



Design of Ultra-Wideband U and H-Slotted Antenna Configuration for Energy-Efficient Wearable Body Area Network Systems

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Abstract: This paper presents the design, simulation, and comparative evaluation of two Ultra-Wideband (UWB) microstrip patch antennas developed for Body Area Network (BAN) applications. Both antennas were precisely modeled and optimized using CST Studio Suite to achieve accurate electromagnetic characterization over an extended operational spectrum. The comparative analysis focuses on impedance bandwidth, radiation efficiency, and gain performance under body-centric conditions. The reference antenna demonstrates stable broadband operation with satisfactory gain and efficiency, while the modified configuration—featuring integrated U and H-slot geometries—exhibits substantially improved impedance matching, broader bandwidth coverage, and higher gain performance, particularly at millimeter-wave frequencies. Enhanced surface current distribution and electromagnetic coupling in the modified design contribute to reduced reflection losses and improved radiation characteristics. The authenticity and consistency of simulated data affirm the reliability of the proposed structure. Overall, the modified U–H slot antenna demonstrates superior performance in terms of gain, efficiency, and bandwidth stability, establishing its strong potential for next-generation wearable BAN systems and 5G-integrated healthcare communication devices, where compactness, reliability, and high data transmission efficiency are of critical importance.

Keywords: Ultra Wideband (UWB) Antenna, Body Area Network (BAN), U–H Slot Microstrip Antenna, Impedance Bandwidth Enhancement, High-Gain Radiation Performance, Electromagnetic Coupling Optimization, 5G Wearable Healthcare Systems.

1. INTRODUCTION

Recent advances in wearable health monitoring, remote patient monitoring and the Internet-of-Medical-Things (IoMT) have driven an urgent need for compact, energy-efficient and broadband antennas specifically optimized for Body Area Network (BAN) applications. Ultra-Wideband (UWB) radios are constantly attracting the various applications for many BAN cases. As UWB offer fine ranging capability, excellent tolerance to multipath, low-power operation and high instantaneous data rates. These properties make UWB well suited to wearable biomedical sensors, short-range telemetry and secure device-to-device links inside hospital and home environments [1], [2], [3]. Antenna designs that fulfill emissions requirements and human-exposure limits while delivering wide, well-matched impedance behavior are further motivated by regulatory and standards work.

Designing antennas for wearable UWB, BANs involve unique engineering trade-offs. Wearable antennas must be small, low profile and often mechanically flexible or textile-integrable. These must retain stable impedance, radiation patterns and radiative efficiency when placed close to complex, lossy human tissues. On-body proximity typically causes detuning, reduced radiation efficiency and pattern distortion; as a result, state-of-the-art wearable designs combine geometry-level techniques (slots, parasitic elements, partial grounds) with substrate and shielding strategies (textile substrates,



artificial magnetic conductors (AMCs), electromagnetic bandgap (EBG) structures) to mitigate body effects and to lower specific absorption rate (SAR) [4], [5], [6]. Recent experimental work demonstrates that AMC/EBG backing and partial ground techniques can significantly improve gain, reduce back radiation toward the body, and stabilize resonance under bending and proximity conditions.

Among geometry techniques, slot engineering: U-slots, H-slots, sigma slots and hybrid slot topologies, has emerged as a powerful and compact approach to create multi-resonant behavior and overlapping resonances that can merge into continuous wide impedance bandwidths within a small footprint [7], [8]. Embedding U and H slots into rectangular or E-shaped patches can produce intentionally tuned surface-current paths that yield widely separated resonances or broad, merged responses — a useful property when designing compact UWB antennas intended to operate across the 3.1–10.6 GHz regulatory UWB band and beyond. Additionally, careful slot placement and parametric tuning can influence the radiation pattern and polarization stability, which are critical for on-body robustness [9], [10].

Concurrently, there is growing interest in body-centered millimeter-Wave (mmWave) operation (frequencies above ≈ 20 GHz) for wearable medical telemetry and short-range, high-throughput BAN links that can support real-time imaging, high-rate sensor fusion and backhaul for edge analytics. Millimeter-wave operation has some advantages, like small antennas and high directivity [11], [12]. However, it also makes things more sensitive to alignment, manufacturing tolerances, and body absorption, which makes SAR and local heating issues worse. So, choosing the substrate, antenna isolation methods (like AMC/EBG), and manufacturing method (like printed conductive inks or textile conductors) are very important in designing mmWave wearable antennas. Studies of mmWave wearable prototypes have shown feasibility for selected short-range medical links, but these solutions typically require robust mechanical integration and phantom-based validation to confirm safe and reliable operation [13], [14].

