

Chapter 1: Introduction

This chapter provides a comprehensive overview of Wireless Capsule Endoscopy (WCE) technology, highlighting its significance and current challenges. It then delves into the specific requirements and challenges associated with implantable/ingestible antenna design and RF rectifier design. Additionally, it introduces the concept of Characteristic Modal Analysis (CMA) as a powerful tool for antenna optimization. Finally, the chapter clearly outlines the research motivation, objectives, and roadmap for the subsequent chapters. By addressing the aforementioned limitations, this research endeavours to significantly advance WCE technology, unlocking its full potential for enhanced diagnosis and improved patient care.

1.1 Wireless Capsule Endoscopy

The human gastrointestinal (GI) tract is one of the most complex and abstruse parts of the human body. Extending from the mouth to the anus, it is approximately 30 feet long (9 meters). To navigate this intricate system, medical professionals use a revolutionary device known as the Wireless Capsule Endoscopy (WCE) [1-6]. WCE is a small, pill-like device that is swallowed by the patient. As it travels through the GI tract, it captures detailed images that are transmitted wirelessly to an external receiver for later analysis. This non-invasive method of endoscopy has several advantages over traditional endoscopy procedures. It provides full-length coverage of the GI tract, from the esophagus to the colon, which is not possible with traditional endoscopy [7-8]. Moreover, it offers high diagnostic accuracy, making it a valuable tool in the detection and diagnosis of various GI diseases.

1.1.1 Background and Evolution of Capsule Endoscopy

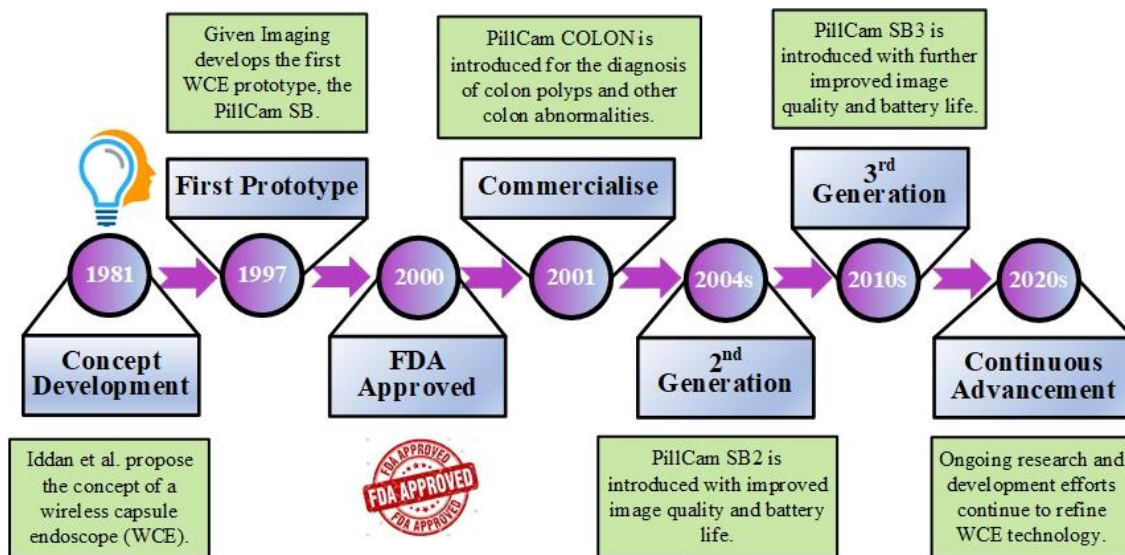


Fig. 1.1: Evolution of Capsule Endoscopy: A Timeline of Innovation

The evolution of capsule endoscopy can be visualized through a comprehensive timeline, as depicted in Fig.1.1: "Evolution of Capsule Endoscopy: A Timeline of Innovation."

This diagram encapsulates the key phases in the development of wireless capsule endoscopy (WCE) technology.

The timeline can be broadly categorized into three main phases:

1. Concept Development (1981-1997):

- In 1981, Israeli scientists Gavriel Iddan and David Goren proposed the revolutionary concept of a wireless capsule endoscope (WCE). This small, pill-sized device integrates a camera and other sensors, offering a non-invasive means of capturing images within the digestive tract [1].
- The patient swallows the WCE, and as it travels through the digestive tract, images are taken and transmitted to a recorder worn by the patient, typically attached to their belt [9-10].

2. Commercialization (2000-2010):

- The pivotal phase of commercialization began in 2000 with the approval of the first WCE, the PillCam SB, by the US Food and Drug Administration (FDA). Primarily designed for diagnosing diseases of the small intestine, such as Crohn's disease and celiac disease, the PillCam SB marked a significant milestone [11-12].
- In 2004, the PillCam COLON was introduced, specifically tailored for the diagnosis of colon polyps and other abnormalities in the colon.

3. Continuous Advancement (2010-Present):

- Post-2010, the field of capsule endoscopy has witnessed a continuous stream of advancements in technology [13-16].

- Ongoing innovations include the development of smaller capsules, improvements in image quality, and longer battery life.
- Some newer capsules boast additional features, such as the capability to measure temperature and pH levels within the digestive tract.

This timeline underscores the transformative journey of capsule endoscopy, from its conceptualization by Iddan and Goren to its current state of advanced diagnostic capabilities.

