Design of a Novel Reconfigurable Wearable Antenna Based on Textile Materials and Snap-on Buttons

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Abstract. A novel wearable reconfigurable patch antenna is presented for wireless body-area applications at 2.4 GHz industrial, scientific, and medical (ISM) band. Textile and clothing materials are solely employed within the wearable antenna design process and reconfiguration mechanism. Specifically, by engaging or disengaging four pairs of metallic snap-on buttons, the textile antenna can exhibit an omnidirectional radiation pattern with linear polarization or a broadside radiation pattern with circular polarization enabling both on- and off-body wireless communication, respectively. A multi-layer tissue phantom is applied to emulate a realistic wearing environment. The resonance and radiation performance characteristics of the proposed antenna are examined in both radiation states. A parametric analysis regarding key design parameters is conducted. The specific absorption rate (SAR) is, also, assessed in terms of safety.

Keywords: Body-area networks · Reconfigurable antenna · Snap-on buttons · Textiles · Wearable antenna

1 Introduction

Wireless body-area networks (WBANs) are an emerging interdisciplinary technological field applied to improve personal and professional life routine in applications such as healthcare and entertainment, consumer electronics, military, and rescue services. Within the framework of WBAN systems, on-body and off-body wireless communication channels are established by integrating wearable antennas. The on-body links enable the wireless propagation of vital signals along human body; maximum antenna radiation is necessary along body surface [1]. In contrast, the off-body links allow communication between wearable antennas and external devices far away from the human body; maximum radiation is required in broadside direction normal to body surface [1]. The functionality of WBAN systems can be improved by applying antennas that achieve switching radiation properties. In practical, a radiation pattern reconfigurable antenna can support in a single wireless unit both the collection of vital physiological signals

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from body-mounted sensor nodes and the data transmission in external base stations for remote healthcare monitoring, for instance [2].

Electronic switches integrated into the antenna structure are typically used to achieve the necessary reconfiguration. In [3], a conformal wearable antenna that electronically switches its radiation properties between broadside and monopole-like mode at 5.2 GHz has been proposed. Four PIN diodes were incorporated into the antenna to promote pattern reconfiguration. In [4], a textile antenna has been presented based on a metamaterial structure. Six switchable stubs enable antenna omnidirectional or broadside radiation at 2.4 GHz. In [5], a beam-steering patch antenna has been proposed for wrist-wearable applications at 6 GHz. Different beam directions are achieved by altering the state of two switches. Clothing accessories can, also, be used as passive switches. In [6], commercial metallic snap-on buttons have been applied as detachable shoring vias to split the radiation pattern of a textile patch antenna into two main beams at 3.6 GHz. In [7], two reconfigurable textile antennas that employ a conductive Velcro tape and zip fastener have been presented for operation at 2.4 GHz. Antenna polarization can be changed from linear to circular at will, by altering the state of the applied clothing components.

In this paper, a reconfigurable wearable antenna is designed for wireless on/off-body applications at 2.4 GHz industrial, scientific, and medical (ISM) band. The research challenge lies in the entirely use of textile and clothing materials within the antenna design process. A single-layer microstrip-fed patch antenna printed on textile fabric is adopted as the radiating element aiming at design simplicity and low-profile. The radiation-pattern and polarization reconfiguration mechanism are induced by incorporating four pairs of metallic snap-on buttons that serve as detachable shorting vias into the antenna structure. Circular polarization is achieved through antenna structure perturbation. The novelty of the proposed study lies in the design of a textile antenna that achieves both radiation pattern and polarization reconfiguration at fixed frequency of operation. Research works found in the literature present antenna designs with single radiation reconfiguration capabilities.

This paper is organized as follows. Section 2 presents the design of the proposed textile reconfigurable antenna and the equivalent tissue-simulating model. In Sect. 3, the simulation results including antenna resonance and radiation performance under both radiation configurations are featured. A parametric design analysis is conducted. Specific absorption rate (SAR) is, also, assessed. Conclusions follow in Sect. 4.