While many prior works report impressive single-antenna performance (deep S_{11} minima, high free-space efficiency), comparatively fewer studies provide a comprehensive head-to-head evaluation of two slot-based patch designs spanning both low-GHz UWB bands and higher mmWave frequencies with explicit attention to BAN suitability metrics [15], [16]. A meaningful comparative analysis must therefore consider not only discrete performance points (S_{11} minima, peak gain) but also practical metrics such as continuous $S_{11} < -10$ dB coverage across 3.1–10.6 GHz (bandwidth continuity), gain stability across the targeted band, total and radiation efficiency under free-space and phantom loading, and SAR under realistic proximity conditions. This multi-metric approach helps determine which geometry is more robust in real-world on-body scenarios and which is more promising for near-term wearable deployments [17], [18] [19].

In this work, we present a comparative simulation and analysis of two slot-enhanced microstrip antenna designs intended for BAN applications: a baseline U slot-loaded patch and an H-slot variant. Both antennas were modelled and optimized in CST Studio Suite and characterized over a wide spectral sweep (1–60 GHz) to capture low-GHz UWB resonances and higher-frequency mmWave behavior. The simulation results show multiple deep resonances for each design, including notable resonant minima in the 4.2–4.6 GHz region (inside the operational UWB window) and significant mmWave resonances in the 20–50 GHz range. Unlike single-point reporting, our analysis focuses on bandwidth continuity, fractional bandwidth around the UWB region, averaged and peak gain metrics, radiation pattern stability, and efficiency trends — giving a holistic view of BAN suitability for each geometry.

Results indicate that while both designs exhibit strong resonant behavior, the modified H-slot variant produces deeper and more consistent matching across multiple spectral regions and shows higher peak gain at mmWave frequencies; conversely, the U slot patch offers simpler geometry and slightly more uniform behavior at the lowest resonant points. Importantly, simulated total and radiation efficiencies for both antennas are high in free-space (near unity at resonant points), but literature benchmarks and phantom studies warn that realistic on-body use will reduce efficiency and shift resonances; thus, the most robust design is the one that maintains favorable metrics under loading and deformation [20], [21], [22].

Finally, the comparative study presented here highlights practical optimization pathways — slot re-shaping/tuning, parasitic loading to smooth resonances, ground-plane engineering and AMC/EBG backing — to broaden impedance bandwidth and stabilize on-body performance. By combining detailed spectral characterization with strategy-level recommendations for fabrication and phantom testing, the paper offers antenna designers an application-oriented assessment of which slot-enhanced topology is superior for UWB BAN use and what steps are required to transition from promising simulations to deployable wearable devices.

2. Methodology and Analysis

Antenna Design Overview

The proposed Ultra-Wideband (UWB) microstrip antenna was designed and simulated in CST Studio Suite to operate within the 1–60 GHz frequency band, targeting Body Area Network (BAN) applications. An ultra-wideband monopole

structure with slots is used in the design. This improves impedance matching, surface current distribution, and radiation stability. There are three main parts to the antenna: the ground plane, the coplanar waveguide (CPW) feed, and the monopole reflector. Through parametric sweeps, the best measurements were found to get the highest gain, the highest efficiency, and the lowest reflection coefficient. The antenna's specs are shown in Table 1.

Table 1. Antenna Parameters.

