# *In Situ* Measurement of UHF Wearable Antenna Radiation Efficiency Using a Reverberation Chamber

Gareth A. Conway, William G. Scanlon, Charlie Orlenius, and Chris Walker

***Abstract*—The radiation efficiency and resonance frequency of five compact antennas worn by nine individual test subjects was measured at 2.45 GHz in a reverberation chamber. The results show that, despite significant differences in body mass, wearable antenna radiation efficiency had a standard deviation less than 0.6 dB and the resonance frequency shift was less than 1% between test subjects. Variability in the radiation efficiency and resonance frequency shift between antennas was largely dependant on body tissue coupling which is related to both antenna geometry and radiation characteristics. The reverberation chamber measurements were validated using a synthetic tissue phantom and compared with results obtained in a spherical near field chamber and finite-difference time-domain (FDTD) simulation.**

***Index Terms*—Bodyworn antennas, on-body communications, wearable antenna radiation efficiency.**

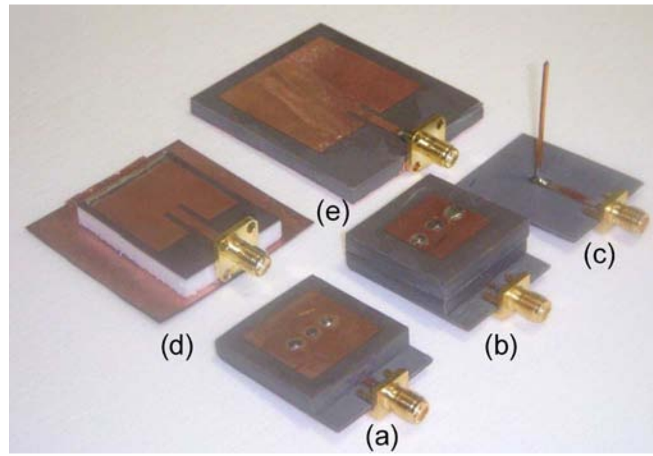


Fig. 1. Antennas: (a) HMMPA_5, (b) HMMPA_10, (c) monopole, (d) MPA-S, (e) MPA-F.

## I. Introduction

RECENT research initiatives in wearable antennas have focused on the design of efficient low-profile solutions for operation in close proximity to the user's body [1]–[3]. It is widely accepted that antennas in close proximity to a lossy medium experience bulk power absorption, radiation pattern distortion, and resonant frequency shift [3]–[6], effects which may be further compounded when the antenna is mounted on a small groundplane. It is therefore essential to understand these effects and their relationship with antenna characteristics such as radiating mode and geometry with respect to body proximity and groundplane arrangement to enable the design of optimized antennas for wearable systems.

Over the last seven years, the reverberation chamber has become established as an accurate tool for measuring the radiation efficiency of small antennas, as well as complete mobile terminals [7]–[9]. The present letter describes, for the first time, results for wearable antenna radiation efficiencies using human test subjects, measured using a reverberation chamber. The chamber used was a shielded room of size $2.4 \times 2.4 \times 2.4$ m, and it was equipped with two mechanical plate stirrers, polarization stirring, and platform stirring. Radiation efficiency and resonance frequency results are presented for three different low-profile microstrip patch antennas placed on the chest of nine test subjects at 2.45 GHz. The results are compared to a quarter wave monopole antenna on the same size of groundplane, mounted normal to the tissue surface and a microstrip patch (MPA-F) excited at its fundamental mode $(\mathrm{TM}_{10})$. Section II of this letter describes the antennas used and details the validation of radiation efficiency measurements in the reverberation chamber. Wearable antenna radiation efficiency and resonant frequency shift results for the human test subjects are presented in Section III. The letter concludes with a summary of the findings and suggestions for further work.

