Characterization of a Plain Broadband Textile PIFA

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Abstract. *Bandwidth characteristic of a wearable antenna is one of the major factors in determining its usability on the human body. In this work, a planar inverted-F antenna (PIFA) structure is proposed to achieve a large bandwidth to avoid serious antenna reflection coefficient detuning when placed in proximity of the body. The proposed structure is designed based on a simple structure, in order to provide practicality in application and maintain fabrication simplicity. Two different types of conductive textiles, namely Pure Copper Polyester Taffeta Fabric (PCPTF) and ShieldIt, are used in order to proof its concept, in comparison with a metallic antenna made from copper foil. The design is spaced and fabricated using a 6 mm thick fleece fabric. To cater for potential fabrication and material measurement inaccuracies, both antennas' performance are also investigated and analyzed with varying physical and material parameters. From this investigation, it is found that the proposed structure's extended bandwidth enabled the antenna to function with satisfactory on-body reflection coefficients, despite unavoidable gain and efficiency reduction.*

Keywords

Textile antennas, conformal antennas, broadband antennas, planar inverted-F antenna (PIFA), on-body communication.

1. Introduction

A wearable antenna is an essential part in any Wireless Body Area Network (WBAN) application. They are electronic nodes being made flexible enough to be worn and to work on or in-proximity to a user's body. Effective implementations of BANs are seen to potentially contribute to huge advancements in emergency services, medical, military, identification, navigation, sports, etc. However, degradation of antenna performance when worn on the human body has been one of the major deterrents in its successful implementation, be it in terms of frequency detuning, bandwidth reduction, and efficiency degradation or radiation distortion [1]. In other words, ideally, a wearable antenna must be designed to be immune enough for on-body operation. Moreover, a flexible antenna made from textile is regarded as a realistic candidate due to the advancements in conductive textile materials and the ergonomic properties that it is able to offer. Previous researches have mainly investigated detuning in proximity of human head and hand [2], which is not necessarily applicable in WBANs. On the contrary, prospective on-body antenna locations in WBANs are mainly concentrated on the upper torsos, arms and legs. Thus, an accurate characterization of material enables researchers to accurately predict fundamental degradations in proximity of the human body.

In that perspective, various researchers have came up with a multitude of strategies in order to minimize the effect of dielectric coupling to various parts of the body. Prior to that, definition of textile materials' properties is deemed important, and was investigated [3]. Due to the unpredictable measurements when coupled to the body, most researchers have investigated their antenna designs' usability in terms of frequency and bandwidth detuning in proximity of the body [4, 5]. This necessity also originated from the inability of simplified simulation assumptions in predicting antenna performance changes on body. Thus to achieve this objective, the proposed structure's bandwidth has been designed wide enough to cater for frequency detuning and bandwidth degradation when operating on body.

Various textile antenna topologies have been proposed for use in the WBAN domain. While planar structures, based on a microstrip topology are extremely popular, the earliest work in wearable antennas proposed a PIFA as topology [6]. It consists of a radiator, a ground plane, a shorting wall, and a feeding probe. The existence of ground planes in PIFAs helps to avoid serious detuning in operation close to the human user, in contrast to wired antenna structures. Moreover, the property of PIFAs – compact in size and omni-directional in nature – enables ease of on-body mounting and allows reception of randomly polarized arriving signals [7]. Besides that, it also eases resonance tweaking through radiator modification, shorting wall dimension and feeding position changes [8]. A single, narrow band PIFA could be upgraded to function with dual- or multi-band characteristics [9]. Even though the proposed antenna might be slightly thicker than uni-layered microstrip types, recent investigations in [10], [11] have used substrates of at least 3 mm in thickness to realize relatively narrowband microstrip antennas. Moreover, the use of thicker substrates reduces the possibility of antenna bending, which results in an extreme performance degradation.

The work is organized as follows. In the first section, the proposed structure, conductive textiles and substrate are defined. The fabrication tolerances and their effect on the antennas' performance are discussed in the subsequent section. Simulated and measured results for the fabricated antenna prototypes are then presented. Finally, an investigation of the antennas when operating on body is performed and discussed.

2. Antenna Design

Three types of antennas are investigated in this work. One of them utilizes a metallic copper foil with a thickness, *t*, of 0.035 mm, whereas the other two materials are conductive textiles from LessEMF Inc. While both textiles are made from the same polyester base material, each has different thickness, and is coated using different metallic conductors. The first textile – Pure Copper Polyester Tafetta Fabric (PCPTF) is a 0.08 mm thick plain woven polyester textile, coated using only copper to provide a surface resistivity (R_s) of less than 0.05 Ω/sq. The second textile, ShieldIt™, is twice as thick (0.17 mm), is a rip-stop woven polyester, and is coated using both nickel and copper. This textile also provides less than 0.05 Ω/sq of surface resistivity [12].

