Hindawi Publishing Corporation
International Journal of Antennas and Propagation
Volume 2015, Article ID 319894, 7 pages
http://dx.doi.org/10.1155/2015/319894

Research Article

Novel Multiband Metal-Rimmed Antenna for Wearable Applications

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Received 27 September 2014; Revised 22 December 2014; Accepted 26 December 2014

Academic Editor: Renato Cicchetti

A novel multiband antenna with an unbroken metal rim for wearable applications is presented. In order to achieve a wideband behavior, minimizing at the same time the size of the clearance area on the antenna ground plane, a novel feeding structure is proposed. This is achieved by connecting the metal rim to the ground plane thus allowing generating one lower-frequency resonance without occupying a large area. An additional resonance is then obtained using a suitable shorting patch. In this way, the proposed antenna presents a broadband behavior, while the width of the clearance area on the ground plane is of only 2 mm. The antenna performances in free-space and on a human phantom simulating a human body are analyzed by means of numerical simulations. Finally, the specific absorption rate (SAR) is analyzed to establish the antenna reliability in wearable applications. The experimental results demonstrate superior and stable performances of the metal-rimmed antenna when it is employed in wearable applications.

1. Introduction

With the increasing demands for tracking, navigation, portable communication, and public safety requirements, utilization of wearable devices is becoming more and more important. As a typical part of the wearable communication systems, the wearable antennas [1–15] also present fast growth in the last decade, which should simultaneously meet the requirements of Bluetooth, WIFI, GPS, and personal communications standards. Meanwhile, metal-rimmed wearable devices, such as smart watches, have also been proposed to solve the needs of the solidity and good-looking. However, the metal rim as well as the human body exerts a great influence on the antenna performances. Under such circumstances, the minimization of the antenna size becomes much more challenging.

In the previous studies, different methods have been proposed to reduce the antenna size for wearable applications, such as the EBG structure [6, 15], the shorted patch method [7], and the active antennas [8]. However, when applied to metal-rimmed wearable antennas, most of the mentioned methods can hardly meet the required demands. This is mainly due to the electromagnetic effects caused by the added metal rim, which leads to higher Q antenna factors and consequently to a quite narrow bandwidth. In addition, in the past, the metal rims have been usually considered as a negative factor; thus, design approaches to reduce the influence of the metal rim have been adopted.

In this paper, a novel T-shaped feeding structure, used to connect the ground plane directly to the metal rim, and a shorting patch used to excite a second antenna resonance are proposed and analyzed in detail. By means of the T-shaped junction, the antenna can be easily and stably excited. In particular, by fully exploiting the metal rim, the size of the clearance area on the ground plane is greatly minimized, while a wide frequency band, between 1500 and 2300 MHz, is realized. Consequently, the metal-rimmed antenna can be usefully employed for wearable applications. The width of the clearance area on the system ground plane is only 2 mm. In this case, more space can be left to accommodate other components. The performance of the radiating structure in free-space and in the presence of a human body has been analyzed by means of commercial software based on the FDTD method (CST Microwave Studio). The analyses, validated by

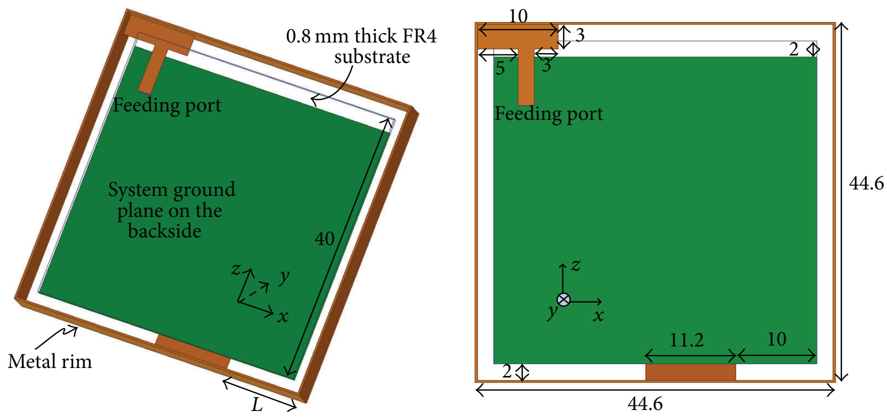


Figure 1: Configuration of the proposed metal-rimmed antenna for wearable applications. (a) Geometry of the metal-rimmed antenna. (b) Detailed dimensions of the proposed antenna. All dimensions are in millimeters.

