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Numerical and Experimental Evaluation of Phantoms for Off-Body Wireless Communications

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Abstract— **The effects of a numerical and a physical phantom on different antenna configurations are evaluated. Input response, radiation patterns and efficiency are considered in the presence of the phantoms. In order to validate the phantoms as a substitute for human tissue, these effects are compared to those experienced due to the proximity of the human body. The detuning effects on a patch antenna due to the phantom were demonstrated and shown to match the effects of the human body. The radiation pattern of a loop antenna was measured on and off the phantom. The presence of the phantom was found to reduce the efficiency of the loop antenna by 88%.**

I. Introduction

Body-centric wireless communications are a growing area with great potential for healthcare applications. Elderly people represent an increasing part of the population who often require constant monitoring and need to be kept in hospital, which in turn generates substantial costs to healthcare bodies and governments. The availability of health monitoring systems would benefit these people who might be able to stay at home rather than in hospital. Patients with chronic decease such as Alzheimer's sufferers who require constant monitoring would also benefit from this technology as it would be possible to track them down on a permanent basis. Telemedicine has been shown to reduce the number of hospital visits patients require [1] and is therefore perceived as an enabling technology to reduce costs and provide comfort to a growing part of the population.

Antenna development for heath monitoring systems suffers from the fact that the antenna is generally designed in isolation and only afterwards tested on the body. Return loss is usually measured, along with two-dimensional radiations patterns in the principal planes to test the validity of the design. However measurement of radiation patterns in the whole 3D space is essential in understanding the behaviour of the antenna and identifying nulls in the response. It is difficult to measure an antenna on the body and derive three-dimensional radiation patterns in an anechoic chamber as the device under test has to be rotated in all directions.

As it is not generally practical for persons to undergo these manipulations, it is therefore vital to establish a reliable technique for the measurement of on-body antennas and furthermore that the measurements are taken in a controlled environment. To this end reliable phantoms that simulate the human body need to be developed. Numerical phantoms can be achieved by considering suitable electrical parameters that simulate the human tissue. A numerical phantom created using the Finite-Difference Time-Domain (FDTD) method was used in [2] where the numerical phantom was combined with antenna simulations calculated using CST Microwave Studio in order to predict on-body antenna behaviour. A flexible hand phantom was developed in [3] in order to characterise the performance of mobile handset antennas in different positions. However, physical phantoms tend to be complex and expensive systems with limited shelf life and are not generally readily commercially available.

For this reason, in order to facilitate 3D radiation pattern measurements at the University of Bristol, the suitability of a phantom, developed for medical applications in the Oncology Department of the University, has been evaluated and this contribution reports some preliminary results for this study. In a first step, the phantom is brought close to a patch antenna and its effectiveness to produce the same detuning effect as actual body parts on the reflection coefficient is assessed. The phantom is then rolled in a cylindrical shape to simulate a wrist/arm and results are derived for a loop antenna. In both cases, a numerical model is established with results simulated by the FDTD software developed at the University of Bristol. This ensures that a useful numerical tool that can be used hand in hand with measurements is constructed for antenna design purpose. Radiation patterns and efficiency calculations show the effect of the phantom on the performance of the antenna.

II. The Phantoms

The human body is composed of a number of different tissues all with unique electromagnetic properties. Each of these has a different effect on antennas in body-centric communication systems. The electromagnetic properties of these tissues are frequency dependent. Conductivity, relative permittivity, loss tangent and penetration depth for a number of different human body tissues were calculated at 2.45 GHz in [4]. For body-worn communication systems the main influential tissues are skin (ε_r = 20-38 depending on wet or dry), muscle (ε_r = 53) and fat (ε_r = 5), however, the overall contributing factors will be dependent on the position of the antenna on the body.

The physical phantom was created out of a mixture of TX151, Polythene Powder and water (ε_r = 80); a similar mixture as that proposed in [5]. The relative permittivity of the phantom was measured at 3 GHz as ε_r = 47, close to that of muscle [4]. A dielectric constant of 45 – 50 was sought after because this would give a good representation of human flesh (skin, muscle, fat). At higher frequencies, the dielectric constant of the phantom decreases. The phantom can be classed as a solid (wet) phantom and can be moulded into different shapes with varying thickness. For the measurements taken in section III the phantom was a solid block of about 30 mm thick, whereas in section IV it was rolled into a cylinder and held in place with Clingfilm. The Clingfilm was found to have negligible effect on the antenna characteristics.

