Low-profile Button Sensor Antenna Design for Wireless Medical Body Area Networks

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Abstract— A button sensor antenna (BSA) for wireless medical body area networks (WMBAN) is presented, which works through the IEEE 802.11b/g/n standard. Due to strong interaction between the sensor antenna and the body, a new robust system is designed with a small footprint that can serve on- and off-body healthcare applications. The measured and simulated results are matched well. The design offers a wide range of omnidirectional radiation patterns in free space, with a reflection coefficient (S11) of −29.30 (−30.97) dB in the lower (upper) bands. S11 reaches up to −23.07 (−27.07) dB and −30.76 (−31.12) dB on the body chest and arm, respectively. The Specific Absorption Rate (SAR) values are below the regulatory limitations for both 1-gram (1.6 W/Kg) and 10-gram tissues (2.0 W/Kg). Experimental tests of the read range validate the results of a maximum coverage range of 40 meters.

Clinical Relevance— WMBAN technology allows for continuous monitoring and analysis of patient health data to improve the quality of healthcare services.

I. INTRODUCTION

WMBAN has received high interest in recent years. One of the most significant components of WMBAN is the wearable antenna, which is in high demand for applications such as health monitoring, physical training, and navigation, as shown in Fig.1. In WMBAN, most of the research activities focus on the antenna design and its implementation [1]. Some studies look at the materials' properties and stability, as well as how they affect the antenna performance. Other research examines the influence of the human body on the design performance and SAR values. Wearable antennas are designed to be flexible. In many of these designs, the antenna is made of textile materials and takes planar shapes.

However, fully textile antennas have some shortcoming. Their performance can be drastically affected by bending, stretching, crumpling and other deformations. In contrast, small rigid and semi-rigid designs such as button antennas that can be worn on shirts and be a part of jeans offer rigidity to maintain antenna performance. A button sensor antenna using copper conductive materials can increase the antenna’s efficiency [2-3]. Numerous investigations on the button antennas have been published in the last few years [2-9]. Thanks to the fast designs of low-power circuits on-body sensor antennas can be used for a long time.

In this manuscript, our main goal was to design a BSA that would easily meet the important requirement: (1) multiband frequencies, (2) small size (for example a button to improve the users comfort: a small PCB button, with an electronic device that could be easily fit into a handwatch enclosure), (3) high stability in performance, and (4) maximum read range. This manuscript is organized as follows. Section II briefly describes the design requirement and related studies. In Section III, the button sensor antenna’s performance is discussed. Finally, Section IV presents some concluding remarks.

Figure 1. Healthcare design in the WMBAN system.

I. SYSTEM REQUIREMENT

This section describes the system requirements and design choices. The button antenna and backbone electronics are both investigated. Further, an appropriate design process is chosen, as shown in Fig. 2. Based on the material property and investigation, the textile material is a low lossy material. This BSA design is a semi-flexible using the felt, and
ShieldIt for substrate and ground, whereas a roger substrate was used for a top PCB button radiator.

Figure 2. System architecture for the button sensor antenna.

A. Button Antenna Topology

The BSA is demonstrated in Fig. 3, we utilized the CST simulation tool for simulations. The radio-frequency (RF) antenna was constructed on a button-shape PCB and Rogers’s substrate (RT/Duroid 5880). This substrate has a thickness (t) of 1.574 mm, a dielectric constant (εr) of 2.2, and a loss tangent (tan δ) of 0.0009 S/m, which was placed on a 1.50 mm felt substrate with an εr of 1.4 and a tan δ of 0.044 S/m. There is an air gap of 3.76 mm between the PCB layer and the felt substrate. The conductive ground layer is made of ShieldIt, with an area of 45 mm × 45 mm, a thickness (t) of 0.17 mm, and a conductivity (σ) of 1.18 × 10^5 S/m. ShieldIt layer was glued on the bottom side of the felt substrate.

The conductive parts on the top side of the PCB with a radius of 8 mm are as follows: a pin-fed patch on the bottom side of the PCB, and an asymmetrical capacitive patch connected to the bottom patch on the top side, which is also short-circuited to the ground plane by a via (cylindrical pin). The coaxial feed and the via (cylindrical pin) have diameters of 1.27 mm and 1.22 mm, respectively. Glue was used to adhere the ShieldIt ground plane to the felt substrate. For the SMA connector and its galvanic connection to the ShieldIt layer, a through-hole was made. In addition, the center asymmetrical slot was capacitively coupled to the bottom patch. Staircases and extra load were utilized to achieve a compact size. Therefore, the BSA radius (a) can be determined by [9]:

$$ a = \frac{F}{\left\{1 + \frac{2h}{\pi \varepsilon_r \sigma} \left[\ln \ln \left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{1/2}} $$

$$ F = \frac{8.791 \times 10^9}{\varepsilon_r} $$

where h is the substrate thickness and εr is its dielectric constant. The fringing makes the patch electrically larger, the effective radius (a_e) is given by [3]:

$$ a_e = a \left\{1 + \frac{2h}{\pi \varepsilon_r \sigma} \ln \ln \left(\frac{\pi a}{2h}\right) + 1.7726\right\}^{1/2} $$

$$ f_r = \frac{1.8412c}{2\pi a_e \sqrt{\varepsilon_r}} $$

where c: speed of light, and f_r: resonance frequency.

B. Design of Printed Circuit Board

Eagle, version 7.7.0 design tool was used to create the design. After validating the simulation, the schematic design was transferred to a PCB prototype, as indicated in Fig. 4.

Figure 3. Structure of the BSA (dimensions in the given mm): (a) the side view; (b) the top view; and (c) the fabricated BSA.

Figure 4. PCB Design. (a) Simulated PCB design, and (b) fabricated PCB prototype.
To keep the schematic design as small as possible, surface mount components are used. The diameter of this PCB is 45 mm. The prototype was optimized and designed on FR4 material, which has an $\varepsilon_r$ of 4.2, tan $\delta$ of 0.02, and a thickness of 1.6 mm. The developed wireless sensor module was then properly programmed for RSSI using the IEEE 802 b/g/n standard and incorporated with a button antenna via a T-shaped matching circuit. The ESP8266 is a Wi-Fi-enabled integrated circuit. The 26 MHz Crystal Oscillator, 4MB Flash memory, USB to FTDI connector, Step-down regulator (3.3 V), power supply, and 2.4 GHz RF transceiver are all included in ESP8266 EX wireless module. An enclosure as shown in Fig. 5, similar to a hand watch cover, was designed and 3D printed. The button antenna was placed on top of the cover module, and they were connected through U.FL connector.

Fig. 5. 3D covers of the BSA (a) Simulated, and (b) fabricated.

II. RESULTS AND DISCUSSION

To find the optimum design parameters a parametric study was conducted while yielding a realizable structure. The time-domain solver in CST MWS was used for the design and parametric tolerance analysis. Simulations and measurements were done in the frequency 1 to 7 GHz.

A. Button Sensor Antenna Locations

Fig. 6 illustrates the simulated $S_{11}$ of the BSA for different feeding points. We investigated changing the feeding point has a considerable impact on the impedance matching and resonant frequency bands. Therefore, the long edge provided better performance as compared to other points. It can be seen how changing the button sensor antenna's feeding point has a considerable impact on the impedance matching level and resonant frequency bands. Due to the presence of the lossy tissues, the radiation pattern has become wider with high stability for the on-body case. As illustrated in Fig. 7, an omnidirectional radiation pattern is obtained.

Fig. 6. $S_{11}$ of the BSA for different feed locations.

B. Body Phantom Models

It is necessary to study BSA while being placed on the body and tissues, as shown in Fig. 8. For the chest model, a flat body model, with a dimension of 200 × 200 × 50 mm$^3$ was used. The thicknesses are as follows (in mm): skin
(4), fat (8), and muscle (30), with an extra gap layers between each layers (8mm).