2 Antenna Design

The geometry of the proposed fully-textile reconfigurable patch antenna is shown in Fig. 1. A 0.97 mm thick felt material (relative permittivity ε_r of 1.64 and loss tangent $tan\delta$ of 0.033) is used as the antenna substrate. A square patch is printed onto the textile substrate with a full ground plane. The patch surface and the ground plane are made of conductive fabric (Nora-Dell, Shieldex) with a conductivity σ of 1.54×10^6 S/m and a thickness of 0.13 mm.

Four pairs of commercial metallic snap-on buttons are symmetrically located into the diagonal directions of the antenna structure, as depicted in Fig. 1 (S1, S2, S3, and S4 positions), to promote radiation-pattern and polarization reconfigurability at 2.4 GHz band. The snap-on buttons have been proved a robust mechanical and radio frequency connection for wearable systems since they can provide detachability with suitable RF performance up to 5 GHz [8]. In the proposed design concept, four male buttons are soldered into the patch surface and can serve as shorting vias when they are engaged to their female counterparts attached onto the ground plane layer. When the male parts are engaged to the female ones, the textile antenna operates in a monopole-like state exhibiting omnidirectional radiation for on-body wireless links. When the buttons are disengaged, the antenna operates as a conventional half-wave mode microstrip antenna presenting broadside radiation for off-body communication. Furthermore, to promote polarization reconfiguration the patch layer is corner-truncated and is loaded with a pair of diagonal stubs to efficiently produce a pair of degenerated modes. Hence, circular polarization (CP) is generated in the off-body radiation state. On the other hand, linear polarization is adopted within the on-body radiation mode.

Antenna feeding is realized through a stepping microstrip line instead of a coaxial cable to enhance wearer's comfort. The origin of the coordinate system is placed into the ground plane center. Ansys HFSS and CST MWS electromagnetic software packages are used for the antenna design process and the extraction of numerical results. The antenna design parameter values are recorded in Table 1.

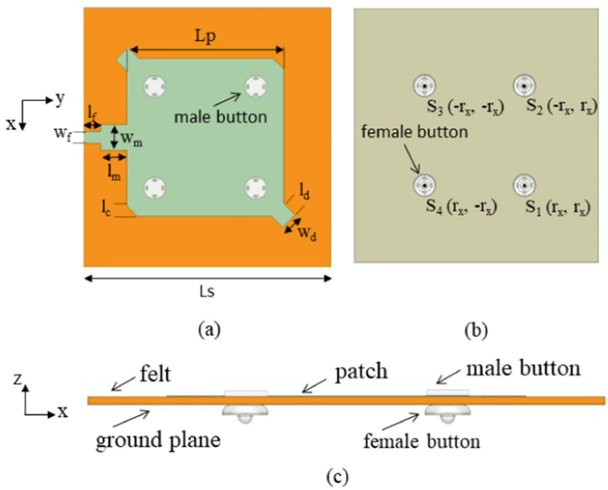


Fig. 1 Configuration of the proposed textile reconfigurable antenna: (a) top view showing the four male buttons on the patch surface, (b) bottom view showing the four female buttons on the ground plane layer, and (c) side view showing all antenna elements (not in same scale).

Considering antenna integration onto human body, a three-layered tissue model that consists of skin (thickness 1.3 mm), fat (thickness 10.5 mm) and muscle (thickness 20 mm) is employed as shown in Fig. 2 [2]. The dielectric constants of the applied tissues are evaluated at 2.44 GHz and are listed in Table 2 [9]. To emulate realistic wearing conditions, the antenna is placed at 3 mm distance from the tissue model. Felt material ($\varepsilon_r = 1.2$, $tan\delta = 0.001$) is used to fill the space.

Table 1. Antenna geometrical parameter values [in mm].

