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Miniaturized Antenna Design for Monitoring of Individual Pollinators in Smart Farm Environment

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Miniaturized Antenna Design for Monitoring of Individual Pollinators in Smart Farm Environment

MSc Electronics

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Statement of Originality

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Abstract

The decline in pollinator populations, especially honeybees, necessitates innovative conservation strategies. This research focuses on developing advanced technological solutions for identifying and tracking individual pollinators, primarily honeybees, without affecting their natural behaviour. The study began with a survey of existing tracking technologies such as RFID, SAR, and various antenna designs, followed by an analysis of the physical characteristics and load-bearing capacities of honeybees, bumblebees, and drones. The key challenge was to develop miniature, lightweight tracking devices. This research designed antennas with dimensions of 6x6x6 mm^3 and a weight of 0.30g. Initial experiments using loop antennas demonstrated mutual induction at considerable distances. The study then explored RC tank circuits, using ADS software to design systems resonating at 900MHz. These efforts culminated in a dual tank circuit system with improved signal strength and range. Further, the research investigated subharmonic tags that receive signals at 900MHz and transmit at half this frequency. Extensive simulations optimized key parameters such as FR4 thickness and loop shape, resulting in a subharmonic tag with significantly reduced power loss and a functional range of 1.3 meters. The final tag dimensions were 10.6x6.096x1.45 mm^3, suitable for honeybees. This research advances pollinator tracking and conservation by proposing a miniaturized, efficient, and non-intrusive tracking system. The findings contribute to wildlife tracking technologies and offer practical solutions for monitoring and conserving pollinator populations.

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1. Introduction

Pollinators, especially bees, are fundamental to the health of both natural ecosystems and agricultural systems. They are vital in the reproductive processes of a vast majority of plant species, a function that underpins the biodiversity of the planet. The intricate relationship between pollinators and flowering plants is a cornerstone of terrestrial ecosystems. These insects, which primarily include honeybees, bumblebees, and a variety of other species, are responsible for the pollination of about 75% of all flowering plants and nearly 35% of global agricultural crops [1, 2]. This biological interaction is crucial not only for the production of a wide range of fruits, seeds, and nuts but also contributes significantly to the genetic diversity within plant populations. This diversity enhances resilience against environmental stressors like pests, diseases, and changing climatic conditions.

Beyond their ecological importance, pollinators have a substantial economic impact. In agriculture, their role is indispensable for the production of numerous crops, which are crucial for human nutrition and health. The economic value of pollination services provided by these insects is estimated to be in the billions, highlighting their critical role in global food production and the economy [2].

However, pollinator populations are experiencing a concerning decline, attributed to factors such as habitat loss, pesticide use, climate change, and the spread of diseases and parasites. This decrease poses a significant threat to the biodiversity of flowering plants, ecosystem integrity, and agricultural productivity. The ramifications of this decline could have profound consequences for global food security and economies, necessitating urgent attention and action [1, 2]. The decline in population can be seen in the figure 1 which is research carried out by team of scientists while they were studying the crops and quality of crops. The figure shows a rapid decline in the population from 1950 onwards indicating that the population is less than the half in just 50

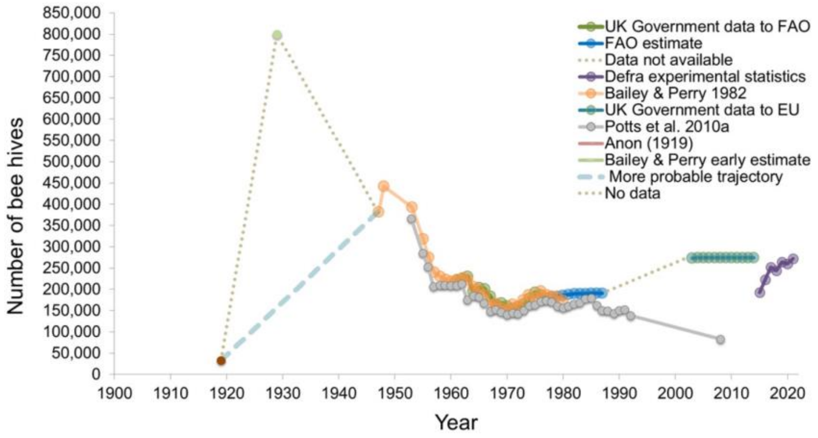


Figure 1 Decline of honeybee population [3]

1.1 Aims and Objectives

Central to these challenges is the need to develop tracking mechanisms that are both minimally invasive and sufficiently robust to withstand the rigors of natural environments. The small size and delicate nature of these insects impose strict limitations on the weight and dimensions of any attached tracking device. It is paramount that these devices do not impede the natural behaviours and flight patterns of the bees, as doing so would not only be ethically questionable but also skew the data collected, rendering it unreliable for scientific purposes. The primary goal of this research is to develop a minimally invasive, efficient, and durable tracking system for pollinators, specifically honeybees. This involves several key objectives:

- Develop tracking devices that are small and lightweight enough to avoid hindering the natural behaviour and flight patterns of pollinators.
- Target dimensions of 6x6x6 mm^3 and a weight threshold of 0.30g for the tracking devices.
- Explore and integrate advanced technologies such as RFID, SAR, and
- Investigate and optimize the use of loop antennas and RC tank circuits for effective signal transmission and reception.
- Develop energy-efficient tracking systems to ensure adequate battery life or incorporate innovative energy-harvesting solutions to power the devices.

- Optimize the power consumption of the tracking devices to prolong operational periods without frequent maintenance.
- Ensure the tracking devices are durable and resilient against diverse environmental conditions, including damp, dense foliage, and dry, open fields.
- Conduct extensive testing to validate the durability and reliability of the devices in real-world settings.
- Extend the range and accuracy of the tracking systems beyond current technological capabilities, ensuring effective monitoring over longer distances.
- Use simulation models (e.g., ADS software) to design systems resonating at specific frequencies (e.g., 900MHz) for optimal performance.
- Develop and refine subharmonic tags capable of receiving and transmitting signals at high frequencies, allowing for simultaneous transmission and reception through a single loop antenna.
- Optimize key parameters such as FR4 thickness, ground plate size, track thickness, and loop shape to enhance system efficiency.
- Address ethical considerations in the design and implementation of tracking devices, ensuring they do not harm the pollinators or disrupt their natural behaviors.
- Develop tracking solutions that respect the well-being of pollinators and comply with ethical guidelines for wildlife research.

1.2 Research Gap

In response to the crisis mentioned previously and shown in figure 1, there is a growing need for innovative research to understand, monitor, and support pollinator species. Developing technologies for tracking and studying the behaviour and movements of pollinators in their natural habitats can provide invaluable insights. This information is crucial for devising effective conservation strategies and mitigating adverse impacts on these essential species. The quest to effectively monitor and study pollinators, particularly honeybees, presents a unique set of technological and biological challenges.

Additionally, the tracking technology must be resilient to a range of environmental factors. Pollinators, especially bees, often traverse through diverse conditions – from damp, dense foliage to dry, open fields. This variability demands a tracking solution that is not only lightweight and compact but also durable and weather resistant. Furthermore, the energy requirements for such devices are a critical consideration. Given the limited space for a power source on a small-scale tracker, ensuring adequate battery life or developing innovative energy-harvesting solutions is a significant hurdle [1].

From a technological standpoint, the tracking of small, fast-moving subjects like bees over considerable distances adds another layer of complexity. Traditional tracking methods, such as GPS, are impractical due to size, weight, and power constraints. Alternative technologies, like RFID and various forms of radio telemetry, have their own limitations in terms of range, accuracy, and the potential for interference with the bees' natural behaviour [35]. Moreover, the high density of bee populations in certain areas can pose challenges for individual identification and tracking, necessitating a system capable of distinguishing between numerous individuals simultaneously.

The overarching challenge, therefore, is to create a tracking system that is sensitive and precise enough to provide meaningful data, yet unobtrusive and sustainable enough to be practically applied to small pollinators. This necessitates not only advancements in miniaturization and power efficiency but also a careful consideration of the ecological and ethical implications of attaching devices to living creatures [4].

In addressing these challenges, this research explores the boundaries of current technologies, pushing for innovative solutions that can be practically and ethically applied to the study of pollinator behaviours and patterns. The development of such technology not only aids in the conservation of these crucial species but also enhances the understanding of their roles in ecosystems and agriculture, providing valuable insights for future ecological and agricultural strategies.

This research is motivated by the shortcomings of existing pollinator tracking methods. A deeper comprehension of pollinator behaviour and environmental interactions is necessary due to the declining pollinator numbers and their vital role in agriculture and ecosystems. Data gathering is limited by size, weight, and power limitations in the monitoring systems now in use. The scientific community's ability to safeguard these important species and conservation efforts are hampered by this technical divide [4].

The primary motivation of this research is to bridge this technological gap by developing a tracking system that is both minimally invasive to the pollinators and capable of providing detailed, reliable data over extended ranges and periods. Recognizing the delicate balance between the need for detailed data and the ethical considerations of attaching devices to living creatures, this study aims to innovate in a manner that respects the well-being of the pollinators.

A multidisciplinary strategy combining information technology, engineering, ecology, and biology is needed to meet this issue. It focuses on increasing power economy, boosting data transmission, and minimising tracking devices for pollinators like honeybees. The objective is to create a tracking system that permits in-depth research on pollinator behaviours without endangering their well-being or natural activities. To get beyond current tracking constraints, the research investigates sophisticated antenna designs, loop inductors, and subharmonic tagging methods. This initiative is a part of a larger effort to encourage sustainable agriculture and protect biodiversity. A compact, lightweight, and energy-efficient tracking device for pollinators—more especially, honeybees—is the goal of this research. This entails overcoming miniaturisation obstacles while maintaining operation in a range of environmental settings. Increasing the tracking's accuracy and range will help monitor pollinators more precisely and over longer distances. To do this, new approaches to energy management, data transmission techniques, and antenna design are needed to ensure efficient communication across extended distances in a variety of environments.

Another key aspect of this study is to ensure that the tracking system can differentiate individual pollinators within a population. This capability is essential for studying the intricate patterns and behaviours of these insects on an individual level, providing insights into their interactions with the environment, navigation methods, and response to various stimuli. In addition to technological innovation, the research is committed to addressing the ethical considerations involved in attaching devices to living creatures. This commitment guides the design process, ensuring that the welfare of the pollinators is a paramount concern. The study also aims to contribute to the broader understanding of pollinator ecology and conservation, providing data that can inform strategies to protect these vital species. The scope of the research extends beyond the development of a single tracking system. It encompasses a comprehensive investigation into various technological solutions, including loop antennas, RFID systems, subharmonic tags, and RC tank circuits. Each of these technologies is explored for its potential to contribute to a more effective and ethical tracking solution. The research also includes extensive simulation and field testing to validate the effectiveness of these technologies in real-world scenarios. Ultimately, this study aims to set a new standard in pollinator tracking, offering a tool that can significantly enhance the understanding of these crucial species. The insights gained from this research have the potential to inform a wide range of applications, from ecological research and conservation efforts to agricultural practices and biodiversity management. By pushing the boundaries of what is currently possible in pollinator tracking, this research contributes to the critical task of protecting and preserving the natural world for future generations.

2. Literature Review

2.1 Overview of Pollinators Ecology

Pollinator ecology, encompassing the diverse interactions between pollinators and flowering plants, is a critical aspect of both natural ecosystems and agricultural systems. Pollinators, such as bees, butterflies, birds, bats, and various other species, play a pivotal role in the reproductive cycles of a vast majority of flowering plants, which constitute a substantial portion of the world's flora [1, 2, 5]. This mutualistic relationship is not only fundamental to the maintenance of biodiversity but also crucial for the functioning of ecosystems, providing food, forming habitats, and offering a wide range of resources for many animal species.

The ecological significance of pollinators extends beyond their role in plant reproduction. They are integral to the conservation of biological diversity and the adaptation of human food production systems to climate change. With nearly 90% of wild flowering plant species depending on animal pollination for successful sexual reproduction, the health and stability of natural habitats are inextricably linked to the well-being of pollinator populations [5, 6]. These interactions are particularly crucial in maintaining the genetic diversity within plant populations, enhancing their resilience against environmental stressors.

In terms of agricultural impact, pollinators are indispensable in the production of a large proportion of human food crops. More than 75% of the world’s leading global crop types benefit from animal pollination in terms of production, yield, and quality [1]. This includes a wide array of fruits, vegetables, nuts, and seeds, which are essential for human diets and nutrition. The economic value of pollinators is substantial, with around 5-8% of current global crop production, equating to an economic impact of between 235 and 577 billion American dollars worldwide, being directly ascribed to animal pollination [1, 2, 5].

However, pollinators face numerous challenges and threats in the modern world. Habitat loss, disease, parasites, environmental contaminants, and the effects of climate change are contributing to a decline in pollinator populations. The alteration of natural landscapes and intensive agricultural practices have reduced the availability of food and nesting resources for these species. The decline in pollinator populations not only threatens the biodiversity of flowering plants but also poses significant risks to global food security and economies [5].

In recent decades, there has been a growing recognition of the importance of pollinators in regulating ecosystem services supporting food production, habitats, and natural resources. The increasing role of pollinators in food production is evident from the threefold rise in the production volume of pollinator-dependent crops over the last fifty years [5]. This makes agricultural systems more dependent on the services provided by these pollinators.

Despite the challenges in providing exact numbers and insights into the extent of the threat to pollinators, research indicates declines in the abundance and diversity of these species. In regions like Northwest Europe and North America, there have been observed declines at local and regional scales. For insect pollinators, national and regional assessments indicate high levels of threat for some bee and butterfly species, with often more than forty percent of bee species being threatened. The population decline of butterflies in Europe is at thirty-one percent, while nine percent of bee species available for research are threatened [5, 29].

Pollinators are not only crucial for the conservation of biological diversity but also for human food production systems. Their role in adapting these systems to climate change is increasingly critical. The loss of pollinators and the decline in pollination services are concerning issues that require urgent attention. The ecological significance of pollinators is embedded in their contribution to ecosystems, agriculture, and the global economy. The conservation of these species is not only an ecological imperative but also a necessity for sustainable food production and the preservation of biodiversity.

2.2 Causes and Consequences of Pollinators Decline

The decline of pollinators, a key component of global biodiversity and essential agents in ecosystem services, has garnered significant concern from the scientific community and conservationists alike. The causes of this decline are multifaceted, encompassing a range of anthropogenic factors that collectively contribute to the diminishing populations of these crucial species [7].

The primary causes of pollinator decline include habitat destruction, land management practices, and widespread pesticide use [7, 8]. Habitat destruction, resulting from urbanization, deforestation, and other forms of land-use change, erodes the natural habitats and foraging grounds of pollinators. This loss of habitat not only reduces the availability of food sources but also fragments the landscapes essential for the movement and reproduction of pollinator species. Land management practices, particularly those associated with modern agriculture such as grazing, use of fertilizers, and crop monoculture, further exacerbate the loss of suitable habitats for pollinators. These practices often result in the degradation of the ecological balance, impacting the diversity and abundance of wildflowers and other plants critical for pollinator sustenance [5].

Pesticide use in agriculture and pest control is another significant contributor to the decline of pollinators. Insecticides, herbicides, and fungicides, often used to protect crops from pests and diseases, can be lethal to pollinators or impair their ability to forage, navigate, and reproduce. Even sub-lethal doses of pesticides can have chronic effects on pollinator health, affecting their immune system and making them more susceptible to diseases and parasites [5, 7, 8].

Climate change also plays a role in pollinator decline, altering the distribution and abundance of many species. Changes in temperature and weather patterns can disrupt the synchrony between flowering plants and their pollinators, affecting the reproductive success of both parties. Extreme weather events, such as droughts and heavy rains, can further impact the availability of floral resources and suitable nesting sites for pollinators [9].

The consequences of pollinator decline are profound, impacting both ecological and human systems. The loss of pollination services has a direct impact on the reproduction of flowering plants, leading to a decrease in plant diversity and abundance. This reduction in plant diversity can have cascading effects on entire ecosystems, affecting other species that depend on these plants for food and habitat [7-9].

In terms of agricultural impact, the decline of pollinators poses a significant threat to food security. Many crops depend on animal pollination for fruit and seed production, and the reduction in pollinator populations can lead to decreased crop yields and quality. This not only affects the availability and diversity of food but also has economic implications for farmers and communities reliant on agriculture. The global economic value of pollination services is estimated in the billions, underscoring the critical role of pollinators in supporting agricultural systems [1, 2, 7].

Moreover, the decline in pollinator populations has broader implications for human nutrition and health. A significant portion of the global diet, including fruits, vegetables, nuts, and seeds, is dependent on animal pollination. The reduction in the availability of these food sources due to pollinator decline can lead to nutritional deficiencies and associated health problems in human populations. The loss of pollinators could result in increased rates of vitamin A and folate deficiency, with potential consequences for global public health [7].

2.3 Existing Pollinator Tracking Technologies

The tracking and monitoring of pollinators, particularly bees, have seen significant advancements with the development of new technologies. These advancements are crucial for understanding pollinator behaviour, optimizing pollination in agriculture, and addressing the global decline in pollinator populations. The current technologies for tracking pollinators include a range of methods from manual observation to sophisticated automated systems using artificial intelligence (AI), remote sensing, and other innovative approaches.

One of the most significant advancements in pollinator tracking is the use of AI. By installing miniature digital cameras and computers in agricultural settings, such as greenhouses, researchers have been able to track the movement of bees and other insects as they pollinate flowers [10]. Custom AI software analyses video footage to build a comprehensive picture of pollination behaviour over a wide area. This technology enables the collection of detailed data on pollinator movements, types of insects, and their flower visits. The AI-driven system provides critical insights into the efficiency of pollination and helps optimize resource use for increased food production. The system's ability to process large volumes of data and track individual insects among complex foliage represents a significant leap in pollinator monitoring technologies. But to collect the information, there must also be a sensing and actuation system. Drones and antennas of different types are used to collect the data [10, 11].

The use of satellites and drones has opened new horizons in pollinator tracking [30]. Remote sensing technology provides vital information to protect pollinators by monitoring floral resources over extensive areas. These technologies can assess the availability and distribution of flowering plants, which are crucial for pollinator sustenance. Satellites offer a broad-scale view, while drones provide detailed, localized data. By combining these technologies, researchers can gain comprehensive insights into the habitats and foraging patterns of pollinators, aiding in conservation efforts [11, 12].

Managing the vast amounts of data generated by digital pollinator tracking systems requires sophisticated software [10, 31]. These software tools use hybrid detection models, combining AI-based object-detection capabilities with separate algorithms for precise identification of insects and flowers. The software is designed to be efficient in data processing, saving on computing power and providing accurate assessments of pollinator populations and their activities. This includes identifying insect movements within video sequences to avoid double-counting and analysing the type and number of flower visits by different insects [10, 12].

Hybrid detection models leverage the strengths of AI and traditional algorithmic approaches. AI-based object detection employs convolutional neural networks (CNNs) to identify and classify objects within video frames. CNNs are particularly effective for image recognition tasks due to their ability to learn spatial hierarchies and patterns in pixel data. By training these networks on large datasets of labelled images, the system can accurately detect and classify various pollinator species and flowers [31, 32]. To further enhance detection accuracy, these models are often supplemented with algorithms that track individual insects across multiple frames. This helps in distinguishing between different individuals and reducing errors such as double counting.

Efficient data processing is crucial for handling the continuous stream of video data captured by digital pollinator tracking systems [33]. Edge computing is often employed to perform initial data processing closer to the data source, reducing the volume of data that needs to be transmitted to central servers. This approach not only reduces latency but also lowers the bandwidth requirements for data transmission. Edge devices equipped with GPUs or specialized AI accelerators can run complex neural network models in real-time, enabling immediate identification and tracking of pollinators [11].

To ensure accurate assessments of pollinator activities, the software must integrate multiple data sources, including video feeds, environmental sensors, and RFID tags [34]. Data fusion techniques are used to combine information from these diverse sources, providing a comprehensive view of pollinator behaviour and interactions. For instance, RFID data can be used to verify the identity of individual insects detected in video footage, while environmental sensors provide context about the conditions in which the pollinators are operating [9, 34].

The software must also include robust data storage and management capabilities. Databases optimized for time-series data, such as InfluxDB or TimescaleDB, are commonly used to store the continuous stream of data generated by tracking systems [35]. These databases enable efficient querying and analysis of large datasets, facilitating the extraction of meaningful insights from the collected data.

Machine learning algorithms play a critical role in analysing the data collected by pollinator tracking systems. Supervised learning techniques, such as support vector machines (SVMs) and random forests, can be used to classify different behaviours exhibited by pollinators [32-35]. For example, these algorithms can distinguish between foraging, nesting, and other activities based on the movement patterns and interactions recorded in the data. Unsupervised learning methods, such as clustering algorithms, can identify emerging patterns and trends that were not explicitly labelled in the training data.

One specific application of machine learning in pollinator tracking is the analysis of flower visitation patterns [36]. By examining the frequency and duration of visits to different flowers, researchers can gain insights into pollinator preferences and the health of plant-pollinator networks. Techniques such as sequence analysis and time-series forecasting can be employed to predict future visitation patterns based on historical data, aiding in the planning of conservation efforts and the management of agricultural pollination services.

Advanced visualization tools are essential for interpreting the complex data generated by pollinator tracking systems. Interactive dashboards and geographic information systems (GIS) can visualize pollinator movements and activities in real-time, providing researchers and conservationists with intuitive access to the data [31]. These tools can highlight key trends and anomalies, enabling quick identification of potential issues and areas requiring further investigation.

To ensure the reliability and accuracy of the tracking system, rigorous validation and testing are necessary. This involves comparing the system's output against manually annotated ground truth data to assess its performance. Metrics such as precision, recall, and F1 score are used to evaluate the accuracy of the detection and tracking algorithms. Continuous monitoring and periodic retraining of the AI models are also essential to maintain their performance over time, particularly as environmental conditions and pollinator behaviours evolve.

The application of these technologies has a direct impact on agriculture and food production. By understanding the pollination dynamics in crops, farmers can make informed decisions to enhance pollination efficiency. For instance, in crops like strawberries, which require a minimum number of insect visits for optimal fruit development, AI-driven tracking systems can provide critical data on whether the crops are receiving adequate pollination [12]. This information enables farmers to adjust hive locations, modify greenhouse conditions, and introduce attractant flowers to improve crop yield. Such interventions are vital for meeting the growing global food demand sustainably.

Despite the advancements in pollinator tracking technologies, several challenges remain. The high cost and technical complexity of these systems can be a barrier to widespread adoption, particularly in small-scale and resource-limited agricultural settings. Additionally, there is a need for further research to understand the long-term impacts of these technologies on pollinator behaviour and health. Future developments in pollinator tracking may involve integrating various technologies to create comprehensive monitoring systems that are accessible, cost-effective, and ecologically sensitive.

2.4 Challenges in Pollinator Tracking

Pollinator tracking, a crucial aspect of ecological research and conservation efforts, faces numerous challenges that range from technological limitations to ecological and ethical concerns. Understanding these challenges is key to developing effective strategies for monitoring and protecting these vital species.

1. Technological Limitations: The primary challenge in pollinator tracking is the development of tracking devices that are both effective and minimally invasive. The small size and delicate nature of pollinators, particularly bees, limit the size and weight of devices that can be attached to them. This imposes constraints on the battery life, range, and data capacity of the tracking devices. Traditional tracking methods like GPS are impractical due to their size, weight, and power requirements. While alternative technologies like RFID and radio telemetry offer potential solutions, they also have limitations in terms of range, accuracy, and potential interference with the pollinators' natural behaviour [13].

2. Environmental Factors: The varied and often harsh environmental conditions in which pollinators live pose additional challenges for tracking. Devices must be resilient to factors like temperature extremes, humidity, and precipitation. Additionally, the tracking technology must be robust enough to function in diverse ecological settings, from dense forests to open agricultural fields, without being obstructed or damaged [11].

3. Data Management and Analysis: The vast amount of data generated by pollinator tracking systems, especially those employing video or high-resolution imaging, requires sophisticated data management and analysis tools. These tools must be capable of processing large datasets to extract meaningful insights about pollinator behaviour, movement patterns, and interactions with their environment [10-12].

4. Ecological Complexity: Pollinators interact with a complex ecological web that includes a variety of plant species, other pollinators, and predators. Understanding these interactions is critical for effective tracking and conservation efforts. However, the complexity of these interactions poses a significant challenge, requiring a multidisciplinary approach that combines expertise in ecology, biology, and technology.

5. Ethical Considerations: Attaching tracking devices to living creatures raises ethical concerns that must be addressed. The welfare of the pollinators should be a paramount consideration, ensuring that the devices do not harm them or adversely affect their natural behaviours. This necessitates careful design and testing of tracking technologies to minimize their impact on the pollinators’ health and well-being.

6. Habitat Loss and Fragmentation: The loss and fragmentation of natural habitats due to human activities like agriculture, urbanization, and mining are major challenges for pollinator tracking and conservation. Habitat loss reduces the availability of food sources and nesting sites for pollinators, while fragmentation can isolate populations and hinder their movement and reproduction [3]. Tracking technologies must be able to monitor pollinators across fragmented landscapes to understand their movement patterns and identify critical habitats that need protection.

7. Pesticides and Pollution: The widespread use of pesticides in agriculture poses a significant threat to pollinators. Pesticides can be lethal to pollinators or impair their ability to forage, navigate, and reproduce. Tracking technologies must be able to assess the impact of pesticides on pollinator populations and provide data that can inform more sustainable agricultural practices [7].

8. Climate Change: Climate change is altering the distribution and behaviour of pollinators, with implications for their interactions with flowering plants. Warming temperatures and changing weather patterns can disrupt the synchrony between pollinators and plants, affecting reproductive success and food availability [7]. Tracking technologies must be able to monitor these changes and provide data that can inform conservation strategies in a changing climate.

9. Non-Native Species: The introduction of non-native species can disrupt local ecosystems and compete with native pollinators for resources. Tracking technologies must be able to differentiate between native and non-native pollinators and assess the impact of non-native species on local pollinator populations.

10. Citizen Science and Public Engagement: Engaging the public in pollinator tracking through citizen science initiatives is a promising approach but comes with its own set of challenges. Ensuring the accuracy and reliability of data collected by citizen scientists, as well as effectively communicating the importance of pollinator conservation to the public, are key challenges in leveraging citizen science for pollinator tracking.

11. Parasites and Diseases: Parasites and diseases, such as Varroa mites and Colony Collapse Disorder, are major threats to pollinators, particularly honeybees [6-9]. These threats can affect the health and survival of pollinator populations, making tracking and monitoring even more critical. Understanding the spread and impact of these threats is essential for developing effective management and conservation strategies.

12. Funding and Resource Allocation: Adequate funding and resources are essential for developing and deploying effective pollinator tracking technologies. However, securing funding for research and conservation efforts can be challenging, especially in the face of competing priorities and limited budgets.

13. Collaboration and Information Sharing: Effective pollinator tracking, and conservation require collaboration and information sharing among researchers, conservationists, policymakers, and other stakeholders. However, coordinating efforts across different sectors and regions can be challenging, particularly in the context of differing priorities, methodologies, and goals.

2.5 Advancements in miniaturization and power efficiency

The field of pollinator tracking has witnessed significant advancements in miniaturization and power efficiency, key aspects that are transforming the way researchers’ study and understand these vital creatures. The integration of cutting-edge technologies and innovative methodologies has led to the development of smaller, more efficient, and less invasive tracking devices, offering new insights into pollinator behaviour and ecology.

1. Miniaturization of Tracking Devices: The miniaturization of tracking devices has been a game-changer in pollinator research. The development of smaller and lighter devices has made it possible to track smaller species without hindering their natural behaviour. Technologies such as RFID (Radio-Frequency Identification), radar, lidar, and lightweight GPS trackers have been refined to sizes suitable for attachment to even small insects like bees [11]. These advancements have allowed for the detailed study of pollinator movements, interactions with plants, and responses to environmental changes, providing crucial data for conservation efforts.

2. Power Efficiency Improvements: Alongside miniaturization, significant strides have been made in improving the power efficiency of tracking devices. The challenge of maintaining a balance between device size and battery life has led to the development of energy-autonomous devices and the use of energy-harvesting technologies. Innovations in battery technology, along with the integration of solar cells and other renewable energy sources, have extended the operational lifespan of tracking devices, enabling longer-term studies of pollinator behaviour and migration patterns [13].

3. Integration of Advanced Sensors and Wireless Networks: The integration of advanced sensors and wireless sensor networks has facilitated real-time monitoring and data collection from pollinators in the field. 'Smart' hives equipped with sensors provide detailed information on hive health, bee activity, and environmental conditions [13, 14]. These systems often incorporate IoT (Internet of Things) technology, allowing for remote monitoring and data analysis, which is critical in understanding the impacts of environmental stressors on pollinator populations.

4. Automated Visual and Audio Monitoring Systems: Automated visual and audio monitoring systems, including motion detection and machine learning-based species identification, have revolutionized the study of pollinator behaviour. High-resolution cameras and audio sensors can capture fine-scale behaviours of pollinators over extended periods [11-13]. These systems provide detailed insights into pollinator-plant interactions, foraging patterns, and responses to environmental changes, contributing to a deeper understanding of pollinator ecology.

5. E-Ecology Platforms: The emergence of e-ecology platforms leverages the aforementioned technologies to acquire and understand large spatiotemporal datasets [14]. These platforms facilitate the collection, analysis, and interpretation of complex ecological data, informing knowledge gaps and environmental policymaking. The development of such platforms requires collaborative partnerships between academia, industry, and conservation organizations, ensuring a cross-disciplinary approach to pollinator research.

6. Challenges and Future Directions: Despite these advancements, challenges remain in further miniaturizing tracking devices while ensuring their functionality and reliability. Future research and development are needed to create even smaller, more energy-efficient tracking solutions that can be widely deployed across diverse species and environments. Additionally, the integration of different tracking technologies to form comprehensive monitoring systems represents a significant area for future exploration.

7. Ethical and Ecological Considerations: As tracking technologies advance, ethical and ecological considerations must be at the forefront of their development and application. The welfare of pollinators must be carefully considered to ensure that tracking devices do not adversely affect their health or behaviour. Furthermore, the data gathered from these technologies should be used responsibly to inform conservation strategies that protect and sustain pollinator populations.

2.6 Subharmonic and RFID Tag Technology in pollinator tracking

Subharmonic Tag Technology (SubHT): Subharmonic tags represent a novel class of chip-less and battery-less tag-based Wireless Sensor Networks (WSNs) [15]. These SubHTs are revolutionary in their ability to remotely and continuously sense Points of Interest (PoIs) with extraordinary sensitivities and dynamic ranges, using low-cost components on printed substrates [15-17]. Unlike previous harmonic tags, SubHTs operate in full duplex by transmitting sensed information on a dedicated channel different from the interrogation channel. This is achieved through a period-doubling mechanism, allowing SubHTs to transmit on a passively generated carrier frequency, which is half of the interrogating signal frequency. SubHTs show remarkable efficiency in generating output signals from received input power, enabling lower coupling loss values (CL-values) and significantly higher Signal-to-Noise Ratios (SNRs) at the receiver than harmonic tags. This translates to more accurate wireless sensing and longer communication ranges. The first prototype of a SubHT demonstrated these capabilities by remotely measuring temperature with a sensitivity and dynamic range far superior to traditional methods, even when using commercial off-the-shelf components [13].

RFID Technology in Pollinator Tracking: RFID technology has been widely researched for tracking pollinators, particularly in the context of bee monitoring. RFID tags, when attached to pollinators like bees, allow researchers to track their movements and gather data on their behaviour and interactions with the environment. These tags are particularly useful in studying the foraging patterns, nest-site fidelity, and other critical aspects of pollinator ecology [11]. Advancements in RFID technology have led to the development of smaller, more energy-efficient tags that can be attached to individual insects without significantly impacting their natural behaviour [13]. The data collected via RFID systems are invaluable in understanding the dynamics of pollinator populations and can inform conservation strategies.

Both SubHT and RFID technologies face challenges in further miniaturization and improving power efficiency to make them more suitable for tracking smaller pollinator species. The integration of these technologies into broader ecological studies requires careful consideration of their impact on the behaviour and health of the pollinators. Future advancements in these technologies are expected to provide even more detailed insights into pollinator behaviour and contribute significantly to conservation efforts.

3. Methodology and Experimental Work

Developing an effective methodology for researching pollinator tracking, particularly for small species like honeybees, required a multifaceted approach integrating various technological and ecological studies. Here is a detailed explanation of the methodology used in this research:

1. Initial Research and Technology Assessment: The research began with an in-depth investigation of technologies capable of detecting miniature objects. This involved studying various antenna types, Synthetic Aperture Radar (SAR) technology, RFID tracking, and inductor antennas. Simultaneously, a comprehensive review of the biological aspects of honeybees, bumblebees, and drones was conducted, focusing on their physical dimensions and the weight they can carry. This dual approach helped in identifying the technical and biological constraints relevant to pollinator tracking.

2. Antenna Development and Miniaturization: The core of the research involved developing the smallest possible antennas that would be effective for tracking yet light enough not to impede the bees' natural behaviour. Target dimensions were set at 6x6x6 cubic mm, with a maximum weight limit of 0.30g. The decision to use loop antennas was based on their simplicity in energy transfer. The experiments were conducted to observe mutual induction at different frequencies and voltages using coils designed with specific properties. The goal was to achieve effective signal transmission at minimal weight and size.

3. Exploration of Tank Circuits: To enhance the range and efficiency of the system, the research explored the use of tank circuits. This involved using capacitors in parallel with coils to achieve specific resonant frequencies and improve the range of signal detection. Simulations in ADS software were employed to test different circuit configurations - series, parallel, and mixed - to determine which provided the best output quality.

4. Simulation and Optimization of Subharmonic Tags: Further advancements were made through the development and optimization of subharmonic tags using CST studio. This phase involved altering various parameters of the tags, such as FR4 thickness, ground plate size, and loop shape, to maximize their efficiency. The aim was to significantly reduce power loss in the elements, thus enhancing the effective range of the tags.

5. Addressing Simulation vs. Reality Discrepancies: A crucial part of this research was identifying and addressing the discrepancies between simulation results and the actual performance of the subharmonic tags. This involved understanding the non-linear effects of the varactors in the tags and adjusting the design to accommodate these effects. The simulations were therefore matched with the experimental results of the original tag. The original subharmonic tag could receive and then send the signal back at a distance of 13m as proved experimentally. The original tag was redesigned in the simulation and power received was noted for it to be correlated with the distance. The power received by the tag was then reduced due to the size reduction which was then matched with original power to measure the range of the signal or ability of the proposed miniature sub-harmonic tag.

6. Refining and Finalizing the Design: The culmination of these extensive research efforts was the establishment of an optimized design for the tracking system. The final design achieved the set objectives in terms of size, weight, and operational range, marking a significant advancement in the field of pollinator tracking.

3.1 Researching Radar Technologies

SAR technology, known for its ability to create high-resolution images by utilizing the motion of the radar antenna over a target area, was initially considered due to its impressive spatial resolution and its capability to operate in all weather conditions, day and night. SAR's ability to generate detailed images independent of illumination and its various applications in remote sensing and mapping made it a candidate for tracking small objects across large areas [18, 19]. However, the complexity, size, and energy requirements associated with SAR systems posed significant challenges. The technology, typically mounted on aircraft or spacecraft, requires sophisticated infrastructure and substantial power, making it impractical for tracking individual insects like honeybees. The need for equipment that could be miniaturized and would not adversely affect the pollinators' natural behaviours led us to conclude that SAR, while potent for broad environmental monitoring, was too complex for direct application in pollinator tracking (Capella Space, Wikipedia, EOSSAR, Alaska Satellite Facility) [20].

RFID technology, which offers unique identification and tracking capabilities at shorter ranges, was also scrutinized. Its potential for miniaturization and low power consumption made RFID an attractive option. However, RFID systems, particularly passive tags, have limited range and require proximity to readers, posing logistical challenges for tracking pollinators across their natural habitats [11]. Active RFID tags, although capable of longer range, are larger and require more power, which could burden small pollinators [13]. These limitations, coupled with the absence of RFID systems that offer both minimal impact on pollinators and the desired long-range tracking capability, led us to explore simpler methods more suited to this research objectives.

Considering the limitations identified with both SAR and RFID technologies for the specific application of this research, it was decided to pursue a more straightforward approach: electromagnetic induction between two coils, using loop antennas. This decision was driven by the potential for significant miniaturization, lower energy requirements, and the non-intrusive nature of loop antennas. Loop antennas presented a balance between effective range of detection and minimal physical and behavioural impact on pollinators, promising a practical solution for detailed tracking and study of pollinator behaviour.

3.2 Loop Antennas

In the methodology of this research, the simplicity of electromagnetic induction was leveraged to create a viable tracking mechanism for pollinators. This basic but powerful principle hinged on the mutual induction between two coils—a primary coil connected to an AC power source and a secondary coil where the induced voltage was measured.

The primary coil, designed with a precise number of turns and dimensions, was crucial for establishing a strong magnetic field. With 10 turns, a coil length of 0.2 mm, and a radius of 0.35 cm, the coil produced an inductance of 1.4 μH. The primary coil is shown in Figure 2. This was calculated using the inductance formula for a solenoid, $L = \mu_0 \mu_r \frac{N^2 A}{l}$, where μ_0 is the permeability of free space, μ_r is the relative permeability of the core material, N is the number of turns, A is the area of the coil, and l is the length of the coil [19]. The area A was computed as (πr^2), leading to an area of 25.5 cm^2 for the primary coil. The coil's weight was a mere 9 mg, ensuring that it did not significantly impact the mobility of the pollinators.

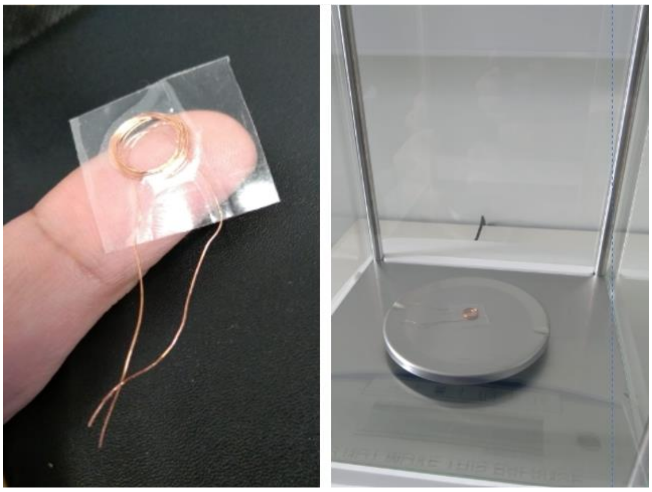


Figure 2 Primary coil for the testing of inductor antennas.

The secondary coil (as shown in Figure 3), larger in size with a radius of 5 cm and 70 turns, served as the induction recipient. The objective was to observe mutual inductance over a range of distances, up to the maximum distance at which the induced signal remained detectable. The results indicated that at a distance of 2 cm, the signal became faint, pointing to the inverse square law's impact on electromagnetic induction—the strength of the induced signal decreases with the square of the distance from the source.

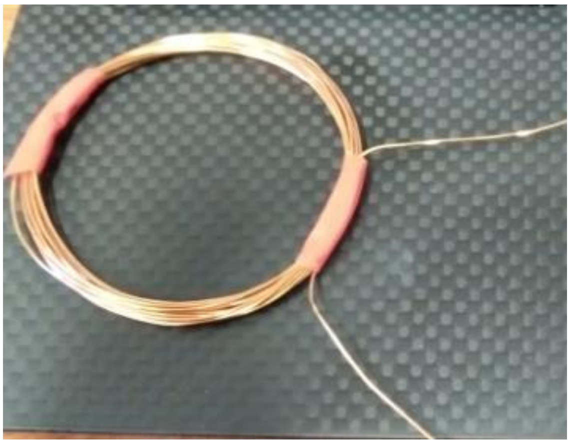


Figure 3 Secondary coil with bigger radius and comparably bigger number of turns as compared to primary coil.

Through these experiments, the induced voltage across varying distances was recorded. At the closest proximity of 0.1 cm, a high induced voltage of 4.6 V was measured, which decreased as the distance increased, highlighting the efficiency of energy transfer at close ranges. The observations were consistent with the theoretical calculations and provided a clear indication of the relationship between distance and induction efficacy. The measurements of distance against the measured voltage are shown in the Figure 4 with the plot showing the exponential drop in the voltage as distance is increased.

The setup for the experiments included a standard oscilloscope to measure the output voltage on the secondary coil. The distance between the two coils, capturing the induced voltage at each point was carefully adjusted, which provided a set of data points that formed the basis of the analysis. The results charted a clear decline in voltage with increasing distance, as demonstrated by the measurements: 3.36 V at 0.5 cm, 1.17 V at 1 cm, decreasing to 0.28 V or 280 mV at a distance of 2 cm. Beyond this point, at 2.5 cm, the voltage dropped below the detection threshold of the measuring instruments. The measurements were carried out using an oscilloscope and a signal frequency being measured was clearly observed in the secondary coil as shown in figure 5.

Distance	Voltage
0.1 cm	4.6 V
0.5 cm	3.36 V
1 cm	1.17 V
1.5 cm	0.52 or 520 mV
2 cm	0.28 or 280 mV
2.5 cm	- -

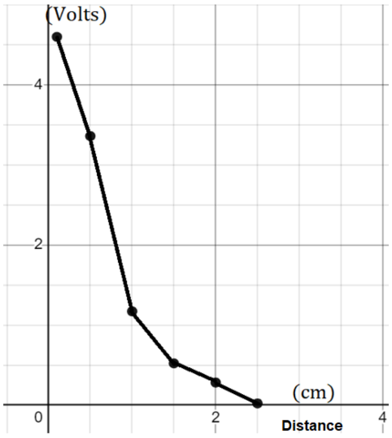


Figure 4 Table shows the range at which the voltage in secondary coil was measured and the amount of voltage in secondary coil as well. The graph shows the plot of voltage against distance. The Initial voltage in the primary coil is kept constant.

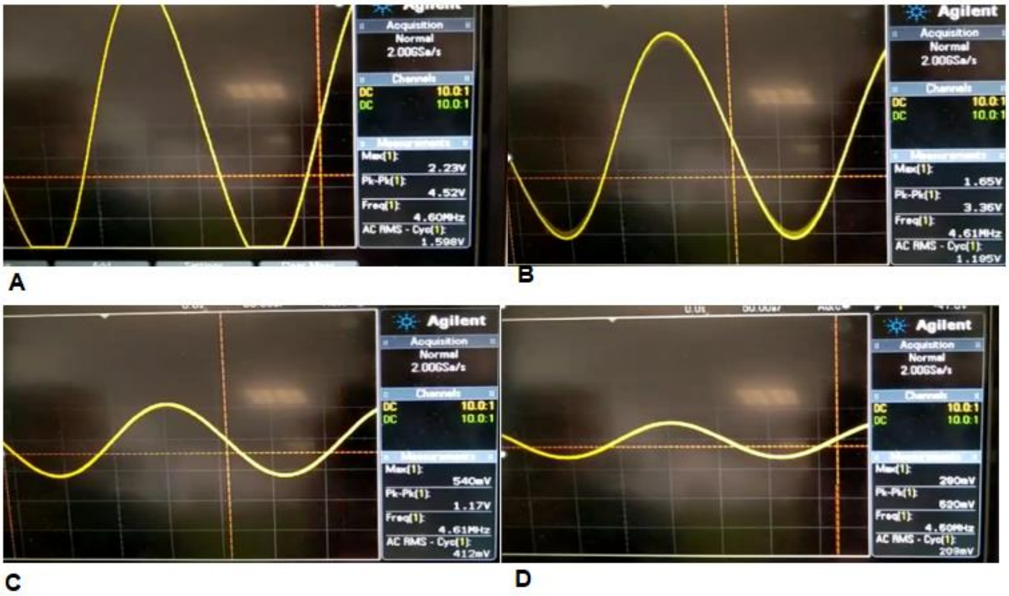


Figure 5 The oscilloscope is used to measure the voltage in the secondary coil. A, B, C and D show voltage while the distance between the coils is increased respectively.

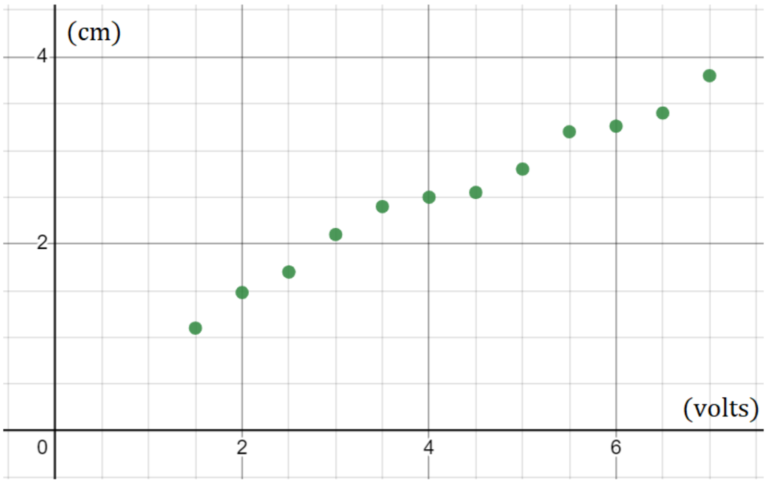
These empirical results were pivotal in shaping the next steps of this research. They underscored the potential and the limitations of using loop antennas for pollinator tracking. With the data in hand, the research was aimed to extend the range of detection while maintaining the lightweight and compact form factor required for application on pollinators.

The concept of directivity is a critical factor when designing antennas for any application, including pollinator tracking. Directivity refers to the degree to which the antenna focuses energy in a particular direction. An antenna with high directivity sends out a beam of energy that is narrow and focused, which is ideal for long-distance communication [19, 20]. However, for the application of tracking pollinators, it is required to use an antenna with a more omnidirectional pattern to ensure the detection of the signal from the tagged insect regardless of its orientation relative to the receiving antenna [13].

Mutual induction, a key principle in experimental setup, depends heavily on several parameters of the coils involved. The mutual inductance between two coils can be expressed through a modification of Neumann's formula, which, in its simplest form, is $M = k\sqrt{L_1 L_2}$, where M is the mutual inductance, k is the coupling coefficient (ranging from 0 for no coupling to 1 for perfect coupling), and L_1 and L_2 are the self-inductances of the coils. The coupling coefficient k is dependent on the relative positioning of the coils, their distance from each other, and their respective shapes and sizes [19, 20].

The voltage induced in the secondary coil due to mutual induction is governed by Faraday's law of electromagnetic induction and can be calculated using the formula $\mathrm{V} = -\mathrm{M}\frac{\mathrm{dI}}{\mathrm{dt}}$, where V is the induced voltage, M is the mutual inductance, and $\frac{\mathrm{dI}}{\mathrm{dt}}$ is the rate of change of current in the primary coil. In practice, the induced voltage will also be affected by the resistance and capacitance of the circuit, which form an RLC circuit with the inductance [21-24]. The resonant frequency of this RLC circuit, where the inductive and capacitive reactance cancel each other out, is given by $\mathrm{f}_0 = \frac{1}{2\pi\sqrt{\mathrm{LC}}}$.

The oscilloscope, functioning as the measurement tool in the secondary coil, can be upgraded to enhance precision. During experimentation with a DSX1204, a 4-channel oscilloscope, we modified the experiment to ascertain the minimum received signal, which registered at 20μV. This measurement was taken while adjusting voltage levels and noting the corresponding distance at which the minimum voltage was recorded. Figure 6 displays the recorded measurements. Notably, with an increase in primary side voltage, the minimum voltage observed in the secondary side occurred at a greater distance. The experimental setup is shown in Figure 7.



Voltage	Distance
1.5 V	1.1 cm
2 V	1.48 cm
2.5 V	1.7 cm
3 V	2.1 cm
3.5 V	2.4 cm
4 V	2.5 cm
4.5 V	2.55 cm
5 V	2.8 cm
5.5 V	3.2 cm
6 V	3.26 cm
6.5 V	3.4 cm
7 V	3.8

Figure 6 The table shows the distance and measured induced voltage while the chart shows the plot

Figure 7 Experimental setup with tank circuits, device on the right was used to excite the primary coil

Through the experiments, the induced voltage across a range of distances to determine the efficiency of energy transfer was carefully measured. As expected, the induced voltage displayed an inverse relationship to the distance between the coils, affirming the theoretical foundations of electromagnetic induction. These results, while promising, also emphasized the need to optimize coil design for maximum directivity and energy transfer efficiency—parameters critical to the success of the pollinator tracking system.

3.3 Tank Circuits

In the progression of this research into pollinator tracking, the resonant circuits were studied, specifically tank circuits. The aim was to miniaturize the tracking system while extending its operational range. Tank circuits, which consist of a capacitor and an inductor in parallel, are known for their ability to resonate at specific frequencies [23]. The resonant frequency of such a circuit is determined by the inductance (L) and capacitance (C) and is given by the formula:

$$\mathrm{f_0} = \frac{1}{2\pi\sqrt{\mathrm{LC}}}$$

Used the Advanced Design System (ADS) software by Keysight to developed systems to resonate at around 900 MHz, a frequency suitable for this application given its balance of range and antenna size. To achieve 900 MHz, the formula for resonant frequency f_0 was utilized. Following components were utilized because of their availability in the laboratory.

$C = 6.254\text{x}10^{-15}F$

$L = 5\text{x}10^{-6}H.$

$$fo = \frac{1}{2\pi\sqrt{L * C}} = \frac{1}{2\pi\sqrt{5\text{x}10^{-6} * 6.254\text{x}10^{-15}}} = 900\ MHz$$

Experimented with different configurations of these tank circuits: series, parallel, and mixed. The mixed configuration—a series circuit on one side and a parallel circuit on the other—proved to yield better output quality, signifying an optimal arrangement for this research's purposes. The series RLC tank circuits and Mixed RLC tank circuits are shown in the figure 8 and figure 10 respectively while figure 9 and figure 11 show the simulation results. The result of the simulation is the frequency sweep in the load resistor on secondary side which shows the voltage in that component compared to the voltage on primary side. The results depict the performance of series and mix configuration to show that the secondary side is coupled much efficiently with primary side for mixed configuration as compared to series configuration. The primary and secondary side of mixed configuration is showed in figure 12. Figure 13 shows the at 2.4 GHz frequency, the voltage in primary side of the mixed RLC configuration is 5.96 V while the voltage in secondary side of the configuration is dropped due to non-ideal conditions of mutual inductance which are accounted for in these simulation by decreasing the coupling factor 'k' to 0.8, and the voltage on secondary side is dropped to 2.583 V. This is a clear example of relationship between mutual inductance factor 'k' and output voltage. 'k' depends upon distance between the coil which means distance between the coils effects the output exponentially.