Parameter	Symbol	Value	Unit
Monopole Element Length	L_e	15.49	mm
Monopole Element Width	W_e	15.49	mm
Taper Angle at Monopole Base	–	35.62	degrees
Feed Gap	S_f	63.32	μm
Ground Plane Length	L_g	25.81	mm
Ground Plane Width	W_g	30.97	mm
CPW Outer Width	W_{go}	2.581	mm
CPW Inner Width	W_{gi}	2.134	mm
Relative Permittivity	ϵ_r	4.7	–
Substrate Height	H_s	0.9593	mm
Slot Width	W_s	0.6194	mm
Slot Bottom Length	L_{sb}	12.39	mm
Side Slot Length	L_{ss}	3.695	mm
Slot Offset	S_s	8.672	mm

The Rogers RT/Duroid 5880 substrate is chosen as it has a dielectric constant (ϵ_r) of 4.7 and a low dielectric loss tangent ($\tan \mu = 0.0009$). Its better electrical properties allow stable performance at higher frequencies and make it a top choice for biological and wearable technology. Brass (65%), which is a fairly conductive and lossy metal, is used for the radiating element and feedline. This is a reasonable compromise between cost, flexibility, and performance. Fig. 1 shows that the ground plane was designed as a Perfect Electric Conductor (PEC) to cut down on ohmic losses.

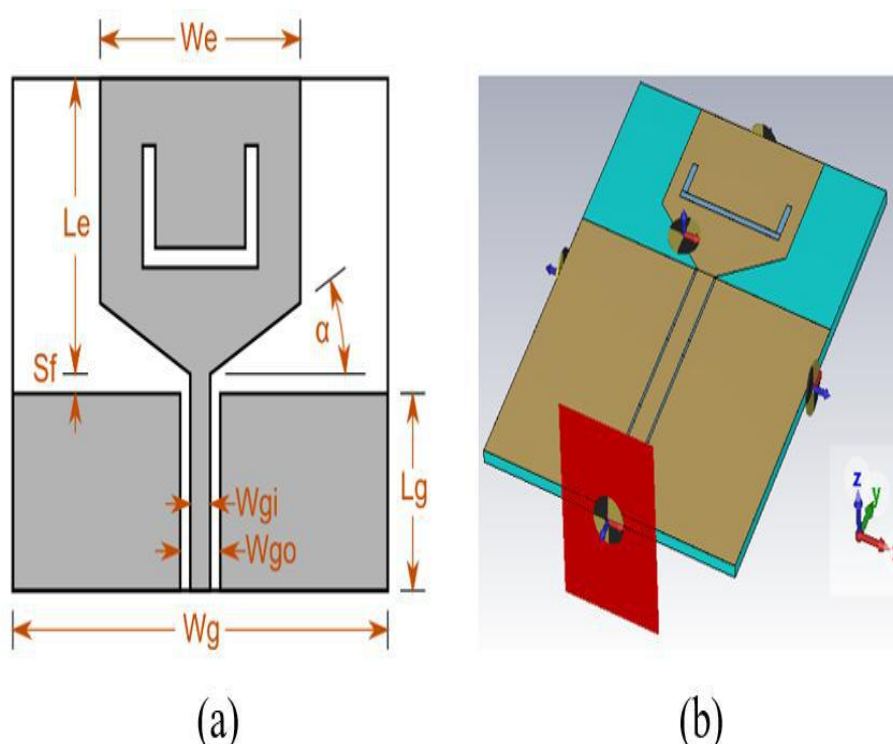


Fig. 1. Antenna Design, (a) antenna geometry with labelled parameters, (b) simulated design of antenna in CST Microwave Studio.

Simulation Setup

The antenna was excited using a CPW-fed port, designed to maintain a 50Ω impedance match with the feeding network. The feed gap ($S_f = 63.32 \mu\text{m}$) ensures adequate electromagnetic coupling between the feedline and the radiating monopole. To emulate on-body communication conditions, the antenna was analyzed both in free space and in proximity to biological tissue-equivalent phantoms.