The numerical phantom was created using the FDTD method and was assigned a relative permittivity of 47. The cell size for the phantom was kept below $\lambda_g/20$ at 2.45GHz, which meant a cell size of less than 0.75mm. The antennas and environments for the simulations were modelled using the same method.

III. Detuning Effects

A patch antenna was constructed in order to test the detuning characteristics of the phantoms on the input response. The patch antenna is a common choice for on-body communications as they are small, cheap and easy to construct, sometimes on a textile substrate to increase comfort to the wearer. The antenna had dimensions of 40x60mm and was placed on a ground plane of 60x80mm with FR4 substrate (ε_r = 4.5) and was resonant in the 1 – 3 GHz range. These frequencies were chosen as they are often considered for use in remote health monitoring systems as they can be used in cooperation with existing networks such as ZigBee [6]. The measured and simulated input response can be seen in Fig. 1. The measured resonant frequency occurs at 1.75GHz with a magnitude of -30dB. A second resonance is present at 2.4GHz.

To evaluate the detuning effects of the physical phantom, the input response of the patch antenna was measured when the phantom was placed 1cm above the patch antenna. The patch antenna was then positioned within 1cm of different body parts namely the hand and forearm. These results can be seen in Fig. 2. For the forearm and hand, the effects are very similar. The first resonance saw the magnitude decrease from -30dB to -9dB when in proximity of the forearm, and to -8.5dB in the case of the hand. When the phantom was placed in close proximity of the patch antenna similar results were measured, with the magnitude of the first resonance increasing to -9dB. In contrast to the first resonant frequency of the patch antenna, the second resonance saw an increase in magnitude when placed in the proximity of the phantom/body.

The numerical phantom shows very similar effects on the input response of the patch antenna. This can be seen in Fig. 3, where the simulation is compared to the measured results. The magnitude of the first order resonance is decreased to -7dB when the phantom is placed 1cm above the patch antenna. The difference in frequency between simulated and measured results was present in the original simulation of the patch antenna, so is not due to the presence of the phantom. The model was run for a sufficiently long time to allow the resonances in the time response to damp down. Without this a ripple will appear in the input response of the simulated data. Under the simulated circumstances the second order resonance is only slightly affected.

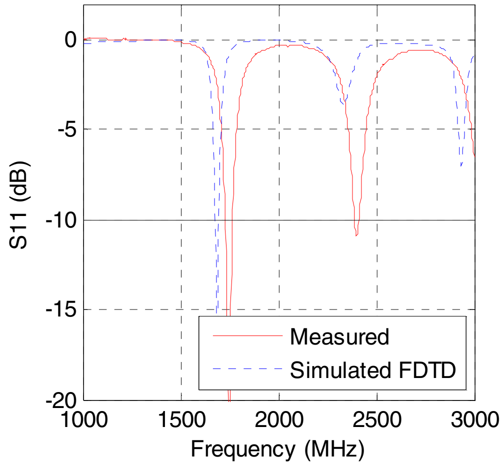


Fig. 1 Input Response for measured and simulated patch antenna

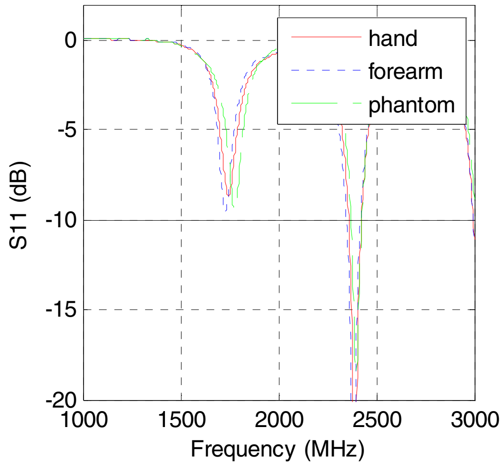


Fig. 2 Measured input response of patch antenna with different objects at 1cm distance from patch

