Appl. Phys. A (2016) 122:423
DOI 10.1007/s00339-016-9912-2

Applied Physics A
Materials Science & Processing

Textile artificial magnetic conductor jacket for transmission enhancement between antennas under bending and wetness measurements

Kamilia Kamardin[1] · **Mohamad Kamal A. Rahim**[2] · **Peter S. Hall**[3] ·
Noor Asmawati Samsuri[2] · **Tarik Abdul Latef**[4] · **Mohammad Habib Ullah**[4]

Received: 15 August 2015 / Accepted: 27 November 2015 / Published online: 21 March 2016

Abstract Textile artificial magnetic conductor (AMC) waveguide jacket for transmission enhancement between on-body antennas is proposed. Transmission characteristics between antennas with different orientations and placements are studied. Significant transmission enhancement is observed for all tested positions. Bending and wetness measurements are also conducted. Bending is found not to give significant effect to the antennas and AMC performance, while wetness yields severe performance distortion. However, the original performance is retrieved once the antennas and AMC dried. The proposed AMC jacket will act as a new approach for efficient wearable body-centric communications.

1 Introduction

The implementation of wearable antennas in on-body communication has been getting much attention due to its attractive properties [1–4]. However, its drawbacks invite new studies to be carried out. Due to the distinct properties of the human flesh [5], wearable antennas experience performance degradation which results in distortion of input impedance and radiation characteristics. Furthermore, the radiation that penetrates into the human body is a concerning health issue [6]. On-body propagation channels are also exposed to fading and shadowing effects. They are also subjected to variation due to local scattering, geometry of the body and its movements [7]. In addition, the human body causes unwanted high transmission loss between antennas.

Good transmission between antennas is crucial for an efficient wireless networking system within human body. The presence of human body introduces high transmission loss between on-body antennas. High transmission loss can disrupt the reliability of the wireless networking system within the human body which is not desirable. To overcome the drawbacks of wearable antennas, a new approach using sheet-like waveguide [5, 8] was introduced. Waveguide sheet is capable of reducing the on-body distortions by providing an independent transmission path for waves to propagate without interference. This research intends to improve the transmission between on-body antennas by using textile artificial magnetic conductor (AMC) waveguide sheet.

In this study, a conformal jacket that acts as a communication medium is proposed. The waveguide jacket will complement wearable antennas to enable better wave propagation. Transmission characteristics between the antennas with different orientations and placements in on-body environment are studied. The proposed antennas and waveguide sheet are also tested under wearable and body-centric measurements.

2 Textile CPW monopole and AMC design

Initially, textile CPW monopoles and AMC are designed and simulated using CST Microwave Studio. The substrates for both antennas and AMC are made of fleece

---

✉ Kamilia Kamardin
kamilia@utm.my

[1] Computer Systems Engineering Group, Advanced Informatics School, Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia

[2] Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia

[3] School of Electronic, Electrical and Computer Engineering, University of Birmingham, Birmingham, UK

[4] Department of Electrical Engineering, Universiti Malaya, Kuala Lumpur, Malaysia

fabric while the conducting parts are made of Shieldit fabric. The fleece used in this study has permittivity $\varepsilon_r = 1.3$, tangent loss $\delta = 0.025$ and thickness $h = 1$ mm. The conductive Shieldit fabric is lightweight and flexible and is made of nickel and copper with polyester as the base. It is a rugged material and has hot melt adhesive backing that allows easy fabrication. The Shieldit fabric has conductivity $\sigma = 100$ S/m, surface resistivity $\rho = 0.01$ Ω/m and thickness 0.17 = mm.

A unit cell characterization using CST transient solver is performed to design the AMC array (Fig. 1a). The unit cell simulation represents infinite array by manipulating the boundary conditions in CST. A simple geometry of square AMC structure is proposed in this study due to the limitation of textile materials as well as constraints in fabrication. Such design is simple, low cost and easy to fabricate apart from giving satisfactory performance. Initially, theoretical equations are referred in order to have a rough parameters' estimation of the AMC unit cell. Following that, unit cell simulation is conducted to investigate the reflection phase characteristics of a square textile AMC.

The AMC is designed to have in-phase reflection at 2.45 GHz. After performing rigorous parametric studies and comparing different fabrics, the optimized reflection phase diagram is obtained for fleece AMC at 2.45 GHz (Fig. 1b). The optimized AMC patch size is 51 mm with 2 mm gap between the patches. The fleece AMC jacket comprises of 20 × 7 conductive patches backed with a ground plane, while the CPW monopole has a measured bandwidth of 11.22 GHz operating from 1.78 until 13 GHz. Figure 2a illustrates the simulation settings of CPW monopoles above AMC waveguide sheet. On the other hand, Fig. 2b shows the orientations that are used for the CPW monopoles.

Figure 3 shows the positioning of the antennas above the AMC waveguide jacket. In this study, horizontal and vertical orientations are investigated. Horizontal orientation is represented by positions A, B, W, X and Y for the parallel arrangement, whereas positions H, G, Z and V correspond to diagonal arrangement. As for the vertical orientation, parallel placements consist of positions K, P and Q, while diagonal placements consist of positions H, G, Z and V. Positions horizontal A and B have the same distances with positions X and Y, respectively, but are placed at different positions on the array.

Measurement of CPW monopoles above AMC waveguide jacket is conducted rigorously in this work to validate the simulation findings. Figure 4 shows the measurement settings of the monopoles above the waveguide jacket. Measurements are conducted in both vertical and horizontal orientation with several placements in parallel and diagonal arrangements. Rohacell material that has

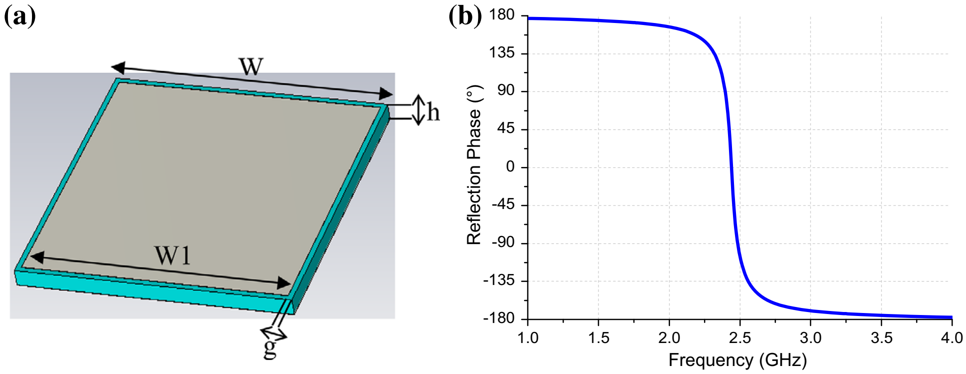

Fig. 1 **a** Unit cell of textile AMC, **b** optimized reflection phase of textile AMC

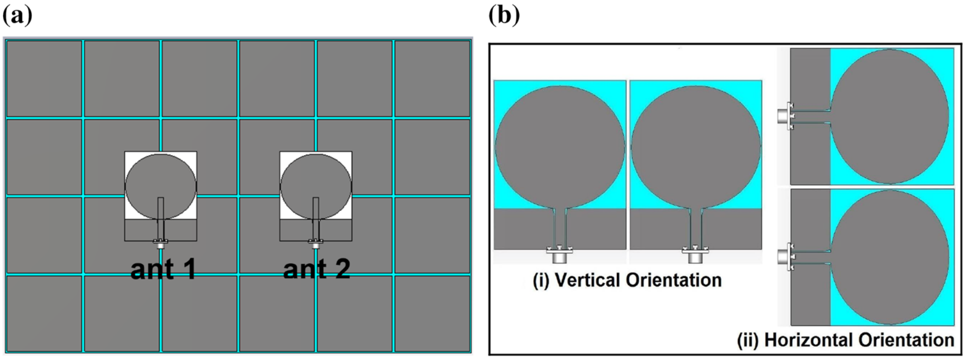

Fig. 2 Textile CPW monopoles above AMC sheet **a** simulation layout, **b** antenna's orientation

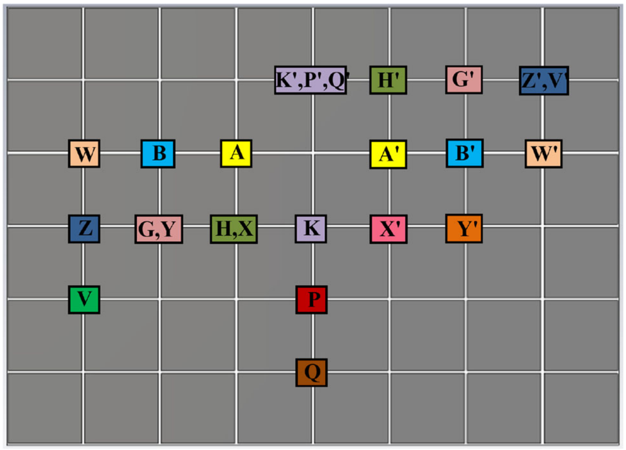

Fig. 3 Antenna's positioning above AMC waveguide sheet

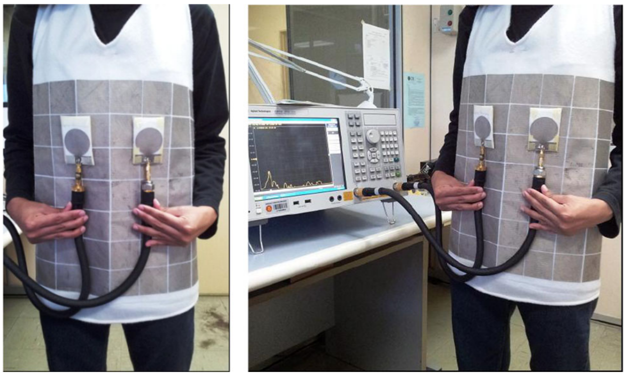

Fig. 4 Textile AMC waveguide jacket with CPW monopoles on-body measurement

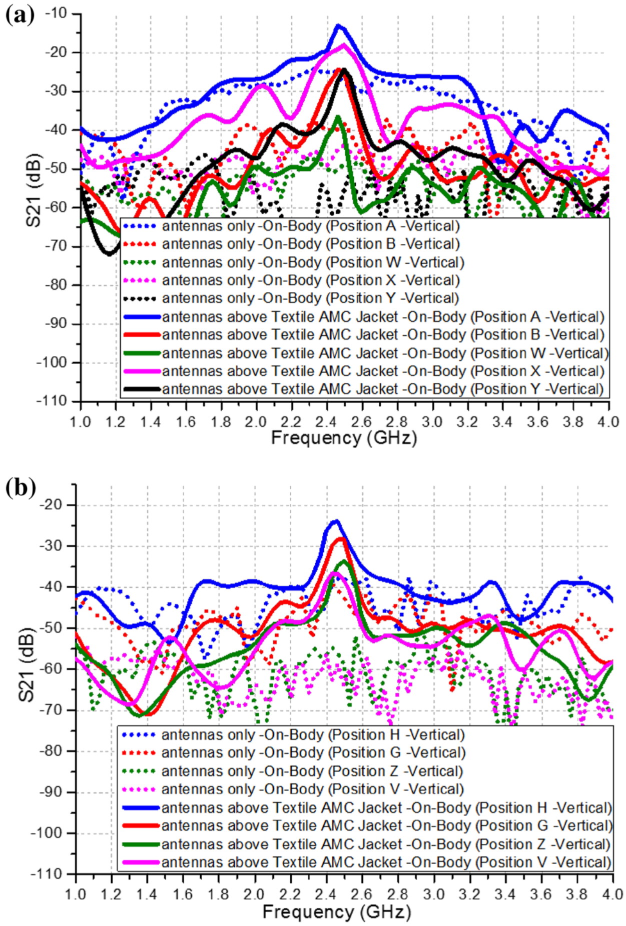

Fig. 5 Measured S_{21} of textile CPW monopoles above AMC Jacket in on-body environment with vertical orientation **a** parallel, **b** diagonal

permittivity close to air is used to represent the 5 mm air gap in the simulation.

3 Results and discussions

3.1 On-body transmission

The measured S_{21} results are plotted in Figs. 5 and 6. Figure 5 shows the transmission performance in vertical orientation for parallel and diagonal placements, whereas Fig. 6 shows the S_{21} values for horizontal orientation, also in parallel and diagonal arrangements. From the results, it is observed that the transmission performance of the monopoles improves significantly when placed above the waveguide jacket for all the positions in both vertical and horizontal orientations.

For the vertical orientation, the transmission peaks are −13.1, −24.4 and −36.5 dB for position A, B and W, respectively, at 2.45 GHz, when the monopoles are positioned above the waveguide jacket (Fig. 5a). Positions X and Y obtain −19 and −27.2 dB peaks with the presence of the jacket. S_{21} results of position X and Y are relatively close to the results of position A and B since they have the same distance, respectively, but with different positioning. On the other hand, the peak values of vertical diagonal transmission are −24, −28.5, −34.8 and −36.7 dB for position H, G, Z and V, respectively, at 2.45 GHz.

For the parallel arrangement of horizontal orientation, the S_{21} peaks for position K, P and Q are −17.8, −20.3 and −22.4 dB at resonance, with the presence of AMC jacket (Fig. 6a). The transmission between monopoles above the AMC jacket in parallel horizontal orientation shows significant improvement, compared to when the on-body monopoles are radiating without the AMC. On the other hand, Fig. 6b shows the transmission results of horizontal diagonal arrangement that gives S_{21} values of −21.9, −30.6, −42.2 and −41.8 dB for position H, G, Z and V, respectively, at 2.45 GHz when the on-body monopoles are placed above the AMC jacket.

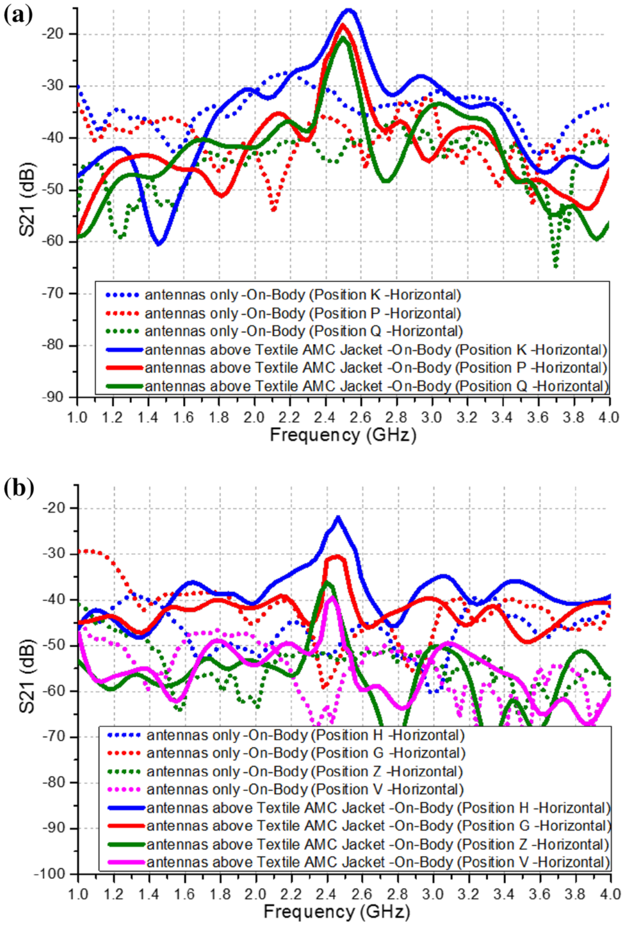

Fig. 6 Measured S_{21} of textile CPW monopoles above AMC Jacket in on-body environment with horizontal orientation **a** parallel, **b** diagonal

Table 1 Measured S_{21} of textile CPW monopoles with waveguide jacket at 2.45 GHz

	Parallel			Diagonal	
	Antennas only	With AMC		Antennas only	With AMC
Vertical					
A	−24.9	−13.1	H	−37.8	−24
B	−40.3	−24.4	G	−39.5	−28.5
W	−50.3	−36.5	Z	−56	−34.8
X	−44.8	−19	V	−58.7	−36.7
Y	−61.1	−27.2			
Horizontal					
K	−30.9	−17.8	H	−51.5	−21.9
P	−36.6	−20.3	G	−55.6	−30.6
Q	−44.6	−22.4	Z	−53.2	−42.2
			V	−60.9	−41.8