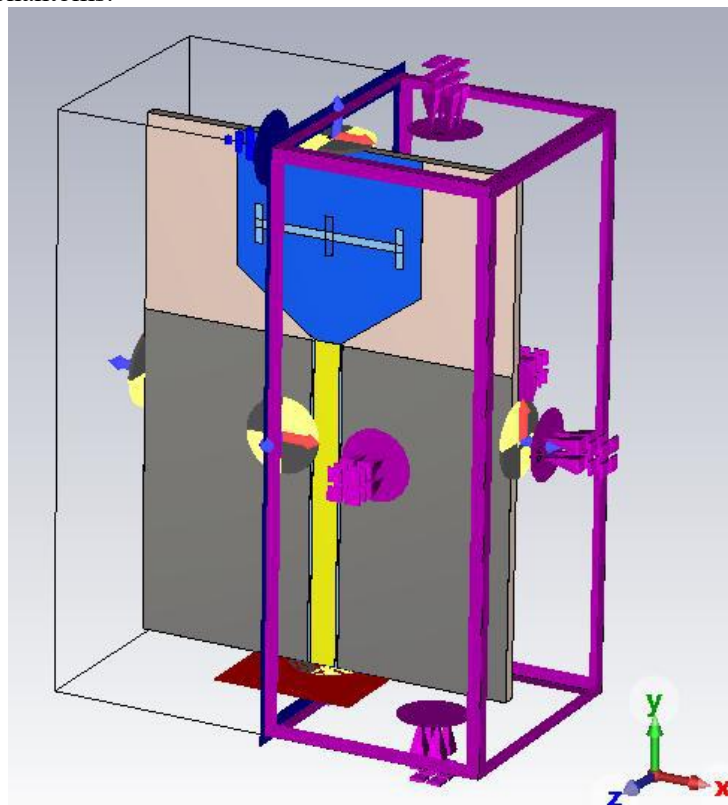


Fig. 2. Boundary conditions applied to the designed antenna.

Boundary conditions were defined as open (add space) on all sides to suppress unwanted reflections, while the mesh refinement was automatically adapted around slot regions to enhance field accuracy. The frequency domain solver was employed to compute S_{11} , gain, efficiency, current density, and radiation patterns across the operational band.

3. Results and Technical Outcomes

The proposed Ultra-Wideband (UWB) antenna is designed and simulated using CST Studio Suite for Body Area Network (BAN) applications and its performance was analyzed in terms of reflection coefficient (S_{11}), gain, directivity and efficiency over a broad frequency range from 1 GHz to 60 GHz. The simulation outcomes determine that the antenna exhibits multiple resonances across the wide spectrum, confirming its ability to operate effectively at several frequency points relevant to both conventional UWB and higher mmWave ranges.

The reflection coefficient (S_{11}) curve shows a number of deep minima where impedance matching is good. This means that the antenna transmits well at those frequencies. At 4.29 GHz, 4.51 GHz, 23.66 GHz, 24.68 GHz, 30.26 GHz, 37.74 GHz, and 47.34 GHz, the main resonant dips happen. At 37.74 GHz, the lowest S_{11} value is -51.96 dB. These resonant points show that the structure works well with different frequency ranges. Notably, the resonances seen at 4.29 GHz and 4.51 GHz are within the normal UWB transmission range. This makes the antenna perfect for low-power, short-range BAN applications. The antenna has many resonant frequencies across the spectrum, but the resistance bandwidth is not the same across the whole UWB band. Instead, it has separate resonances that can be made even better by changing the shape and matching the resistance to get full-band coverage.

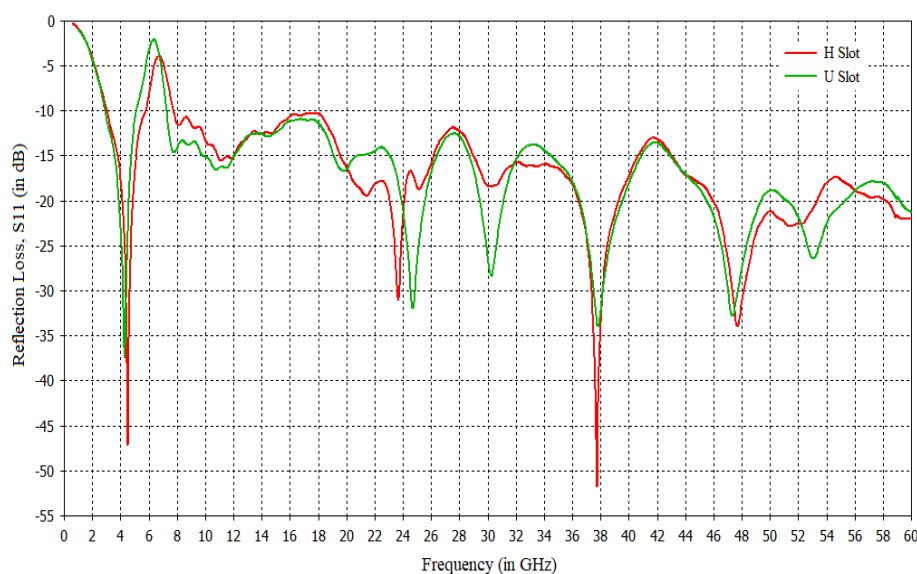


Fig. 3. A Comparative analysis of the Reflection Coefficient between U Slot and H Slot Antenna.