experimental measurements, have shown that the proposed antenna has good electromagnetic performances. The paper is organized in 4 sections. In Section 2, the metal-rimmed antenna topology and the related design considerations are discussed, while the experimental results are presented in Section 3. Finally, in Section 4, some concluding remarks are reported.

2. Antenna Design and Topology

Figure 1(a) shows the geometry of the proposed metal-rimmed antenna for wearable applications. The structure of the proposed antenna is composed of a rectangular metal patch (dimensions of $40 \times 38\,\text{mm}^2$) printed on a FR4 dielectric substrate (dimensions $40 \times 40\,\text{mm}^2$ and thickness of 0.8 mm), acting as ground plane, while an unbroken metal rim placed at some distance from the ground plane, and grounded at two specific points, is excited by means of a suitable T-shaped feeding line connected by means of a via hole to an SMA connector (see Figure 4). The dimensions of the circuit board have been chosen so as to simulate the size of the most popular wearable devices [3, 15]. The metal rim, consisting of a copper sheet of thickness of 0.5 mm, is kept at a distance of 2 mm from the circuit board. Figure 1(b) depicts the detailed dimensions of the metal-rimmed antenna for wearable applications.

Different from the traditional design concept, the proposed antenna employs the metal rim as radiating element thus minimizing the clearance area on the ground plane. Typically, the metal rim has a total length of 176 mm, which is capable of generating fundamental and high-order resonances to achieve wide bandwidth. The shorting patch, adopted to introduce a dual-resonance at 1570 MHz and 2110 MHz so as to cover the operative frequency bands of the GNSS/DCS/PCS/UMTS2100/LTE2300 systems, is also employed to increase the solidity of the proposed wearable device. It should be noted that the overall size of the clearance area is small, meaning that more space is left to accommodate other components such as sensors and monitoring modules [1–3]. Accordingly, the proposed antenna is valuable for wearable applications, especially for metal-rimmed cases.

For a better comprehension of the physical mechanisms responsible for the antenna behavior, the simulated surface current distributions at the resonant frequencies of 1570 and 2110 MHz are plotted in Figure 2. To better highlight the current paths responsible for the emissive effects, lines with arrows have been added to Figures 2(a) and 2(b). From Figure 2(a), it can be seen that at 1570 MHz the surface current is widespread within the ground plane, presenting a phase inversion along the secondary diagonal of the rectangular ground plane. In this case, the upper left edge and the lower right edge contribute to a half-wavelength resonant mode at about 1570 MHz. A higher concentration of the surface current along the edge of the circuit board is observed at 2110 MHz (see Figure 2(b)), while the emissive phenomenology is similar to that observed at lower frequency. In particular, the upper and lower left edges of the metal rim contribute to a half-wavelength resonant mode at about 2110 MHz, since in these regions the current exhibits its maximum value. In conclusion, the metal rim produces a dual resonance allowing the antenna to cover the frequency band between 1500 MHz and 2300 MHz. Compared to the traditional patch antennas, the proposed antenna takes full advantages of the metal rim to realize a broadband frequency behavior. Moreover, the space on the circuit board is reduced allowing reducing the size of the antenna with respect to more traditional design concepts [9, 11].