1.1.2 Significance in Medical Practice

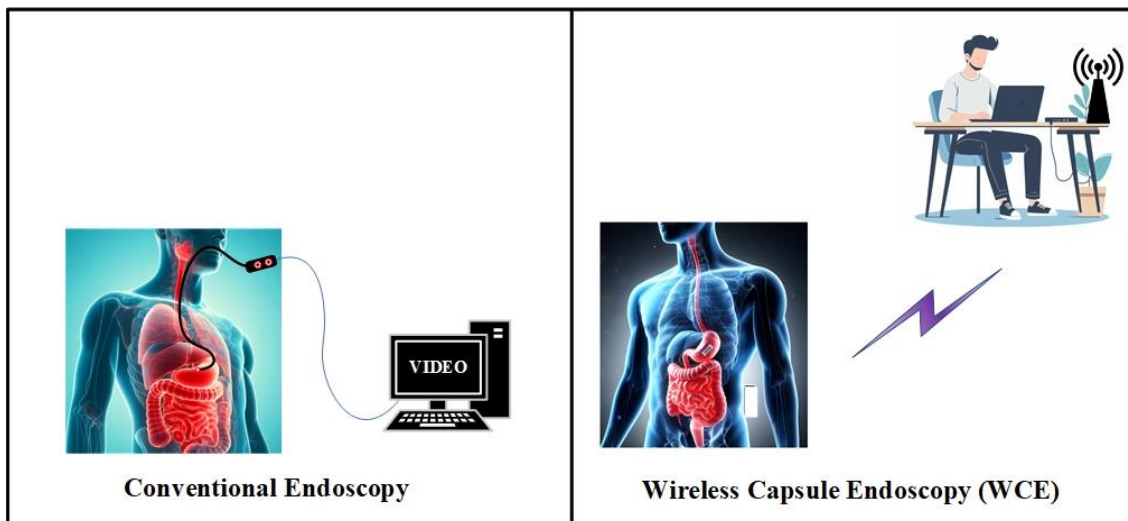


Fig. 1.2: Methodological Comparison in GI Imaging (AI-generated base, edited in Microsoft Visio).

A comparative illustration in Fig. 1.2 depicts the divergent approaches in gastrointestinal imaging—traditional endoscopy (left) versus the non-invasive Wireless Capsule Endoscopy (WCE) technique (right). WCE has demonstrated remarkable efficacy in diagnosing and monitoring various GI diseases. Its unparalleled capability in detecting elusive conditions, especially obscure gastrointestinal bleeding, addresses challenges faced by traditional methods. Additionally, WCE plays a vital role in diagnosing Crohn's disease, celiac disease, tumors, cancers, ulcers, and infections [7].

However, the integration of WCE into medical practice is not without challenges. While the device cost is decreasing, it remains a hurdle for many patients. Limited accessibility due to constrained availability in medical facilities adds to the challenges. Interpretation of WCE images demands specialized training, making it a time-consuming process. Risks, such as capsule retention in the GI tract, further highlight complexities. Ethical considerations, including patient privacy and informed consent, underscore the need for a balanced and responsible deployment of this advanced technology.

The transformative potential of WCE in GI diagnostics is evident. Overcoming these challenges positions WCE as a cutting-edge tool, redefining how we approach the diagnosis and monitoring of gastrointestinal conditions. Its non-invasive nature and high diagnostic accuracy make it invaluable in modern medicine. As advancements continue and challenges are addressed, WCE stands at the forefront of innovative practices, poised to shape the future landscape of GI diagnostics.

1.2 Implantable and Ingestible Antenna Design: Requirements and Challenges

As a critical component of wireless capsule endoscopy, implantable antennas play a pivotal role in facilitating communication within the human body. The intricate nature of this application necessitates a comprehensive understanding of the requirements and challenges associated with implantable antenna design. In this section, we delve into the multifaceted landscape of implantable antenna design, exploring the essential requirements that guide their development and the formidable challenges that researchers and designers must address.

1.2.1 Requirements for Implantable Antenna Design

❖ Biocompatibility

One of the fundamental prerequisites for implantable antennas is biocompatibility. The materials chosen for these antennas must seamlessly integrate with the human body, ensuring that the presence of the antenna does not elicit adverse reactions. Biocompatibility is not only about material compatibility but extends to the overall impact of the antenna on the physiological environment, emphasizing the need for unobtrusive and safe integration.

❖ Size Constraints

Miniaturization is a central challenge in implantable antenna design. The size constraints imposed by the human body demand antennas that are scaled down to fit within confined spaces without causing discomfort or hindering normal bodily functions. Striking a delicate balance between size and functionality is crucial, as the success of wireless capsule endoscopy depends on the unobtrusive presence of these miniaturized antennas.

❖ Frequency Bands

The landscape of frequency bands crucial to implantable antenna design is intricately regulated by the Federal Communications Commission (FCC), each serving distinct purposes within the realm of medical communication. One pivotal category is the Medical Device Radio Communication Service (MedRadio), comprising sub-bands spanning from 401 to 457 MHz. This spectrum is dedicated to supporting low-power, low-data-rate telemetry, facilitating the monitoring of vital signs and the transmission of data to external devices. The specificity of these sub-bands caters to the nuanced requirements of medical applications, ensuring efficient and reliable communication within this designated frequency range.

Table 1.1: FCC Regulations for Medical Device Frequencies and Power Limits

| Band | Frequency | Maximum EIRP | Description |
|---|---|----------------------------|---|
| Medical Device Radio Communication Service (MedRadio) | 401 – 406 MHz 413 – 419 MHz 426 – 432 MHz 438 – 444 MHz 451 – 457 MHz | -16 dBm (25 μ W) | Sub-bands used for low-power, low-data-rate telemetry for monitoring vital signs (e.g., heart rate, temperature) and sending data to external devices in medical implant communication systems. |
| Medical Implant Communication Service (MICS) | 402-405 MHz | -16 dBm (25 μ W) | Narrowband, low-power, low-data-rate telemetry for monitoring vital signs and sending data to external devices. |
| Wireless Medical Telemetry Service (WMTS) | 608-614 MHz 1395-1400 MHz 1427-1432 MHz | -36 dBm (0.25 μ W) | Sub-bands used for low-power, low-data-rate telemetry applications, such as monitoring vital signs. |
| Industrial, Scientific, and Medical (ISM) bands | 2400- 2500 MHz | 20 dBm (100000 μ W) | Various medical applications, including telemetry, and data communication. |

A closely related category is the Medical Implant Communication Service (MICS), operating in the frequency range of 402-405 MHz. MICS is characterized by its narrowband nature, facilitating low-power, low-data-rate telemetry specifically designed for monitoring vital signs. This allocation reflects the careful consideration given to the unique demands of medical implant devices, where precision and energy efficiency are paramount.

