter.