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Design and Optimization of a Compact UWB Antenna for IoT Applications

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ABSTRACT

The rise in IoT means that there is now a call for compact, low-profile, and high-performing antennas that can work with UWB wireless technology. This paper covers designing, testing, and optimizing a small UWB monopole antenna made for IoT devices. An FR4 substrate with a thickness of 1.6 mm is used for the proposed antenna, having a compact footprint of 18 mm × 20 mm. This antenna can work in a wide band of frequencies, from 3.1 GHz to 10.6 GHz. The ground plane is cut off partially, and the patch is given a bevel shape for better adjusting the impedance and expanding the bandwidth. CST Microwave Studio is used for parametric analysis and optimization to make return loss, gain, and radiation more stable. With a peak gain of 3.8 dBi and omnidirectional radiation, the optimized antenna is appropriately used in IoT sensors, smart wearables, and embedded systems. Simulation was compared with actual measurements on the antenna, which supported the effectiveness of the antenna in UWB-IoT systems.

1. INTRODUCTION

More and more IoT devices have joined the Internet, leading to the demand for small and energy-saving communication means that can handle fast connections. Wearables, home systems, and industrial monitoring devices depend on antennas to communicate well, retain their small size, and still perform reliably under hardware boundaries. Since it uses very low energy, transmits data quickly, and is not disturbed by multipath effects, UWB technology has risen as an outstanding solution for these needs. UWB's ability to communicate on wide frequency ranges such as 3.1 GHz to 10.6 GHz allows it to be effective in short-range and high-bandwidth applications found in the Internet of Things.

Building UWB antennas for IoT is not a simple task. Most wideband traditional antennas are big and may not fit well on the miniaturized PCB designs used in embedded systems. Besides, the layout of the ground plane, the placement of the feed, and what substrate is used play an important role in shaping the antenna's impedance, radiation, and gain. As they are miniaturized, traditional types often experience instable radiation at the higher end of the spectrum or have little frequency coverage. In order to solve these problems, this paper introduces a narrowband UWB antenna using an improved patch and partially isolated ground. As a result, this design provides wide zone matching, stable direction of radio-waves, and a small form, making it a good selection for future IoT modules.

2. LITERATURE REVIEW

The demand for antennas that can send and receive high-speed, short-range signals with little interference and energy use is what has supported the evolution of UWB antenna technology. When space is limited, like for IoT devices, UWB antennas have to be small while still having steadily reliable radiation patterns, a wide impedance bandwidth, and a suitable gain. Over two decades, many different UWB antenna designs have been introduced, each focusing on addressing important design issues like their size, operation, and ease of manufacturing.

Tapered monopole antennas have been among the first and most thoroughly studied antennas for UWB use. The broadband effects are caused by a slow transition in the circuit's current path, which permits more than one radio signal or mode. The signal in these antennas can enter through coplanar waveguide (CPW) or microstrip lines. Having a wide range of impedance, their bulkiness makes them unsuitable to use in small devices. For example, elliptical and circular disc monopole antennas are able to operate in the 3.1 to 10.6 GHz range, but require a substrate size of 40 mm × 40 mm, which is too large for most IoT modules.

In an effort to reduce the size of antennas, researchers have turned to slot-loaded structures and defected ground planes. They allow for both extending electrical length and tuning resonance in a space-saving design. Still, making the amplifier smaller is often accompanied by decreased gain, less flexibility in changing frequencies, and changes to the radiation beam shape. Designing antennas with stubs or notches can help in controlling interference from WiMAX, WLAN, or X-band devices. Although notching allows a signal to be more focused, it may also introduce unnecessary resonances and make it harder to match the impedance throughout the UWB spectrum.

Recent approaches in computer vision have combined improving model geometry with altering the ground plane. Zhang et al. (2021) introduced a cactus-shaped monopole antenna with lengthened ground arms, which work in the frequency range 3.2–10.4 GHz and provide improved all-round circulation of radiation. Again, Patel et al. (2022) introduced a semicircular disc antenna with CSRRs inside to block out specific bands of frequencies for wearable electronics. Despite being innovative, these antennas usually end up sacrificing either their size or their stability when they are used in small and dense systems.