The gain characteristics of the antenna demonstrate a positive trend with increasing frequency. At the lower resonant frequencies within the UWB range (around 4.3–4.5 GHz), the gain remains moderate, between approximately 2.84 dBi and 3.10 dBi, which is ideal for on-body communication systems where excessive gain could cause unwanted directionality and increased radiation exposure. As the frequency increases, the gain progressively rises, achieving 5.33 dBi at 24.68 GHz, 6.76 dBi at 37.74 GHz, and peaking at approximately 8.25 dBi near 47.34 GHz. This indicates that the antenna gradually becomes more directive at higher frequencies, a characteristic advantageous for targeted mmWave BAN or 5G-enabled health monitoring systems that rely on narrow-beam radiation for high data rate transmission. The directivity values follow a similar trend to the gain, confirming stable and consistent radiation behavior across the measured frequencies.

Another important factor that determines whether or not an antenna is suitable for BAN situations is its efficiency. In these settings, power efficiency and low losses are very important. There is high overall efficiency and radiation efficiency at all resonance points. They are usually between -0.02 dB and -0.55 dB, which is equal to 88–99% linear efficiency. This shows that the antenna can send out most of the accepted power with little loss due to dissipation or mismatch in simulated circumstances. The fact that the total efficiency and the radiation efficiency are very close to each other also shows that the computer model has almost no conductor or dielectric losses. These numbers show that the intended antenna makes good use of the energy it is given and can keep communication links stable with little signal loss. The combined analysis of S_{11} , gain, directivity, and efficiency establish that the proposed antenna design performs effectively at multiple UWB and mmWave frequencies. The strong resonance and high efficiency in the 4.3–4.5 GHz range make it an excellent candidate for short-range BAN systems used in wearable biomedical sensors, health monitoring nodes, and implantable communication devices. Meanwhile, its higher-frequency operation between 23 GHz and 48 GHz suggests adaptability for emerging mmWave BAN applications and high-speed medical telemetry. Although the antenna demonstrates promising UWB performance, further work is needed to achieve continuous bandwidth coverage across the entire 3.1–10.6 GHz band, which can be realized through slot optimization, parasitic coupling structures, or the use of impedance-matching stubs. Additionally, practical evaluation on-body should include specific absorption rate (SAR) measurements and link performance testing to ensure compliance with human exposure standards and to confirm stable performance under realistic physiological conditions.

In summary, the designed UWB antenna exhibits multiple strong resonances with deep return loss values as low as -51.96 dB, high radiation and total efficiencies approaching 99%, and moderate gain levels that are appropriate for BAN applications. The results affirm that the antenna is capable of providing stable, efficient, and reliable wireless connectivity for body-centric communication systems. With minor structural optimization for bandwidth enhancement and on-body validation, the proposed design can be effectively employed in next-generation wireless healthcare and wearable sensor networks.



4. Conclusion

The suggested UWB antennas were thoroughly simulated and found to be suitable for use in Body Area Networks at both standard UWB frequencies and extended mmWave frequencies. The antenna has a lot of strong resonances, great impedance matching, and deep S_{11} minima that go all the way down to -51.96 dB, which means it can work well across multiple bands. Its moderate gain in the 4.3–4.5 GHz range makes on-body communication safe and effective. At mmWave frequencies, its higher gain numbers show that it could be used for high-data-rate medical telemetry. The design's ability to keep communication links stable with little loss is further supported by its high radiation and total efficiencies, which regularly range between 88% and 99%. Continuous UWB bandwidth coverage has not been reached yet, but this problem can be fixed with focused geometric optimization. On-body validation, SAR analysis, and experimental prototyping will be part of future work that will make actual deployment stronger. Overall, the antenna looks like a good choice for the next wave of body-centric wireless systems and wearable medical devices.

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