The Wireless Medical Telemetry Service (WMTS) extends the regulatory framework with sub-bands at 608-614 MHz, 1395-1400 MHz, and 1427-1432 MHz. These sub-bands are strategically earmarked for low-power, low-data-rate telemetry applications, emphasizing their significance in monitoring vital signs within the medical context. The

deliberate allocation of frequency ranges within WMTS highlights the FCC's commitment to ensuring interference-free communication for medical devices, contributing to the reliability and effectiveness of these technologies.

Furthermore, the Industrial, Scientific, and Medical (ISM) bands, spanning 2400-2500 MHz, form a versatile category supporting various medical applications. Telemetry and data communication find a home within this spectrum, demonstrating the flexibility and adaptability of these bands for different purposes in the medical domain. The 20 dBm Maximum Equivalent Isotropically Radiated Power (EIRP) limit set by the FCC for the ISM bands ensures a balance between robust communication capabilities and adherence to safety standards. The FCC's meticulous regulation of frequency bands plays a pivotal role in shaping the landscape of implantable antenna design for medical devices. Each allocated band serves a unique purpose, reflecting the diverse communication needs within the medical field, while stringent power limits safeguard against interference and promote the safe and effective operation of these devices.

❖ **Bandwidth**

Implantable antennas must provide ample bandwidth to accommodate the diverse data streams encountered within the human body. The challenges posed by the internal environment necessitate antennas with broad bandwidth, allowing for the seamless transmission of data relevant to medical diagnostics. A wide bandwidth is a key factor in ensuring the reliability and efficiency of communication within the body.

❖ **Radiation Performance**

The internal environment of the human body presents a challenging backdrop for implantable antennas. Despite the complexities, these antennas must exhibit efficient radiation performance to transmit and receive signals effectively. The radiation

characteristics of implantable antennas are critical for capturing high-quality medical data, making radiation performance a non-negotiable requirement for their successful deployment.

1.2.2 Challenges in Implantable Antenna Design

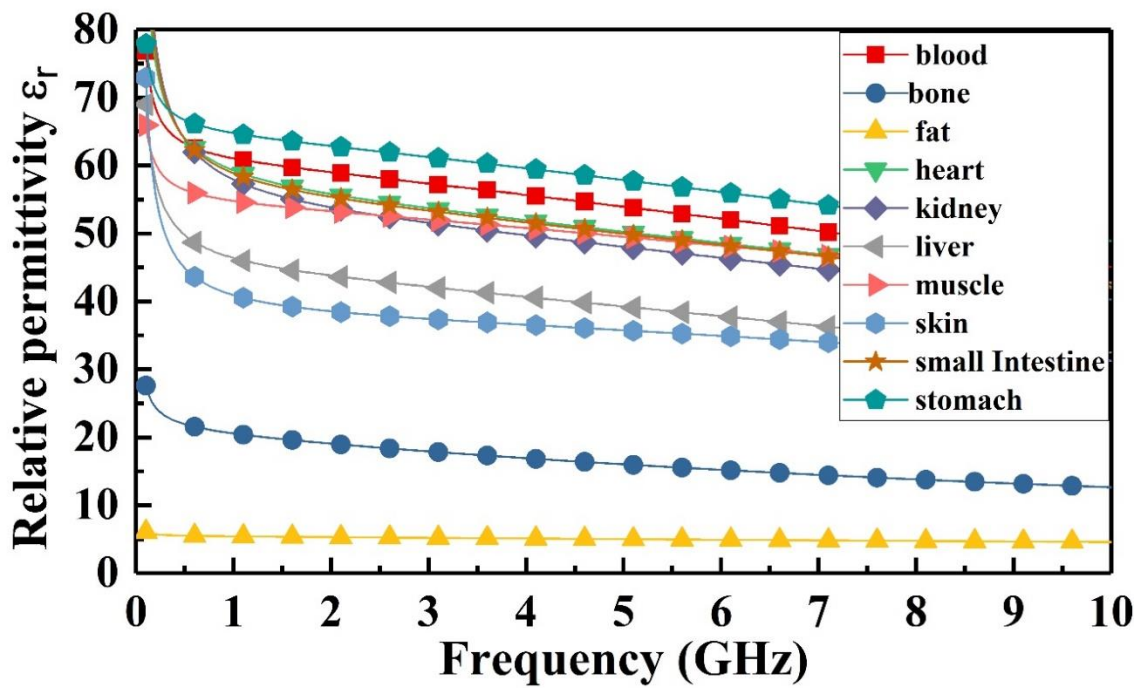
❖ Lossy Media

Human tissues, characterized by high levels of signal absorption and reduced antenna gain, introduce a significant challenge in implantable antenna design. Mitigating signal loss while maintaining signal integrity becomes a critical consideration. Researchers and designers must explore innovative strategies to overcome the inherent losses associated with the highly absorptive nature of human tissues.