The structure of the proposed PIFA is shown in Fig. 1. A shorting plate with a width *Ww* is positioned at the edge between a ground plane sized at G_L x *Gw*, connected to a top radiator with a length and width of R_L x *Rw*. The structure is fed using a 50 Ω SMA probe from the bottom of the two layered structure, positioned at a horizontal distance of f_h and vertical distance of f_v from the edge of the shorting plate. The antenna is spaced by a polyester fleece textile with thickness, S_h = 6 mm, between its ground plane and top radiator. Notice that *Gw* and *Rw* are sized similarly, while the shorting wall is positioned at the specific location for practical simplicity, enabling it to be fabricated using a single piece of textile.

Measurement using a cavity method shows that felt possesses a relative permittivity, ε_r= 1.45 and $\tan\delta$ = 0.044. This material is chosen as the antenna's substrate as to enable ease of integration onto the users' clothing. CST Microwave Studio is utilized to simulate this structure at a desired frequency of 2.45 GHz. The textiles are defined as lossy metals in order to simplify the analysis. The antenna dimensions are summarized in Tab. 1. The conventional PIFA design equation in [13] has been found to be too limited in terms of dimensional accuracy. Moreover, its main purpose is only to provide an estimated PIFA resonance instead of providing dimensional estimates of each component to a satisfactory extent. Thus, the initial design calculation in this work is carried out using an experimentally derived formula in [14], which is suitable for antennas smaller than S_h+*Rw*+R_L < λ:

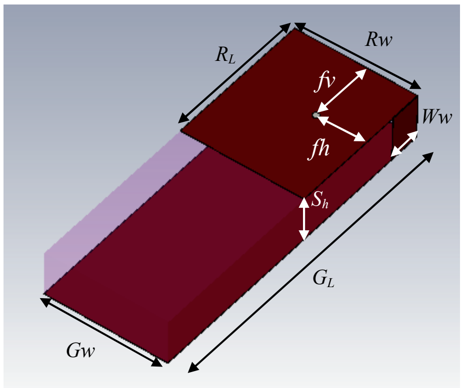


Fig. 1. Dimensions of the proposed plain broadband PIFA.

Parameter	Calculated	Cop Foil	PCPTF	ShieldIt
G_L	50.0	50.0	50.0	50.0
Gw	19.0	19.0	19.0	19.0
R_L	24.0	23.0	23.0	21.0
Rw	19.0	19.0	19.0	19.0
f_h	9.5	8.5	7.5	8.0
fv	12.0	10.5	10.5	10.5
Ww	6.0	4.0	5.0	5.0

Tab. 1. Dimension summary of the fabricated PIFAs (all in mm).

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

This equation enables a better estimation of the R_W and R_L. The approximate size of the radiator is 19 x 24 mm, while optimized values of 19 x 23 mm are obtained with CST. One of the reasons for this variation is the simplification and curve fitting of the distance between shorting plate and feeding point.

3. Sensitivity Analysis

Despite the reasonably simple PIFA structure proposed, fabrication process and tools will still be a cause for inaccuracies, even when non-flexible materials are used. Thus, it is always a good practice to predict antenna performance changes prior to fabrication, so that unexpectedly large variations could be foreseen and avoided. In this section, small antenna parameters' changes, with an offset of ±2.0 mm against optimized dimensions, are studied using the solver. The six physical parameters which have been observed to affect the antenna significantly are the radiator dimensions (*Rw* and R_L), shorting wall width