Name	Value	Name	Value
Ls	74	l_f	5.0
Lp	45	w_f	3.3
l_d	2.5	l_m	7.3
w_d	5.2	w_m	7.5
l_c	3.0	r_x	14.5

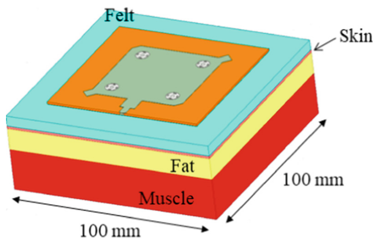


Fig. 2 Numerical three-layered tissue model.

Table 2. Permittivity (ε_r), conductivity (σ), and mass density (ρ) of the tissues used in this study.

Tissue	ε_r	σ (S/m)	ρ (kg/m^3)
Skin	38.01	1.46	1100
Fat	5.28	0.10	920
Muscle	52.74	1.73	1040

3 Reconfigurable Textile Antenna Performance

3.1 On-Body Antenna Operation State

Figure 3 (black line) illustrates the simulated reflection coefficient |S11| frequency response of the designed reconfigurable patch antenna when the snap-on buttons are engaged serving as shorting vias. The antenna presents a resonance frequency at 2.44 GHz and the obtained 10-dB impedance bandwidth is 87 MHz covering the ISM frequency band. A parametric analysis regarding snap-on buttons' position (r_x) within the antenna structure is, also, superimposed in Fig. 3. Based on the numerical results, a frequency shift of about 60 MHz is observed when the buttons are moved by 1 mm (r_x = 15.5 mm) towards the antenna's corners with respect to their initial location (r_x = 14.5 mm). This implies that proper buttons' positioning is significant to ensure the desired antenna operation at specific frequency.

Furthermore, the simulated normalized radiation patterns of the antenna in xz- and xy-planes are presented in Fig. 4(a) and (b), respectively. An omnidirectional radiation pattern with vertical polarization, normal to the patch surface, is achieved which fulfils the requirements for on-body communication. The calculated peak gain in the azimuth plane is −6.4 dBi. The maximum gain is calculated to be −1.5 dBi at 2.44 GHz.

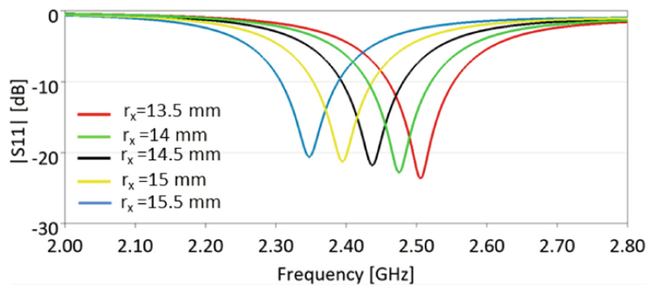


Fig. 3 Simulated reflection coefficient characteristics of the proposed reconfigurable antenna design for different snap-on buttons position (r_x) under monopole-like mode.

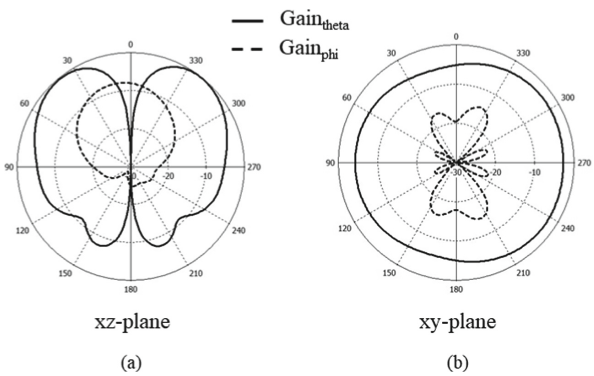
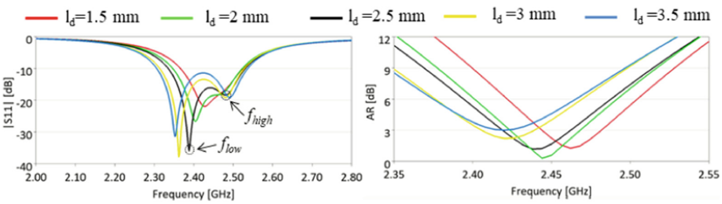


Fig. 4 Simulated normalized radiation patterns of the proposed reconfigurable antenna design at 2.44 GHz under monopole-like mode in: (a) xz-plane, and (b) xy-plane, respectively.