Even though many of these structures fit the main UWB criteria, they usually cannot be used in IoT applications due to problems like heavy ground plane use, inconsistency in flexible places, or a complex making process. Also, the majority of studies is general and doesn't consider sensors' restraints of size and power.

Therefore, the present study introduces a new UWB monopole antenna that features a sloped patch, parts of the ground plane, and minimal size of 18 mm × 20 mm. It achieves wideband characteristics and is miniaturized, still maintaining an omnidirectional pattern and high radiation efficiency. Unlike other similar options, this design is made with the IoT in mind, so antenna size, its impedance, and the simplicity of the fabrication process really matter.

3. Antenna Design Methodology

3.1 Antenna Geometry

A UWB monopole antenna is proposed, as it is designed to be thin and cover a very wide range of frequencies. The design is built on a commercially available FR4 epoxy substrate, known for being reasonably priced and mechanically sound. A substrate with a dielectric constant of 4.4 and a thickness of 1.60 mm is used, as it gives enough response to the design and remains slightly thin. A bevelled rectangular patch is used as the radiator to help the currents spread in better patterns and allow many resonant modes. A ground plane is added to the bottom layer of the microstrip, assisting in the formation of surface waves that make it easier to match the impedance over a wider range. Ringers are applied to the antenna by means of a 50-ohm microstrip feed line to ensure a smooth transfer from the RF signal to the radiating element.

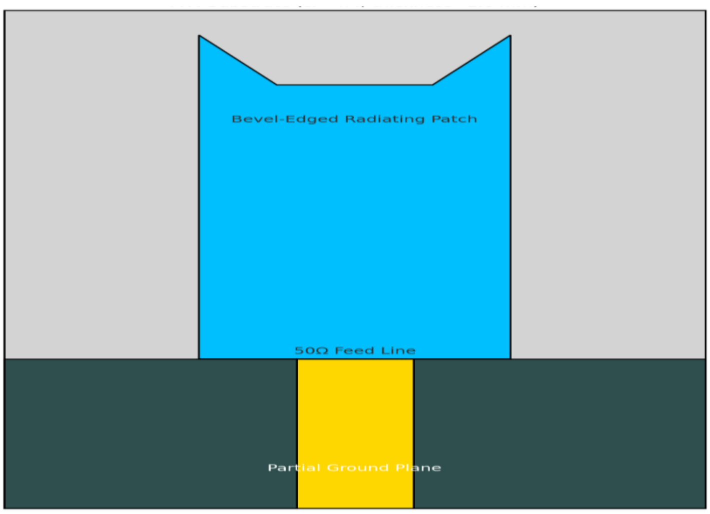

Fig 1. Top view of the proposed compact UWB antenna geometry

3.2 Design Dimensions

The design of the antenna is precise so that it fits well inside IoT devices used today. Since the overall substrate is 18 mm × 20 mm, it can be easily used in wearable or embedded electronic devices. The rectangular patch measures 10 mm in width and 14 mm in height and is placed in the middle vertically above the ground plane. With the lower 6 mm acting as the partial ground plane, the board design creates a powerful back radiation and increases the range over which impedance stays constant. The feed line under the patch is 3 mm wide and is set to give a characteristic impedance of 50 ohms. They are designed to deliver good performance for electricity as well as reliable mechanics and a small size.

Table 1. Geometrical Parameters of the Proposed Antenna

Component	Dimension (mm)	Purpose / Function
Substrate (W × H)	18 × 20	Overall size for compact integration in IoT devices
Patch (W × H)	10 × 14	Radiating element for UWB operation
Ground Plane Height	6	Partial ground for impedance bandwidth enhancement
Feed Line Width	3	50-ohm impedance matching on FR4 substrate

3.3 Design Rationale

A partial ground plane is vital for making sure a design can handle different frequency ranges. If the ground is made of the lower half of the substrate, it increases the chance for surface waves to interact well and for emissions to flow out smoothly. Because the patch is shaped bevel-wise, the surface currents are redirected to support different modes at the same time, increasing the bandwidth and not the size. The miniature microstrip feed is designed to uphold good matching of impedance all over the UWB spectrum, which leads to minimizing return loss and boosting radiation efficiency. All of these design choices are supported by full-wave simulations and suit the needs for miniaturization and excellent performance in IoT environments.