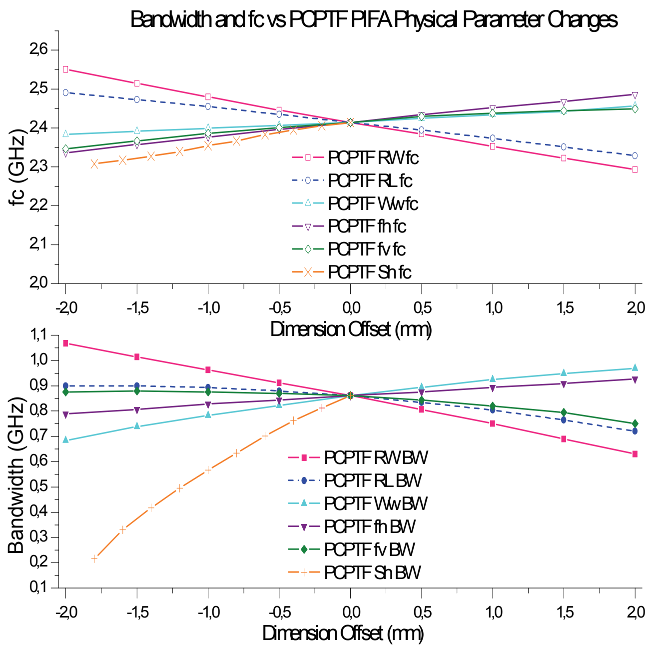
(*Ww*), feeding location (f_h and fv) and substrate height (S_h). Besides that, material parameter effects (relative permittivity, ε_r, conductivity, σ, and loss tangent, $tan\delta$) on the antenna's performance are also looked into by observing the -10 dB bandwidth (*BW*), center frequency (f_c), total efficiency (η_{tot}) and gain.

3.1 Physical Antenna Parameters

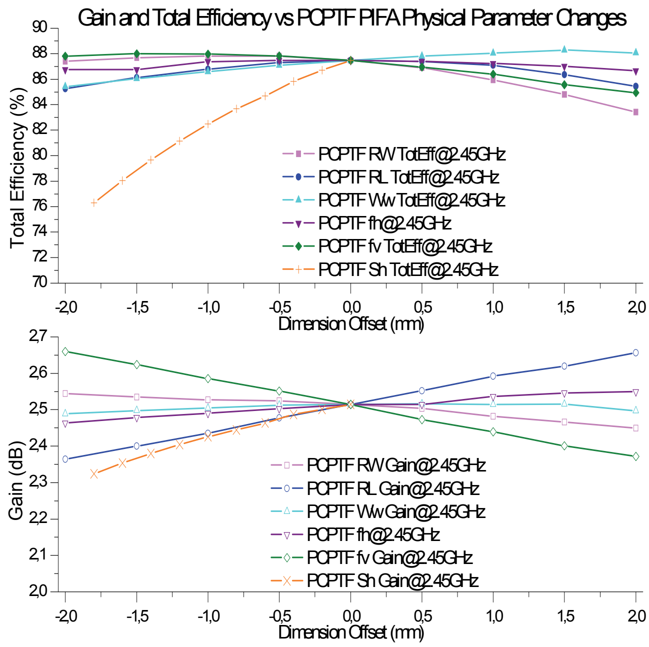
In Fig. 2(a), a steady upwards f_c shift can be observed as the horizontal feed location (f_h) is moved inwards and *Ww* is lengthened, for both PCPTF and ShieldIt PIFAs. When fv is being vertically moved downwards, however, both antenna types behave differently. ShieldIt PIFA is seen to experience a slight downwards f_c shift, while it is otherwise for the PCPTF PIFA. The increment of *Rw* and R_L, on the other hand, is seen to obey conventional antenna resonance principles. A longer electrical length is seen to move f_c downwards at a consistent rate for both antenna types. S_h, seen as the most sensitive parameter, is investigated in case of thickness reduction only. This is due to the fabrication process which only allows the possibility of substrate compaction. f_c is spotted to be moving downwards with S_h reduction, and this f_c shift is seen to affect the ShieldIt PIFA more seriously compared to the PCPTF PIFA.

With the increase in f_c for both f_h and *Ww*, a simultaneous increase of *BW* is observed. For fv, changes did not affect the *BW* when moved vertically upwards, but started decreasing significantly when moved downwards for the PCPTF PIFA. The ShieldIt PIFA, in Fig. 3(a), showed a steady *BW* decrease when fv is moved from -2 mm to +2 mm vertically. Even though the increment of *Rw* and R_L are seen to have a similar effect on f_c, the effect is different for the *BW*. For the PCPTF PIFA, *Rw*'s and R_L's increment both reduced the *BW*. R_L for ShieldIt, however, maintains more or less the same *BW*, except when it is reduced more than 1.5 mm. *BW* decline caused by S_h is quite considerable, causing both PIFAs to be non-functional when reduced up to S_h= 4 mm.