The summary of the transmission performance of CPW monopoles with and without AMC jacket is given in Table 1. From the measured results, the transmission performance is found to be improved at all positions under test with the introduction of AMC waveguide jacket. Significant S_{21} enhancement is obtained for all the parallel and diagonal positioning in both vertical and horizontal orientations. Such results give possibility for the realization of textile-based AMC waveguide jacket for wearable applications. The transmission between the antennas is enhanced as the electromagnetic waves are being concentrated onto the AMC sheet. Therefore, the AMC jacket creates a new transmission path for the antennas; hence, minimizing the distortions caused by the human body. From the results, the transmission performance is observed not to be affected by the orientation of the antennas. In addition, although the S_{21} transmission decreases as the distance between the antennas increases, the transmission is still enhanced for all the tested positions, when having the AMC jacket. As such, the proposed textile AMC waveguide jacket is found to be reliable for the implementation in wearable wireless on-body communications.

3.2 Bending and wetness measurements

The proposed antennas and waveguide sheet are also tested with wearable and body-centric measurements, i.e. bending and wetness experiments. Two polystyrene cylinders are used as the bending set-up to demonstrate bending condition in human body. Polystyrene cylinders with diameter of 250 mm and 310 mm that mimic the size of small torso and large torso, respectively, are used in the bending measurement. These cylinders that represent the size of human's torso are used since the AMC sheet is relatively large and are meant to be worn around the torso area. The dielectric constant of the polystyrene is 1.06, i.e. close to the permittivity of air.

Figure 7 shows the CPW monopoles with AMC sheet under bending condition with small and large cylinders. In this study, the monopoles are positioned in a vertical orientation above the AMC surface. As shown in Fig. 7, a thin cellophane tape is used to maintain stable positions of the monopoles above the AMC and bending curvature.

Figure 8 shows the S-parameters results for CPW monopoles above AMC sheet under bending and flat conditions. S_{11} and S_{21} plots are presented for both small and large bending cases as well as the flat state. From the S-parameters results, a reasonable match between bent and flat cases is obtained. High S_{21} peaks are observed for both large and small bending cases. The S_{21} peak for large bending case is −11.4 dB at 2.56 GHz, while the small bending case yields a −13.1 dB peak at 2.62 GHz. The bent cases show slight drop of S_{21} peaks compared to the flat case of −8.5 dB at 2.5 GHz. Despite the shift of S_{21}

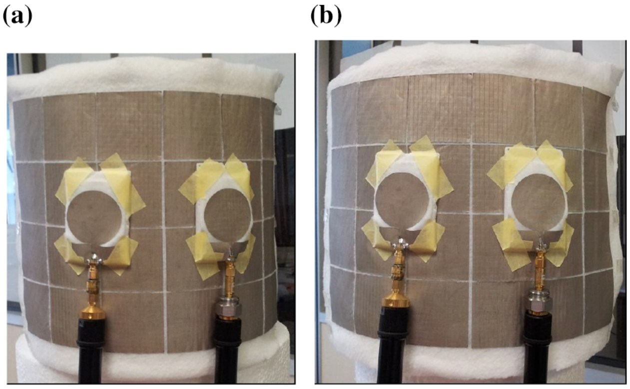

Fig. 7 Textile CPW monopoles with AMC sheet under bending condition **a** small, **b** large

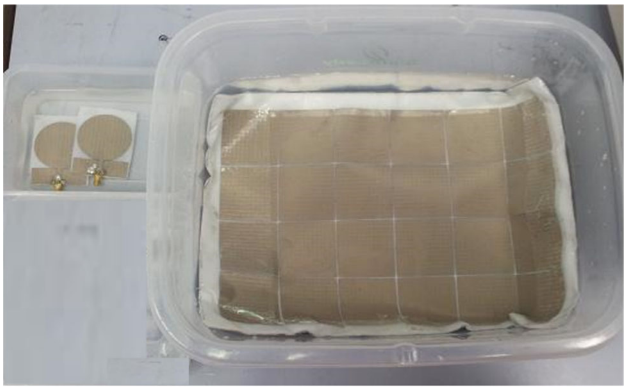

Fig. 9 CPW monopoles and AMC soaked into water for wetness measurement

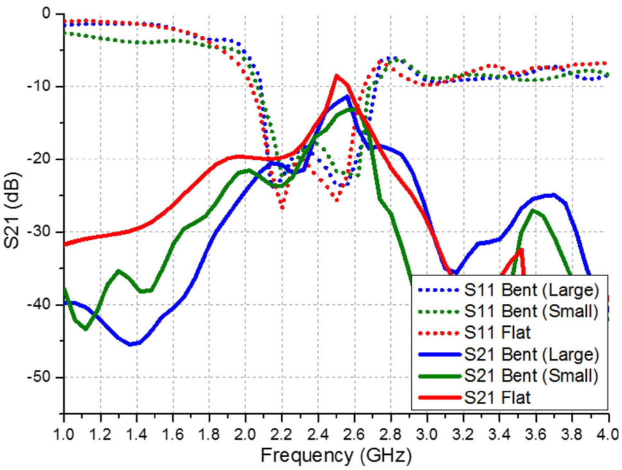

Fig. 8 Measured S_{11} and S_{21} of textile CPW monopoles above AMC under bending condition

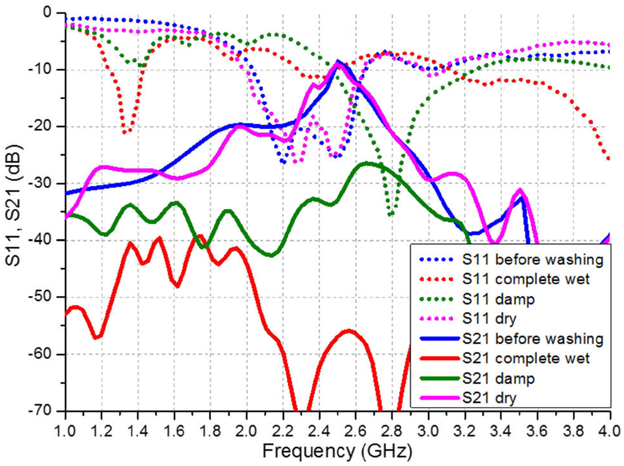

Fig. 10 Measured S_{11} and S_{21} of textile CPW monopoles above AMC under wet condition

peaks, a high transmission performance is still achieved at the frequency of interest, i.e. 2.45 GHz for all the cases with −13.3 dB for flat, −13.5 dB for large bending and −16 dB for small bending cases. Such results indicate that the transmission performance of CPW monopoles above AMC sheet is minimally affected by bending.

In general, results show that bending yields minor effect towards the S-parameters performances. However, small deviations are observed which are mainly due to the increase in gap between patches resulted from the bending. In addition, a smaller bending curvature yields a higher deviation in comparison with large bending because the smaller cylinder creates a higher degree of bending compared to larger cylinder. Moreover, small bending associates with smaller elementary size of the AMC unit cell, hence leading to more apparent effect compared to large bending. As can be seen in Fig. 8, smaller elementary size of AMC unit cell leads to a slight resonant shift to higher frequency. However, generally all the deviations are small; hence, the antennas with AMC configurations remain to exhibit a good performance.

Next step is to test the textile CPW monopole and AMC under wetness condition. The monopoles and AMC are soaked into water for more than 12 h as shown in Fig. 9. The return loss of the antenna is then measured under complete wet state as shown in Fig. 10. Following that, the monopoles and AMC are left to dry for damp and completely dried versions, in order to be measured.

Graph in Fig. 10 shows the S_{11} and S_{21} results of the CPW monopoles with AMC under conditions of before washing, complete wet, damp and dry. Severe distortions are observed for the completely wet configuration for both the S_{11} and S_{21} results. The transmission for the wet case is seen to shift to the lower frequency. On the other hand, damp antennas and AMC show a resonance at 2.66 GHz with peak of −26.47 dB. It is predicted that the deviation towards slightly higher frequency is contributed by the properties' change in the AMC sheet since moisture is still left when it is still in damp condition. Moreover, since monopole is an ultra-wideband antenna, the deepest resonance of the antenna alone does not occur at 2.45 GHz. It is predicted that due to these reasons resonance at 2.45 GHz cannot be achieved for the damp state. Finally, the S-parameters of dry monopoles and AMC are measured and compared to the original before washing result. Results show good matching between dry and before washing curves. The fully dried configuration reads −9 dB at 2.5 GHz compared to −8.5 dB at 2.5 GHz for the before washing case.