The shorting patch plays an important role in improving the antenna bandwidth and impedance matching. To better understand the function played by the shorting patch on the antenna performances, a parametric study has been performed. In particular, the magnitude of the computed antenna reflection coefficients, as a function of the distance L between the shorting patch and the right side of the metal rim (see Figure 1), is shown in Figure 3. From Figure 3, it appears that when the distance L varies in the range from 7 to 17 mm, the resonant modes move to higher frequencies. Therefore,

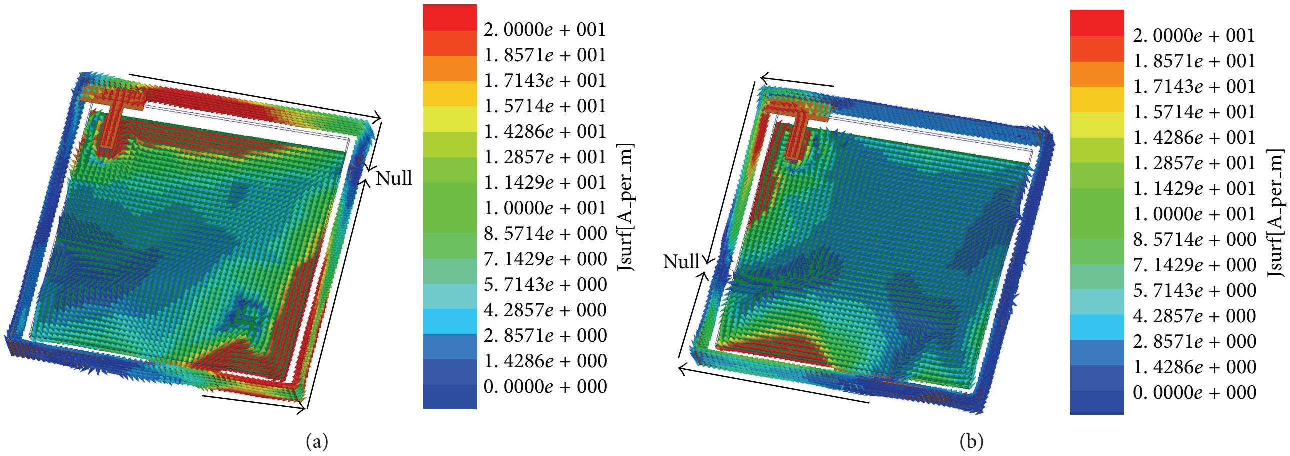


FIGURE 2: Simulated current distributions at resonant frequencies: (a) 1570 MHz, (b) 2110 MHz.

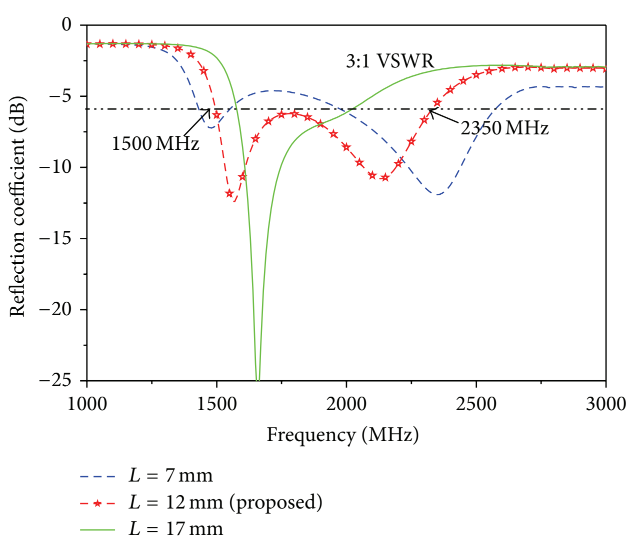


FIGURE 3: Antenna reflection coefficient versus frequency as a function of L.

the performance of the proposed antenna can be optimized by choosing an appropriate value of the parameter L.