Fig. 2(b) demonstrates the significance of S_h compaction towards η_{tot} and gain reduction. Decrement of S_h by 2 mm is seen to decrease η_{tot} by about 10 % for the PCPTF PIFA. A more serious decline is seen for the ShieldIt PIFA, see Fig. 3(b). A similar 2 mm S_h reduction caused about 12% degradation in η_{tot}. The alteration of other physical PCPTF PIFA parameters (*Ww*, R_L, and feeding location), meanwhile, only caused a maximum of 4 % decline when their dimensions are varied less than ±2 mm. A maximum η_{tot} change of 9 %, on the other hand, is observed for the ShieldIt PIFA as its similar physical parameters are varied. The largest change in η_{tot} for ShieldIt is caused by the shift of vertical feeding location, fv, while for PCPTF, it is caused by changes to *Rw*. Additional radiator area as a result of R_L and *Rw* extension is seen to add to the η_{tot} for the ShieldIt PIFA, while *Ww* is seen not to produce any influence besides contributions to antenna matching.



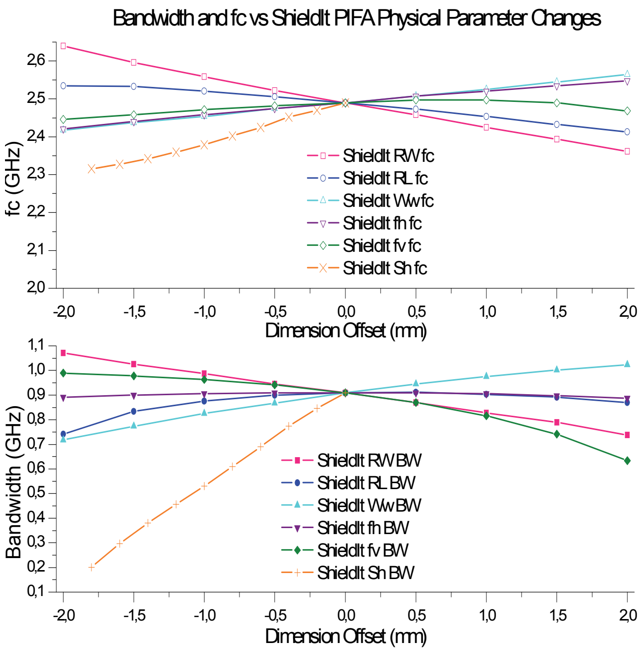
(a)



(b)

Fig. 2. Performance of PCPTF PIFA with varying physical parameters (a) bandwidth and f_c; (b) gain and η_{tot}.

Physical changes in the ShieldIt PIFA dimensions is more significant with respect to its gain compared to the PCPTF PIFA. A maximum of 3.5 dB change in gain is observed for PCPTF, while 4.5 dB is observed for ShieldIt when varied within ±2 mm. Nonetheless, the behavior of each parameter change is similar for both antennas. It is seen that both the ShieldIt and PCPTF PIFAs' gain are constant with the variation of *Ww*. S_h reduction is seen to affect the gain the most, with about 0.2 dB decrement for a 2 mm reduction, observed in both antenna types. The increase of *Rw*, and the movement of fv downwards, also reduces the gain for both antennas reasonably. On the contrary, R_L increase and f_h location movement inwards are also both seen to increase the gain at similar rates.



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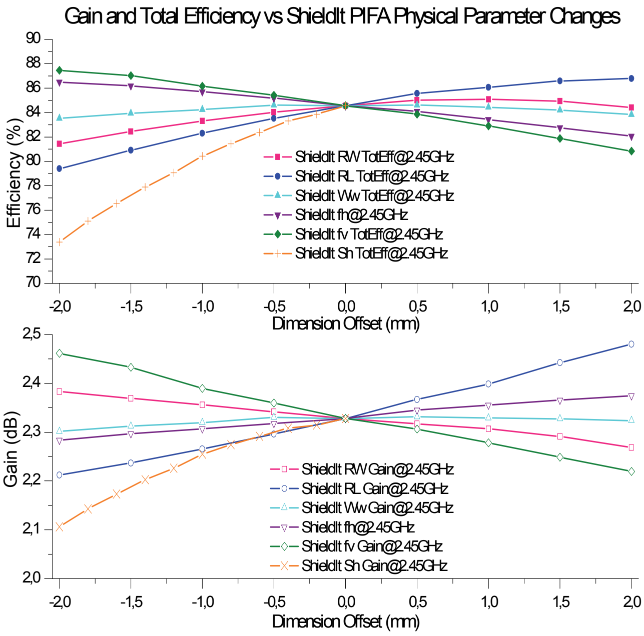
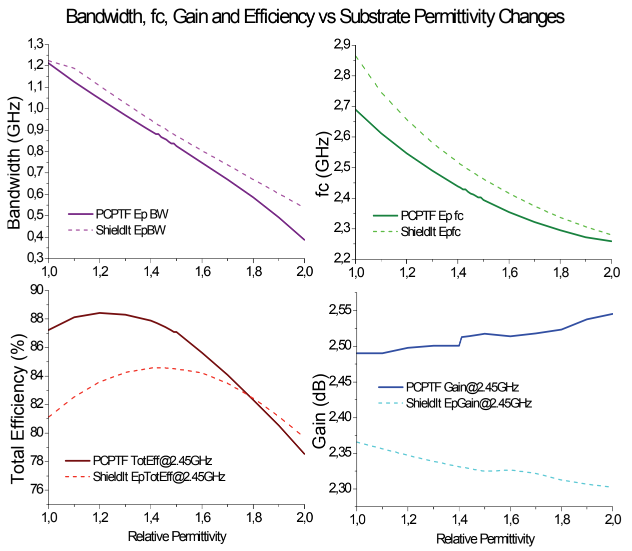


