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Conceptualizations of High-Performance Antennas for Use in Wearables

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***Abstract* - A type of antennas that can be worn on the body for lengthy periods of time without losing performance is what this study aims to create. The following qualities should be present in the suggested antennas: (1) being ergonomic and conformal to prevent any discomfort; (2) minimizing radiation into the human body for safety reasons while also ensuring a high on-body radiation efficiency; and (3) utilizing reasonable materials and manufacturing processes to reduce the overall cost and maintain a certain level of robustness. These characteristics are listed in descending order of importance. The belt buckle was chosen as the foundation for the suggested antenna designs because it had all of these desirable characteristics. The belt buckle's metal has a rigid structure that allows the designs to be both effective and strong. Two unique inventive types of belt antennas will be covered in this thesis. The second one is based on a design resembling a single tongue buckle, while the first one is based on a design resembling a pin buckle. An internal reverberation chamber is being built in order to precisely measure the on-body radiation effectiveness of the suggested antennas. Textile electromagnetic bandgap materials are being investigated and used with the second belt antenna in order to improve the on-body radiation efficacy of the antenna from its present level of roughly 40% to a level of over 70%.**

Keywords –Electromagnetic band gap materials (EBG), Metamaterials, Specific Absorption rate (SAR), Reverberation Chambers, and Artificial magnetic conductors have all been used to refer to these technologies.

1. INTRODUCTION

An investigation into the design of high-performance wearable antennas is the subject of this thesis. The investigation begins with the concept and motivation for the study, then moves on to background research and theoretical development, followed by design, fabrication, testing, and evaluation of the newly developed, one-of-a-kind concepts and procedures. In this chapter, we will take a look at the evolution of wireless communications and antennas from a historical perspective. The challenges involved in developing wearable antennas that have high on-body radiation efficiency are brought to light in this article for the sole reason that these challenges serve as the impetus for this effort. In the year 1864, James Clark Maxwell compiled and produced a set of equations that are now collectively referred to as Maxwell's Equations [1]. These equations set the foundation for wireless communication and specified the properties of electromagnetic waves. Engineers and scientists have spent a significant amount of time and effort over the course of a number of years working diligently to develop communication systems that do not need the use of physical wires. This has had the effect of profoundly changing how the world operates for the betterment of mankind. This journey began in 1886, when German scientist Heinrich Hertz used an experiment in which he combined two resonant metal rings to demonstrate the reality of electromagnetic waves predicted by Maxwell's Equations [2]. [2] This experiment combined two resonant metal rings. These rings have the potential to be considered the very first loop antennas ever developed. Antennas are necessary components for the operation of any wireless communication system. They are responsible for converting electromagnetic waves that are guided along transmission lines into waves that can freely propagate in the environment. Various kinds of antennas have been designed in order to suit the specific or ideal requirements of a communication system. These requirements include the radiation band, size, form, capacity to concentrate energy, and efficiency. The year 1901 saw the beginning of the

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use of electrical dipole antennas in the transmission of the first wireless signals over the ocean [3]. Yagi-Uda antennas were first developed in 1926, and ever since then, they have seen widespread application in the fields of shortwave communication and television transmission [4]. Since its inception in 1938, contemporary horn antennas have been put to work in a variety of applications, including point-to-point communications, as feeds for satellite dishes and radar antennas, and more [4]. The 1960s witnessed the widespread use of printed circuit board (PCB) technology, which led to the introduction of low-profile planar antennas like the microstrip patch [5]. These patch antennas have a metallic ground plane at the bottom, a dielectric substrate layer in the middle, and a metallic patch on the top. Together, these three layers make up the antenna. Because they could be directly integrated with printed circuits and were fairly easy to create in a range of shapes and quality, antennas could be swiftly built to fulfil unique system demands. This made it possible to build antennas in a short amount of time. The illustrations in figure 1-1 show some examples of the antennas mentioned earlier.

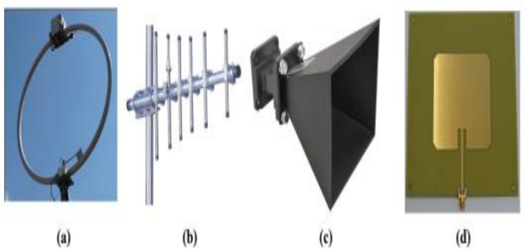

Figure 1-1 : Examples of different antenna types: (a) Loop antenna. (b) Yagi-Uda antenna. (c) Horn antenna. (d) Microstrip patch antenna.