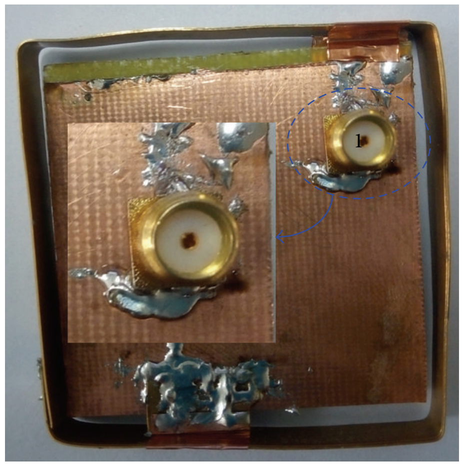
3. Experimental Results

The metal-rimmed antenna for wearable applications, whose photo is shown in Figure 4, was fabricated and tested. The numerical results have been performed by means of commercial software based on the FDTD technique (CST Microwave Studio), while the experimental measurements have been carried out using an Agilent Vector Analyzer E5071B and a SATIMO StarLab. In addition, to verify the suitability of the metal-rimmed antenna for wearable applications, the performances of the antenna have been also simulated and tested when it is attached on the wrist of a human body phantom, whose dielectric relative permittivity and conductivity are 35 and 1.8 S/m, respectively.

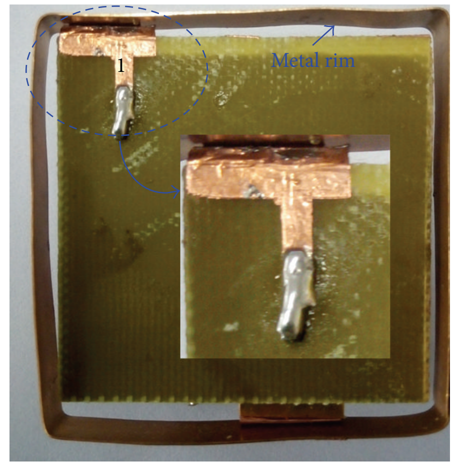
3.1. S-Parameter. Figure 5 shows the measured and simulated antenna reflection coefficients in free-space and on the wrist of the human body phantom. From Figure 5, it appears that the measurements are in good agreement with the simulated results for the two considered cases. Moreover, by comparing the measured results for the two considered cases, it is seen that the variations of the antenna reflection coefficients are limited and acceptable. This demonstrates that the proposed antenna is usable when worn on the wrist of the human body. In particular, the measured bandwidth, based on the −6 dB threshold level, is 1500~2350 MHz in free-space, while the bandwidth is almost the same when a human body phantom is considered. Therefore, the operating band is not significantly affected and the antenna can cover the operative bands of GNSS/DCS/PCS/UMTS2100/LTE2300 operation for wearable applications.

3.2. Radiation Pattern. The radiation characteristics were tested in a SATIMO StarLab. Figures 6(a) and 6(b) depict the measured 2D radiation patterns for xoz, yoz, and xoy plane at 1700 and 2100 MHz, respectively. The measurement was also conducted considering the antenna radiating in free-space and on the wrist of the human body phantom. It is noted that the human body blocks the radiated signals in the xoy plane. Meanwhile, complementary E_φ and E_θ are also achieved in free-space and with the human body phantom at 1700 and 2100 MHz. Consequently, the proposed metal-rimmed antenna is valuable for practical wearable applications.

3.3. Efficiency and Gain. The antenna efficiency and gain measured in free-space and on the wrist of the human body phantom are depicted in Figures 7 and 8, respectively. From Figure 7, it is observed that the measured antenna efficiency with the human body phantom is lower than in free-space, which is mainly due to the absorption of the human body phantom. However, the measured antenna efficiency is still more than 50% for all the desired bands, suggesting that the proposed metal-rimmed antenna is applicable to wearable applications. As expected, the measured peak gain when



(a)



(b)

FIGURE 4: Fabricated metal-rimmed antenna for multiband wearable applications.