(b)

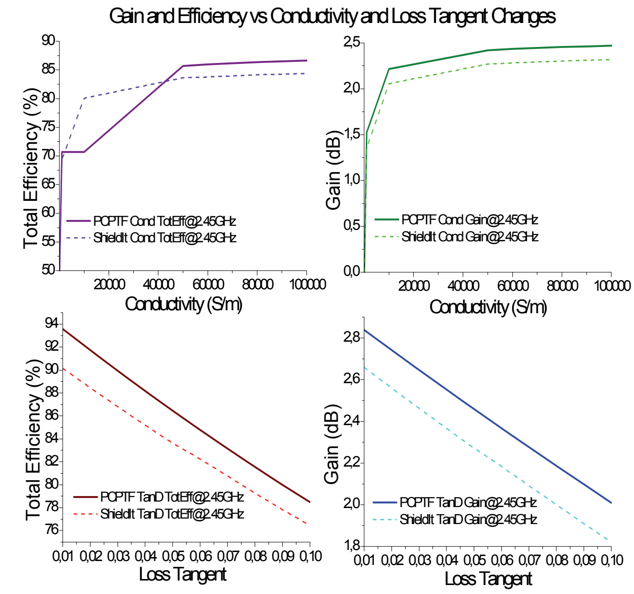
Fig. 3. Performance of ShieldIt PIFA with varying physical parameters (a) bandwidth and f_c; (b) gain and efficiency.

3.2 Material Parameters

Fig. 4 presents the changes of BW, f_c, η_{tot} and gain with respect to material inaccuracies (ε_r, σ and $tan\delta$). Generally, a wrong estimation of ε_r will have larger consequences on BW and f_c. Increasing ε_r from 1.0 to 2.0 causes about 400 MHz downwards f_c shift and reduces the BW by 800 MHz for the PCPTF PIFA, see Fig. 4(a). For the ShieldIt PIFA, changes to BW are quite similar, while its f_c variation occurs at a slightly higher rate. f_c decreases 550 MHz when ε_r for the PCPTF PIFA is increased from 1.0 to 2.0, while at the same time, this results in a 10% reduction of η_{tot}, from 88 % to 78%. The ShieldIt PIFA, meanwhile, shows a maximum η_{tot} of 84 % when ε_r= 1.5, which is then reduced by about 1 % in the extreme cases of ε_r= 1.0 and ε_r= 2.0. Gain for the PCPTF PIFA is seen to be increasing by about 0.05 dB when ε_r is increased from 1.0 to 2.0, while a decreasing trend is seen for the ShieldIt PIFA, also by about 0.05 dB. In general, variation of the the PIFAs ε_r will not cause more than 10 % of η_{tot} changes and 0.05 dB of gain variation, indicating a stable design topology. Moreover, inaccuracy in the prediction of ε_r is seen not to affect gain in any significant way.



(a)



(b)

Fig. 4. Performance of PCPTF PIFA with varying material parameters: (a) substrate permittivity, (b) conductivity and loss tangent.