## II. Validation of Reverberation Chamber

### A. Antenna Geometry

The five antennas used in this study are shown in Fig. 1 [10]. All of the microstrip patch antennas were constructed using a groundplane and patch metallization of a dielectric substrate with $\epsilon_r = 2.33$ (Taconic TLY-3, PTFE woven glass). Using FDTD simulations, the antennas were optimized for tissue mounted operation at the ISM (industrial Scientific and Medical) frequency allocation of 2.4–2.5 GHz [11], [12] with a nominal resonant frequency of 2.45 GHz. The higher mode microstrip patch antennas (HMMPA) were designed to radiate tangentially to the body surface, similar to a monopole when mounted normal to the body, by exciting them at a higher resonant mode. Such antenna characteristics are desirable for efficient over the body surface communication, e.g., for a network of wireless medical sensors. The MPA-F antenna

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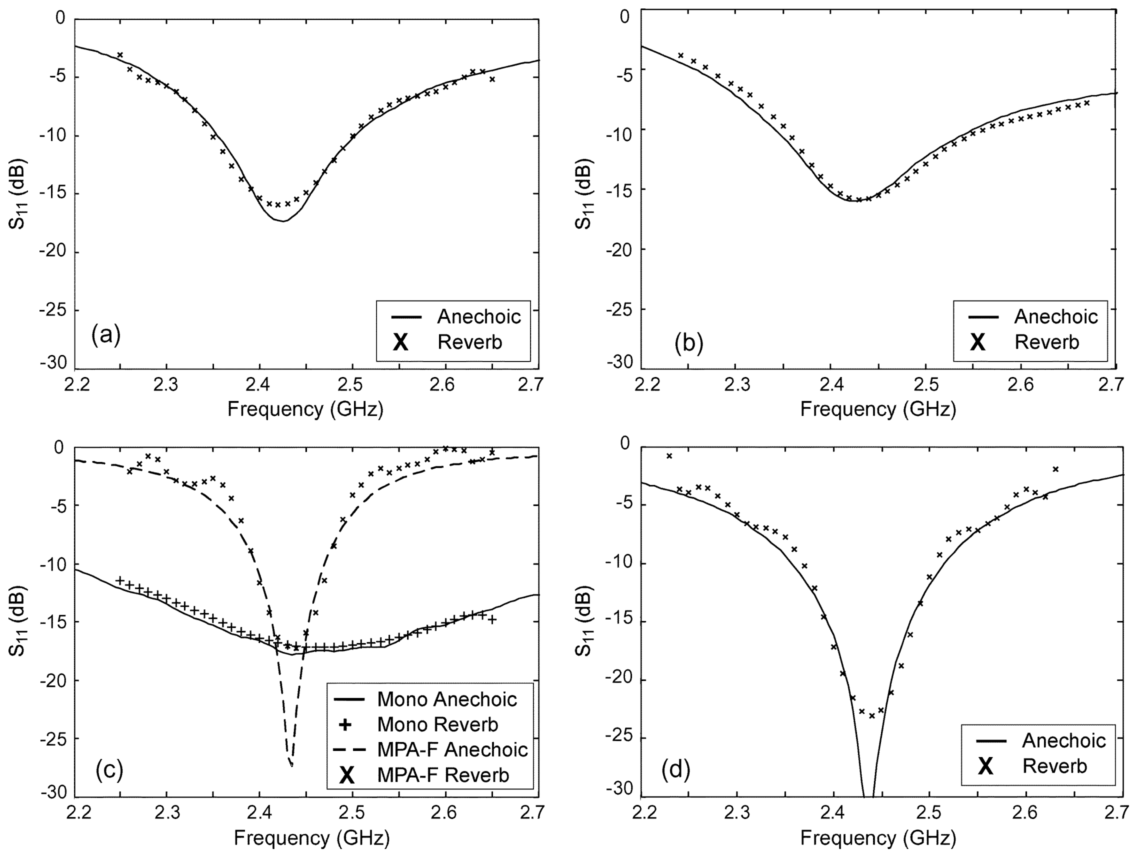


Fig. 2. Antenna return loss: (a) HMMPA_5, (b) HMMPA_10, (c) monopole and MPA-F, (d) MPA-S.

radiates with maximum gain normal to the patch surface, and is therefore more suitable for off-body channels. Antennas (a)–(c) in Fig. 1 have 30 $\times$ 37 mm groundplanes and (d) and (e) have 50 $\times$ 50 mm and 50 $\times$ 60 mm groundplanes, respectively. The HMMPA_5 has a height of 5.5 mm and a patch element size of 22 $\times$ 22 mm. The HMMPA_10 has a height of 10.5 mm with a patch element size of 18 $\times$ 18 mm. The monopole element is 33 mm in length with diameter of 1.2 mm. The MPA-F has an element size of 37 $\times$ 36 mm and overall height of 5 mm. The MPA-S antenna (Fig. 1(d)) uses a shortening wall on the electrical length of the antenna for size reduction and has an element size of 26 $\times$ 27 mm with an overall height of 5.5 mm. Rohacell HF 51 foam ($\epsilon_r = 1.07$) was used between the element and groundplane to increase the impedance bandwidth of the MPA-S.