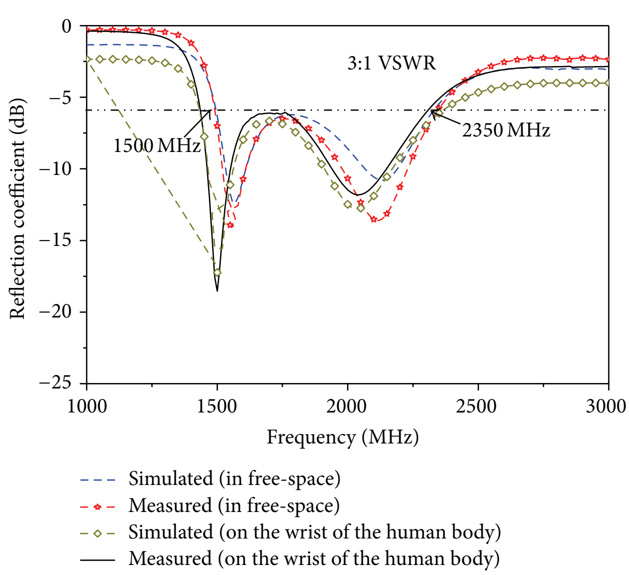


FIGURE 5: Antenna reflection coefficient versus frequency in free-space and on the wrist of the human phantom.

the human body phantom is considered is less than that in the free-space (see Figure 8), while the peak gain is over 1.6 dB in the whole operative bands, implying also that the metal-rimmed antenna is valuable for wearable applications [3].

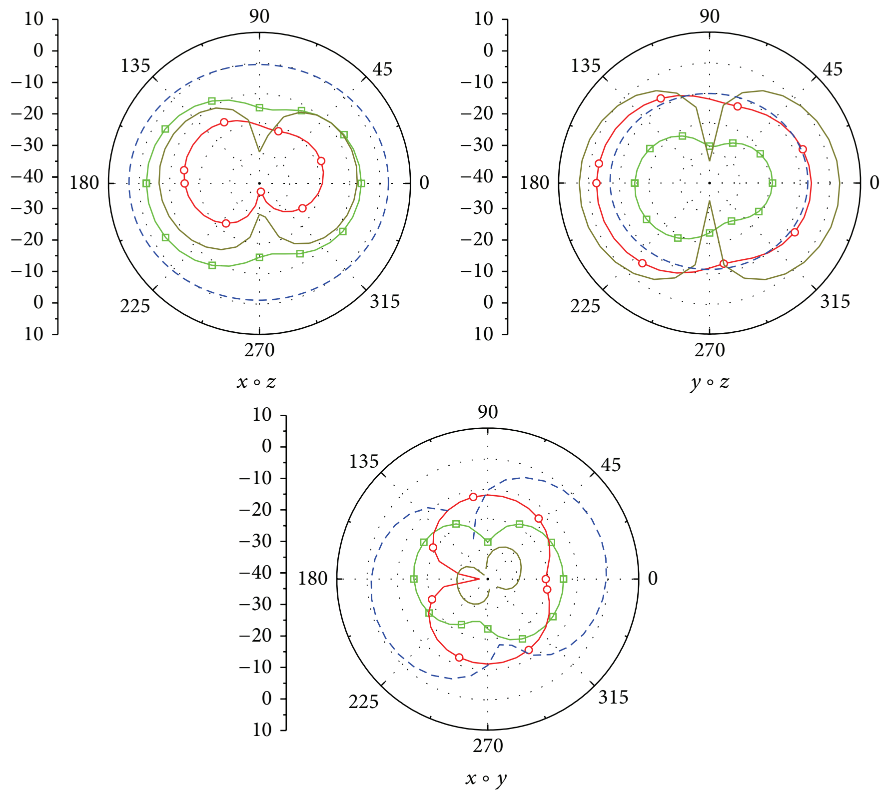
3.4. Specific Absorption Rate (SAR). The specific absorption rate (SAR) is an important parameter to measure the power deposition in a human body when it is exposed to an electromagnetic field. Therefore, this parameter, which is closely related to safety consideration, since low SAR means that less electromagnetic energy is absorbed by the human body [16, 17], can be used as a useful criterion to establish if a wearable antenna presents suitable safety guarantees for the user. The SAR simulation, concerning 1 g of tissue, referring to 0.125 W of transmitting power, has been carried out using the simulation models describing the two typical operative scenarios reported in Figure 9. The numerical results for a homogeneous phantom model, concerning the 1 g SAR values, and the corresponding antenna reflection coefficients are listed in Table 1. The peaks of the simulated SAR values in the front and on the wrist of the human body phantom are 0.78 and 0.75 W/kg, respectively. Both of these values are less than that required by the FCC limitation (1.6 W/kg), confirming that the metal-rimmed antenna is quite suitable for practical wearable applications [16, 17].