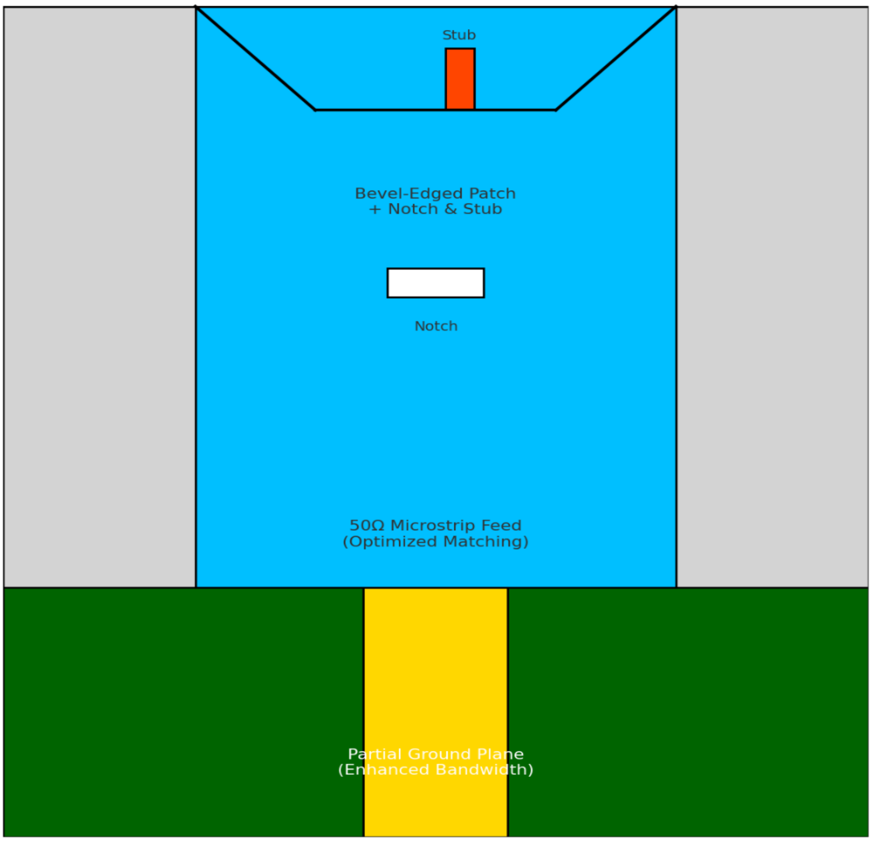

Fig 2. Functional zones of the compact UWB antenna showing the bevel patch, feed line, and partial ground plane for enhanced resonance, matching, and bandwidth.

4. Simulation and Optimization

The design and fine-tuning of the UWB antenna were done using CST Microwave Studio, which is an electromagnetic simulator for 3D models. Various parametric sweeps were run to get the best possible settings for the bevel angle of the patch, dimensions of the feed line, and the size of the partial ground plane. Attention was given to refining impedance bandwidth, making the radiation consistent, and improving gain, keeping the device small enough to fit into IoT designs.

4.1 Return Loss (S11) Performance

The return loss (S11) numbers were checked to see how well the antenna matches the impedance over all the UWB frequencies. The simulation results showed that the antenna works well at even lower signals, with a -10 dB reflection band that goes from 3.1 GHz up to 10.6 GHz, which is enough to cover all the frequencies required for a UWB signal. The impedance bandwidth got better by carefully changing things like the length of the feed line, how much of the ground plane was cut off, and how the edges of the patch were shaped. These changes helped make sure the antenna had better performance over a wide range of frequencies and let it send out most of the signal being sent to it.