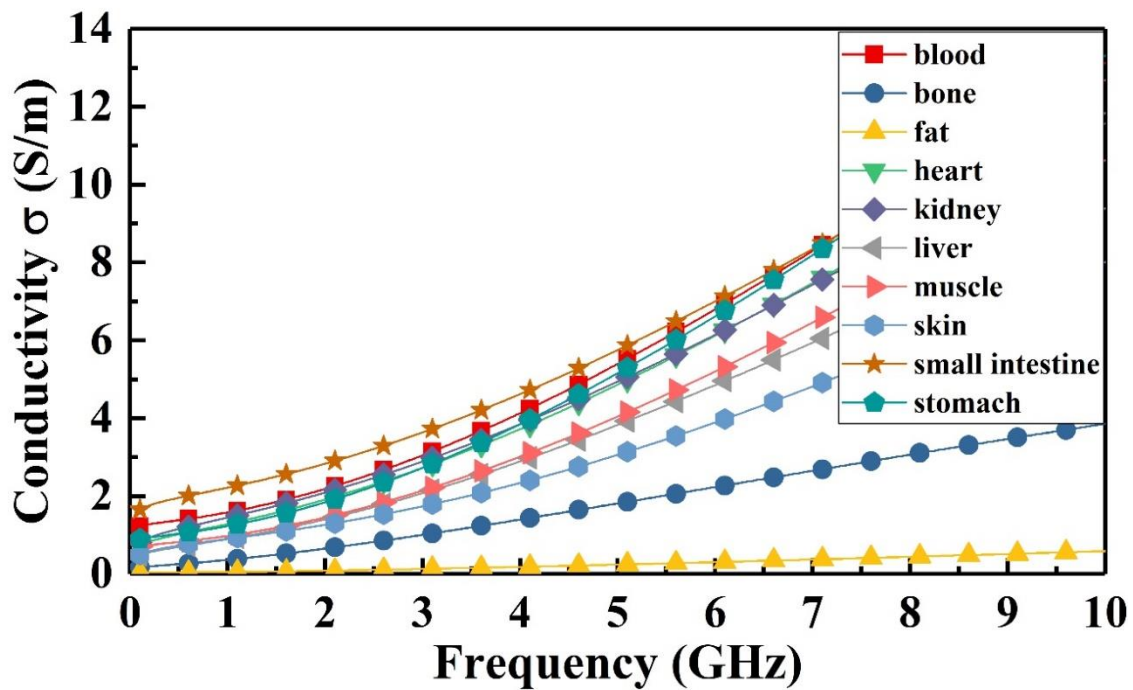
❖ Variability in Tissue Properties

The human body is characterized by significant variability in tissue properties, encompassing parameters such as permittivity and conductivity. This inherent diversity in tissue characteristics poses a substantial challenge in the design of antennas, particularly in the context of biomedical applications. Antennas utilized in medical devices must navigate the dynamic and distinctive electromagnetic properties exhibited by various tissues within the human body.

Engineers and designers face a formidable task in developing antennas that can not only accommodate but also adapt to the wide-ranging electromagnetic properties inherent to different tissues. The dynamic nature of tissues, coupled with variations in permittivity and conductivity, necessitates antenna designs that can flexibly respond to the unique electromagnetic environment encountered during medical procedures.



(a) Relative Permittivity



(b) Conductivity

Fig. 1.3: Relative permittivity and conductivity of different human tissues over frequency

Figure 1.3 provides a visual representation of the relative permittivity and conductivity of diverse human tissues across different frequencies. This graphical depiction aids in understanding the intricate variations in electromagnetic properties encountered by antennas within the human body. The variations illustrated in the figure underscore the complexity that antenna designers must grapple with to ensure optimal performance in diverse medical scenarios.

Accommodating this variability in tissue properties is crucial for the effectiveness of medical devices utilizing antennas. It requires a nuanced approach in antenna design, considering the specific electromagnetic characteristics of tissues relevant to the targeted medical application. The challenges posed by this variability drive ongoing research and innovation in antenna design, aiming to enhance adaptability and performance across the spectrum of tissue properties encountered in the human body.

❖ **Movement and Posture Changes**

The dynamic nature of the human body, characterized by constant movement and posture changes, introduces challenges for implantable antenna performance. Antennas must be designed to retain optimal functionality despite shifts in position, ensuring continuous and reliable data transmission during activities such as walking, bending, or changes in posture. This dynamic adaptability is essential for the effectiveness of implantable antennas.

❖ **Patient Safety (SAR)**

Patient safety is of utmost importance when designing implantable antennas, and managing the Specific Absorption Rate (SAR) is a critical aspect of this process. SAR, a critical metric used to assess the absorption of radiofrequency (RF) energy by human tissues, represents the amount of RF power absorbed per unit mass of tissue.

Mathematically expressed as $SAR = \Delta W / \Delta t \times 1/m$, where ΔW represents absorbed RF power, Δt is the exposure time, and m is the tissue mass. Upholding safety standards demands strict adherence to guidelines such as IEEE C95.1-2019 for 10g tissue (requiring SAR averaged over 10 g of tissue must be less than 2 W/kg) and IEEE C95.3-2021 for 1g tissue (average SAR over any 1-gram cube of tissue should not exceed 1.6 W/kg). These standards, endorsed by the FCC in the US and ICNIRP globally, establish stringent limits for RF exposure, ensuring the well-being of patients.

The intricate process of implantable antenna design requires meticulous consideration of SAR limitations, often prompting adjustments in antenna geometry, material selection, and simulation methodologies to ensure an even distribution of energy. The IEEE C95.1-2019 standard, specifically tailored for human exposure to RF electromagnetic fields, sets limits for the specific absorption rate in tissues, thereby safeguarding against potential health risks. Simultaneously, IEEE C95.3-2021 provides guidelines for protecting the general public from exposure to electric, magnetic, and electromagnetic fields. Integrating these standards into the design process enables implantable antennas not only to meet medical requirements but also to adhere to rigorous safety measures, underscoring a dedicated commitment to patient safety in the dynamic landscape of medical technology.

1.3 RF Rectifier Design: Requirements and Challenges

1.3.1 Requirements for RF Rectifier Design

❖ High Efficiency

One of the foremost requirements for RF rectifiers is high efficiency. This parameter is crucial for maximizing the power transferred from the RF source to the load, particularly in energy harvesting applications where power availability is often limited[17-20].

Achieving high efficiency ensures that the system can make the most of the available RF power for sustained operation.

❖ **Low Input Power Operation**

Given the prevalence of low-power scenarios in WPT and EH systems, RF rectifiers must operate efficiently at low input powers [21-24]. This becomes especially pertinent for ultra-low-power devices common in sensor networks and the Internet of Things (IoT). The ability to extract usable power from weak RF signals is instrumental in extending the operational lifespan of these devices.