3.2 Off-Body Antenna Operation State

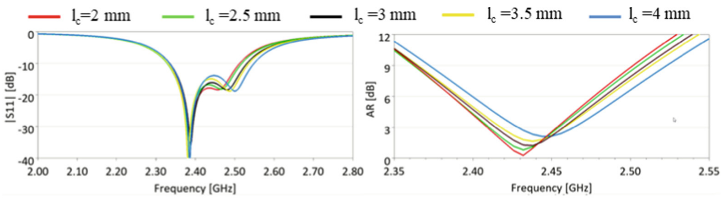
When the snap-on buttons are disengaged, the proposed textile antenna operates as a typical microstrip patch and its simulated reflection coefficient |S11| frequency response is illustrated in Fig. 5(a) (black line). The antenna presents a broadband resonance response around the 2.44 GHz frequency of interest. The 10-dB impedance bandwidth is 195 MHz fully covering the ISM frequency band. By implementing diagonal stub loading and corner truncation into the patch layer (see Fig. 1), the fundamental mode of the proposed antenna is split into modes f_{low} and f_{high}, as shown in Fig. 5(a). The two resonance modes produce the wide impedance bandwidth. In addition, the split modes satisfy the condition of equal amplitude and orthogonal phase to achieve circular polarization. The simulated axial ratio (AR) response of the proposed antenna is presented in Fig. 5(b) (black line). The 3-dB AR bandwidth is 43 MHz exhibiting satisfactory CP behavior.

A parametric analysis regarding the diagonal stubs' length (l_d) is, also, superimposed in Fig. 5(a) and (b). It is obvious that the variation of stubs' length impacts on the response of the mode f_{low}, while the higher mode seems to be nearly unaffected. Furthermore, Fig. 6(a) and (b) depicts the antenna |S11| and AR frequency response by altering the truncated corners' length (l_c). The design parameter l_c controls the upper mode f_{high}, while the lower frequency mode remains stable. It seems, also, that the diagonal stubs' length (l_d) exerts stronger influence on the AR response. It should be noted that in Figs. 5 and 6, black line represents the |S11| and AR when all antenna geometrical parameters are at their nominal values (see Table 1). Colored lines correspond to the numerical results when the value of one geometrical parameter of interest changes.



(a) (b)

Fig. 5 (a) Simulated reflection coefficient characteristics and (b) AR response of the proposed reconfigurable antenna design varying diagonal stub's length (l_d) under broadside mode (rest of geometrical parameters are at their nominal values). (Color figure online)



(a) (b)

Fig. 6 (a) Simulated reflection coefficient characteristics and (b) AR response of the proposed reconfigurable antenna design varying truncated corner's length (l_c) under broadside mode (rest of geometrical parameters are at their nominal values). (Color figure online)

In Fig. 7, the simulated surface current distribution onto the patch layer is presented at 2.44 GHz, when the snap-on buttons are disengaged. As can be observed, the surface current rotates in the clockwise direction. This produces left-handed CP waves in the broadside radiation mode.

Furthermore, the simulated normalized radiation patterns of the textile antenna in xz- and yz-planes are presented in Fig. 8(a) and (b), respectively. A broadside radiation pattern with circular polarization is accomplished which is suitable for off-body channels. The peak gain is 1.1 dBi at 2.44 GHz. The cross-polarization level is below −20 dBi which allows good polarization purity.