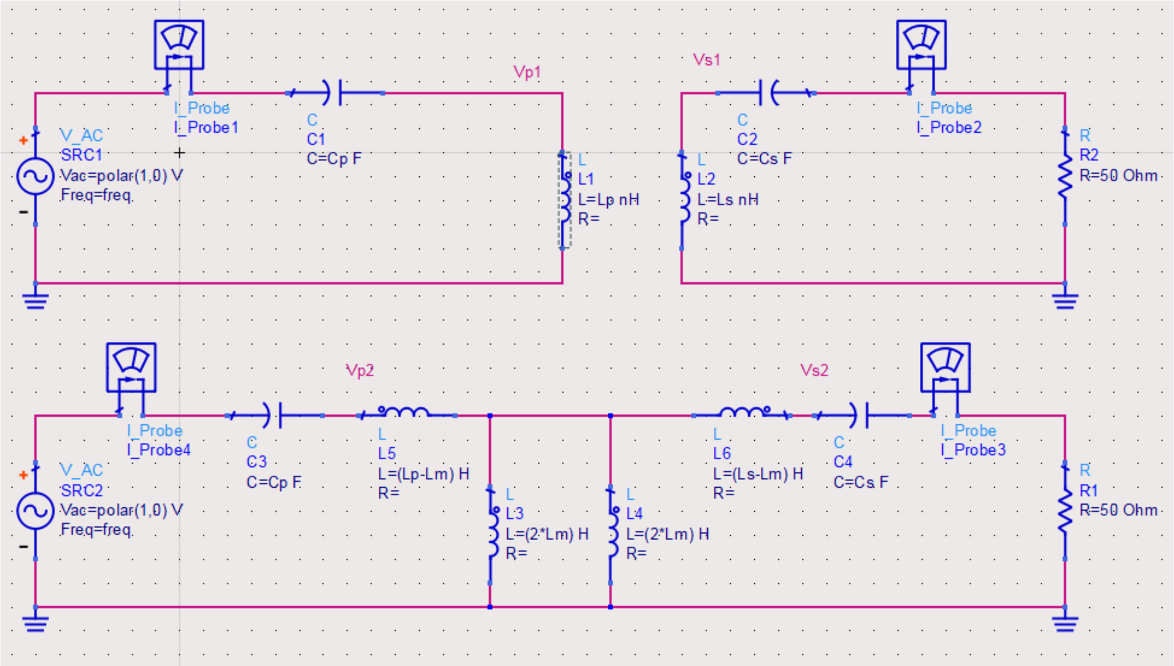


Figure 8 Series RLC Tank circuit

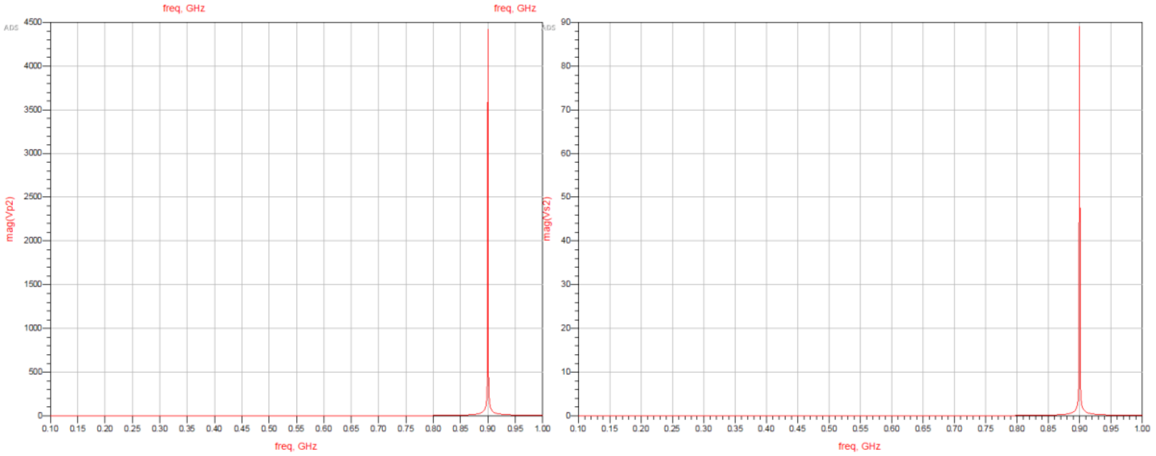


Figure 9 Simulation results showing the resonating frequency of series RLC tank circuits

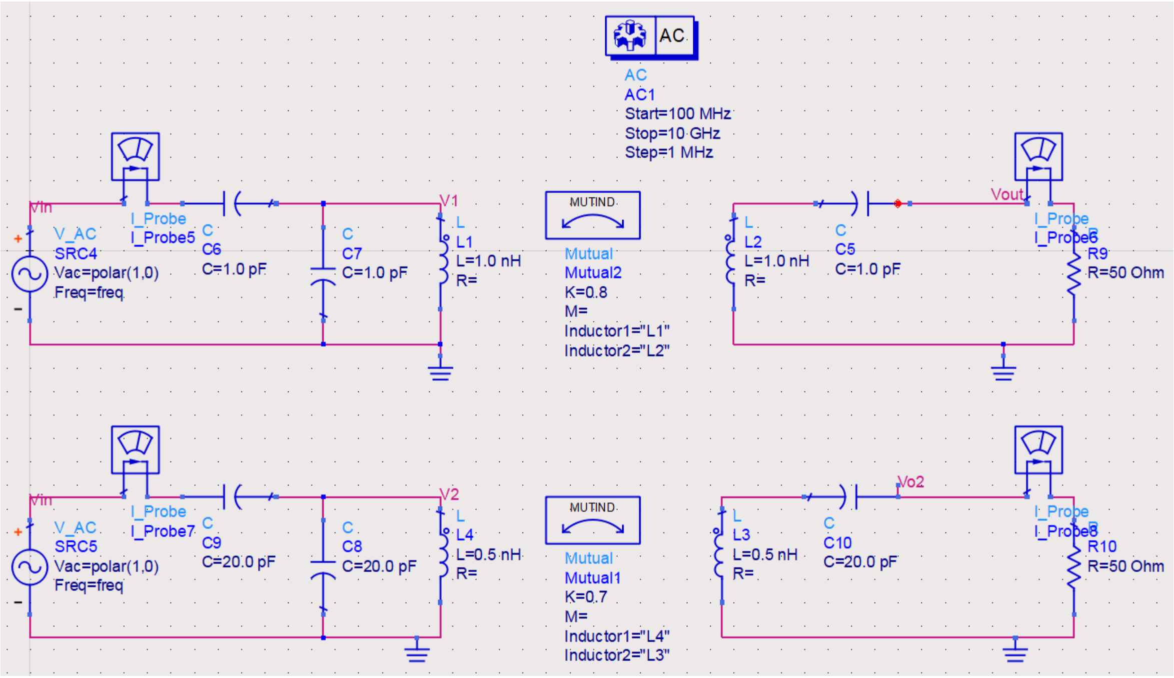


Figure 10 Mixed Configuration, Parallel and series together

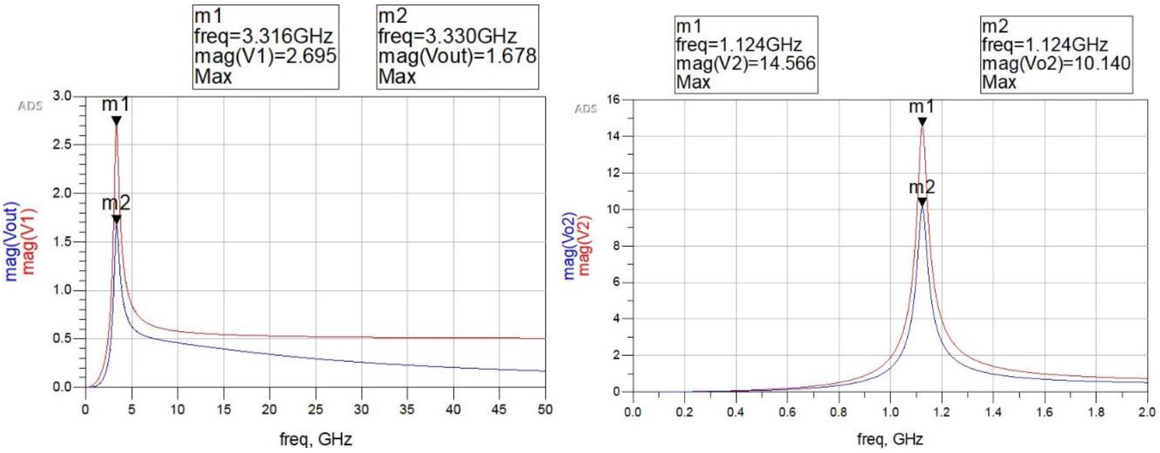


Figure 11 Simulation results showing the resonating frequency of mixed RLC tank circuits

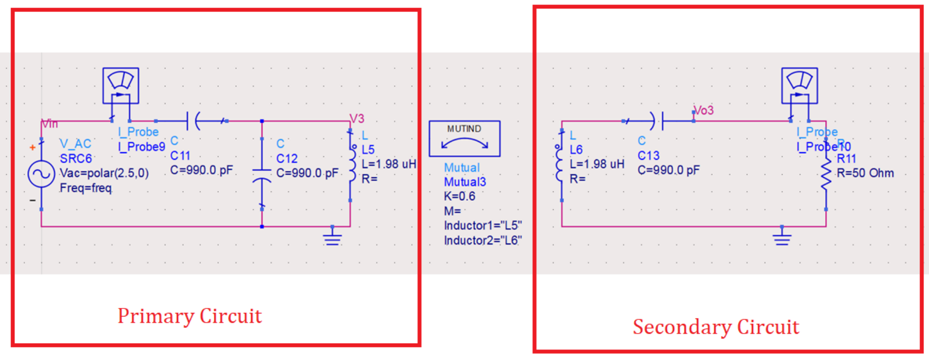


Figure 12 Mixed RLC tank circuit configuration with inductor and capacitor values selected based on available components in the laboratory

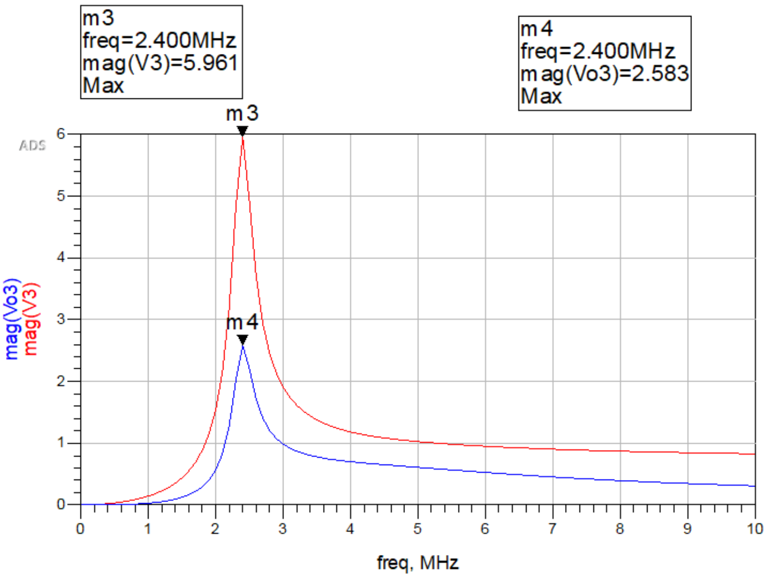


Figure 13 Simulation results showing the resonating frequency of series RLC tank circuits design to operate at 2.4MHz based on available components in the laboratory

The simulations within the ADS environment utilized available components in the market. The inductors valued at 1.98 and 1.96 µH, and a capacitor of 990 pF were utilized. To determine the resonant frequency with a 1.98 µH inductor and a 990 pF capacitor, the resonant frequency formula is applied, which yielded:

$$\mathrm{f}_0 = \frac{1}{2\pi\sqrt{1.98 \times 10^{-6} \times 990 \times 10^{-12}}} = 3.6\,MHz$$

This calculation provided the expected resonant frequency for the tank circuit, guiding the selection of components that would achieve the target frequency of 900 MHz. However, to precisely reach 900 MHz, adjustment of the capacitor and inductor values is required. To extract the experimental results corresponding to simulation results, the same circuit was designed on a prototype board as seen in figure 14. The board on the left-hand side shows the primary circuit which is placed at a certain distance on a measuring ruler away from the secondary side. The secondary circuit is connected to a frequency sweep function of high accuracy 4 channel oscilloscope which provide shows the peak at resonance frequency as shown in figure 15. After measuring the peak values at different distances for different input voltages, the results in table 1 are compiled. The results show an exponential decrease in the output voltage but at the same time higher distance is achieved for the increase in voltage in primary side.

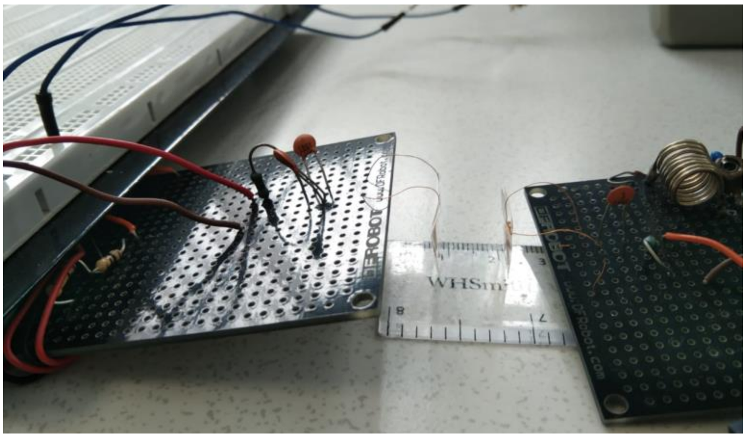


Figure 14 Experimental setup with distance being measured between two coils of mixed RLC tank circuit configurations

A clear signal can be seen in time and fft anaylsis.