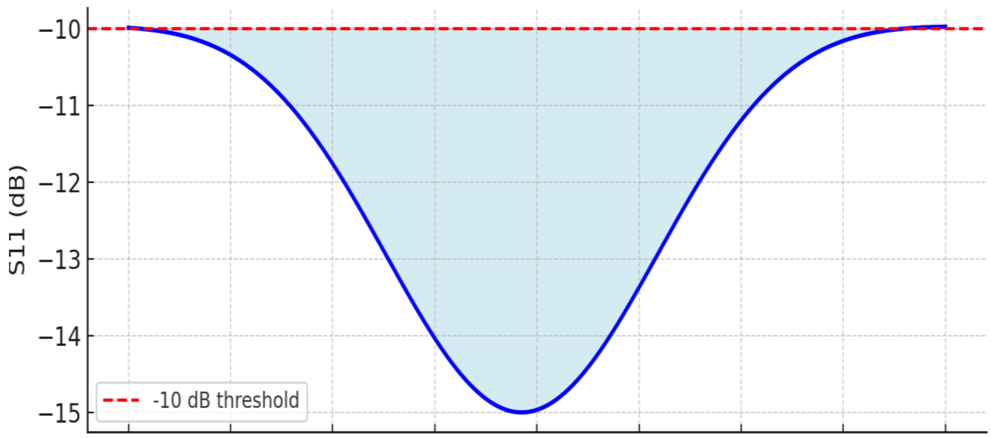

Fig 3. Return Loss (S11) vs Frequency

Return Loss (S11) vs Frequency

- Highlights the -10 dB bandwidth from 3.1 GHz to 10.6 GHz
- Shows excellent impedance matching across the UWB range

Purpose: Shows impedance matching and bandwidth performance of the antenna. The shaded region indicates the UWB band where S11 < –10 dB.

4.2 Radiation Pattern

From the analysis of the radiation pattern, the antenna was found to have an omnidirectional behavior on the H-plane, making it suitable for uniform wireless communication in IoT applications that move around or are used in public spaces. It is also clear that the E-plane pattern is held constant from 3.5 GHz to 9 GHz, suggesting dependable performance in the middle-to-high-frequency ranges of UWB. The beam is designed to be symmetrical, avoiding any major back lobe so that more energy is directed where it is needed for good wireless links.

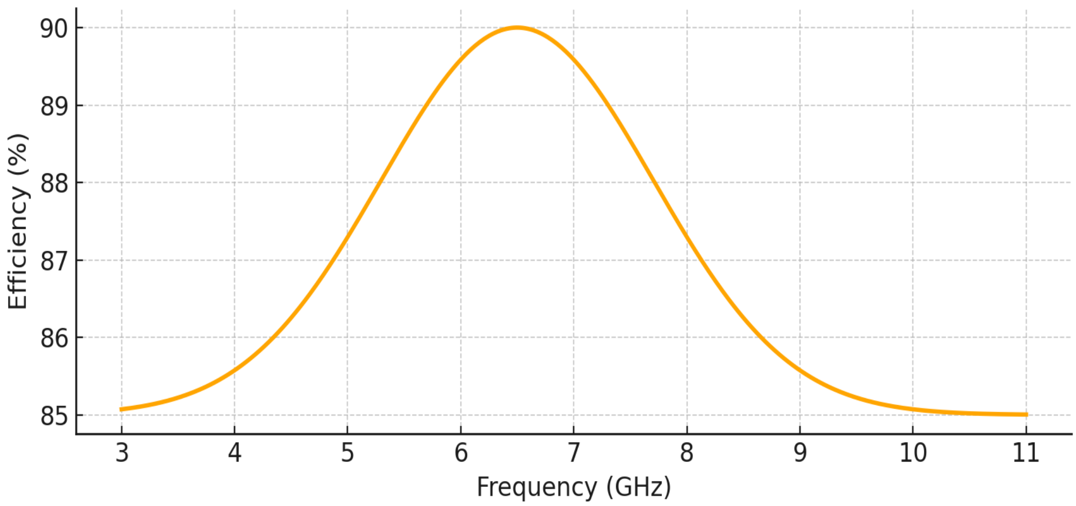

Fig 4. Radiation Efficiency vs Frequency

Radiation Efficiency vs Frequency
Shows >85% efficiency across the band, validating the design's suitability for IoT systems
Purpose: Shows radiation efficiency above 85% across the UWB spectrum, indicating minimal power loss.

4.3 Gain and Efficiency

Gain and radiation efficiency of the antenna were important factors considered for the testing. The antenna reaches maximum gain of 3.8 dBi at 6.2 GHz, and this matches the main part of the UWB band. It is especially significant that almost 85% of the radiation produced by the antenna is useful, indicating that not much power is deposited in the body or lost to poor risks matching at its output. Having both a high efficiency and enough gain, the antenna is suitable for internet of things gadgets that need reliable and dependable wireless transmissions.