❖ **Wide Bandwidth Operation**

The variable nature of RF signals in WPT and EH applications demands that RF rectifiers operate over a wide bandwidth. This accommodates the diverse frequencies used for wireless power transfer and energy harvesting, accounting for fluctuations in signal frequency based on factors such as distance and obstacles between the transmitter and receiver [25-27].

❖ **Compact Size and Lightweight Design**

In applications like wearable and implantable devices, the size and weight of the RF rectifier play a pivotal role. To minimize the overall size and weight of WPT or EH systems, RF rectifiers should be designed to be small and lightweight. This enhances the feasibility and comfort of integrating these systems into devices that interact closely with the human body.

1.3.2 Challenges in RF Rectifier Design

❖ **Achieving High Efficiency**

While high efficiency is a requirement, achieving it over a wide bandwidth and at low input powers poses a considerable challenge. Factors such as the diode threshold voltage

and other inherent characteristics can impede efficiency, especially when dealing with low input powers.

❖ **Overcoming Diode Threshold Voltage**

Diodes, fundamental components in RF rectifiers, present a challenge due to their threshold voltage. This minimum voltage required for diode conduction poses efficiency challenges at low input powers. Designers must grapple with strategies to overcome or mitigate the impact of diode threshold voltage on overall efficiency.

❖ **Impedance Matching Complexity**

To maximize power transfer, the impedance of the RF rectifier must align with that of the antenna and load. Achieving this impedance matching, especially over a wide bandwidth, poses a significant challenge. Designers must navigate complex impedance landscapes to optimize power transfer efficiency.

❖ **Mitigating Harmonic Generation**

Diodes, while essential for rectification, introduce the challenge of harmonic generation. Harmonics of the input RF signal can decrease efficiency by diverting power away from the desired DC conversion [28-29]. Effectively mitigating harmonic generation is crucial for maintaining high overall system efficiency.

1.4 Characteristic Modal Analysis (CMA) in Antenna Design

1.4.1 Introduction to Characteristic Modal Analysis (CMA)

Characteristic-mode analysis (CMA) is a method to study the natural current patterns and radiation characteristics of arbitrary structures. It provides physical insight and enables a deterministic design approach for antennas and scatterers.

Characteristic modal analysis (CMA) is a powerful technique for studying the resonant behaviour of antennas and scatterers. It is based on the concept of characteristic modes, which are the natural modes of a structure that can be excited by any arbitrary source. The characteristic modes form an orthogonal set of currents on the surface of the structure and an orthogonal set of fields in the far-field region. Each characteristic mode has an associated eigenvalue that indicates its resonant frequency and bandwidth.

CMA was first proposed by Garbacz and Turpin in 1965, who derived the eigenvalue equation for the characteristic modes of perfectly electric conducting (PEC) bodies [30-31]. They showed that the characteristic modes form an orthogonal set of surface currents over the PEC body, and the corresponding characteristic fields form an orthogonal set of radiated fields over the far-field sphere. The eigenvalues of the characteristic modes indicate the modal significance and the modal quality factor, which are important parameters for antenna performance evaluation. Since then, CMA has been refined and developed by numerous researchers, including R.F. Harrington and J.R. Mautz, who introduced the eigenvalue equation for characteristic modes in 1971.

1.4.2 Principles of Characteristic Modal Analysis (CMA)

At its core, CMA is founded on the principle that the electromagnetic fields within an antenna structure can be represented by a set of orthogonal modes. Each mode possesses distinct resonant frequencies, radiation patterns, and field distributions, all dictated by the structure's geometry and electrical properties. By solving an eigenvalue problem for the antenna structure, CMA determines resonant frequencies and field distributions, offering a comprehensive solution for antenna designers [32].

Performance Matrix as Eigenvalues, Characteristic Angle, and Modal Significance Values with their Physical Significance

❖ Eigenvalues

The physical interpretation of the eigenvalues can help to classify the characteristic modes into three types: resonant, inductive, and capacitive. The resonant modes have zero eigenvalues and balanced electric and magnetic field energies. They are associated with the natural resonances of the PEC body and can produce strong radiation. The inductive modes have negative eigenvalues and dominant magnetic field energies. They are associated with the inductive coupling of the PEC body and can produce weak radiation [33-37]. The capacitive modes have positive eigenvalues and dominant electric field energies. They are associated with the capacitive coupling of the PEC body and can produce weak radiation.

Mode classification: Depending on the sign of the eigenvalue, we can classify the mode into different types:

- Resonant mode: When $\lambda_n = 0$, the stored magnetic and electric field energies are equal. This means the mode is at resonance and has the highest radiation efficiency.
- Inductive mode: When $\lambda_n < 0$, the stored magnetic field energy is larger than the electric field energy. This means the mode is inductive and has a lower radiation efficiency than the resonant mode.
- Capacitive mode: When $\lambda_n > 0$, the stored electric field energy is larger than the magnetic field energy. This means the mode is capacitive and has a very low radiation efficiency.

❖ Modal significance

Modal significance is a measure of how much a characteristic mode contributes to the total radiated power of an antenna or scatterer. Modal significance is proportional to the square of the modal excitation coefficient, which depends on the source distribution and the modal current. Modal significance can be used to identify the dominant modes that determine the radiation characteristics of an antenna or scatterer, such as the resonant frequencies, bandwidth, directivity, and polarization.

Modal significance (MS): A parameter that indicates how well a characteristic mode (CM) can be excited by an external source and how much it contributes to the radiation of an antenna structure.

$$MS = \frac{1}{1 + j\lambda_n} \quad (1.1)$$

Where λ_n is the eigenvalue of the nth CM.

- Resonance condition: A CM is considered to be resonant when MS is close to 1, which means λ_n is close to 0. This implies that the CM has low reactance and high radiation efficiency.
- Threshold for MS: A CM is considered to be significant for radiation when MS is greater than 0.6, which means λ_n is less than 0.75. This implies that the CM has moderate reactance and acceptable radiation efficiency.