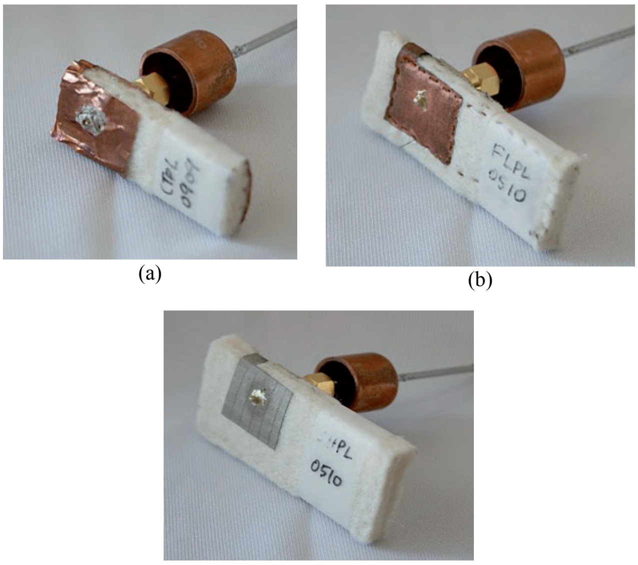
However, the study presented in Fig. 4(b) tells otherwise. Changes in σ and $tan\delta$ result in more significant changes to η_{tot} and gain, while the variation of f_c is small and unobservable. *BW*, meanwhile, is enlarged by 300 MHz when σ is less than 100 S/m for both antennas, which is unacceptable considering its effects on η_{tot} and gain. Analyzing conductivities, lowering σ from $2.5{\cdot}10^5$ S/m to $5{\cdot}10^4$ S/m is already enough to degrade the PCPTF's η_{tot} by about 15 %, while the ShieldIt PIFA's η_{tot} is decreased by only 5% when going down from $1.18{\cdot}10^5$ S/m to $1{\cdot}10^3$ S/m. This is also about 100 times lower than the nominal calculated value. Beyond this threshold, both antennas are seen to function very poorly, with theoretical η_{tot}'s of less than 50 %. Gain is seen to maintain at levels of more than 2 dB as long as σ is larger than the threshold of $\sigma > 1{\cdot}10^3$ S/m. Next, an investigation on loss tangent was carried out by sweeping its values from $tan\delta = 0.01$ to $tan\delta = 0.10$. As expected, both antennas show significant amounts of η_{tot} degradation, -14 % for PCPTF and -12 % for ShieldIt, while gains are also degrading steadily by about 0.8 dB for both antenna types.

This analysis shows that aside from ε_r, realistic amounts of inaccuracies for the other two material parameters will not affect the PIFA's performance in terms of f_c and *BW* significantly. Loss tangent and conductivity changes, on the contrary, are more significant on η_{tot} and gain. A similar behavior is observed for an identical parameter variation when an analogous analysis is carried out on PIFAs built using ShieldIt, which is about twice thicker than PCPTF, and copper foil, which is about twice as thin compared to PCPTF. In general, although the PIFAs' physical parameters i.e Rw and R_L, f_h and fv, Ww and S_h produce the most impact on its conduct in free space, the effect of specific material parameters (i.e $tan\delta$, ε_r and σ) should not be ignored to ensure an accurate prediction of antenna performance.

4. Results and Discussion

4.1 Experimental Results

Both PIFAs were prototyped using different conducting materials to operate at $f_c = 2.45$ GHz. A single piece of conductive textile or foil is cut into the desired shape and fastened over a 6 mm thick felt fabric to form the PIFAs. A bottom-to-top hole was created, enabling the insertion of a 50 Ω SMA connector. A high frequency conductive epoxy, model 129-4 from Epotek Inc. was used to ensure the SMA-to-textile connection at room temperature without soldering. Fabrication using this simple method provides an estimated accuracy of ca. 0.2 mm. Note that much larger changes (2 mm) were used in the parametric investigations presented in the previous section. The fabricated antennas are shown in Fig. 5, and the antennas are both sewn onto the fleece fabric to enable better mechanical robustness. The fleece fabric substrates are dimensioned larger than the PIFAs in order to emulate practical conditions, especially during antenna integration onto users' clothing.



(a) (b) (c)

Fig. 5. Fabricated PIFA prototypes using (a) copper foil; (b) PCPTF; and (c) ShieldIt.

It can be seen from Tab. 3 that the discrepancy between the calculated and measured f_c for all three prototypes is less than 3.7 %. The measured *BW*s are also consistent with the simulations. Measurements basically produced about 200 MHz more *BW* compared to simulations. In general, no significant differences have been found among the three prototypes, due to the high similarity in terms of surface resistivity. Measurements of the gain and efficiency were carried out in a Satimo-64 anechoic chamber. All PIFAs generated simulated gains of about 2 dB and efficiencies of about 80 %. Measured gain levels are between 1.5 and 2.2 dB, while measured efficiencies in free space are between 76 % and 85 %. In general, the copper foil PIFA produced better η_{tot} and gain compared to both textile antennas, due to the higher conductivity (theoretically about 200 times better).

