The Performance of On-Body Wearable Antennas in a Repeatable Multipath Environment

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Abstract—**The performance of antennas designed for on-body channels is usually evaluated in an anechoic environment. However, it is also appropriate to determine their performance under multipath conditions since the presence of off-body paths may significantly improve on-body links for some antennas. This was investigated by considering the on-body performance (|S_{21}| path gain) of a range of wearable antennas in the repeatable multipath environment of a reverberation chamber using a tissue-equivalent experimental phantom, representative of human muscle tissue at 2.45 GHz. These results were compared with the equivalent measurements taken in an anechoic far-field chamber. The study shows that antennas which radiate tangential to the body surface, supporting a surface wave propagating mode, perform favorably in both environments, which is advantageous in reliable system design.**

Index Terms—**Wearable antennas; on-body channels; multipath fading.**

I. INTRODUCTION

There has been recent interest in body area networking where computing devices communicate wirelessly over the body surface [1]. Reliable wireless system design in close proximity to the human body is largely dependant on channel conditions and antenna characteristics [1-2]. The mobile nature of the human body requires that wearable antennas operate in a range of diverse environments. Many wearable applications may be deployed in strong multipath environments, such as a patient wearing a wireless sensor network while walking around a hospital ward. In these conditions on-body devices may communicate via propagating waves diffracted or reflected from nearby objects in addition to creeping (trapped surface) waves that follow the dielectric-air interface at the body surface. However, in the absence of multipath, the main mechanism for propagation around the body is via a creeping surface wave. Ideally the performance of wearable devices should be independent of the environment in which they are used. Therefore, in this paper we use the repeatable environment of a reverberation chamber to evaluate the over the body surface communication (known as the on-body channel) performance of wearable antennas in a highly multipath environment at 2.45 GHz. The results are compared with measurements performed in an anechoic far-field chamber.

II. ON-BODY PROPAGATION MEASUREMENTS

The |S_{21}| path gain performance of two antennas placed on opposite sides of a tissue equivalent phantom was used to evaluate the on-body performance in a multipath environment. Measurements were conducted with a Rohde & Schwarz ZVB8 vector network analyzer in a reverberation chamber in the range 2.25 to 2.65 GHz. Fig. 1 shows the test set-up in the 2.4 x 2.4 x 2.4 m chamber which used plate (one horizontal and one vertical) and platform (rotational) mode stirring. A physical phantom filled with a lossy glycol based dielectric solution, used to represent human muscle tissue at 2.45 GHz (ε_r = 53.58, σ = 1.81 S^{-1}), was developed as an antenna performance evaluation test bed [3].

Rohacell HF 51 foam with a relative permittivity of ε_r = 1.07 was used to space the antennas 4 mm above the phantom to allow for coaxial cables and connectors. Emerson and Cuming Eccosorb LS-16 and LS-24 microwave absorbing foam with an insertion loss of 1.5 dB/cm and 11 dB/cm, respectively, were used to minimize spurious radiation from, and coupling between, the coaxial cables.

Five different antennas were evaluated including low-profile (λ/20) Higher Mode Microstrip Patch Antennas (HMMPA) that were designed to radiate tangentially to the body surface by exciting them at a higher resonant mode. Such antenna characteristics are desirable for efficient over the body surface communication [4-5]. The HMMPA consisted of a groundplane and patch metallization on a dielectric substrate with ε_r = 2.33 (Taconic TLY-3, PTFE woven glass). The HMMPA-5 antenna (Fig. 1.b.i) had a height of 5.75 mm and a patch element size of 22 x 22 mm. The HMMPA-10 (Fig. 1.b.ii) had a height of 10.5 mm with a patch element size of 18 x 18 mm. The monopole antenna (Fig. 1.b.iii) was 33 mm in length with a diameter of 1.2 mm. The MPA-F (Fig. 1.b.v) is a microstrip patch antenna (element size 37 x 36 mm, height 5 mm) excited at its fundamental mode (TM_{10}). This antenna radiates with maximum gain normal the patch surface and is therefore more suitable for off-body channels. The MPA-S antenna (Fig. 1b.iv) uses a shortening wall on the electrical length of the antenna for size reduction and has an element size of 26 x 27 mm with an overall height of 5.75 mm. Rohacell HF 51 foam (ε_r = 1.07) was used between the element and groundplane of the MPA-S to increase the antenna impedance bandwidth. The antennas in Fig. 1.b(i-iii) had 30 x 37 mm groundplanes and (iv, v) had 50 x 50 mm and 50 x 60 mm groundplanes, respectively.

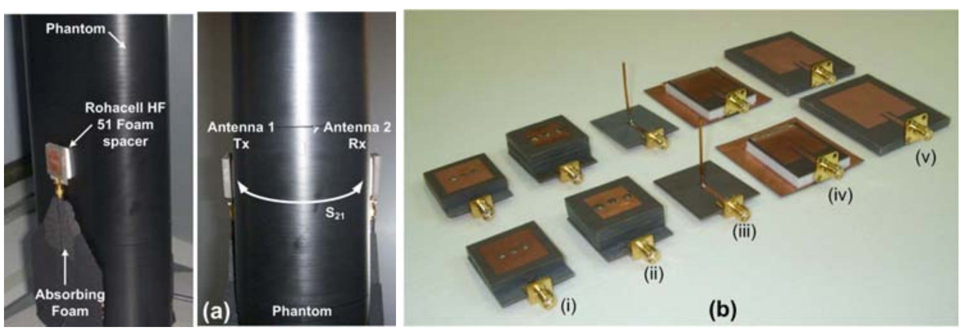

Fig. 1. (a) $|S_{21}|$ measurement set-up in reverberation chamber on the tissue phantom. (b) antennas used in this study (i) HMMPA 5 mm (ii) HMMPA 10 mm (iii) Monopole (iv) MPA-S (v) MPA-F.

The reverberation chamber generates a repeatable strong multipath environment with fading characteristics which closely follow the Rayleigh distribution. This was confirmed using maximum likelihood estimation on the full set of channel gain results for the HMMPA-5 antenna on-phantom link. The analysis showed that the Nakagami-*m* distribution gave the best fit (Fig. 2), with a fading parameter m = 1.19 (the Nakagami distribution is equivalent to Rayleigh when m = 1). This is in agreement with measured mobile on-body studies in a multipath indoor environment [2]. All of the antennas were subjected to identical multipath conditions by following the same computer controlled set of stirrer / platform positions.

III. Antenna Performance on Lossy Medium

For each antenna, the phantom-mounted $|S_{11}|$ reflection co-efficient measured in the reverberation chamber (averaged over all plate / platform positions) was compared to results obtained in an anechoic far-field chamber (Fig. 3). The measured return loss results were in good agreement with anechoic measurements and show that all the antennas had sufficient bandwidth for the 2.45 GHz ISM Band. The phantom mounted radiation efficiency, η, for each antenna was also measured using the reverberation chamber. The MPA-F and MPA-S antennas were significantly more efficient (η = 75% and 61 %, respectively) than the other types because of their larger groundplanes. The efficiency results for the monopole, HMMPA 10 mm and HMMPA 5 mm antennas were 53 %, 43 % and 37 %, respectively. In practice, it is important to consider the trade off between antenna efficiency and antenna size since this is a critical design parameter for wearable devices. For example, the HMMPA antenna was specifically designed to be mounted on a small (<0.3 λ @ 2.45 GHz) groundplane.

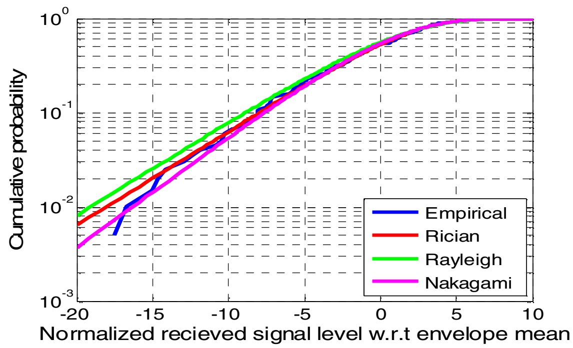

Fig. 2. Empirical and maximum likelihood estimated theoretical Nakagami (m = 1.19, Ω = 1.22), Rice (K_{dB} = 0.65) and Rayleigh (σ = 0.78) cdfs for the HMMPA-5 antennas in the reverberation chamber.