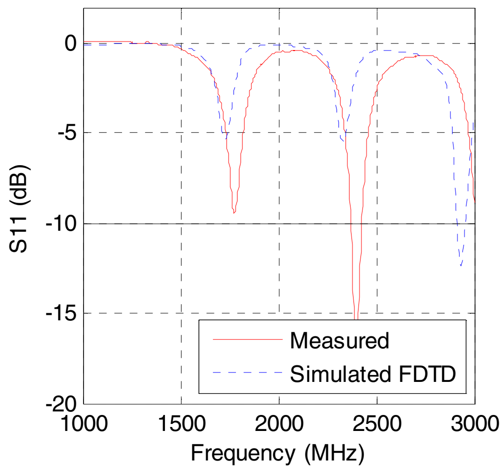


Fig. 3 Input response of measured and simulated patch antenna within 1cm of phantom

IV. Effects on Radiation Patterns of a Wire Loop Antenna

The physical phantom was rolled around a plastic tube in order to create a cylindrical phantom to mimic the arm. The phantom was mounted on a wooden base in order to make it practical to be placed in the anechoic chamber. The same setup was created in FDTD. A wire loop antenna with a radius of 37mm was used to measure the effects of the phantom on the antenna's radiation patterns. The phantom arm was pointing in the z-direction, with the loop in the x-y plane, as in Fig. 4. This would appear to represent the case where a person is lying on their back with the arm stretched vertically, however, the antenna patterns can easily be rotated to show other orientations. A balun was used for the experimental measurements in order to suppress the currents in the coaxial cable. For measurements of the loop antenna in isolation, the phantom was replaced with a cardboard tube.

The wooden base that the phantom was mounted to had dimensions of 400x400mm, similar to that of a human torso. The length of the phantom was 200mm and the radius 35mm. In all measurements absorbing material was placed above the wooden base in order to reduce reflections from the surface. Whilst the wooden base is not directly related to a body part, its interference with the measured radiation patterns may still be relevant. For body worn antennas, the body will provide a certain amount of blockage, reflection, and diffraction which will be critical to the performance of the antenna on the body. Body shadowing effects have been shown to influence the performance of handset antennas in [7]. The suitability of the blockage effects of the base will be confirmed by comparing with body reflections at a later date.

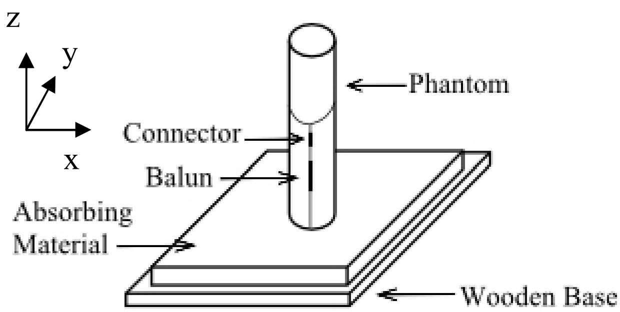


Fig. 4 Loop antenna and phantom

The detuning effects due to the presence of the phantom can be seen in Fig. 5. The resonance at 1.3 GHz has been shifted down by 500 MHz. This shows how the loop antenna has been affected when placed in the presence of the human body. The loop antenna was designed to fit around the arm/phantom and therefore is not well matched but it is obvious that any matching must be optimized with the loop in situ as the input response varies with loop position. Due to the constraints placed on the physical dimensions of the loop antenna by the size of the human body, the loop antenna is electrically large at the desired frequencies. Matching and control of modes in the wire loop to improve performance will be considered in the next stage of this work. Designing the antenna within the limits imposed by the body is one way of designing body worn antennas and may therefore allow small and comfortable antennas to be used. Measurements for the 3D radiation patterns were taken at 2.4 GHz, where the levels are similar. The full 3D radiation patterns in terms of relative gain for the loop antenna in isolation can be seen in Fig. 6. The patterns for the case where the loop antenna is mounted on the phantom arm are shown in Fig. 7. In the latter case the maximum measured signal decreased by 10.5dB.