❖ Characteristic angle

The characteristic angle is defined as the angle between the modal electric field and the modal current on the surface of the PEC body. It indicates the reactive or resistive nature of the characteristic mode. A characteristic angle of 0° or 180° means the mode is purely

resistive, while a characteristic angle of 90° or 270° means the mode is purely reactive. The characteristic angle can also be used to determine the optimal feeding position and orientation for exciting a desired mode. Generally, a mode can be efficiently excited when the feeding current is aligned with the modal current and the feeding electric field is perpendicular to the modal electric field. Therefore, the characteristic angle can help to design the feeding structure for a PEC antenna based on the CM theory.

1.5 Motivation and Research Objectives

1.5.1 Motivation

In an era where medical technology is advancing at an unprecedented pace, there is an unrelenting quest for innovative solutions to enhance the diagnosis, monitoring, and treatment of a wide range of medical conditions. One of the most transformative domains within the field of medical electronics is wireless capsule endoscopy (WCE), offering a minimally invasive and patient-centric approach to visualizing the gastrointestinal tract. The motivation for this PhD thesis, "Design and Development of Dual-Band Antenna and Rectifier System for Wireless Capsule Endoscopy," is firmly rooted in addressing pressing challenges within the realm of wireless ingestible capsule technology.

Wireless capsule endoscopy, since its inception, has played a pivotal role in reshaping the field of gastroenterology. It provides a non-invasive and painless avenue for inspecting the interior of the gastrointestinal tract, delivering invaluable insights for clinicians in the detection and diagnosis of conditions such as Crohn's disease, ulcerative colitis, and gastrointestinal bleeding. However, despite its immense potential, WCE technology is accompanied by a series of constraints and limitations, serving as the impetus for this research.

❖ **Challenges in Wireless Capsule Endoscopy**

Conventional wireless capsules deployed for endoscopic examinations are constrained by their design, operational range, and energy harvesting capabilities. These constraints present notable challenges that impede the widespread adoption of wireless capsule endoscopy in clinical practice.

- 1. Bandwidth Limitation:** The utilization of a single band for wireless communication within capsule endoscopy restricts data transmission rates and the capacity to deliver high-resolution images. The integration of a dual-band antenna system offers an opportunity to broaden the data-carrying capacity, thereby enhancing the diagnostic value of the procedure.
- 2. Energy Harvesting:** Capsule endoscopy relies on batteries for power, which curtail the operational lifespan of the capsule. The development of an efficient rectifier system capable of harnessing energy from the body's RF environment allows for extended capsule operation, potentially enabling real-time monitoring and prolonged examination periods.
- 3. Miniaturization and Biocompatibility:** The design and development of capsule technology necessitate a delicate equilibrium between miniaturization, efficiency, and biocompatibility. The development of a compact dual-band antenna system and an efficient rectifier technology is critical for minimizing the capsule's size while maximizing its performance.
- 4. Regulatory Compliance and Patient Safety:** Ensuring that wireless capsule endoscopy systems conform to regulatory guidelines, particularly in relation to Specific Absorption Rate (SAR) limits, is imperative for patient safety. This research seeks to address safety concerns while preserving optimal system performance.

❖ **Advancing Capsule Endoscopy Through Dual-Band Antennas and Rectifiers**

The motivation for this PhD thesis is deeply entwined with the aspiration to confront these challenges head-on and augment the capabilities of wireless capsule endoscopy. The crux of this endeavour lies in the development of a dual-band antenna system. By enabling the capsule to operate in both the 1.4 GHz Wireless Medical Telemetry Services (WMTS) band and the 2.45 GHz Industrial, Scientific and Medical (ISM) band, this research aims to expand the bandwidth available for data transmission. The capacity to capture and transmit high-resolution images and video in real time has the potential to significantly enhance the diagnostic potential of capsule endoscopy.

Furthermore, the design and development of an efficient dual-band rectifier system hold immense promise in improving the operational efficiency of wireless capsules. By harvesting RF energy from the surrounding environment, the capsule can potentially extend its operational time, thus allowing for more comprehensive examinations and data collection. Such advancements have the potential to elevate wireless capsule endoscopy from its current diagnostic role to real-time monitoring, a capability with profound implications for healthcare.

❖ **Biocompatibility and Patient Safety**

One of the central considerations in this research is to ensure that technological advancements do not come at the expense of patient safety or biocompatibility. The motivation to adhere to SAR limits and other regulatory guidelines underscores our unwavering commitment to the well-being of patients undergoing capsule endoscopy. Achieving a harmonious equilibrium between technical innovation and patient safety is a fundamental objective of this research.

❖ **Relevance and Impact**

The impact of this research transcends technological innovation; it is intrinsically linked to improving healthcare outcomes. Wireless capsule endoscopy has already made substantial contributions to the early detection of gastrointestinal diseases and the reduction of invasive procedures. This research seeks to amplify these contributions by addressing technological limitations, thus making capsule endoscopy more accessible and effective.

The impact of this research is multifaceted. It aligns with broader healthcare goals of mitigating patient discomfort, facilitating early disease detection, and enhancing the quality of medical data acquired during endoscopic examinations. Ultimately, the motivation for this PhD thesis is to drive technological advancements in wireless capsule endoscopy, ushering in a new era of patient-centric, minimally invasive healthcare.

In conclusion, the motivation for this PhD thesis is deeply rooted in the commitment to advancing medical technology and enhancing the lives of patients. By addressing the limitations of existing wireless capsule endoscopy systems through the development of dual-band antennas and rectifiers, this research aspires to transform the landscape of gastroenterological diagnostics. The pursuit of innovation in wireless capsule endoscopy is not solely technological; it is a commitment to enhancing the healthcare experience, enabling early disease detection, and contributing to the well-being of individuals worldwide. This motivation serves as the guiding light in the journey outlined in this thesis, and it is the driving force behind our mission to improve medical outcomes.