Because of the recent increase in the number of wirelessly connected wearable devices, antennas now need to be able to operate in an environment that is centered on the human body. Wearable antennas are antennas that are specifically intended to function effectively in an environment that is complicated and close to the body. The term "wearable antennas" applies to all of these types of antennas. The term "wearable antennas" refers, in general, to antennas that continue to operate even while the device is being worn. Wearable antennas may be found in a variety of devices, including smartwatches, wristbands, eyewear such as Google Glass, and action cameras. (GoPro). The main operating frequencies for these devices are 2.45 GHz and 5.8 GHz, and they make use of Wi-Fi or Bluetooth. Because of the close closeness of the human body to the antenna in wearable electronic devices, designers of wearable antennas must contend with a one-of-a-kind set of design problems. These problems include assuring the safety of users, overcoming obstacles to efficiency, and retaining ideal radiating properties while still being ergonomic and suitable for the intended usage.

2. LITERATURE REVIEW

C. Biancotto and P. Record [75] et al., in their work on MSA using EBG-based triangular lattice dielectric rods, which are used to efficiently construct H-Plane directed patterns, The calculations and testing that were done based on the recommended model revealed great agreement, and the antenna worked very well for wireless applications owing to its FBR of 27 dB, average gain of 11 dB, and fractional bandwidth of 31%.

L. Dang and colleagues came up with an antenna that has three bands and is optimized for use in WLAN and WiMAX applications. In contrast to other antennas, this one consists of a microstrip feed line and a ground plane that has a few simple slots cut into it. Moreover, this antenna features a carved-in ground plane. The experimental findings are compared to the measurements of the manufactured prototype, which have a resonant frequency of 5.6 GHz and a bandwidth of 1300 MHz. Additionally, the center frequency of the manufactured prototype is 2.7 GHz, and it has a bandwidth of 600 MHz. The manufactured prototype also has a center frequency of 3.5 GHz, and it has a bandwidth of 430 MHz.

M. Naser-Moghadasi [77] and his colleagues developed a monopole antenna that may be used for wireless communications as part of their research. A parametric study of the design was performed for a variety of operating frequencies, and the results showed that the design exhibited omnidirectional radiations in addition to progressive gain. In addition to this, the size of the antenna has been reduced to 20201 mm3.

Ratnesh Pandey and his colleagues came up with the idea for a construction for an electromagnetic bandgap that was based on a patch slot antenna and resembled microstrip teeth. The antenna had a gain of between 5.5 and 6.5 DB while operating at the working frequency of the C-band. After undergoing testing and validation with the help of a prototypic model, the antenna that was produced went on to be used as a transponder in the C-band spectrum in applications that were developed for the satellite and military industries.

Research on the actual radiation pattern and active element pattern of an EBG-Based Circular Waveguide Rod Array was carried out by Y. Fu and colleagues in their study. A research of well-verified elimination scan blindness employing EBG structure was shown by the results. This was in contrast to an examination of general aspects of the EBG analysis done on patterns.

K. Payandehjoo and colleagues modeled and produced two different multi-antennas so that they could conduct tests to determine their radiation patterns, input impedances, gains, efficiencies, and the influence of mutual coupling. The mutual coupling effect was reduced by the proposed antenna thanks to the use of an EBG structure designed to resemble a mushroom. As a result, the radiation properties were enhanced. The EBG structure achieves a diversity gain of 3.3 dB at a received power for 99% of transmission trails by using a reverberation chamber. This results in an increase in received power. At 5.2 GHz, there is a separation of 28 decibels (dB) between the two.

In their study, C. Menudier and colleagues explored the "phase center research" of the EBG antenna. [Citation needed] He proposed the use of an antenna that provided coverage from several beams, was capable of being directed to a reflector, and was less expensive than beam shaping equipment. The purpose of the current model is to provide information on the exact placement of the phase-centric EBG structured antenna. According to the findings of the research, this method worked better than more traditional feeds such as horn in terms of overall effectiveness.

The design of the structure incorporates the MEMS-based FSS reconfigurable antenna that was presented by G. M. Coutts et al. [86]. This antenna can activate simultaneously on all of the objects by employing a realistic bias network, and it is incorporated into the design of the structure that was designed. The MEMS get their necessary mechanical support from the substrate. With the newly developed MEMS, it is feasible to build pieces of the EBG structure that are capable of being reconfigured. Using this EBG structure, the recommended model is examined, tested, and verified while operating in the Ka band.