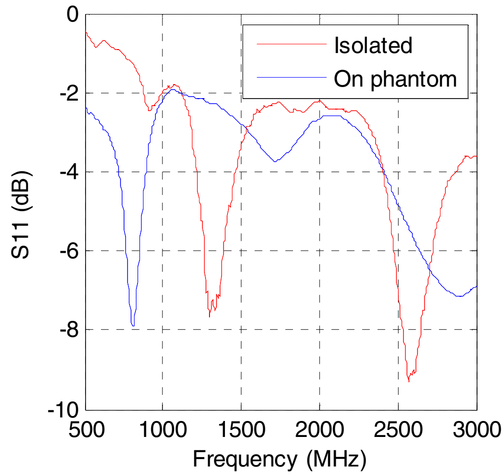
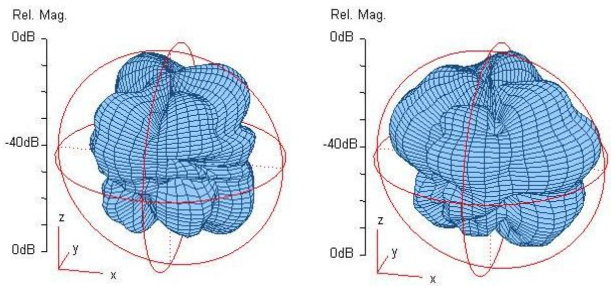
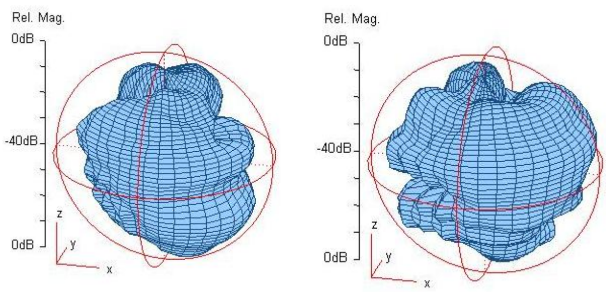


Fig. 5 Measured input response for loop antenna



(a) (b)

Fig. 6 Vertical (a) and horizontal (b) radiation patterns for loop antenna not on phantom at 2.4 GHz



(a) (b)

Fig. 7 Vertical (a) and horizontal (b) radiation patterns for loop antenna on phantom at 2.4 GHz

TABLE I
RADIATION CHARACTERISTICS OF LOOP ANTENNA

	Without Phantom	With Phantom
Max. Directivity (dBi)	6.4	5.4
Efficiency relative to Loop Antenna without phantom	–	12 ± 4%

The difference in efficiency of the antenna when moved from isolation to on-body was calculated using the technique presented in [8]. The equation used for calculating the efficiency is given in equation (1); where η_m is the mismatch efficiency and η_Ω accounts for the conductor and dielectric losses, and hence in this case body absorption. In this case the reference is the loop antenna when off the body, and the AUT is the case when the antenna is mounted on the phantom.

$$\frac{\oiint_s |E_{AUT}|^2 dS}{\oiint_s |E_{REF}|^2 dS} = \frac{\eta_{mAUT}\eta_{\Omega AUT}}{\eta_{mREF}\eta_{\Omega REF}} \quad (1)$$

The radiation characteristics of the loop antenna on and off the phantom are displayed in Table I. It was found that the efficiency of the loop antenna was reduced by 88% when placed on the phantom arm compared to when off the phantom while the maximum directivity fell by 1dB. The tolerance in the efficiency level of ± 4% accounts for triple travel and other cable effects. The introduction of the phantom significantly reduced the radiation levels from the antenna. The interference due to the wooden base is important as it forms nulls in the pattern where the signal has diffracted around the base. An FDTD model with the same setup is currently under development to verify these effects, the tight radius of curvature involved in this experiment imposing additional constraints on the modeling, though simulation results are expected to be presented at the Conference. The 3D radiation patterns can be rotated and combined with propagation and ray-tracing data in order to help the design of on-body antennas in different scenarios.

V. CONCLUSION

This paper reports the validation of a numerical and a physical phantom developed in order to aid the design of on-body antennas. A physical tissue equivalent phantom was generated using a mixture of TX-151, Polythene Powder, and water to produce electromagnetic properties comparable to those of the human body. Experiments showed that the phantom was proved to have the same influence as a human hand and arm in terms of detuning effects when brought close to a patch antenna. A numerical phantom in a model created using the FDTD software also showed similar effects to the physical phantom.

The effect of the phantom on the radiation patterns of a wire loop antenna was measured. It was shown to distort the patterns, whilst reducing the efficiency by 88% compared to the isolated case. The measured maximum radiation from the loop antenna was reduced by 10dB while directivity fell by 1dB. At the frequency of interest the reflection coefficient is only -4dB, however this will be corrected for in situ with the body in the next stage of this work. An FDTD model is currently being developed in order to confirm the effects experienced on the wire loop antenna in the presence of the phantom. The full on-body 3D radiation patterns will aid the design of body worn antennas, and the data can be combined with environmental propagation and ray-tracing azimuth and elevation data in order to further evaluate the performance of the antennas.

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