## *B. Radiation Efficiency on Tissue Phantom*

Radiation efficiency and return loss measurements were made using a physical tissue phantom in both the reverberation chamber and a spherical near field chamber and compared with FDTD simulation (SEMCAD X, Schmid & Partner Eng. AG, Zurich, Switzerland). The $400 \times 200 \times 100$ mm phantom was constructed from Nylon 6 with a 2-mm wall thickness. The permittivity and conductivity of the phantom solution were chosen to represent human muscle tissue at 2.45 GHz ($\epsilon_r = 53.58$, $\sigma = 1.81\ \mathrm{S}^{-1}$). The tissue solution consisted of: de-ionized water 79.7%, sodium chloride 0.25%, Triton X-100 (polyethylene glycol mono phenyl ether) 16%, DGBE (diethylene glycol butyl ether) 4%, and boric acid 0.05% at $25^\circ\mathrm{C}$. The antennas under test were spaced 4 mm from the phantom surface using Rohacell HF 51 foam to allow for the protrusion of the coaxial connector. The results in Table I show that there was 1 dB or less discrepancy between simulated and measured radiation efficiency and excellent agreement between near-field and reverberation chamber measurements, with all results within 0.5 dB of each other. Similarly, the measured antenna return loss in the reverberation chamber was in good agreement with results obtained in an anechoic chamber (Fig. 2). With this validation of the reverberation chamber, radiation efficiency measurements were then performed for the five wearable antennas using live human subjects.

# III. Wearable Antenna Measurements

## *A. Radiation Efficiency*

The reverberation chamber was used to measure the radiation efficiency of the five wearable antennas for nine human subjects. The main advantage of the reverberation chamber is that it can be used for live measurements as any test subject movements will positively contribute to additional modes, thereby reducing measurement uncertainty. On the contrary, efficiency measurements made in a near or far-field anechoic chamber would require the test subject to remain perfectly still during scanning and any slight movements would reduce accuracy.

The human test subjects were all male, aged between 23 and 40, weighed between 70 and 110 kg with a height range from

TABLE I
MEASURED AND SIMULATED PHANTOM MOUNTED RADIATION EFFICIENCY AT 2.45 GHz

| Antenna | Simulation (%) [loss, dB] | Near-Field (%) [loss, dB] | Reverb (%) [loss, dB] |
|---|---|---|---|
| HMMPA_10 | 49.0 [3.1] | 38.9 [4.1] | 42.8 [3.7] |
| HMMPA_5 | 45.0 [3.5] | 37.6 [4.2] | 37.1 [4.3] |
| Monopole | 58.5 [2.3] | 51.0 [2.9] | 53.4 [2.7] |
| MPA-F | 65.6 [1.8] | 67.0 [1.7] | 75.1 [1.2] |
| MPA-S | 65.7 [1.8] | 61.0 [2.1] | 61.2 [2.1] |

TABLE II
MEASURED *IN SITU* WEARABLE ANTENNA CHARACTERISTICS IN REVERBERATION CHAMBER (NINE TEST SUBJECTS)

| Antenna | efficiency mean (%) [loss, dB] | efficiency s.d. (%) | s.d. resonant frequency (MHz) [%] | mean bandwidth (MHz) [%] |
|---|---|---|---|---|
| HMMPA_10 | 41.2 [3.8] | 5.2 | 17.6 [0.7] | 218.6 [8.9] |
| HMMPA_5 | 33.7 [4.7] | 2.9 | 17.4 [0.7] | 138.9 [5.7] |
| Monopole | 49.3 [3.1] | 3.8 | 16 [0.7] | 400.0 [16.4] |
| MPA-F | 72.1 [1.4] | 2.9 | 4.3 [0.2] | 96.6 [3.9] |
| MPA-S | 47.0 [3.3] | 6.4 | 20.8 [0.8] | 152.1 [6.2] |

1.7–1.9 m. The reverberation chamber was specifically designed for wearable antenna measurements using live test subjects and had an accuracy standard deviation of 0.5 dB [13]. The antennas were mounted 4 mm from the body surface on the chest of each subject, consistent with the phantom measurements. The test subjects were asked to remain stationary during measurements to minimize the risk of changing the antenna-body separation, but it is inevitable that there were breathing effects and other minor body movements. Furthermore, the presence of the test subjects will introduce a significant loading of the reverberation chamber, changing the average transmission level. Therefore, a calibration of the average transmission level was performed for each individual subject, to achieve the correct absolute values of the measured radiation efficiencies. For each antenna, the radiation efficiency was averaged over the full bandwidth (83 MHz) of the ISM 2.45-GHz band (Table II and Fig. 3).