Furthermore, the muscle layer has an $\varepsilon_r$ of 52.7 and 48.2, and a $\sigma$ of 1.95 and 6.0 S/m, at 2.4 GHz and 5.6 GHz, respectively [8-9]. On the arm, a simple layered model was utilized. For the on-body communication described in [4], a phantom with a 50 mm (radius: $R$) and a 150 mm (length: $L$) was selected for the human arm. Although the BSA center frequency was affected by the presence of the lossy tissue, it still operates in the appropriate band. The various possible bending conditions that we considered are depicted in Fig. 9. Therefore, the BSA has robustness against a bending radius of $R = 50$ mm. The link budget ensure a reliable link budget with the range of 40 meters, as shown in Fig. 10 (a). As shown in Fig. 10 (b), it depicts the measured $S_{11}$ in various situations. The SAR values were calculated, which shows the BSA can be safely operated.

Figure 8. $S_{11}$ on body phantom models (in mm, 2, 3, and 5).

Figure 9. Effect of bending of the BSA: (a) free space, (b) layered chest phantom, and (c) arm cylindrical phantom (50 mm dia).

Figure 10. (a) Link budget, and (b) Measured $S_{11}$ on the bodies.

III. CONCLUSION

The BSA for WMBAN was presented, which operates at 2.45 GHz and 5.6 GHz, respectively. The BSA is small, with a button form and an area of $45 \times 45$ mm$^2$. This is integrated into a circular wireless sensor module with a 45 mm (diameter) that can be encased in a 3D hand watch. The design demonstrates high stability in performance and range of 40 meters. Currently, there is ongoing work to evaluate its use in a real-time hearing technology prototype [10].

IV. REFERENCES

[1] Jiahao Zhang et al. “A Miniature Feeding Network for Aperture-Coupled Wearable Antennas,” IEEE Trans. Biomed. Circuits Syst., vol. 14, no. 4, pp. 918–927, 2020.
[2] J. Zhang et al, “Dual - Band Dual - Polarized Wearable Button Array with Miniaturized Radiator,” IEEE Trans. Biomed. Circuits Syst., vol. PP, no. November, p. 1, 2019.
[3] X. Y. Zhang et al, “Dual-Band Dual-Mode Button Antenna for On-Body and Off-Body Communications,” IEEE Trans. Biomed. Circuits Syst., vol. 11, no. 4, pp. 933–941, 2017.
[4] S. Yan et al, “Design of Wideband Button Antenna Based on Characteristic Mode Theory,” IEEE Trans. Biomed. Circuits Syst., vol. 12, no. 6, pp. 1383–1391, 2018.
[5] B. Mandal et al, “A wearable button antenna with FSS superstrate for WLAN health care applications,” Conf. Proc. - 2014 IEEE MTTS Int. Microw. Work. Ser. RF Wir. Technol. Biomed. Healthc. Appl. IMWS-Bio 2014, 2015.
[6] A. E. Farahat et al, “Wearable Button-Like Dual-Band Central Antenna for Wireless Body Area Networks,” Prog. Electromagn. Res. B, vol. 90, pp. 21–41, 2021.
[7] X. Hu et al, “Compact Circularly Polarized Wearable Button Antenna with Broadside Pattern for U-NII Worldwide Band Applications,” IEEE Trans. Antennas Propag., vol. 67, no. 2, pp. 1341–1345, 2019.
[8] H. Xiaomu et al, “Wearable Button Antenna for Dual-Band WLAN Applications with Combined on and off-Body Radiation Patterns,” IEEE Trans. Antennas Propag., vol. 65, no. 3, pp. 1384–1387, 2017.
[9] R. Sreelakshmy and G. Vairavel, “Novel cuff button antenna for dual-band applications,” ICT Express, vol. 5, no. 1, pp. 26–30, 2019.
[10] EPSRC – COG-MHEAR research programmed: http://cogmhear.org.