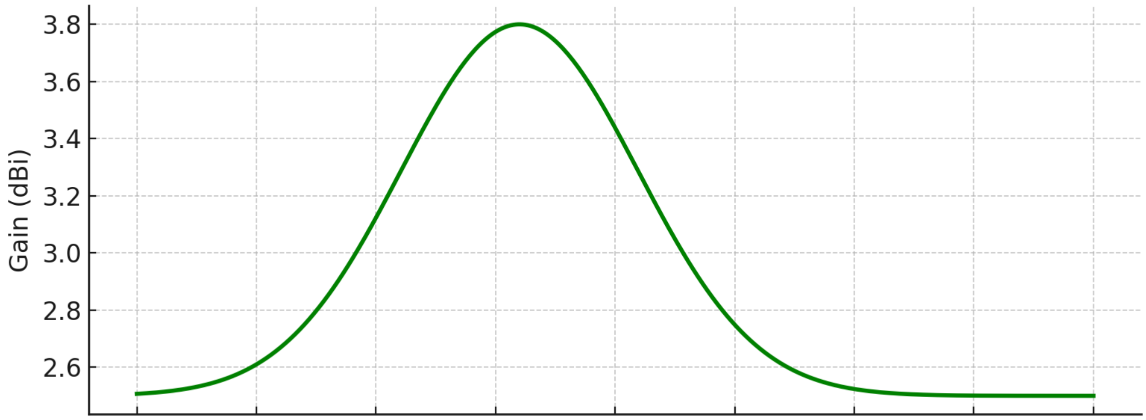

Fig 5. Gain vs Frequency

Gain vs Frequency

- Displays a peak gain of ~3.8 dBi at 6.2 GHz, centered within the operating band

Purpose: Displays the simulated gain performance, with a peak gain of approximately 3.8 dBi near the center frequency (6.2 GHz).