The results show that the efficiency was much more dependant on antenna type than the physical characteristics of the test subject. For example, the HMMPA_5 antenna had an average radiation efficiency of 34% with an s.d. of 2.9%, while the HMMPA_10 had an average radiation efficiency of 42% (s.d. of 5.2%). The MPA-F had the highest radiation efficiency because of the relatively large antenna groundplane and radiation characteristics of the antenna. As this antenna radiates in the off-body direction, there is less power absorbed in the surrounding tissue. Although the MPA-S antenna was placed on a similar size of groundplane to the MPA-F, its efficiency was significantly lower. The addition of the shortening wall on the MPA-S antenna altered the way in which the antenna radiated in comparison to the MPA-F. Hence, there was more radiation in the direction tangential to the body surface, resulting in greater power absorption in the tissue with a corresponding reduction in efficiency. Interestingly, the HMMPA_5 had a lower efficiency than the HMMPA_10. While this appears counter-intuitive, especially considering that the HMMPA_10 had greater dielectric volume, it should be noted that the total radiation efficiency is also affected by coupling to the tissue. Therefore, the HMMPA_5 was less efficient as it had greater antenna-tissue coupling since the patch element perimeter was closer to the edge of the groundplane. Overall, the results show that the measured efficiency for the five antennas studied had a standard deviation of less than 0.6 dB across all test subjects. Furthermore, since this variation in efficiency is relatively small and, more importantly, was of the same order of magnitude as the s.d. of measurement uncertainty in the chamber, no conclusions could be drawn with respect to changes in radiation efficiency between test subjects.

The HMMPA, monopole and MPA-F phantom mounted radiation efficiencies (Table I) lie within the standard deviation of

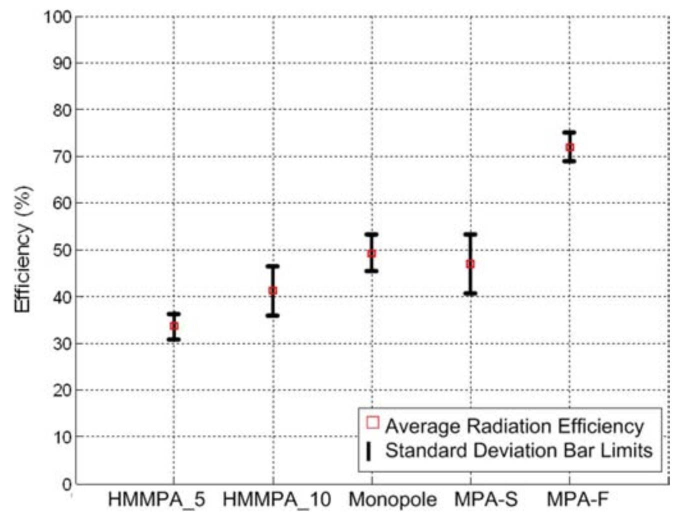


Fig. 3. Measured radiation efficiency as a function of test subject.

the bodyworn efficiency results shown in Table II. This confirms that the phantom may be used as a reasonable test-bed for the experimental and numerical evaluation of wearable antenna radiation efficiency at this frequency. For the MPA-S, the phantom efficiency was slightly higher than the efficiency achieved with the live test subjects. Investigation revealed that the MPA-S input impedance (Section III-B) was sensitive to small changes in antenna-body separation distance. This may have contributed to mismatch losses over the duration of the measurement and therefore a reduction in the total radiation efficiency in comparison to measurements on the tissue phantom where the separation distance was constant.

