Design and on-body evaluations of a low-cost wearable PIFA for on-body applications

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Abstract. A flexible low profile textile antenna based on planar inverted-F antenna (PIFA) structure is presented in this paper. This topology has been chosen due to its design simplicity, relatively large bandwidth and the existence of a full rear ground plane, which shields against the effects of the body. The antenna topology which is designed on a 4 mm-thick felt substrate is presented. Conductive textile (Aaronia-shield) is applied as the antenna’s radiator and ground plane due to its light weight, low surface resistance and good conductivity. The antenna performance in free space and bent conditions in the proximity of human body are studied, followed by a numerical investigation on the influence of relative humidity on the textile antenna performance. The fabricated PIFA is assessed experimentally and is found to be in good agreements with the simulation results. Finally, the antenna is attached to a compact RF module and is evaluated on body in a practical environment. The wireless link quality is also evaluated in an indoor laboratory environment.

Keywords: Textile antennas, planar inverted-F antennas (PIFA), humidity effect, specific absorption rate, link budget.

1. Introduction

In recent years, wearable technologies are increasingly popular and are potentially useful for applications such as in security services (police or military services), rescue applications (firefighters), sports and entertainment. For instance, they can be applied to athletes for health and performance monitoring purposes. The wearable technologies can also be extended to improve the quality of life for people with long term and chronic diseases. Depending on the type of application and activities they perform, various wearable antennas have been presented with different requirements and features. However, they should generally be low-profile, lightweight, simple to fabricate and cost effective. Furthermore, they must feature simple installation and easy maintenance.

There are many types of wearable antennas designed based on conventional topologies such as planar dipoles antenna [1], monopoles [2], planar inverted-Fs (PIFAs) [3], [4], and microstrip patches [5]. These are popular antenna types due to their low cost and ease of fabrication. In this paper, a planar inverted-F antenna (PIFA) is chosen due to their small size and simple design. The availability of a rear ground plane also enables the operation in close proximity to human body. This antenna is a suitable
prototype that fulfills all the mentioned characteristics. This article mainly aims at exploring PIFA from its challenges such as body effect, specific absorption rate (SAR) and humidity effect on the antenna. Thereafter, a fabricated PIFA and its measurement analysis are presented. Due to very limited works discussing antennas link quality at the end, a communication link evaluation with a base station using the proposed is performed.

This article is organized as follows. In Section 1, the design of a PIFA as a wearable antennas will be introduced. Section 2 discusses the sensitivity analysis and the PIFA performance in different conditions, such as in bent situation or in proximity of human body. The assessment of the humidity effects on antenna performance is investigated in the following section, prior to the SAR evaluations. In Section 5, the fabrication of the PIFA and the measurements of its reflection coefficients and radiation patterns is presented. Finally, the antenna is integrated with a wireless module and worn on-body to evaluate its wireless link quality in Section 6, prior to the conclusions.

2. Wearable textile PIFA design

The PIFA’s structure consists of a ground plane, a radiator, a shorting wall and a feeding probe. This antenna is simulated based on [6] to achieve a large bandwidth. Its ground plane prevents serious detuning in operation in the proximity of the human body. The design calculation is based on an empirical formula in [7]. This formula, shown in equation (1), is appropriate for antennas smaller than $S_h + R_w + R_L < \lambda$. In (1) $W_f$ is the width of the feed. The horizontal and vertical distance of a 50 Ω SMA feeding probe from the edge of the shorting plate are $f_h$ and $f_v$, respectively. Other dimensions are marked in Fig.1.

$$f_c = \frac{c}{3R_w + 5.6R_L + 3.7S_h - 3W_f - 4.3\sqrt{f_h^2 + f_v^2}}$$  (1)

The antenna structure is a conventional simple PIFA shown in Figure 1. A 0.17 mm-thick textile, namely ShieldIt is applied as antenna’s conductive part. A 4 mm-thick felt, with a relative permittivity of $\varepsilon_r = 1.45$ and $\tan \delta = 0.044$, is used as the substrate. In order to simplify the analysis, the conductive textile is considered as a good metal (with a conductivity, $\sigma = 5.9 \times 10^7$ S/m). The antenna dimensions are given in Table 1.

![Figure 1. Antenna structure [6].](image)

| Table 1. Summary of the dimension of proposed PIFA. |
|---------------------------------------------|
| Parameter | $W_w$ | $f_v$ | $f_h$ | $R_w$ | $R_L$ | $G_W$ | $G_L$ |
| Size (mm) | 5.0 | 9.5 | 8.5 | 19 | 21 | 19 | 50 |
3. Sensitivity analysis

The first analysis considers the effects of the body tissue presence on the antenna proximity, which is the most common factor affecting the antenna performance. For this analysis, it is assumed that the antenna has been mounted on an arm model. Simulations were performed using CST Microwave Studio (MWS). A four-layered arm model is used in the analysis: bone, muscle, fat and skin (listed from the inner to outer layer). A 15 mm gap between the antenna and human tissue is considered. The thickness of each layer is listed in Table 2 and the model is shown in Figure 4(a). The permittivity, conductivity and density of layers are obtained from CST MWS material library. The length of tissue model is assumed to be infinite due to the use of the open boundary condition.