R. Chantalat [87] and colleagues employed a cassegrain antenna with a side-fed offset when they demonstrated EBG at the Ka band for multi-spot coverage. In order to give coverage for several spots, the antenna was upgraded with a new EBG construction that was based on a multifeed mechanism. As a result of the proposed MSA, the level of sidelobe was brought down to -15 dB, and the radiation beam width was brought up.

M. J. Al-Hasan [88] and colleagues came up with the idea for and went on to develop a millimeter wave (MMW) dielectric resonator antenna (DRA) that was housed inside of an electromagnetic bandgap structure. An investigation was conducted into the properties of the MMW mushroom-shaped, circular patch EBG cell, and the findings revealed a bandwidth of 60 GHz, a gain enhancement of 3.2 dBi, and a preserving bandwidth of (0.7 dB). At 6.5 dBi, an additional backlobe suppression is also achieved, which results in a reduction in the amount of radiation that is directed towards the substrate.

An antenna with a measured gain of 15.6 dBi and an excellent gain bandwidth of 27% with 3 dB gain was proposed by Raheel M. Hashmi[89] and colleagues. The dimensions of the footprint are 1.7 by 02. The measured aperture efficiency is 90%, and the side lobe level that is produced is less than -12 dB, while the level of cross-polarization side lobes is less than -17 dB.

S. Velan and colleagues proved in their presentation of a dual band wearable fractal monopole antenna with an EBG structure that the periodic architecture reduces SAR by more than 15 dB and diminishes the influence of frequency detuning. This was accomplished by using an EBG structure. The prototype operates on the GSM 1800 MHz frequency in addition to the ISM 2.45 GHz band. The performance of the antenna was evaluated for body bending, crumpling, and other impacts, and the Specific Absorption Rate (SAR) was also recorded for future use in applications using wearable technology.

S. Y. Huang et al. developed a novel model of tapered small-size electromagnetic band-gap (S-EBG) structures and published their findings. The idea employs a one-dimensional microstrip EBG structure with a Chebyshev distribution to minimize size while maximizing pass band transmission, preventing ripples in the pass band, and providing an extremely broad stop band. All of these benefits are achieved while keeping pass band ripples to a minimum.

J. Zhang and colleagues proposed using an antenna that was based on EBG in order to bring down the radar cross section (RCS). The proposed periodic structures are shaped like mushrooms and have a frequency core of 5.0 GHz; they also have this frequency center. The EBG could be altered in order to accommodate essential frequency band requirements. When contrasted with the conventional antenna, the RCS patch array with EBG resulted in a decrease of ten decibels (dB).

For the purpose of reducing electromagnetic coupling between closely located UWB antennas, Q. Li, A. P. Feresidis, and other researchers proposed the use of a minute two-layer EBG structure. EBGs are used in the space between the two UWB monopole antennas. The redesign of the antenna resulted in favorable effects, such as a reduction in the amount of mutual interaction between the various sections and an expansion of the operating spectrum. The findings from the measurements showed that there was a positive trade-off, and the results from the simulation were consistent with the real numbers.

3. Dual-band Patch Style Belt Buckle Antenna Design

The most important elements are outlined in the table, and the layout of the design may be seen in figure 3-1. The buckle and pin that are both metallic and part of this style are both made out of brass. At this location, a commercial snap-on button made of stainless steel is being employed. The ground layer consists of a conductive fiber that has been glued to the leather belt. The conductive fiber is produced by the YGM company, which is located in Foshan, China. A value of 0.08 for the loss tangent and 2.9 for the relative dielectric constant were found to be associated with the leather.

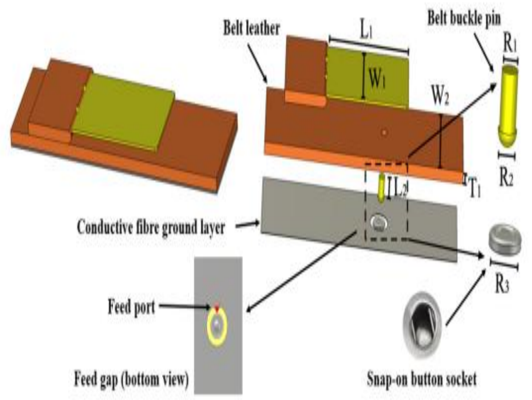

Figure 3-1 : The structure of the proposed belt antenna and key parameters.