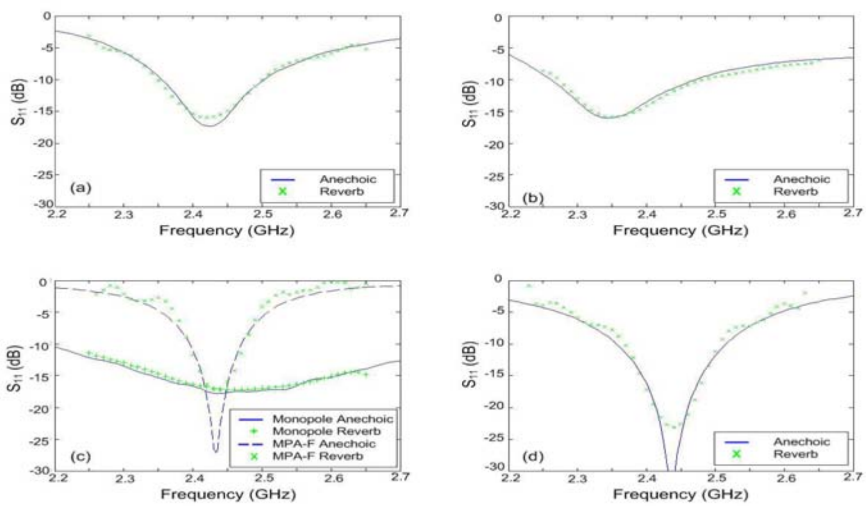

Fig. 3. Comparison of reverberation and anechoic chamber measured return loss for phantom mounted antennas: (a) HMMPA 5 mm (b) HMMPA 10 mm (c) monopole and MPA-F (d) MPA-S.

The $|S_{21}|$ on-body performance results in the multipath environment (Fig. 4.a) show that that there was less than 6 dB difference in maximum path gain between the five antenna types. The differences in path gain performance were primarily due to the differences in antenna radiation efficiency, with the MPA-F being both the most efficient antenna and having the best path gain performance in this multipath environment. However, when compared with path gain results achieved for the same antennas and set-up in an anechoic far-field chamber (Fig. 4.b), the order of merit changed significantly. In the anechoic environment, the HMMPA antennas gave similar performance to the monopole antenna which had the most path gain. Both of these antennas radiate with maximum gain tangential to the phantom surface supporting the dominant surface wave propagation mode and are therefore preferable for anechoic environments. Furthermore, in the multipath environment they maintained a respectable overall performance. On the other hand, the MPA-F antenna had the least path gain in anechoic conditions, (understandably since it radiates with maximum gain in the off-body direction normal to the tissue phantom surface), while its performance in the multipath environment was significantly improved, probably due to the availability of additional propagation modes created from reflected waves.

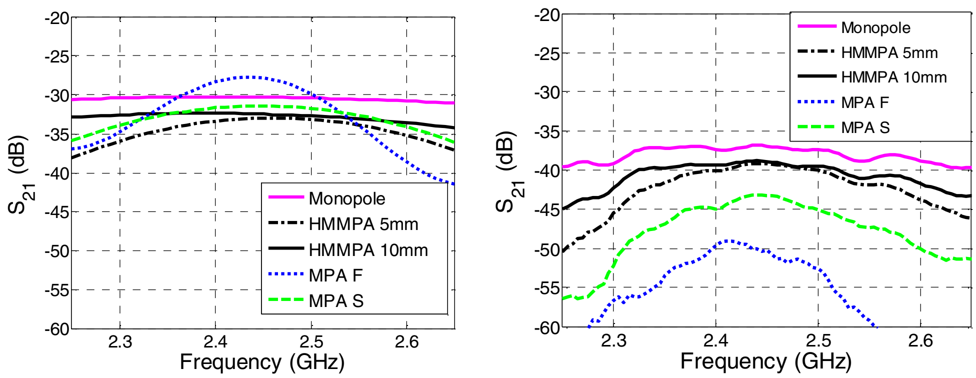

Fig. 4. Comparison of measured $|S_{21}|$ path gain for on-body antennas in (a) multipath environment, (b) anechoic environment [3].

The MPA antenna performance is therefore largely dependant on the degree of multipath in the surrounding environment, which in practical applications may not be as strong as the reverberation chamber test case [2]. Consequently, the performance of the MPA-F and MPA-S antennas will vary between that expected for anechoic conditions and those achieved here depending on the environment in which they are used. Furthermore, the results also show that the on-body performance of the HMMPA antennas was maintained in the strong multipath environment. Therefore, regardless of the environment, efficient and reliable over-the-body-surface communication can be achieved with antennas which maximise the surface wave propagating mode.

IV. CONCLUSION

The on-body coupling performance of five different antennas placed on a muscle tissue phantom was measured for both anechoic and multipath environments. The results show that regardless of the environment, efficient communication over the body surface was achieved with antennas which radiate tangential to the tissue surface, supporting the creeping surface wave propagating mode. However, if the antenna is to be predominantly used in a multipath environment, excitation of this surface wave propagating mode is not as critical as when used in more anechoic environments.

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