The human body is an electrically lossy medium with different complex dielectric constants for each tissue. In Figure 2, the simulation result of the reflection coefficient ($S_{11}$) of the cases with and without the tissues in flat conditions are compared. A minor difference between the two cases is shown, where the presence of the high dielectric constant of the tissue resulting in an extra resonance at 2.26 GHz and shifted the center frequency of 2.45 GHz to about 2.62 GHz. The -10 dB impedance bandwidth of the antenna, however, increased from 700 MHz to 750 MHz approximately. The radiation patterns of antenna with and without human body are compared in Figure 3, where it is observed that the radiation pattern is directed away from the body due to the presence of body tissues.

![Figure 2. Reflection coefficients of the PIFA.](image)

![Figure 3. Radiation patterns of antenna at the $\phi = 0^\circ$ and $\phi = 90^\circ$ cuts.](image)

The antenna is then placed bended around an arm using radii given in Table 2, as shown in Figure 4(b). The reflection coefficients and radiation patterns of the bended antenna are depicted in Figures 5 and 6. As seen from Figure 5, the changes in the radius of the arm did not result in considerable resonant
frequency shift, but instead, having the antenna around a smaller arm radius reduces the antenna bandwidth. Comparisons are then made between the flat case and radii of 67.5 mm and 40.5 mm, which are near to realistic radii of the arms of normal adults. On a 67.5 mm arm radius, the antenna resonates at 2.35 GHz, with bandwidth of 750 MHz while bending on a 40.5 mm arm radius resulted in a slightly lower resonant frequency of 2.32 GHz and a bandwidth of 650 MHz. Note that a 750 MHz bandwidth for the antenna operating in flat condition is observed previously. The dual resonance characteristic remains for 67.5 mm arm radius, but disappeared in the case of the 40.5 mm arm. The antenna’s maximum gain is 3.187 dB and 0.804 dB for larger and smaller arm radii, respectively. This is mainly due to the degradation in radiation efficiency. In general, the bigger the arm radius, the better the antenna performance, as shown in Figure 6.

Table 2. Multilayered human model [8].

| Layer     | Air Gap | Skin | Fat | Muscle | Bone |
|-----------|---------|------|-----|--------|------|
| Thickness | 15      | 2    | 10  | 28     | 12.5 |
| (mm)      |         |      |     |        |      |

Figure 4. 3D view of the two phantom models: (a) flat (b) cylindrical arm.

Figure 5. Comparison of the reflection coefficient ($S_{11}$) simulations of the bent PIFA antenna on the human arm with radii of R = 67.5 mm and 40.5 mm in comparison with planar condition.
Figure 6. Simulations of radiation pattern of the bent antenna in the presence of human body with radii of 67.5 and 40.5 mm at: a) phi=0° cut; and b) phi=90° cut.

The reflection coefficients for the antenna in flat and bent conditions evaluated in free space is shown in Figure 7. In comparison to evaluating on human tissue model in Figure 6, these two results illustrate inconsistencies in terms of resonant frequencies. However, a clear trend in terms of gain can be seen in Figure 8. The antenna resonates at 2.54GHZ with bandwidth of about 730 MHz and the gain of 2.465 dB when bent with 67.5 mm of radius. On the other hand, for 40.5 mm radius, the resonant frequency, bandwidth and gain is about 2.3 GHz, 690 MHz and 2.389 dB, respectively. It is seen from these results that the reduction in the bending radii decreases the antenna gain.

Figure 7. Reflection coefficients of the antenna in bent condition in free space (without human body).
Figure 8. Radiation patterns of the bent antennas in free space and with radii of 67.5 mm and 40.5 mm at: a) phi=0° cut; and b) phi=90° cut.

Next, SAR levels for the bent PIFAs are illustrated in Figure 9(a). In this simulation, an input power of 250 mW is used, resulting in a SAR value of 1.97 W/kg. This does not exceed the ICNIRP standard threshold of 2W/kg averaged over 10g of tissues. Moreover, the 250 mW of input power also meets the FCC standard threshold for power transfer in the 2.43 GHz band, which is also limited to 1 W. In [9], it was reported that the measured SAR for the slotted PIFA (SPIFA) when placed at distance of 10 mm from the body in flat condition using an input power of 100 mW at 2.45 GHz is about 0.5 W/kg. Similarly, simulated SAR for the proposed PIFA under bent condition is 0.807 W/kg when evaluated under the same conditions, indicating a reasonable agreement. The small discrepancies may be due to the slight difference in the evaluation conditions, in which in [9], it is evaluated in flat condition, but in this work, it is evaluated in bend conditions.