Table 4-1: Antenna Geometry Parameters

Symbol	Quantity	Value (mm)
W_1	width of the metal cap	25
W_2	width of the belt leather	30
L_1	length of the metal cap	42
L_2	length of the belt pin	7.7
R_1	radius of the belt pin	3
R_2	radius of the belt pin snap-on	3.5
R_3	radius of the snap-on button	6
T_1	thickness of the leather	3.6

Determination of the dielectric constant and loss tangent of the leather was made using a Keysight N1501A open-ended coaxial cable probe. Figure 3-2 shows the measurement apparatus.

Figure 3-2 : The measurement setup for the electric properties of the leather.

In order to prevent any air gaps from forming, the open-ended testing probe was pressed down firmly on the leather surface without making use of a traditional holder. In order to reduce the effect that the table would have on the measurement, a layer of low-permittivity foam was placed below the leather. The obtained characteristics are around 15% off in accuracy as a result of measurement errors and the constraints of the open-ended coaxial probe. The procedure of making and accurately sizing the patch for the belt buckle needed a lot of trial and error. When the first belt antenna was constructed, a frequency shift of 150 MHz was observed. This is because of a mistake in the measurement of the permittivity of the leather. In order to arrive at an accurate estimate of the permittivity, further simulations were run in line with the findings of the observations. (2.9 for the leather used in this study). When the design specifications were altered, a new buckle for the belt was manufactured from scratch.

The recommended belt antenna operates at 2.45 GHz as a raised patch antenna and includes a TM10 mode along the long side (L1) of the buckle. This antenna also has a TM10 mode. In Figure 3-3, both the E-field distribution and the TM10 mode are shown for your viewing pleasure. To illustrate how the feeding pin affects the manner in which the electrical field is spread, a cross-section of the field in two dimensions was generated via the pin's center. In Figure 3-3 (a), there is a significant E-field distribution behind the snap-on button. This is the location where the voxel human body analysis will subsequently find the biggest SAR value.

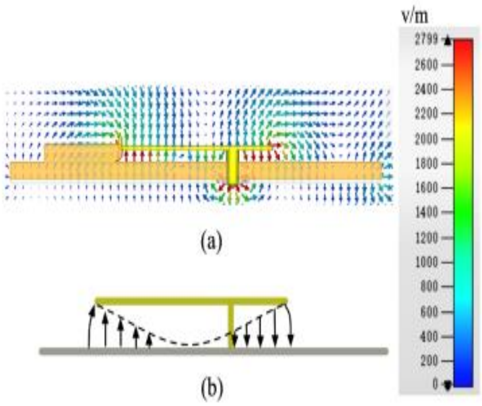

Figure 3-3 : The E-field distribution of the proposed belt buckle at 2.45 GHz. (a) The simulated E-field distribution. (b) A sketch of the operation mechanism: a TM10 mode.

There were two reasons why it was planned that the patch would be elevated. The first reason is because calculations showed that the elevation would reduce loss, and as a result, increase radiation efficiency. This is because the leather material that was utilized for this design, which is frequently employed in the manufacture of belts, has a rather substantial loss tangent. The second issue is that belts that contain pin buckles often have very limited room for adjustment. During the course of the inquiry, a number of the designs for belts were analysed, and it was discovered that the tip of the pin would snag on the leather in certain designs, creating a gap between the metal cap and the leather. Because of the buckle's ergonomic design, it can accommodate belt leathers that differ in thickness and curvature to a limited extent while still fitting well.

During operation of the antenna, the gap should ideally not change too much, thus it was important that the snap-on button be constructed with great attention to detail and planning. As shown in Figure 3-4, it is equipped with a locking mechanism that is comprised of two metallic pins, and its purpose is to establish a secure connection between the original snap-on pin and the holder socket. (b). This configuration also ensures that there will be a consistent spacing between our antenna's ground plane and its radiating patch when it is implemented. The developed belt pin has the same shape as the original snap-on button pin in order to ensure that the locking mechanism is reliable. After the belt pin has been fastened and the belt has been applied to a human body, the majority of the stress will be lateral to the body, and as a result, there will be only a limited effect on the gap between the belt and the bottom of the buckle.

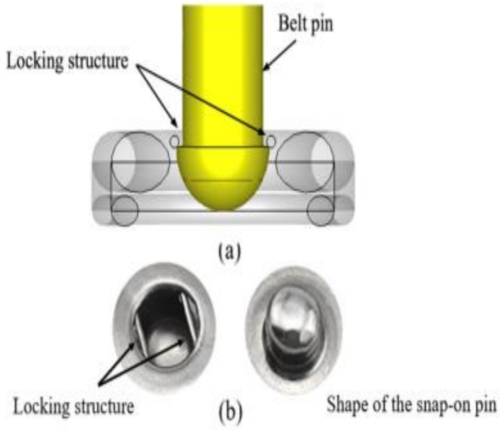

Figure 3-4 : The snap-on button holding structure. (a) Crosssection view of the belt pin and the snap-on button holder. (b) The enlarged view of the snap-on holder (two holding bars) and the original snap-on pin structure.