4.4GHz Received signal

Minimum Resolution

Measure	P1:max(C1)	P2:max(C1)	P3:pkpk(C1)	P4:freq(C1)	P5:max(F1)	P6:min(F1)
value	1.94 mV	1.94 mV	1.89 mV	37.87275215 MHz	-64.1 dBm	-122.4 dBm
status	✓	✓	✓	✗	✓	✓

C1 AVG DC1M
2.00 mV/div
500 µV ofst
6.708 k#
-8.48 mV

F1 FFT(C1)

Timebase 0.00 µs
1.00 µs/div
50.0 kS 5.0 GS/s

Trigger C1
Auto 1.10 mV
Edge Positive

Trace On ☑
Volts/div 2.00 mV
Variable Gain ☐
Offset 500 µV
Zero Offset
Bandwidth Full
Invert ☐
Coupling DC1MΩ
Deskew 0.0 ps
Pre-Processing
Averaging 18 sweeps
Interpolation Linear

Figure 15 An advanced oscilloscope was used to sweep the frequency to detect the slightest of signal induced in the secondary coil

Table 1 Received signal voltage and its power for different input voltages in the primary coil

Distance	0.5	1	1.5	2	2.5	3
Input Voltage						

1	47mV/-23dbm	20mV/-30dbm	14mV/-35dbm	2.7mV/-49.8dbm	2.4mV/-53.7dbm	2.2mV/-54dbm
2	80mV/-18dbm	42mV/-24dbm	21mV/-30dbm	5mV/-44.8dbm	2.7mV/-49.8dbm	2.4mV/-53.7dbm
3	118mV/-13dbm	61mV/-19dbm	35mV/-25dbm	7.5mV/-39.8dbm	4mV/-45.7dbm	3.5mV/-49.7dbm
4	162mV/-9dbm	65mV/-15dbm	38mV/-21dbm	10mV/-35dbm	5.5mV/-41.7dbm	4mV/-46.7dbm
5	201mV/-6dbm	70mV/-12dbm	53mV/-18dbm	12.5mV/-32.8dbm	7mV/-38.7dbm	5mV/-43.7dbm
6	277mV/-7.3dbm	76mV/-19dbm	28mV/-26dbm	14mV/-33dbm	9mV/-37dbm	5mV/-43dbm
7	323mV/-6.2dbm	84mV/-17.5dbm	31mV/-24.5dbm	16mV/-31.5dbm	10.5mV/-35.5dbm	6mV/-41.5dbm
8	371mV/-5.1dbm	92mV/-16dbm	34mV/-23dbm	18mV/-30dbm	12mV/-34dbm	7mV/-40dbm
9	340mV/-5.4dbm	136mV/-14.6dbm	51mV/-21.6dbm	23mV/-28.6dbm	11mV/-32.6dbm	8mV/-38.6dbm
10	425mV/-4dbm	140mV/-15dbm	41mV/-24dbm	27.5mV/-27.6dbm	12mV/-35dbm	5mV/-42dbm

Distance	3.5	4	4.5	5	5.5	6	6.5
Input Voltage							
1	Nil	Nil	Nil	Nil	Nil	Nil	Nil
2	2.01mV/-59dbm	Nil	Nil	Nil	Nil	Nil	Nil
3	2.5mV/-54.5dbm	2.3mV/-58.5dbm	Nil	Nil	Nil	Nil	Nil
4	3mV/-51.3dbm	2.5mV/-56.3dbm	2.2mV/-60.3dbm	Nil	Nil	Nil	Nil
5	3.5mV/-48.5dbm	2.8mV/-52.5dbm	2.4mV/-56.5dbm	2.2mV/-60.5dbm	Nil	Nil	Nil
6	3.8mV/-47dbm	2.6mV/-50dbm	2.2mV/-53dbm	2.18mV/-55dbm	2mV/-64dbm	Nil	Nil
7	4.5mV/-45.5dbm	3mV/-48.5dbm	2.1mV/-51.5dbm	2.5mV/-54.5dbm	2.2mV/-58.5dbm	Nil	Nil
8	5mV/-44dbm	3.5mV/-47dbm	2mV/-50dbm	2.3V/-53dbm	2.5mV/-57dbm	Nil	Nil
9	6mV/-42.6dbm	2.4mV/-46.6dbm	2.2mV/-49.6dbM	2mV/-52.6dbm	2.8mV/-56.6dbM	1.9mV/-64.4dbM	Nil
10	4mV/-47dbm	2.6mV/-50dbm	2.4mV/-52dbm	2.1mV/-56dbm	2.01mV/-60dbm	2mV/-64dbm	Nil

In the experiments, the effects of mutual inductance on the system were also explored. The mutual inductance (M), which influences the voltage induced in the secondary coil, is a function of the primary and secondary inductances and their coupling coefficient (k). The investigation was carried out on how varying the coupling coefficient impacted the voltage output and, subsequently, the transmission range.

The relationship between mutual inductance and distance was also examined. Theoretically, this relationship is expected to be exponential, with power transfer efficiency decreasing as the distance increases. These experimental results confirmed this, showing a rapid decline in induced voltage as the separation between the coils grew.

Additionally, it was observed that a slight shift in signal frequency, indicative of the Doppler effect, which could be utilized to isolate the received signal from noise, enhancing the accuracy of the tracking system.

Throughout these experiments, the voltage induced at varying distances between the coils is carefully documented. The results indicated a clear pattern: as the distance increased from 0.5 cm to 6.5 cm, the induced voltage decreased from 47 mV to levels that were undetectable.

The practical implications of these results were significant for the design of an effective tracking system for pollinators. It was crucial to optimize the antenna design to achieve the maximum possible range without burdening the pollinators. The loop antennas needed to be small enough to attach to a bee without affecting its flight but powerful enough to transmit data over a distance that would be meaningful for tracking their natural behaviour.

3.3.1Lock-in Amplifier

When considering the amplification of signals from tank circuits to extend the range of the pollinator tracking system, lock-in amplifiers present themselves as a sophisticated and effective solution. A lock-in amplifier, also known as a phase-sensitive detector, is capable of extracting a signal with a known carrier wave from an extremely noisy environment, which is essential when dealing with the minute signals we're aiming to boost [25, 26].

The lock-in amplifier works on the principle of homodyne detection and employs low-pass filtering to measure a signal's amplitude and phase relative to a periodic reference. By focusing on a defined frequency band around the reference frequency, a lock-in amplifier can efficiently reject all other frequency components, even when the noise levels are significantly higher in amplitude than the signal of interest [25]. This is particularly advantageous for this research application, where the signals from the pollinators will likely be weak and immersed in environmental noise.

Utilizing lock-in amplification could significantly improve the ability to detect and measure the small voltages generated in the tank circuit experiments. This technique provides not only amplification but also a refinement of the signal by filtering out unrelated noise, thus enabling us to discern the pollinators' location with greater accuracy. The dynamic reserve of modern lock-in amplifiers, some reaching up to 120 dB, demonstrates their capability to measure signals with precision in the presence of overwhelming noise [26].

While the lock-in amplifiers are incredibly versatile and robust, one of their key advantages is the ability to measure both the amplitude and phase of a signal. This dual-phase detection technique, available in more advanced models, outputs both 'in-phase' and 'quadrature' components, from which the overall signal magnitude can be calculated. This feature could be particularly useful for analysing the directional movement and orientation of pollinators, adding another layer of depth to the study.

In digital lock-in amplifiers, which are the norm today, digital signal processing (DSP) has largely replaced analogue models. They offer several advantages over their analogue counterparts, such as broader frequency range, lower input noise, greater stability, and higher dynamic reserve. Furthermore, they can incorporate multiple demodulators, enabling simultaneous analysis of signals with different filter settings or at multiple frequencies [27].

For this project, the lock-in amplifier represents a potential path forward to increase the range and reliability of the tracking system. While this technology has not been implemented in this research, its capabilities align well with the goal of miniaturizing the system and maximizing the ability to discern faint signals from pollinators over greater distances.

3.4 Sub Harmonic Tags

In the course of refining the tank circuit designs for pollinator tracking, the research led to the discovery of subharmonic tags—a technology echoing the miniaturization and frequency precision required. These tags, akin to sophisticated RFID systems, used a modified loop antenna integrated with a series RLC circuit, resonating closely with the prior simulations and experiments. The revelation of subharmonic tags was serendipitous, as they encapsulated the very essence of the goal: to develop a miniature, efficient system capable of tracking the nuanced behaviours of pollinators [13, 14, 28].

These subharmonic tags represented a confluence of the circuit miniaturization endeavours and the broader quest for a robust, fine-grained remote sensing solution. Intrigued by their single-antenna design and their application in advanced wireless sensor networks, understanding their operation—envisioned their adaptation to this project's needs.

The technical details of the SA-SubHT involve its compact design, with a reported area of only 1.3 cm^2, and it's built onto a 12.4 x 10.6 x 1.6 mm^3 FR-4 printed circuit board. It utilizes a UHF ESA occupying 78 mm^2, which, when interrogated at an EIRP of +36 dBm at 890 MHz, generates a detectable subharmonic response at 445 MHz from over 13 m away [28]. The subharmonic response is made possible by two varactors that enable frequency division, crucial for the tag's function. The performance of this tag is significant, as it exceeds the read-range of identical tags by more than three times the distance when the second varactor is substituted with an equivalent linear capacitor. This innovation not only enhances the read-range but also opens new paths for implementing fine-grained remote sensing for Internet of Things applications [28].

This innovative tag operates at an interrogation frequency of 890 MHz and an output frequency of 445 MHz. It's designed around a single varactor within a printed frequency doubler circuit, enabling it to leverage subharmonic oscillation. The size of the tag is notably compact, highlighting its potential for applications requiring minimal space and weight [28].

The system's parametric circuit is instrumental in halving the interrogation frequency, which is a characteristic unique to subharmonic tags. They are tuned to resonate at the interrogation frequency, as well as the subharmonic output frequency, ensuring the signal's integrity and enhancing the read range. This resonant condition is pivotal, allowing for the tag's functionality despite a lower threshold power for activation.

By implementing a meticulous combination of inductors and capacitors, the tag can maximize the voltage swing across the nonlinear varactor elements. This maximization is crucial for maintaining the parametric modulation of the circuit impedance, necessary for the generation and detection of the subharmonic signal.

The research reports that this SA-SubHT, despite its reduced size, manages to maintain a reading range exceeding 13 meters. This impressive range is achieved through an intricate balance of circuit design, choice of materials, and careful consideration of the antenna's radiation patterns.

3.4.1 Previously developed design

The technical specifics of the subharmonic tag (SA-SubHT) design include a variety of finely tuned electrical components and precise physical dimensions. The SA-SubHT, shown next to a U.S. quarter for scale, boasts compact dimensions, with a total board area mentioned as 12.4 x 10.6 mm, and a thickness of 1.6 mm. It utilizes lumped components for the printed frequency doubler circuit, including a series varactor labelled as C_{Var1} with a capacity of 1.4 pF and a tuning range of 30%, and a second varactor, C_{Var2}, at 2.7 pF with the same tuning range flexibility [28].

The specific inductors used are L_B, which is a 4.6 nH inductor, and L_T, a 22 nH inductor. These components work in conjunction with the varactors to facilitate the subharmonic frequency division required for the tag's operation. The exact dimensions of traces, the embedded electrically small antenna (ESA), and the overall size of the ground plate are shown in the figure 16.

3.4.2 Proposed parameters changes

The original SA-SubHT had a layout of 12.5 x 10.6 mm with a height of 1.6 mm. It featured an antenna track width of 1.29 mm, an antenna length of 23 mm, and was built on an FR4 substrate with a thickness of 0.3 mm (figure 16 shows the complete dimensions with antenna gains).