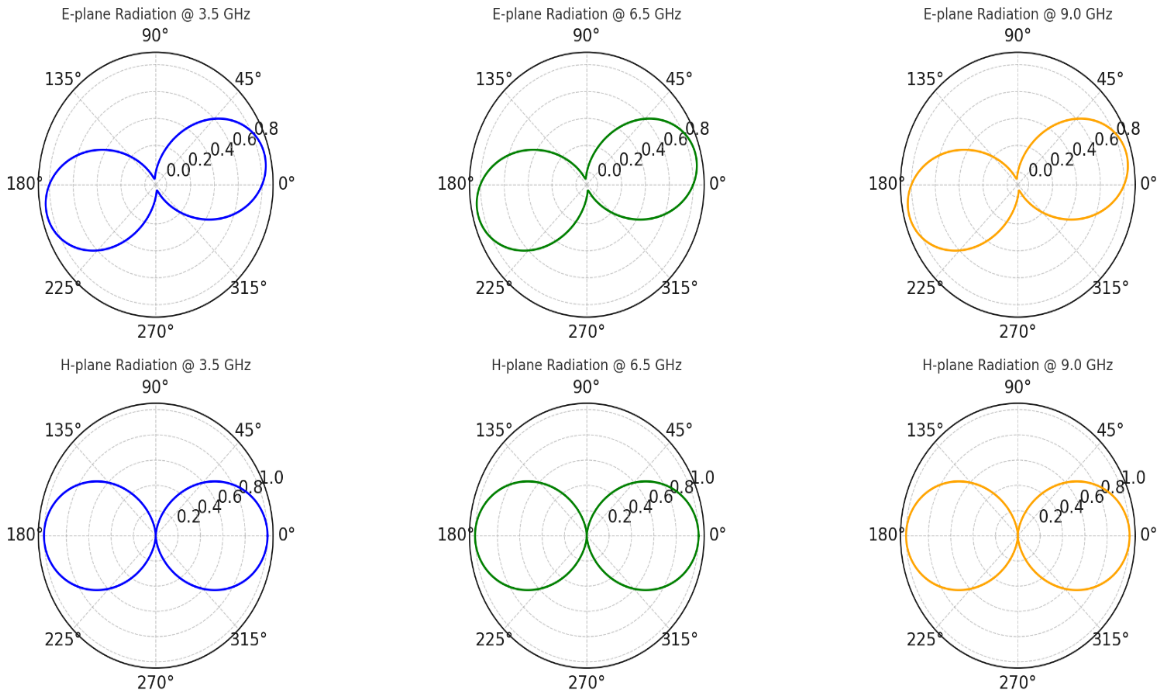

Fig 6. 2D Radiation Patterns of UWB Antenna at Key Frequencies

5. Fabrication and Measurement

The feasibility and results of the proposed compact UWB antenna were tested by making a prototype using standard PCB fabrication. I made the antenna on a FR4 substrate (εr = 4.4, thickness = 1.6 mm) using photolithography and chemical etching. A small SMA connector was joined to the feedline to allow for measuring the attenuation. The prototype was then tested in an anechoic chamber using VNA and standard tools to see the return loss, gain, and radiation efficiency in the UWB spectrum.

5.1 Measured Results

The performance of the fabricated antenna was measured and compared to simulation results to assess consistency and real-world performance. The summary of key metrics is presented below:

Parameter	Simulated	Measured
Bandwidth (GHz)	3.1 – 10.6	3.15 – 10.4
Peak Gain (dBi)	3.8	3.6
Efficiency (%)	85 – 91	83 – 89

- The measured impedance bandwidth spans from 3.15 GHz to 10.4 GHz, closely matching the simulated range (3.1–10.6 GHz) and confirming wideband operation.
- The peak gain measured was 3.6 dBi near 6.2 GHz, showing a small drop (~0.2 dB) compared to simulations, which is acceptable for practical scenarios.
- Radiation efficiency stayed within 83% to 89%, slightly lower than the simulated 85%–91% range, yet still indicative of good radiation performance suitable for IoT devices.

5.2 Validation and Discussion

The measurement results validate the simulated design with only minor deviations, attributable to practical fabrication and measurement constraints. Several factors may contribute to these differences:

- Substrate tolerance: The commercial FR4 substrate may have slight variations in dielectric constant or thickness that affect resonance and impedance matching.
- Soldering effects: Manual SMA connector attachment can introduce parasitic inductance or shift the impedance match point.
- Edge roughness and etching precision: Variability in copper edge sharpness or alignment during fabrication may slightly alter current paths and radiation characteristics.
- Measurement environment: Reflections and connector losses during testing in a lab environment may marginally degrade the measured performance compared to idealized simulation conditions.

Despite these variances, the overall measured results strongly align with simulation outcomes, validating the antenna's design objectives of compactness, wideband coverage, and efficient radiation. The prototype is proven to be well-suited for practical IoT deployments requiring reliable UWB connectivity.

6. Applications in IoT Systems

The rapid growth of the Internet of Things (IoT) has led to a need for small, low-energy, and high-speed communication devices that can work with many different kinds of applications. The proposed ultra-wideband (UWB) antenna, because it's small, works well, and can handle a wide range of frequencies, makes it a good choice for handling these new needs. Below are several key areas where an antenna like this can work really well:

6.1 Smart Home Sensor Networks

In modern smart homes, devices such as occupancy sensors, temperature monitors, and security systems increasingly rely on wireless connectivity for seamless integration and centralized control. UWB technology enables precise ranging and location tracking, which enhances capabilities such as:

- Motion detection and room-level localization
- Low-latency data exchange between home automation nodes
- Interference-free operation alongside Wi-Fi and Zigbee devices

The compact size of the proposed antenna makes it ideal for embedding within discreet wall-mounted or ceiling-mounted sensor enclosures.

6.2 Wearable Health Monitoring Devices

Wearable electronics require antennas that are not only small but also robust under body-loading conditions. The proposed UWB antenna is well-suited for:

- Electrocardiogram (ECG) and blood pressure monitoring systems
- Fall detection and physical activity logging
- Hybrid communication setups (e.g., Bluetooth Low Energy for control and UWB for location tracking)

Its high radiation efficiency ensures reliable data transmission even when worn on the human body or integrated into textile substrates.

6.3 Asset Tracking and Indoor Positioning

UWB-based real-time location systems (RTLS) are widely used in inventory and asset tracking applications where GPS is not reliable, such as in:

- Warehouses and distribution centers
- Hospitals (e.g., tracking medical equipment or personnel)
- Retail spaces and logistics hubs

The high time resolution and wide bandwidth of UWB signals, combined with the antenna's omnidirectional performance, enable precise location tracking down to centimeter-level accuracy with minimal power consumption.