1.5.2 Research Objectives

This PhD thesis, titled "Design and Development of Dual-Band Antenna and Rectifier System for Wireless Capsule Endoscopy," outlines a comprehensive set of research

objectives aimed at advancing the state of wireless capsule endoscopy technology, addressing its existing limitations, and improving the quality of patient care. The primary research objectives are as follows:

- 1. Dual-Band Antenna Development:** The principal objective is the design, development, and implementation of a dual-band antenna system, operating at both the 1.4 GHz Wireless Medical Telemetry Services (WMTS) band and the 2.45 GHz Industrial, Scientific, and Medical (ISM) band. This entails optimizing the antenna for efficiency, miniaturization, and biocompatibility while maintaining exceptional performance.
- 2. Efficient Energy Harvesting:** Another core objective is the creation of an efficient dual-band rectifier system for RF energy harvesting. This technology aims to extend the operational lifespan of wireless capsules by efficiently harnessing RF energy from the surrounding environment.
- 3. Safety and Regulatory Adherence:** Ensuring patient safety and regulatory compliance, particularly with regard to Specific Absorption Rate (SAR) limits, is a critical objective. The research seeks to establish design parameters that adhere to safety regulations.
- 4. System Integration and Testing:** An essential research objective is the successful integration of the dual-band antenna and rectifier system into a functional wireless capsule endoscopy platform. Rigorous testing and validation are imperative to assess the system's performance in real-world scenarios.
- 5. Comparative Analysis and Diagnostic Advancement:** The research aims to conduct a comprehensive comparative analysis between the proposed technology and

existing capsule endoscopy systems, showcasing advancements in diagnostic capabilities, data transmission rates, and energy efficiency.

6. Clinical Relevance and Patient-Centric Healthcare: The ultimate objective is to translate technological advancements into tangible clinical benefits. The research aspires to foster patient-centric healthcare by improving diagnostic accuracy, patient comfort, and the ability to conduct real-time monitoring, thus significantly impacting gastroenterological diagnostics and patient care.

1.6 Thesis Roadmap

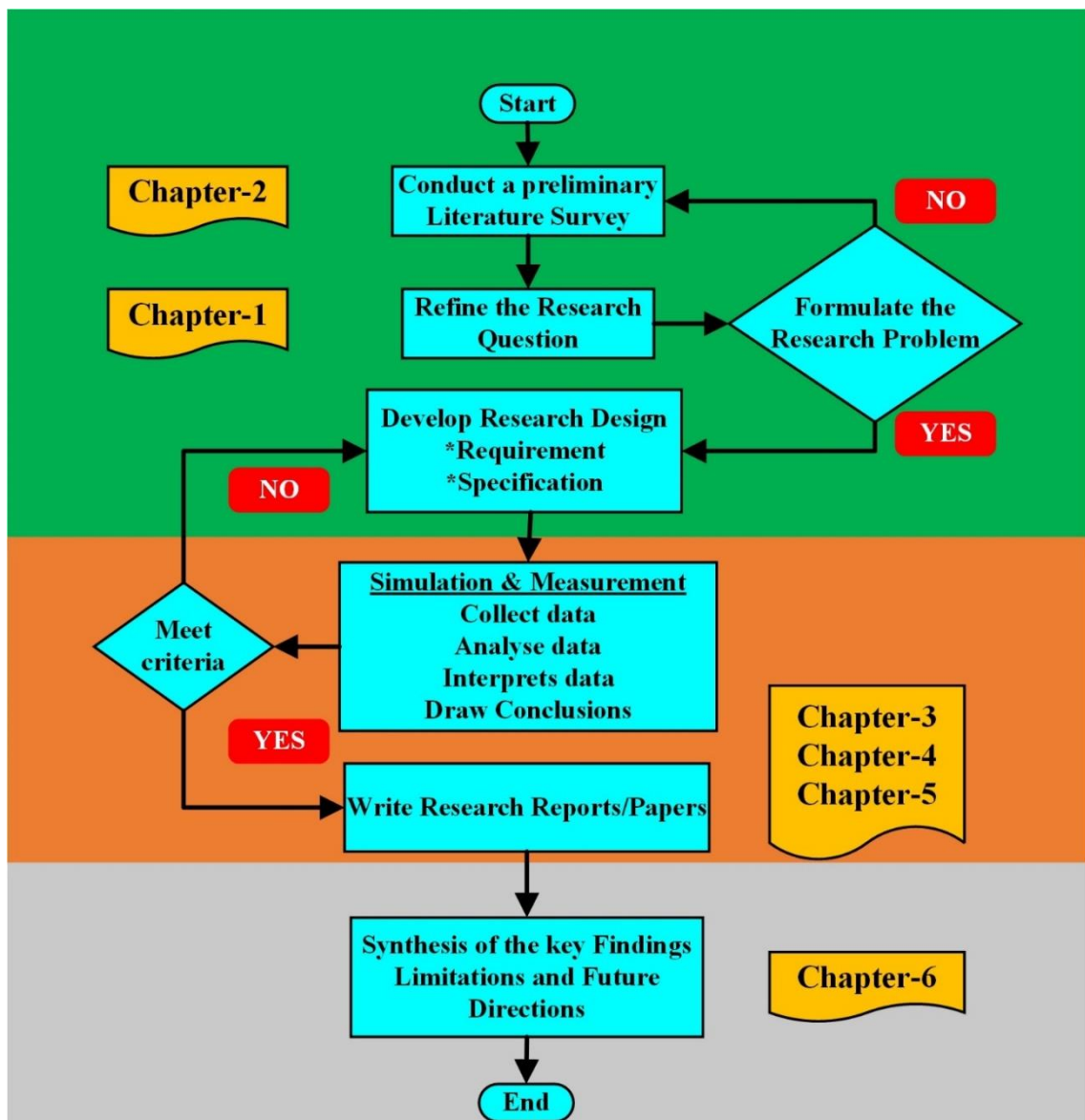


Fig. 1.4: Flow chart of thesis roadmap

The flow diagram in Figure 1.4 shows how the different chapters of the thesis are interconnected to provide a comprehensive and logical presentation of the research objectives, methodologies, findings, and their implications in the field of wireless capsule endoscopy (WCE).