Figure 9. Simulated SAR of the bent PIFA with (a) input power=250mW (b) input power=100mW

4. Effects of Humidity on the Antenna Performance

Generally, humidity or moisture will potentially affects textile antenna performance. Due to the high permittivity of water ($\varepsilon_r = 78$ at 2.45 GHz and 25°C), if it penetrates into a substrate, it may lead to an increase in permittivity. Therefore, to assess the severity of the humidity effect towards antenna performance, a simulation with a varied relative permittivity is performed. It is also assumed that all other properties of the substrate remain unchanged. Note that the initial relative permittivity of this substrate is $\varepsilon_r = 1.45$. Figure 10 shows that as the relative permittivity increases, the resonant frequency...
shifts towards lower frequencies. On the other hand, as the permittivity increases, the $|S_{11}|$ performance is gradually deteriorated such that with a permittivity of about 2, the reflection coefficient degraded to less than -10 dB. This moisture effect simulation results are in good agreement with the measurements performed in [10]. Therefore, the humidity effect on the substrate loss tangent of textile materials can be further investigated in order to estimate this effect more accurately.

![Figure 10](image)

**Figure 10.** Effect of permittivity change (humidity) on reflection coefficient of PIFA.

5. Fabrication and measurements

To fabricate the antenna, felt is chosen as its substrate, while a conductive textile called Aaronia-shield is used for the conductive part. The latter is used as the antenna’s radiator, ground plane and shorting wall, as it is light weight (about 34g/m²), low surface resistance (lower than 0.1Ω/sq) and good surface conductivity. The dimensions of the PIFAs are as listed in Table 1. Both the substrate and conductive textiles are sewn to connect them. A SMA connector is used to feed the antenna by soldering to the ground plane. Figure 11 shows the fabricated PIFA. A comparison between simulated and measured reflection coefficients and radiation pattern of the antenna are shown in Figure 12 and 13 respectively.

![Figure 11](image)

**Figure 11.** (a) Upper and (b) front view of antenna prototype.

As depicted in Figure 12, the antenna operation is centered at 2.5 GHz with a good bandwidth of 750 MHz from 2.25 GHz to 3 GHz. However, in Figure 13, the radiation patterns show disagreement between simulations and measurements. This could be due to slight damage to the substrate during the soldering process, and inaccurate values of the electrical properties of the substrate (permittivity and loss tangent). It was assumed initially that these properties are as listed in [6], but are found to be different in practice. Moreover, the sewing process also causes inaccuracy towards the measurement data.
Figure 12. Comparison between simulated and measured reflection coefficients of the antenna.

Figure 13. Comparison between simulated and measured normalized radiation patterns of the PIFA.

6. Wireless Link Evaluation

From the previous section, it is validated that the antenna is operated from 2.25 GHz to about 3 GHz with less than -10 dB of reflection coefficient. To further evaluate the performance of the antenna in practice, a low-cost NRF24L01 module from Nordic Semiconductor with a nominal transmission range of 1800 m is used. This module is used to collect health data using a series of small integrated thermal sensors, heart beat rate sensors and accelerometers to communicate with the access point located at a distance away in an indoor environment. To obtain real-time test data in a personal computer, a converter was used to connect the RF-antenna system to the computer via its USB port. The fabricated PIFA is then connected to the NRF24L01 module and the USB converter board as presented in Figure 14. The base station (in the form of a laptop) is connected to a monopole antenna to communicate with the wearable system as shown in Figure 15(a). To assess the quality of the link, the wearable system is mounted on a human body to transmit repeated simple bits. The user of this wearable system then moves and the wireless link quality is tracked until it is totally disconnected. The measurement is performed in an indoor laboratory environment and the quality of the wearable system is compared with the case of a simple monopole replacing PIFA when worn on body. It is observed that quality of the link for both are similar with none of them being superior. Next, the wireless link quality is also tested when the base station is moved. The connectivity range of the link is then decreased to around 100 meters due to severe multipath of the indoor environment. The communication between the on-body wearable system to the base station is illustrated in Figure 15(b). The ultimate final goal of this research is to be able to fully integrate the wearable module with the antenna and sensors to track human health, which is aimed to be prototyped in the near future.
Figure 14. Wearable PIFA connected to a NRF24L01 and driver board.

(a) Base station  (b) Wearable mobile system communicating with the base station

Figure 15. (a) The fixed base station for the test and (b) The on-body wearable mobile system while connected to a laptop to track communication quality.

7. Conclusion

A planar inverted-F antenna designed using textile materials is presented in this paper. The design procedure and method of estimating the initial dimensions of this PIFA is discussed, followed by its evaluation in planar and bent conditions, both in free space and on-body. To ensure the safety level of the proposed antenna, specific absorption rate of this antenna is calculated when placed in the proximity of two types of human phantoms, a three-layered rectangular body tissue model, and a similar three-layered cylindrical model replicating an arm. For the latter, two cylindrical radii were used, 67.5 and 40.5 mm to assess the effects of the severity of the bending on the antenna performance. Next, the antenna performance was also evaluated with various humidity levels of the substrate. This is done by changing the relative permittivity of the substrate and assessing the reflection coefficient of the antenna. The optimized antenna was then fabricated and measured, and then compared with simulations performance, in terms of reflection coefficient and radiation patterns. Finally, the proposed antenna is integrated with a wireless module to evaluate its performance in practice when worn on the human body. The quality of the wireless link performed in an indoor laboratory environment is also compared with the performance from a monopole antenna, indicating similarity in performance.
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