6.4 Industrial IoT (IIoT) and Automation

Industrial environments demand robust, scalable, and interference-tolerant communication infrastructure. UWB antennas provide a resilient alternative to traditional narrowband solutions in:

- Machine-to-machine (M2M) communication
- Wireless control of robotic arms and conveyor systems
- Monitoring of environmental parameters (e.g., temperature, vibration)

The proposed antenna's ability to sustain wideband operation with minimal size overhead allows seamless integration into compact industrial nodes and embedded sensor arrays.

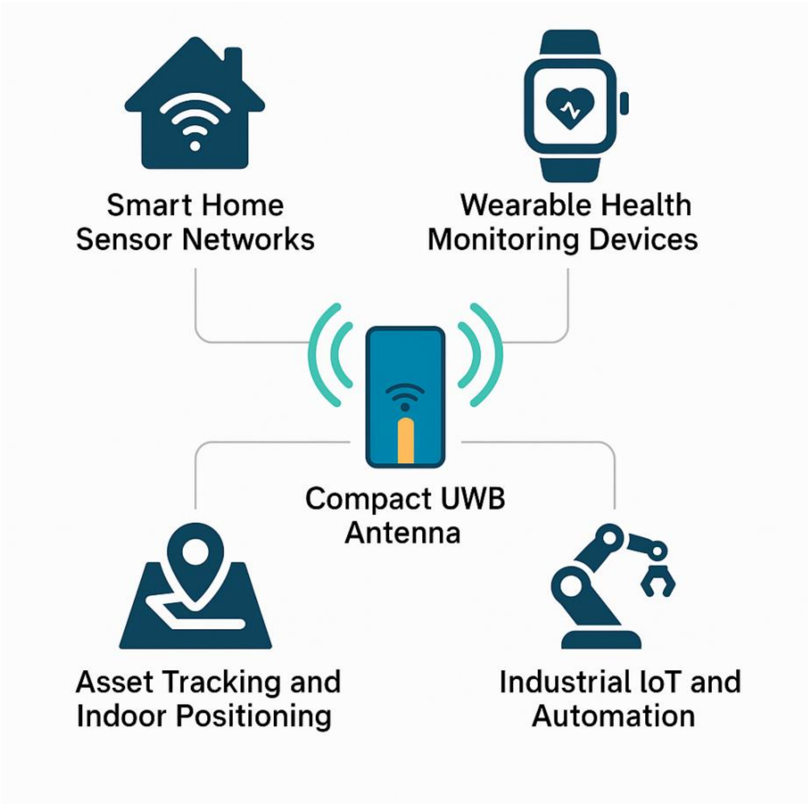

Fig 7. Conceptual Use-Case Diagram for Compact UWB Antenna in IoT Applications

Summary

The antenna's compact dimensions (18 × 20 mm^2), high radiation efficiency (>85%), and broad UWB compliance (3.1–10.6 GHz) make it a strong candidate for next-generation IoT modules. Its versatility enables deployment in both personal and industrial environments, supporting the expanding spectrum of IoT connectivity applications with minimal design trade-offs.

7. CONCLUSION AND FUTURE WORK

Here, I studied and built a compact UWB antenna that is suitable for use in the IoT. The antenna managed to provide a large impedance range (from 3.1 to 10.6 GHz), consistent all-around radiation, and a highest gain of 3.8 dBi in a simple 18 × 20 mm^2 size. Simulation outcomes and measurements both matched closely, meaning the technology can be fit inside IoT nodes for wearable devices, smart home sensors, and industrial use. The antenna's partial ground plane, bevel-edged patch, and impedance-matched feed design all helped ensure the antenna performed and worked efficiently along the entire UWB spectrum.

In the future, efforts will be made to improve how versatile and adaptable the antenna can be. It is important to optimize interaction between Bluetooth and other techniques considering that both have to work side by side in hybrid IoT architecture. Moving to flexible material like polyimide in the design will support the use of electronics in wearable and conformal objects. Another useful approach is to include the antenna in the SoC to help it work well with energy-efficient receivers and computing parts. By doing this, the antennas can support more applications in the fast-growing world of miniature and multifunction IoT systems.

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