Radiation patterns for the PIFAs are shown in Fig. 6. The simulated and measured co-polarized components in both the φ=0° and φ=90° cut show an excellent agreement,

Structure	*BW* Sim (Meas) (MHz)	*fc* Sim (Meas) (GHz)	*η*tot Sim (Meas) (%)	Gain Sim (Meas) (dB)
Cop Foil	792 (1090)	2.46 (2.53)	88.0 (84.9)	2.60 (1.74)
PCPTF	861 (1115)	2.41 (2.48)	87..5 (76.6)	2.51 (1.51)
ShieldIt	909 (1280)	2.49 (2.62)	84.5 (77.2)	2.33 (1.53)

Tab. 2. Summary of simulations and measurements for PIFAs in free space.

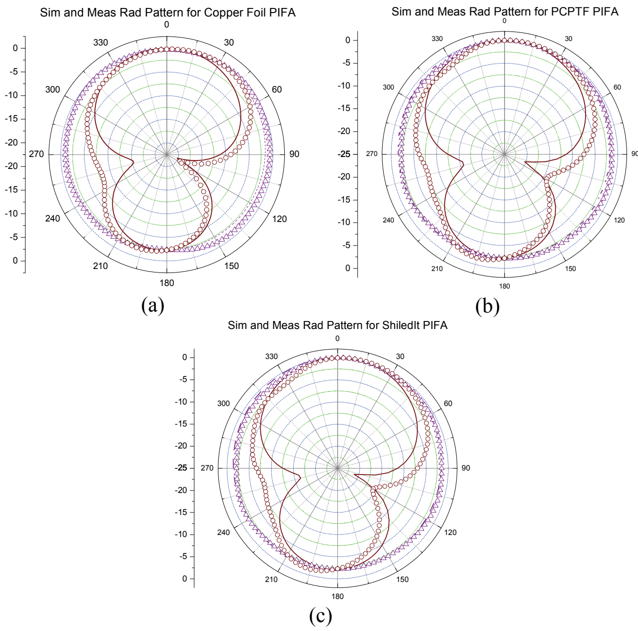


Fig. 6. Simulated and measured radiation pattern for (a) Copper foil PIFA, (b) PCPTF PIFA, (c) ShieldIt PIFA. Legend: (----) simulated $\varphi = 0^o$ plane; (-Δ-) measured $\varphi = 0^o$ plane; (□ □) simulated $\varphi = 90^o$ plane; (-○-) measured $\varphi = 90^o$ plane.

generating a quasi omni-directional pattern in the azimuthal plane. Copper foil PIFAs showed the least simulation–measurement difference, as expected. This is again due to the conductor purity/homogeneity and mechanical robustness, compared to the more flexible textiles.

4.2 On-Body Measurements

It is widely accepted that antenna performance is significantly affected by close proximity to the human body. The level of degradation will be determined mainly by the structure itself, separation distance, and ground plane size. An on surface measurement was not performed since the conductivity of skin of about 1.2 S/m effectively shorts out the antenna and prevents conducting surfaces to pool charges in the intended way [15].

This brings us to the next investigation, which is to validate the PIFAs' operability on users. The antennas are measured on three locations, namely, the chest, shoulder and back. All locations are purposely chosen in order to minimize bending of the overall structure. A ShieldIt PIFA is simulated on the left side of the Hugo model in CST, to evaluate the *BW* and f_c changes due to body coupling. The antennas under test (AUTs) are placed at a distance of 8 mm from the human skin. For chest and back measurements, the AUT is placed at 12 cm from the body's center, and 15 cm from the top of the shoulder. Measurement on shoulder, on the other hand, is carried out by placing the AUTs along its curvature, 10 cm from the beginning of the subject's neck. This is then compared with an on-body measurement using a male human subject of height 178 cm and 88 kg. An 8 mm spacer made from polyester fleece is utilized to emulate simulated antenna-skin spacing, while each antenna location on the body is similar to the simulated setup. They are shown in Fig. 7.