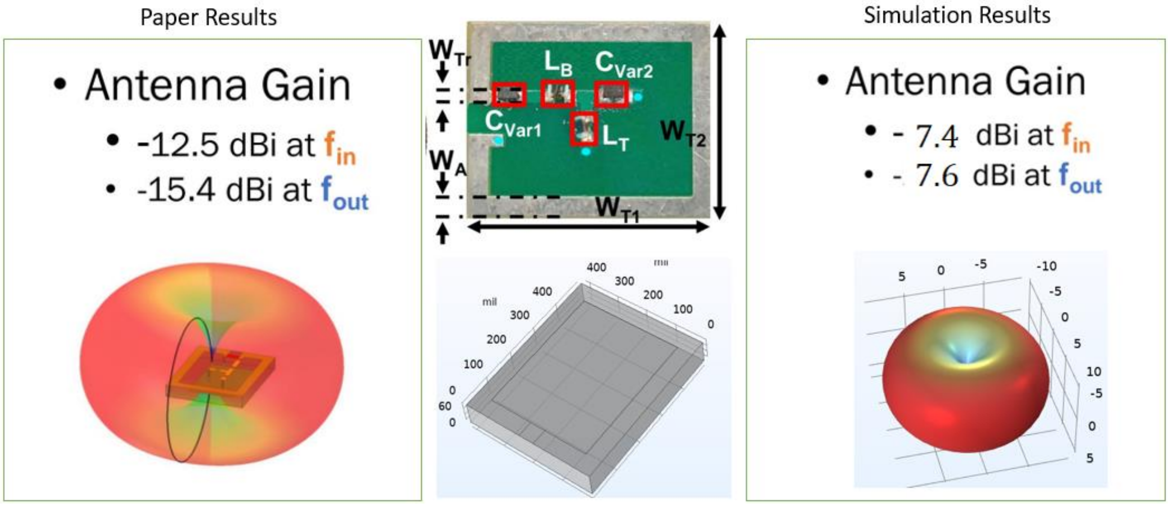


Figure 16 The Difference between the simulation results of the original proposed design and the simulation of the design replicated in this research

In simulation, the power loss in lumped components at specific frequencies is observed, revealing where there was maximum power transfer, indicating resonance. The simulation was carried out in CST studio with original design parameters in the beginning and the results obtained aligned with the claims of resonance frequency of 900 MHz as can be seen in chart on the figure 17. Various design elements were adjusted—such as the ground plane area, track width, circuit topology, via positions, and FR4 thickness—to investigate their effects on the power delivered to these components.

Figure 17 The SubH-tag simulation with results showing the loss in lumped elements

The goal was to retain the tag's original 13-meter or bring it down to a reasonable figure range while downsizing (the size, dimensions and weight) to suit the application. Each modification was scrutinized to assess its impact on the system's overall performance and efficiency.

4. Results and Discussion

In the results chapter of the dissertation, the empirical data collected from the iterative design process of the subharmonic tag (SA-SubHT) is discussed. This section aims to elucidate the impact of varying the physical parameters of the tag on its performance.

4.1 Thickness of antenna

From the analysis, it was discovered that adjusting the thickness of the copper tracks, which constitute the antenna circuits, had a significant effect on power loss in the lumped elements, a critical aspect of the tag's efficiency. By varying the thickness from 0.05 mm to 0.35 mm (as shown in figure 18), it was noted that a thickness of 0.15 mm yielded an optimal balance—demonstrating the same performance as the original 0.3 mm thickness.

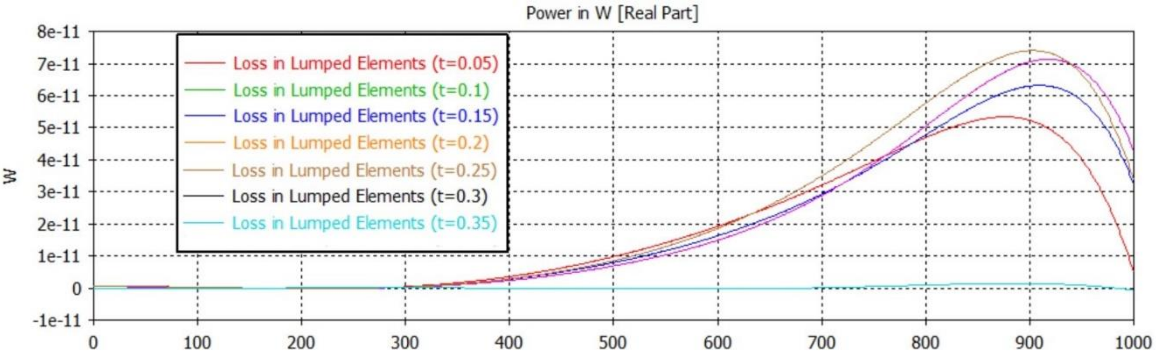


Figure 18 Loss in lumped elements at different thicknesses of antenna (t)

The chart provided illustrates this relationship, indicating that a reduced thickness can achieve comparable power transfer, a discovery that allowed for a decrease in the tag's size and weight without sacrificing performance. This optimization is particularly relevant for the pollinator tracking, where the physical burden on the subject must be minimized. The selected 0.15 mm track thickness represents a pivotal finding, contributing to the miniaturization of the tag while ensuring its functional integrity.

4.2 Antenna Track Width

In the subsequent phase of experimentation, the width of the antenna tracks on the SA-SubHT was modified. The objective here was to evaluate how changes in track width influence the power delivered to the lumped components of the tag. This parameter is pivotal as it affects the tag's ability to effectively receive and transmit signals.

The initial track width was set at the specific measurement of 1.21966 mm. To investigate the impacts of varying this dimension, the track width was adjusted from a narrowed 0.5 mm incrementally up to an expanded 2 mm. The findings indicated that the power values did not drastically differ when the track width was halved from the original dimension. As such, a width of 0.5 mm was ultimately selected for the refined design, with the resulting power in the lumped elements still within an acceptable range compared to the original specifications. The effect on power of the antenna for different track width is shown in table 2 which clearly indicates that the maximum power is received for track width of 1.2196 mm and drops significantly afterwards but the optimal power is received for 0.5mm power which is shown in figure 19. Figure 20, figure 21 and figure 22 show power in lumped components for changing the track width. These results play a crucial role as they also show the quality of the circuit by the bandwidth of the signal received. These results were obtained after changing the dimensions of the track in the original simulation. This decision is informed by the consideration that even minor reductions in material use can lead to significant improvements in the tag's overall weight and size, beneficial for its application in tracking small pollinators.

Table 2 Track width vs the power delivered to the lumped elements of the tag

Track Width in mm	Power in Watts
0.5	4e-11
1	4.1e-11
1.2196	4.5e-11
2	1.6e-9

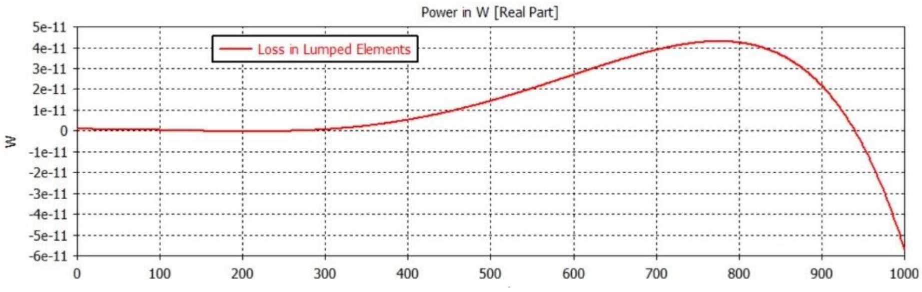


Figure 19 Loss in lumped elements while track width is 0.5mm

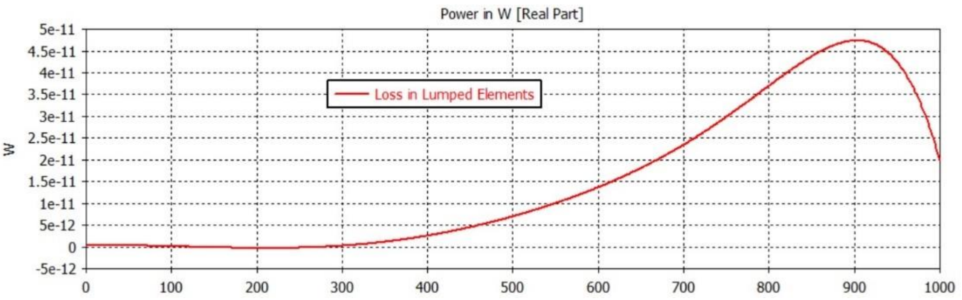


Figure 20 Loss in lumped elements while track width is 1.21966mm

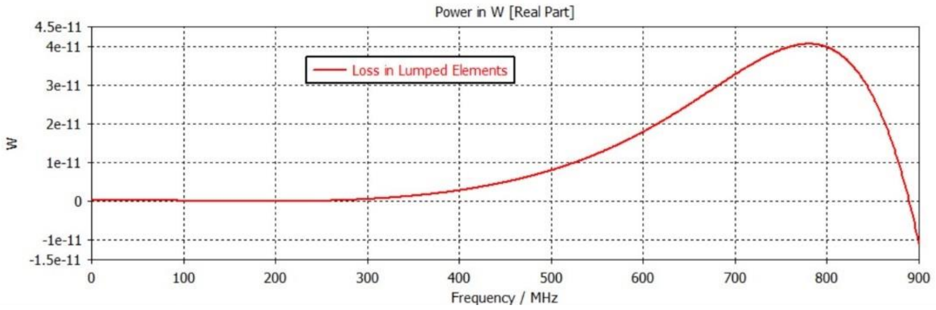


Figure 21 Loss in lumped elements while track width is 1mm.

Figure 22 Loss in lumped elements while track width is 2mm.

4.3 FR04 Thickness

In the examination of the SA-SubHT's substrate thickness, the research found that altering the FR4 thickness significantly influenced the signal quality. The FR4 material, which serves as the foundational layer of the PCB, affects the electromagnetic properties and, consequently, the antenna's performance. Through simulation, it was discerned that any reduction in the FR4 thickness led to a pronounced decrease in signal quality, observed as an increase in power loss in the lumped elements.

Therefore, the original FR4 thickness was retained to ensure signal integrity. Maintaining this parameter was deemed crucial to uphold the tag's operational capabilities, a testament to the sensitive interplay between physical structure and electronic function within the system. The results for different thickness can be seen in the figure 23. The original thickness is shown as a red plot in the figure while the other plots which clearly show less power are shown in other colours.

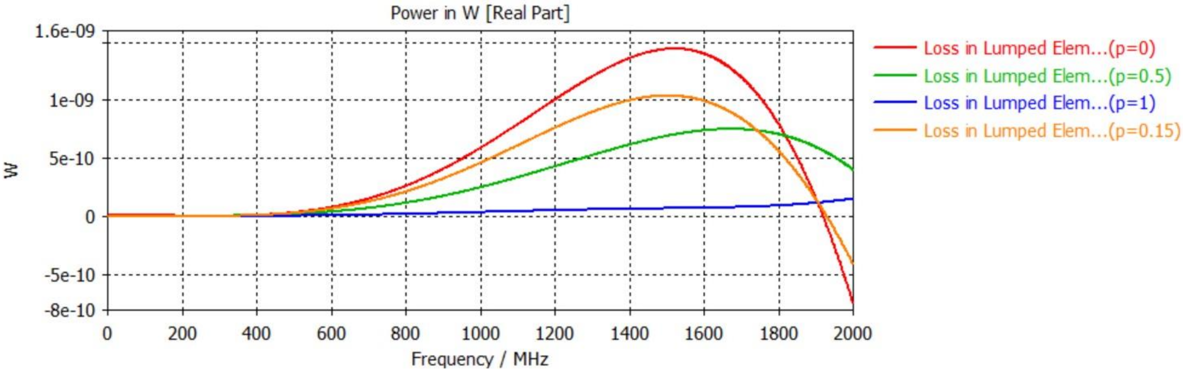


Figure 23 Loss in lumped elements when a thickness value p is subtracted from original thickness of FR04

4.4 Ground Plate Dimensions

The ground plate size on the subharmonic tag plays a vital role in the tag's performance. In attempts to reduce the overall weight of the device, the possibility of minimizing the ground plate dimensions was explored. However, simulation results demonstrated that a larger ground plate significantly improved signal quality and power transfer, reinforcing the importance of this component. Thus, to optimize the tag's performance and maintain a robust signal, the ground plate size was kept unchanged from the original specifications. The decision was based on changing the ground plate dimensions and measuring the power received by the antenna which correlates to power loss in lumped components. The results can be seen in figure 24 and figure 25. The change in ground plate dimensions to half decrease the power by an order of 10 which means the maximum size of ground plate should be ensured but that also comes with the challenge of adding extra weight to the tag. Therefore, it is necessary to find a balance between these two parameters. The preservation of the ground plate dimensions was essential for ensuring the most effective signal propagation and reception.

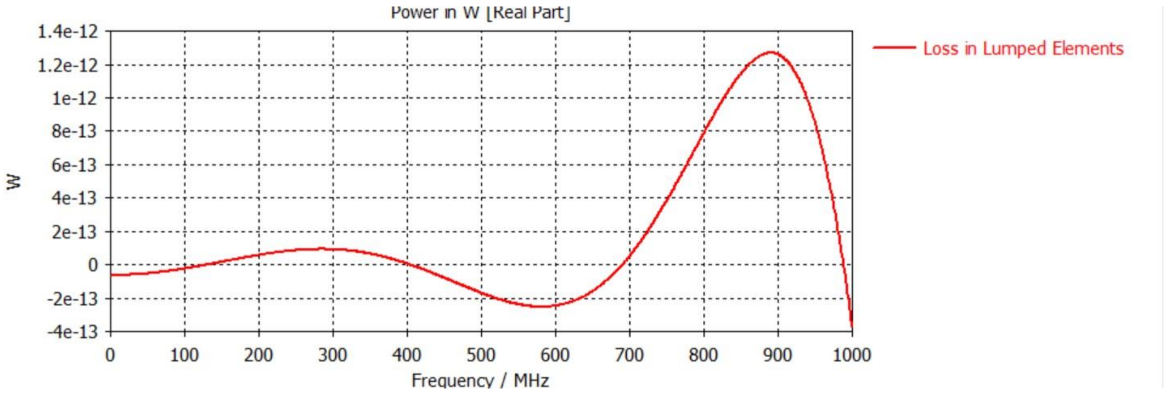


Figure 24 Simulation results: Original ground plate dimensions.