TABLE 1: Simulated 1 g SAR values for the wearable antenna.

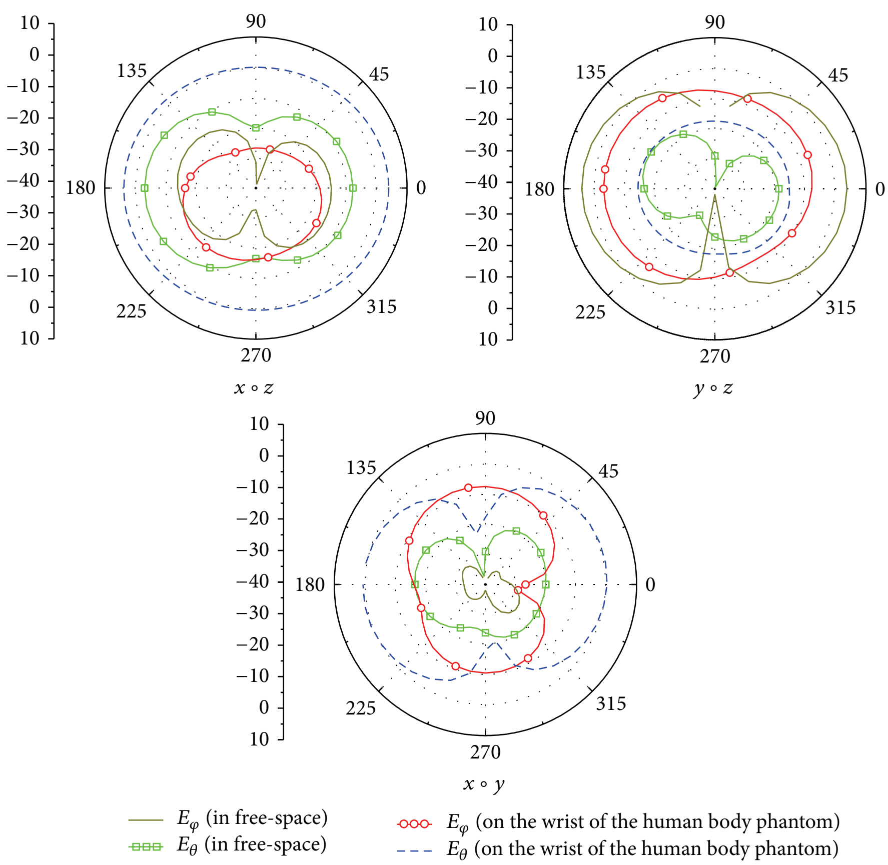
Frequency (MHz)		1550	1700	1950	2100	2300
1 g SAR (W/Kg)	In the front	0.78	0.65	0.62	0.58	0.55
	On the wrist	0.75	0.62	0.59	0.57	0.54
Reflection coefficient (dB)	In the front	−10.1	−7.1	−10.3	−11	−6.3
	On the wrist	−9.8	−6.8	−9.7	−10.7	−6.2

4. Conclusion

A novel metal-rimmed antenna for multiband wearable applications has been presented. The proposed antenna is composed of a radiating metal rim and a novel feeding structure which allows obtaining a compact antenna suitable to cover the frequency band between 1500 and 2350 MHz. The measurements and the numerical results show that the antenna presents good radiation characteristics in terms of gain and efficiency in the whole operative bands. Finally, the simulated SAR results are lower than that indicated by the specific standard concerning the protection of the human being by the exposure to electromagnetic fields, meaning that the proposed metal-rimmed antenna is suitable for practical wearable applications.



(a) 1700 MHz



(b) 2100 MHz

Figure 6: Measured 2D radiation patterns of the proposed antenna at different frequencies: (a) 1700 MHz, (b) 2100 MHz.