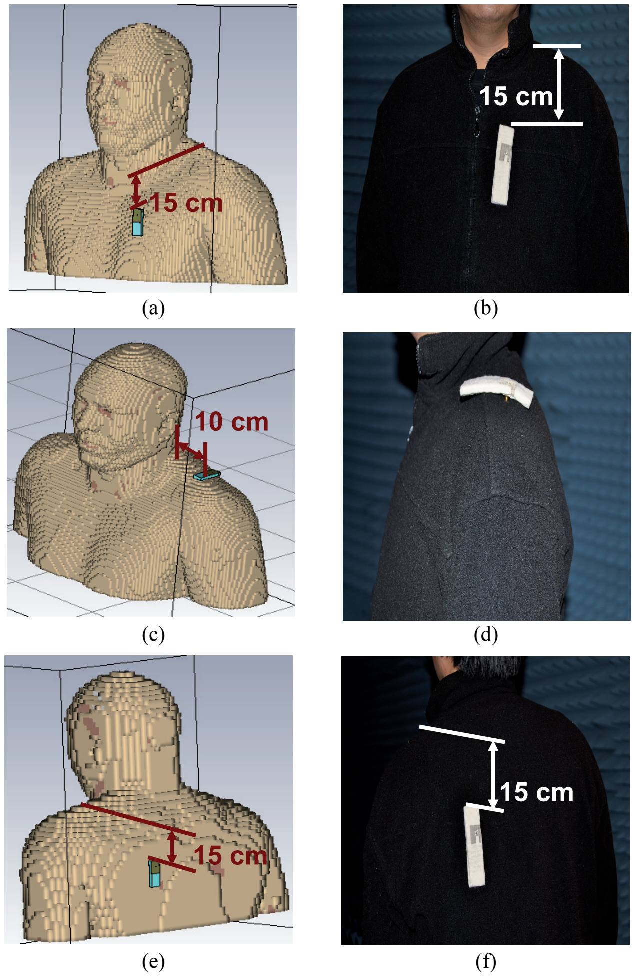


Fig. 7. Simulated and measured on-body locations for (a) chest, simulated; (b) chest, measured; (c) shoulder, simulated; (d) shoulder, measured, (e) back, simulated; and (f) back, measured.

Structure		Free	Chest	Shoulder	Back
Sim (ShieldIt)	BW (MHz)	909	721	1177	1125
	fc (GHz)	2.49	2.45	2.46	2.48
Meas (Cop Foil)	BW (MHz)	1090	1250	1100	1180
	fc (GHz)	2.53	2.52	2.47	2.47
Meas (PCPTF)	BW (MHz)	1115	1200	1160	1270
	fc (GHz)	2.48	2.48	2.47	2.47
Meas (ShieldIt)	BW (MHz)	1280	990	1100	1500
	fc (GHz)	2.62	2.47	2.48	2.62

Tab. 3. Simulated summary of the simulated and measured PIFAs in free space and on body.

As predicted by the simulations, an expansion of the *BW*, with a simultaneous f_c down shifting is observed when the antennas are operated in proximity of the human shoulder and back. The smallest *BW* difference between simulation and measurement is seen when the antenna is placed on the shoulder, with only 77 MHz difference.

These BW differences for the other two on-body positions are quite similar, 269 MHz for chest and 376 MHz for back. This is expected, considering the availability of less area for dielectric coupling and power absorption in the proximity of the shoulder, whereas the antenna would be surrounded by muscle and skin at the other two locations. The larger difference in *BW* between simulations and measurements is a known phenomenon for metallic/dielectric structures with $h > \lambda_i/20$ [5].

Analyzing the free space versus on body simulation results, a ca. 40 MHz downwards f_c shift is expected on body. Measurement results, on the other hand, further verify this observation. Copper foil and PCPTF antennas only experience a small amount of downwards f_c shift, between 11 MHz and 60 MHz, while larger differences are observed for the ShieldIt PIFA. The lowest average shift at all on-body locations is shown by the PCPTF PIFA. Meanwhile, the least f_c shift for on body location is observed when the antennas are mounted on the back, with an averaged shift of 26 MHz for all three antenna types. This is followed by the chest (54 MHz) and shoulder (68 MHz). This indicates operation stability of the textile antennas in the vicinity of the human body.

Simulations also predict that the free space *BW* would vary by ca. ±250 MHz when placed on the body, with the maximum occurring at shoulder placement. This is also seen for the measured ShieldIt PIFA, with maximum changes of ±290 MHz. The shrinking of the *BW* when placed on the chest is also accurately predicted by the simulations. Although the other two antennas behave slightly different, a smaller free space versus on body *BW* change of less than 200 MHz is noticed. Behavior of both copper foil and PCPTF PIFAs is similar, showing the largest free space versus on body difference on the back. This is likely due to the similarity in thickness. In general, copper foil PIFA showed the least measured free space to on body *BW* discrepancy, with an averaged *BW* change for all locations of 87 MHz.

5. Conclusion

A compact and simple PIFA fabricated using conductive textiles, designed to suit wireless body area network application is proposed and discussed. A sensitivity analysis carried out indicates that the antennas' performance is robust with respect to small dimensional changes and material properties' inaccuracies, except for the substrate thickness. Simulated and experimental results indicate that the textile PIFAs are able to operate with a minimum bandwidth of 1200 MHz, 76 % efficiency and 1.5 dB gain, which is satisfactory for application in the intended WBAN frequency band.

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