### *B. Resonant Frequency Measurements*

The resonance frequency for each antenna was also extracted from the reverberation chamber measurements (Table II and Fig. 4). The upper and lower impedance bandwidth ($|S_{11}| < -10$ dB) points are also shown for each antenna. Fig. 4 also shows the 83-MHz ISM band limits using dotted lines. Note that as the monopole had a bandwidth exceeding 400 MHz some of the upper and lower points were outside of the measurement range of 2250–2650 MHz and are not shown. Despite the physical variability in the nine test subjects, the HMMPA antennas maintained the ISM bandwidth requirement. However, the MPA-F did not have sufficient impedance bandwidth although a small increase in patch height above groundplane would correct this. The results show a standard deviation in resonant frequency of less than 1% (at 2.45 GHz)

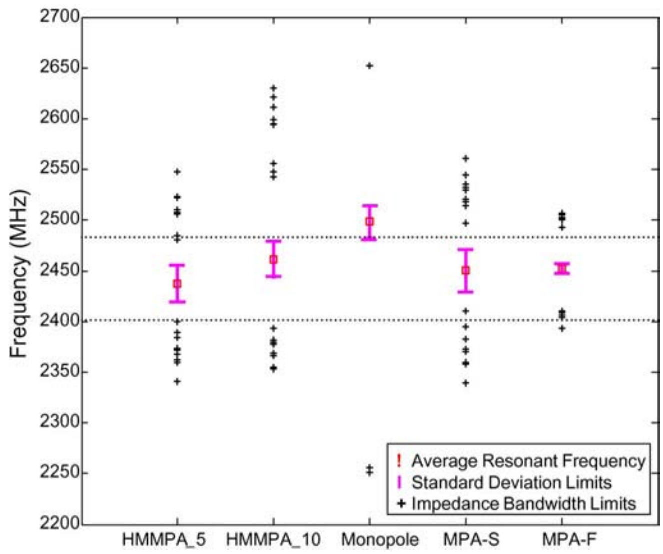


Fig. 4. Antenna resonant frequency as a function of test subject.

for all five antennas. Fluctuations in antenna resonant frequency are caused by antenna-tissue coupling which changes the input impedance of the antenna. The MPA-S antenna had the greatest variation in input impedance across the test subjects at 2.45 GHz (ranging between $41 - j12\ \Omega$ and $62 + j7\ \Omega$), while the MPA-F had the least ($42 - j7\ \Omega$ to $45 - j6\ \Omega$). The HMMPA_5, HMMPA_10 and monopole input impedance ranges were $63 - j7\ \Omega$ to $73 - j4\ \Omega$, $37 - j8\ \Omega$ to $47 - j8\ \Omega$ and $35 - j7\ \Omega$ to $40 - j14\ \Omega$, respectively. Nonetheless, all of these impedances equate to an $|S_{11}| < -10$ dB at 2.45 GHz. The electrical properties of the biological tissue, antenna-tissue separation distance and antenna radiation characteristics determine the level of coupling and thus the level of variation in resonant frequency. These results show that resonant frequency shift is dependant on the antenna type and construction. The MPA-F had the least deviation in resonant frequency shift (0.2%, 4.3 MHz) and although the MPA-S antenna was placed on the same size of groundplane, its standard deviation in resonant frequency shift was much greater at (0.8%, 20.8 MHz). As described earlier in relation to radiation efficiency, this is mainly due to the level of antenna-tissue coupling. The HMMPA and Monopole antennas had similar standard deviation of resonant frequency shift (17 MHz and 16 MHz, respectively) as they were mounted on the same size of groundplane and have similar radiation characteristics.

## IV. Conclusion

We have evaluated radiation efficiency for five wearable antennas on a range of human test subjects. The standard deviation of radiation efficiency between test subjects was less than 0.6 dB and resonant frequency shift was less than 1% at 2.45 GHz. While the test subjects were asked to remain stationary, the measurements included all natural body movements and this is important in the characterization of wearable antennas as it provides more realistic results. The reverberation chamber has been shown to be ideal for wearable antenna measurements using live test subjects. Also, in optimizing and developing antennas, it is important to have a repeatable test-bed in which their performance can be evaluated and compared. The tissue phantom results presented have demonstrated that antenna measurements on this type of platform are sufficiently representative of torso-mounted wearable antenna configurations. This study also provides confidence for future work on compact closely-coupled wearable antenna design. This will include antennas for both on-body and off-body channels, flexible or fabric antennas including full consideration of movement related bending effects.

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