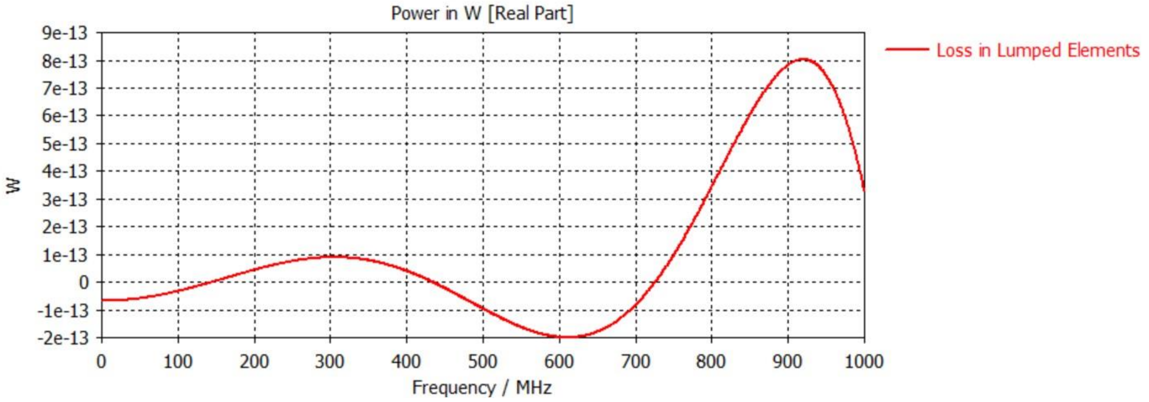


Figure 25 Simulation results: Half of original ground plate.

4.5 Topology of Circuit

It was found that the placement of the circuit components within the centre of the antenna loop significantly impacts performance. Two different topologies were tested: one with the circuitry closer to the antenna walls as shown in figure 26, and another with components dispersed, the optimal results were achieved with the circuitry centralized (as shown by the original tag simulation in figure 17), which minimized the interference from the antenna's own structure.

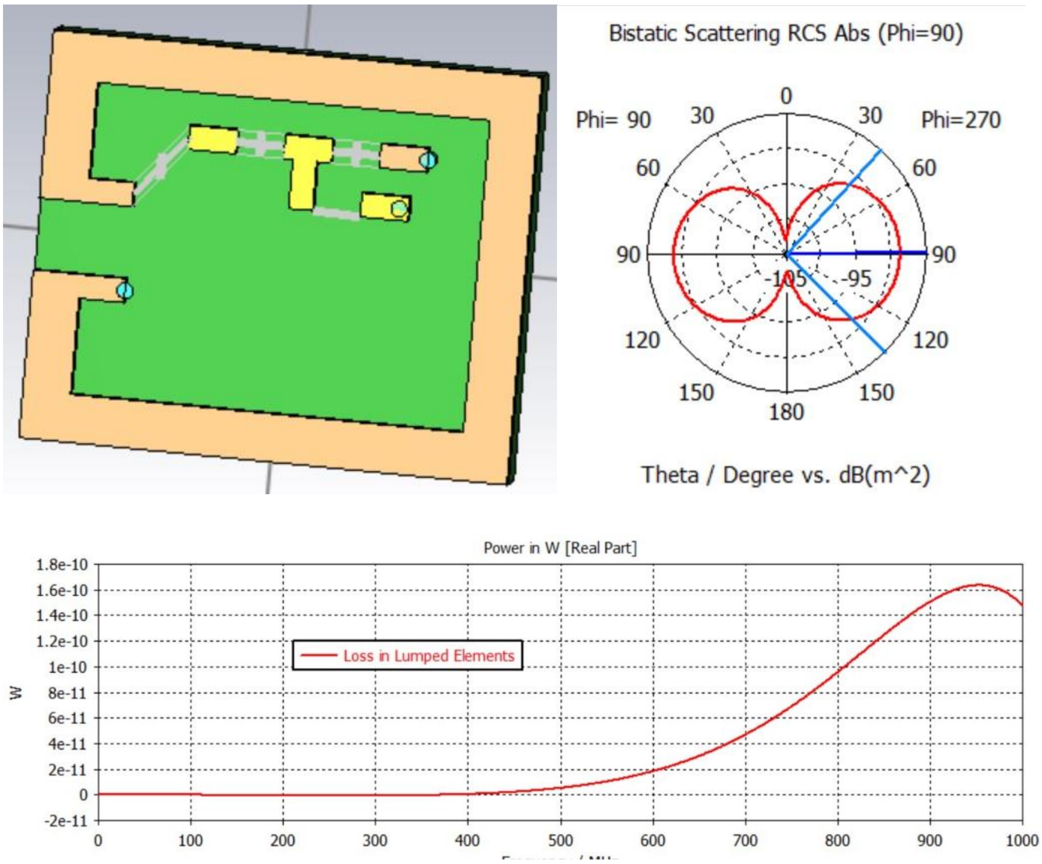


Figure 26 Change in topology of original design, the design of the tag is similar to the original design, but the components are moved closer to the antenna tracks and simulation results are shown in the plot below.

Theoretically, having components at the centre reduces the effect of near-field interactions between the antenna elements and the active components. This positioning allows for more uniform current distribution across the antenna, leading to improved radiation efficiency and a stronger signal. The research, thus, underscored the importance of central placement in enhancing the tag's read range and signal integrity.

4.6 Optimal tag

Upon refining the subharmonic tag (SA-SubHT) design for optimal performance, the following adjustments were made:

- The overall dimensions were reduced to 10.6 x 6.096 x 1.45 mm^3, which is approximately 75% of the original size.
- The antenna thickness was halved from 0.3 mm to 0.15 mm.
- The antenna track width was narrowed from 1.29 mm to 0.649 mm.
- The antenna length was slightly increased from 23 mm to 24.5 mm to maintain the electrical length, ensuring the antenna still resonates effectively.

- The electrical length was adjusted to be slightly more than $\frac{1}{10}$ of the wavelength, accommodating the new physical dimensions while preserving the tag’s resonant properties.
- Power transfer was improved to 4.6 x 10^-12 W, indicating a more efficient energy transfer to the lumped elements despite the tag's reduced size.

These modifications not only made the tag more compact and lightweight but also ensured it met the necessary operational requirements for tracking pollinators over a distance of 1 meter. The proposed changes were implemented, and design is shown in figure 27 with table 3 highlighting the major changes in the parameters. The reconfiguration of the antenna tracks to fill more space within the tag's bounds effectively utilized the area without increasing the overall size, a clever design choice to minimize the footprint while maintaining performance.

The size of the original tag was a quarter of a coin while the size of this new tag is three quarters of the original design. The length of the tag is still large for it to be placed on a small honeybee, but the tag will be optimal for the bees of larger size such as queen bee or the bumble bees. The original tag was meant to be designed for multiple purposes but the reduction in size makes it possible to be used with the pollinators as well. The tag has not been tested with the honeybees because it still requires reduction in its size. There are multiple approaches to reduce the size of the tag even further and are discussed in the future work section outlining major approaches to make the tag suitable for regular size honeybees.

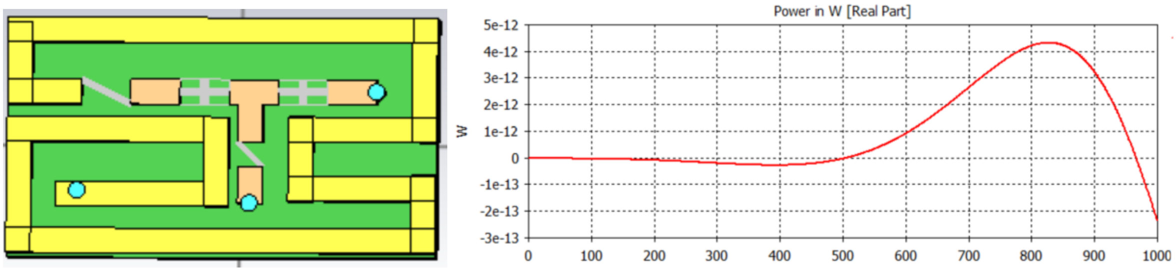


Figure 27 Proposed design for the tag with Optimal conditions. Chart on the right shows the loss of power in watts in lumped components for the new design

Table 3 Comparison table for original and selected design parameters

	Original	**Modified**
L x W	12.5 x 10.6 x 1.6 mm3	10.6 x 6.096 x 1.45 mm3

Antenna thickness	0.3mm	0.15mm
Antenna track width	1.29mm	0.649 mm
Antenna length	23 mm	24.5mm
Electrical length	$\frac{1}{10}\lambda$	Slightly more than $\frac{1}{10}\lambda$
Power transfer	5 e -11	4.6 e -12

5. Conclusion

This research embarked on an ambitious journey to understand and harness various tracking technologies, ultimately focusing on subharmonic frequency techniques suitable for ecological monitoring. The research began with a comprehensive examination of the available literature on pollinator ecology, their declining populations, and the critical need to develop technologies to track and study these vital creatures. The investigation progressed through the exploration of different types of antennas, SAR technology, RFID tracking, and inductor antennas. The goal was to develop a tag small enough to be carried by a pollinator without impeding its natural behaviour, yet robust enough to provide reliable data for ecological studies.

Through a series of intricate experiments and simulations, various physical and electrical parameters were meticulously adjusted. Antenna thickness, track width, the physical layout of the ground plate, and the internal circuit topology were all scrutinized and optimized. It was imperative that these modifications did not significantly diminish the tag's operational range or signal integrity. Through meticulous simulation and experimentation, key design parameters were optimized, culminating in a tag that is 75% the size of its original design. While the final power loss in the lumped elements of the tag registered at 4.6e-12 W—a tenfold decrease from the original tag's power loss of 5e-11 W—this reduction aligns with the theoretical understanding that less power received by an antenna system correlates with a decrease in operational range. Thus, while the modified tag's range is diminished to 1m, this range is adequate for the intended purpose of closely monitoring pollinator behaviour within a limited area. This balance between size, efficiency, and range signifies a significant stride towards realizing practical applications in ecological monitoring and highlights the potential for further innovation in wireless sensor technology.

The research found that although the final power loss in lumped elements was an order of magnitude less than the original design, this translated into a reduced operational range that still met the project's requirements. The final design proposed an SA-SubHT that was 75% the size of the original but still capable of a practical range of 1 meter, confirming the theoretical understanding that power loss correlates directly with the tag's range.

It demonstrates that through persistent innovation and careful consideration of design parameters, one can successfully balance the constraints of miniaturization with the functional demands of wildlife tracking technologies. This work sets a precedent for future ecological monitoring efforts and opens new avenues for the application of sophisticated tracking devices within the field of conservation.

5.1 Future Work

The tag designed in this research is miniature enough to be used with different pollinators and insects, but it can still be reduced in size for it to be optimal for the honey bees. The honeybees can not carry bigger tags and larger weights make them tired and exhausted. To avoid extra burden for the bees, the tags need even more reduction. The tags proposed in this research can be used with queen bees or bumble bees which are slightly larger and they can carry such tags without any hinderance in their everyday life.

There are different approaches which are used to decrease the size of the tag. As it can be seen from this research, the decrease in size of the tag causes the quality factor of the tag and ability of tag to receive power to be decreased as well. To decrease the size of the tag, it is required to increase the quality of the tag first. The implementation of SIW cavity is one of the approaches used by researchers to decrease the size of the RFID tags [38]. Similar techniques can be implements along with capacitor coupling to increase the quality of the tag which will then allow the tag to be reduced even further without effecting the range of the signal. This approach also brings the challenge of adding capacitive plates to the tag increasing the weight and thickness of the plate. The approach of capacitive loading has also been used for slot loop antennas and can be tested on the proposed design as well [39]. Another approach to decrease the size of the tag will be the use of high permittivity material for the substrate. Use of different material can completely change the nature of tags and can allow the tag to achieve higher quality. Similarly, there are other approaches as well such as antenna optimization techniques which refer to the use of miniature antennas including meander-line antenna can be another approach.

All these methods require the tag to be further modified to be used for honeybees. The original tag has been tested already but the proposed modified tag has not been tested in the field due to its size being larger than the required size for honeybees. The tag can be easily manufactured in the laboratory by ordering the suitable components and designing the tag on a PCB. The same approach can be used to test the quality of the tag in the open field as used for the original tag which required a power source and transmitter to transmit the signal at 900 MHz while a receiver which receives all the incoming signal and can identify the signal from the tag. This consists of the sending and receiving antennas, a power amplifier, a second power amplifier, a spectrum analyser that serves as the receiver, and a signal generator that generates the interrogation signal at fin. This arrangement was meant to mimic the design of a traditional IoT reader.

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