Results show that completely wet antennas and AMC yield severe distortions of S-parameters performance. As mentioned before, high relative permittivity of water dominates the permittivity of the substrate, and therefore, the resonance is seen to shift to a lower frequency. As for the damp condition, although the S-parameters results are observed to slowly return to the original state, the exact before washing results cannot be achieved when the antenna and AMC are in damp state. The reason is because in damp condition, moisture is still left in the antenna and AMC. Therefore, the dielectric constant of a damp antenna is still higher than the original's permittivity.

In addition, any normal fabrics are subjected to shrinking after being dried. The level of shrinkage depends on the type of fabrics. Typically, natural fabrics suffer higher shrinkage compared to machine-made fabrics. Therefore, even after being completely dry, the properties of the textile antenna and AMC can still be changed. Since it has been found that wetness contributes to severe distortion of the textile antennas and AMC's performances, serious measures should be applied for future research. To avoid such problem, waterproof material can be used or the textile antennas and AMCs can be shielded with plastic coating to protect them from wetness.

4 Conclusions

Results show that the transmission performance is enhanced with the presence of the waveguide jacket. The S_{21} transmission between the antennas improved up to a maximum of −13 dB when they are placed above of the AMC. The proposed AMC sheet, performed as a subsidiary waveguide that offers an independent path, improves the transmission performance and minimizes the transmission losses. Electromagnetic waves are strongly concentrated into the AMC surface that allows transmission through the waveguide sheet. Hence, a low transmission loss is observed and consequently contributes to the transmission enhancement between antennas. Bending is found not to cause any significant performance disruption. On the contrary, since the proposed antennas and AMC are not made of waterproof material, the performance is distorted under wet condition. However, once the antennas and AMC sheet are dried out, the original performance is achieved. From the results, the proposed textile antennas and AMC waveguide sheet are seen fit to be applied in the body-centric wireless communication.

Acknowledgments The authors wish to thank Malaysian Ministry of Higher Education (MOHE) and Universiti Teknologi Malaysia (UTM) for providing the Research Grant (Vote No: 02K02, 4F277 and 4F360). The authors also wish to thank Communications Engineering group at the University of Birmingham and Universiti Malaysia Perlis for the help, guidance and facilities.

References

1. P. Salonen, H. Hurme, A novel fabric WLAN antenna for wearable applications, in *IEEE international symposium on antennas and propagation*, Columbus, USA, pp. 700–703, 2003
2. K. Ito, N. Haga, Wearable antennas for body-centric wireless communications, in *International conference on applications of electromagnetism and student innovation competition awards (AEM2C)*, Taipei, pp. 129–133, 2010
3. M.A.R. Osman, M.K.A. Rahim, M. Azfar, N.A. Samsuri, F. Zubir, K. Kamardin, Design, implementation and performance of ultra-wideband textile antenna. Prog. Electromagn. Res. B **27**, 307–325 (2011)
4. P.J. Soh, S.J. Boyes, G.A.E. Vandenbosch, Y. Huang, S.L. Ooi, On-body characterization of dual-band all-textile PIFAs. Prog. Electromagn. Res. **127**, 517–539 (2012)
5. K. Eom, H. Arai, Smart blanket: flexible and easy to couple waveguide, in *IEEE topical conference on biomedical wireless technologies, networks, and sensing systems*, USA, pp. 15–18, 2011
6. S. Zhu, R. Langley, Dual-band wearable antennas over EBG substrate. Electron. Lett. **43**(3), 141–142 (2007)
7. P.S. Hall, Y. Hao, *Antennas and propagation for body centric communications systems*, 2nd edn. (Artech House, London, 2012), pp. 63–64
8. K. Eom, H. Arai, Smart suit: wearable sheet-like waveguide for body-centric wireless communications, *3rd Euro,* in *Wireless technology conference,* France, pp. 1–4, 2010