This PhD thesis, titled "Design and Development of Dual-Band Antenna and RF Rectifier System for Wireless Capsule Endoscopy," is structured to provide a comprehensive exploration of the research objectives, methodologies, findings, and their implications in the field of wireless capsule endoscopy.

Chapter 1: Introduction

The first chapter serves as the gateway to the thesis, setting the stage for the entire research endeavour. It commences with an introduction to the field of wireless capsule endoscopy and the critical need for technological advancements in this domain. The chapter lays out the motivation behind the research, identifying key limitations and underscoring the potential for the proposed dual-band antenna and rectifier system to bridge these gaps. It introduces the research objectives and outlines the structure of the thesis. This chapter serves as a foundation, providing readers with a clear understanding of the purpose and significance of the research.

Chapter 2: Literature Review

The second chapter delves deep into a comprehensive review of relevant literature, offering a panoramic view of existing knowledge and research in the field of wireless capsule endoscopy, antenna design, rectifier systems, and biotelemetry applications. It traces the historical development of capsule endoscopy, identifying pivotal milestones and technological breakthroughs. This chapter examines the principles of antenna design for medical telemetry, shedding light on the specific requirements and challenges

involved. It also explores RF energy harvesting techniques and related advancements in the realm of biotelemetry. The literature review equips readers with a solid foundation of existing knowledge and informs them about the state of the art in wireless capsule endoscopy and related technologies.

Chapter 3: Design of Dual-Band Antenna

Chapter 3 forms the heart of the thesis, addressing the first research objective—developing a dual-band antenna system for wireless capsule endoscopy. It commences with an abstract of the research paper (Paper 1) corresponding to this chapter. The chapter elaborates on the characteristics and design requirements of a dual-band antenna and outlines the design methodology. It provides insights into the experimental evaluation, including measurements with a tissue-equivalent phantom liquid model to assess antenna performance. The results and performance of the dual-band antenna are presented and analysed, showcasing the measured impedance bandwidths, peak realized gains, and compactness. The chapter pays special attention to safety and regulatory compliance, evaluating Specific Absorption Rate (SAR) and link margin (LM) to ensure the antenna's safety and alignment with regulatory requirements. A comparative analysis is conducted to highlight the advantages of the proposed antenna in relation to existing designs for capsule antennas in wireless capsule endoscopy applications. Chapter 3 culminates with a concise summary of the findings, affirming the potential of the dual-band antenna to revolutionize wireless capsule endoscopy.

Chapter 4: Dual-Band Rectifier System

Chapter 4 concentrates on the development of a dual-band rectifier system for RF energy harvesting, addressing the second research objective. It commences with an abstract of the research paper (Paper 2) corresponding to this chapter. The chapter elucidates rectifier

design principles, emphasizing the modified T-section matching network. It delves into simulation and optimization, exploring theoretical and simulation studies conducted to optimize the rectifier system. Fabrication and testing are pivotal components of the chapter, as the rectifier system is manufactured and tested to validate its performance, with a focus on efficiency measurements under various input power levels. The chapter proceeds to present and analyse the measured results, emphasizing the dual-band rectifier's efficiency and performance in both the 1.4 GHz WMTS and 2.45 GHz ISM bands. A comparative analysis underscores the advantages of the proposed rectifier system in the context of wireless power transfer (WPT) and implantable medical devices. The chapter concludes with a summary of the findings, affirming the potential of the dual-band rectifier for RF energy harvesting in wireless capsule endoscopy.

Chapter 5: Dual-Band Antenna for Biotelemetry

Chapter 5 marks the exploration of the third research objective, which centres on the development of a dual-band dual-sense (DBDS) circularly polarized suspended plate antenna with an L-probe feed for bio-telemetry applications. This chapter begins with an abstract of the research paper (Paper 3) corresponding to this chapter. The design principles and operational characteristics of the dual-band circularly polarized antenna are unveiled. The chapter elaborates on the fabrication and testing of the prototype antenna, culminating in the presentation and analysis of the measured results, including impedance bandwidths, peak gains, and polarization characteristics. The effectiveness of the DBDS antenna for bio-telemetry applications is validated, emphasizing the communication link measured during dual wide-band implantable antenna design for wireless capsule endoscopy (WCE). Chapter 5 concludes with a summary of the findings, highlighting the suitability of the DBDS circularly polarized antenna for bio-telemetry applications, affirming its potential in the field of wireless capsule endoscopy.

Chapter 6: Conclusion and Future Scope

The concluding chapter synthesizes the key findings of the entire thesis and offers reflections on their implications. It underscores the clinical relevance of the research findings and their impact on patient-centric healthcare. The chapter outlines potential directions for future research and technological advancements in the field of wireless capsule endoscopy, encapsulating the spirit of innovation and the pursuit of excellence. The thesis's journey from inception to realization is encapsulated in Chapter 6, offering a sense of closure while simultaneously opening doors to future possibilities.

❖ Connecting the Dots

The different chapters of the thesis are interconnected in a number of ways. Chapter 1 provides the foundation for the subsequent chapters by introducing the key concepts and motivations of the research. Chapter 2 informs the design and development of the antenna and RF energy harvesting system by identifying the specific gaps in the existing knowledge. Chapters 3-5 build on the concepts introduced in Chapter 1 and the findings of Chapter 2 to develop a dual-band antenna and RF energy harvesting system that meets the stringent requirements of WCE applications. Chapter 6 synthesizes the findings of the thesis to provide a comprehensive overview of the research and its implications for the future of WCE technology.