A quasi-TM30 mode may be seen in the radiation that occurs in the 5 GHz region. The E-field distribution at 5.5 GHz is shown in Figure 3-5 (a), along with an enlarged view of the structure of the connection between the snap-on button and the belt pin. A parallel capacitance is formed in the cavity between the tip of the long feeding pin and the button sockets, as shown in Figure 3-5. This is done in order to counterbalance the inductance that is induced by the long feeding pin.(a). Because its size has an effect on the capacitance values, the size of the snap-on button requires careful consideration in order to achieve correct impedance matching. The E-field distribution close to the feeding pin does not match the conventional TM30 mode because of the transverse electrical field. However, at some locations, most notably close to the radiation boundary, the field distribution continues to correspond to a TM30 mode.

The ground plane was formed with conduit fiber that was adhered to the reverse side of the leather. As a result, the SAR value was able to be kept to a minimum by maintaining an adequate distance between the radiating components and the human body. It is necessary to leave a very little gap between the bottom of the snap-on button and the conductive ground in order to correctly place the feed.

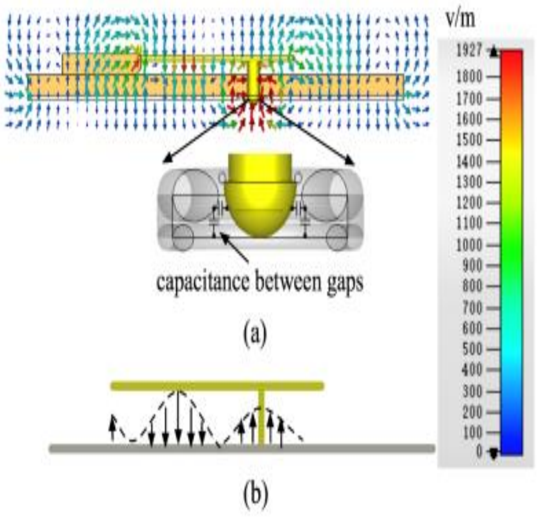

Figure 3-5：The E-field distribution of the proposed belt buckle at 5.5 GHz. (a) The simulated Efield distribution with the snap-on button structure enlarged. (b) A sketch of the operation mechanism: a quasi-TM30 mode.

4. The Measured On-Body Realised Gain and Efficiency

An evaluation of the on-body realized gain was carried out with the assistance of a test subject inside our very own anechoic chamber. (male, 188 cm and 82 kg). During the time that the measurement was being made, the person serving as the test subject maintained an upright posture, and the antenna was attached to the individual's waist. The statistics that were measured are outlined in detail in Table 4–5. In addition to this, a comparison is presented with a variety of cutting-edge wearable technology. Due to the absence of the original performance data, the reference [10] that was provided was altered and re-simulated in the same simulation environment as this investigation. The data that was utilized for comparison in this study came from the re-simulation that was performed. It is important to underline this fact. The same human being served as the research subject for both the off-body efficiency and the on-body efficiency studies, both of which are important aspects of wearable antenna applications. An indoor reverberation chamber with dimensions of 5.4 meters in length, 3.0 meters in width, and 2.8 meters in height housed both the proposed belt antenna and the human subject throughout the experiment. There is one horizontal and one vertical stirrer in the space now being occupied. The lowest useable frequency (also known as LUF) of the chamber is 300 MHz. How the belt antenna was positioned around the waist of the patient being tested so that on-body measurements could be taken. This method is used in order to evaluate the effectiveness of the treatment on the body. The human subject puts a significant amount of weight into the chamber. Before any measurements can be taken, the chamber has to be calibrated with the help of a living human subject. During each measurement, the individual under scrutiny wore the same outfit and carried the same things in his or her pockets as in the previous one. In this particular experiment, stirring was carried out in three different ways: mechanically (2 degrees, 180 observations), polarizationally (two orthogonal linear polarizations), and positionally (position stirring). (4 receiver positions). 1440 measured sample points were gathered for each frequency point that was considered. It was necessary to take a number of samples in order to keep the degree of uncertainty associated with the measurement at a reasonable level. Because it was not necessary for the test subject to spend a significant amount of time inside the chamber, the number of mechanical stirs in each run was kept to a minimum. In order to generate distinct samples from each run, the receiving antenna in the chamber was shifted by a half wavelength in order to accommodate position shifting. The resulting radiation efficiency is shown in Figure 4-1. When the human subject is in close proximity to the belt antenna in any of the frequency bands, there is a possibility that an efficiency loss of around 20 percent will be seen. The measured radiation efficiency is often lower than the figure that was estimated for it, with a few restricted frequency ranges being the exception. During the design and optimization process, the dielectric qualities of the leather were determined at a single frequency point. This is the primary cause of this issue. (2.45 GHz in this case). Because leather has varying characteristics, there will be impedance mismatch over a large frequency band.