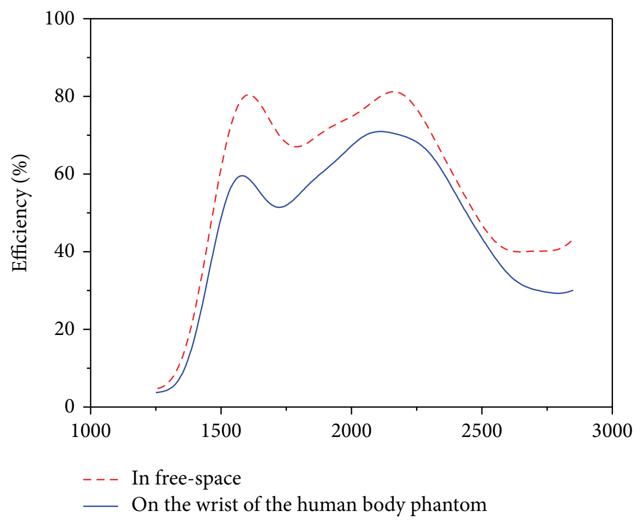


Figure 7: Measured antenna efficiency of the proposed antenna in free-space and on the wrist of the human body phantom.

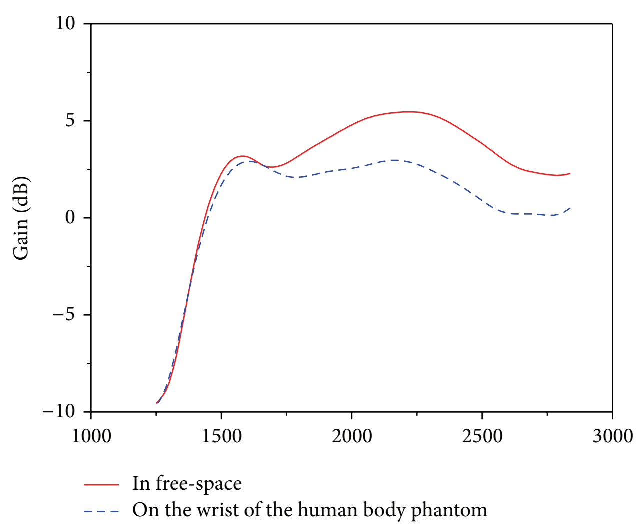


Figure 8: Measured gain of the proposed antenna in free-space and on the wrist of the human body phantom.

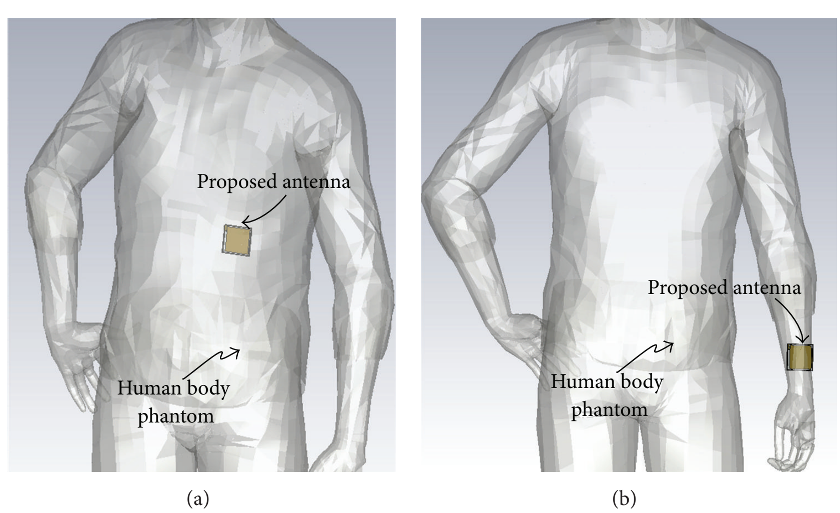


Figure 9: Typical application scenarios for the proposed metal-rimmed wearable antenna (a) in the front and (b) on the wrist of the human phantom.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

This work is supported by the Doctoral Fund of the Ministry of Education (no. 20100111110004) and the National Natural Science Fund Item no. 61370088.

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