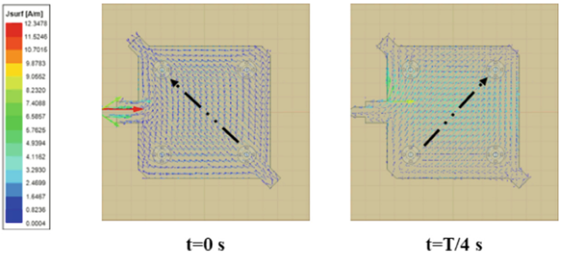


Fig. 7 Simulated surface current distribution at 2.44 GHz under broadside mode.

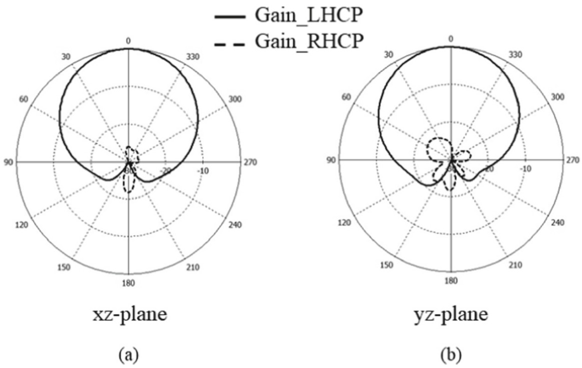
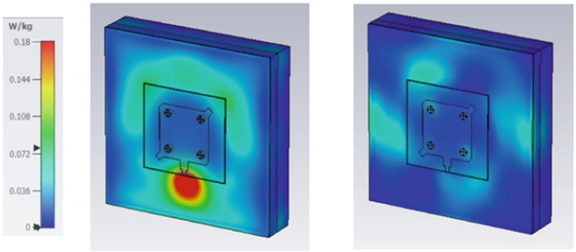


Fig. 8 Simulated normalized radiation patterns of the proposed reconfigurable antenna design at 2.44 GHz under broadside mode in: (a) xz-plane, and (b) yz-plane, respectively.

3.3 Antenna Radiation Safety Performance

Specific Absorption Rate (SAR) analysis is conducted to assess the electromagnetic power absorbed by the tissue model at 2.44 GHz. SAR calculation is realized in terms of radiofrequency radiation exposure safety and constitutes a sufficient electromagnetic dosimetry measure for wearable applications. When the proposed textile antenna is assumed to deliver 0.5 W, the simulated SAR distributions regarding the on- and off-body radiation modes are shown in Fig. 9(a) and (b), respectively. The maximum 1-g average values are 0.237 W/kg and 0.079 W/kg under both operation modes. This implies that the IEEE standards limiting 1-g and average SAR to a value of less than 1.6 W/kg are not violated [11].



(a) (b)

Fig. 9 Simulated SAR distributions averaged in 1 g of tissue for antenna input power = 0.5 W at 2.44 GHz under (a) monopole-like mode, and (b) broadside mode, respectively.

4 Conclusions

In this paper, a compact textile patch antenna with pattern and polarization reconfigurability has been proposed for WBAN applications at 2.4 GHz ISM band. When four snap-on buttons are engaged, a monopole-like radiation pattern with vertical polarization is achieved for on-body communication. Under disengaged buttons, the antenna radiates in a broadside direction with circular polarization which is suitable for off-body channels. Numerical results in terms of resonance, radiation, and safety performance indicate that the antenna is a suitable candidate for wearable healthcare applications. The textile antenna can be integrated into a patient's robe and dynamically select the optimum radiation mode to enable efficient remote health monitoring within hospital facilities or patient's house. In the on-body mode, a wearable control unit can wirelessly collect physiological parameters (e.g., heart rate and temperature) recorded by sensor nodes for data processing. The on-body unit can, then, transmit the data to an external base station via the off-body link for medical assessment.

In our future work, numerical evaluation of the antenna performance characteristics will be conducted by applying an anatomical human body model. The impact of the antenna structural deformation will be examined, as well. The study will be fulfilled with the fabrication and experimental measurement of the antenna design.

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