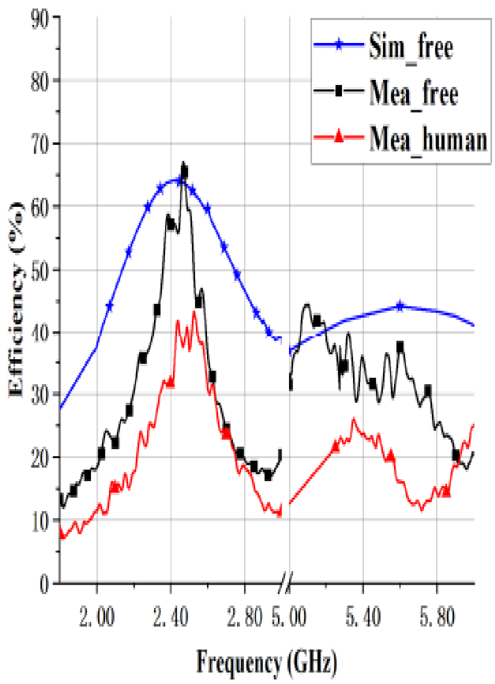

Figure 4-1：Simulated and measured radiation efficiency.

Table 4-1: Comparison of antenna performance with other systems

Ref.	BW(GHz)/%	Realised Gain (dBi)	SAR (10g)
[3] (button)	2.38-2.52/6% 4.92-6.9/36%	0.24 (2.45 GHz) 4.73 (5.2 GHz) 4.29 (5.8 GHz)	0.18 (2.45 GHz) 0.12 (5.2 GHz) 0.13 (5.8 GHz)
[6] (watch)	2.33-2.60/11%	-0.89 (2.45 GHz)	N/A
[7] (zipper)	2.37-2.49/4.92%	5 (2.45 GHz)	N/A
[8] (shoelace)	2.43(center)/11%	9.73 (2.45 GHz)	N/A
[9] (belt)	2.45 (center)/22.8%	2.8 (2.45 GHz) 4.5 (5.25 GHz)	N/A
[10] (belt)	0.7-1.2/55.56% 1.69-2.63/38.37%	-4.16 (0.9 GHz) -8.61 (1.8 GHz) -8.61 (2.45 GHz)	1.90 (0.9 GHz) 1.63 (1.8 GHz) 1.00 (2.45 GHz)
Proposed	2.28-2.53/10.2% 4.88-6.15/23.1%	5.10 (2.45 GHz) 4.05 (5.2 GHz) 3.31 (5.8 GHz)	0.87 (2.45 GHz) 0.83 (5.2 GHz) 0.13 (5.8 GHz)

CONCLUSION

It was proposed that a dual-band belt buckle antenna based on the pin buckle belt might be developed without the need of any specialized low-loss RF substrates. This antenna would be based on the pin buckle belt. On-body realized gain was 5.10 dBi, and the antenna's radiation efficiency at 2.45 GHz was around 40%. The mechanism for feeding consisted of a button and a pin that could be snapped on. Because this structure had a sufficient number of mounting points, the antenna was able to maintain its functionality while being mounted on the body. In order to build a TM10 mode and a quasi-TM30 mode that resembles a microstrip patch antenna, the two resonant frequencies have to be taken into account. In contrast to the construction of a typical loop-based belt buckle, this design restricts radiation to the inside of the human body and ensures that the specific absorption rate in both bands was well below approved safety standards [14–15]. This design also ensures that the specific absorption rate in both bands was well below accepted safety limits. Through the use of the belt antenna, on-body and off-body communication may be maintained with stable performance. It is a system that is trustworthy, extremely effective, and very reasonably priced for applications involving wearable body area networks.

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