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Wet Environmental Conditions Affecting Narrow Band On-Body Communication Channel for WBANs

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Wireless Body Area Networks (WBANs) are rising as the key building blocks of next generation networks in modern health care systems. Research in recent years has focused on channel modelling, energy conservation and design of efficient Medium Access Control (MAC) schemes for WBANs. However, less attention has been paid to the on-body channel propagation analysis. This paper presents the propagation effects of wet clothing on the on-body channel at 0.9GHz, 1.8GHz and 2.5GHz and is germane to signal budgets in body-centric and mobile communication systems. A number of transmission measurements between simple monopoles above a square ground plane, placed on the opposing shoulder and hip, wearing single and multi-layered "rainwater wet" and dry cotton T-Shirts for standing, bending, torso left and right are used to gain insight into general levels of the effect of rainwater on propagation. Measured results are statistically processed to extract the level of transmission enhancement due to a wet on-body channel. Results show that wet clothing is generally beneficial to the channel at popular mobile communications frequencies.

Keywords: Body-centric communication, Narrow-band propagation, Monopole antenna, On-body channel

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1 INTRODUCTION

Sensor nodes that are implanted inside the body constitute a WBAN. The core idea behind WBANs is the provisioning and distribution of remote monitoring of humans and their functions. Rapid ongoing developments in technology have integrated the whole system on a single chip, making it more comfortable and affordable for people under the observation. Depending on the required parameters to be sensed, various sensor network topologies are required [1]. WBANs need to operate properly for long time duration without any battery replacement or recharge, especially for implanted sensors. Therefore, energy management for WBAN protocols is one of the major concerns. Continuous data transmission and sensing through larger distances between communicating nodes may create more energy consumption [1].

Current trends suggest that a possible route for communications devices is the integration into Wireless Body Area Networks (WBANs) [2]. In on-body communications, both the transmitter and receiver are co-located on human body, either directly attached to the skin or clothing. Multimedia, military and medical applications are three main drivers for WBANs. For on-body communication networks, since power is severely restricted, mechanisms for improving the channel are useful. Whenever, there is wireless communication on body from one point to another, On-Body Channel (OBC) exists. In this paper the effects of wet clothing on the on-body channel are investigated which suggests an improvement in the propagation by a margin that can be considered as significant.

Extrapolating from the work of Parsons [3] and his discussion on modes of propagation, we propose the following schema as illustrated in Figure 1. For OBC radio, waves are of two types: surface waves and space waves. Surface waves have been referred to as creeping waves [4] but are very similar in effect to Norton waves [5].

The same space waves mentioned in its discussion by Norton, may have two constituents as direct waves (LOS version) and indirect waves (NLOS version). The indirect wave in on-body communications may also be termed as skin reflected waves. It is worth mentioning here that skin currents are used by the surface waves for its propagation but since skin is not considered as good conductor of electricity so due to attenuation i.e. energy absorption by the skin results in quick reduction in the power, which ultimately leads us to the assumption that these waves do not contribute to the overall propagation model.

If measurements are taken in an anechoic chamber (to avoid multipaths) then extrapolating from Norton we also hypothesis that "the conditions are changed in favour of the skin reflected wave by the curvature of the body since the direct waves are screened off by the curvature of the body, unless they do overcome it by a diffraction process. . . ". Basically the radio wave propagation model given by Norton over the surface of the earth has been assumed to be valid for the skin surface of the human body. Since the expla-

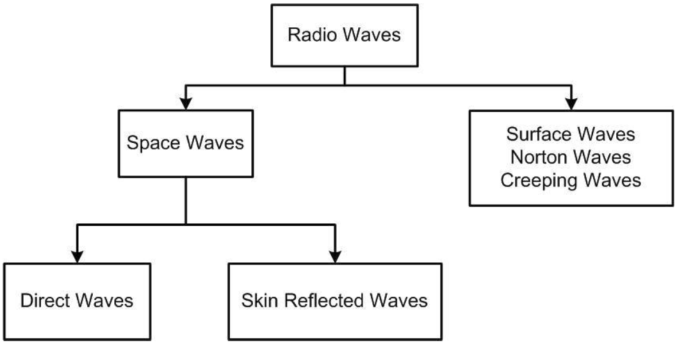

FIGURE 1
Modes of Radio wave propagation on the body

nation regarding the difference between space and surface waves helps in the prediction of the inductive nature of the human body and the stimulus of the currents in the skin.

We chose also to emphasize the following property of the OBC Assumption 1: the attenuation in the skin reflected waves is mainly because of the conductivity and the permittivity of the tissue keeping its natural relation with the distance and also when a human body is exposed to an electric field, its behaviour is heterogeneous in nature. It is to be noted that researchers mainly have considered human body as nonmagnetic in nature. Note that most authors consider the body to be non-magnetic. The research regarding the radio channel models has been conducted in the environments which are deficient of real humans, so the OBC channel models are formulated in this unique environment where wave lengths and human body sizes are comparable. Any local change i.e. the permittivity of the tissue, near the transceivers on the body may cause a significant change in the propagation model and hence the uncertainty in the prediction. For example, a simple walk may cause the increased flow of the blood in upper parts of the skin.

The rest of the paper is organized in the following order: In section 2, related work is reviewed, whereas in section 3 experimental goals and hypothesis for this work are given. Detail of the experiment, antennas and equipment are presented in section 4. Simulated human torso model and measurement results are presented in sections 5 and 6 respectively. Finally, section 7 concludes the paper.

2 LITERATURE REVIEW

A rigorous experimental method is summarized in [4] in which a human phantom was cut into eight slices and various points on the skin for each slice were chosen at 12 degrees intervals. A pair of dipoles was chosen in parallel orientation with human skin surface to measure the vertical component of the E-field for the on-body channel modelling. Same nature of experiments was also performed by researchers in [4] outside and within the anechoic chamber for the channel modelling at UWB bands of frequencies. For UWB radio these same authors present work related to our own paper [6, 7]. Major contributions in this field can be argued to have begun in 2002-2003 with [8, 9]. Work by Zasowski et. al. is also provided by ETH Zurich [10], IMEC (NL), ULB (Brussels) and UCL (Louvain) [4, 6], [7, 11, 12], University of Birmingham and Queen Mary University of London [13, 14], and Queen University of Belfast [15, 16] have also made significant contributions. These papers supported by Norton discussion conclude to a space wave with direct, diffracted and reflected components (skin reflected) and a creeping wave that is not significant.

In on-body antenna measurements, angular gain is an important parameter to be considered and efforts are made to make them stable. If antenna is placed on the human hip and orientation of the body is changed from standing straight to the bending forward position, angular gain is also changed. To minimize this factor omni-directional antennas are always considered as better options. Mismatch is important since antennas in close proximity to the body tend to detune (become electrically larger) [17] resulting in lowering the input impedance which reduces the power into the air interface. Insulating the antenna from the body and the use of a ground plane both reduce the impact of this mismatch factor. For measurements, the effect of multipath, which results in increased delay spread, can be reduced by controlling the environment either greatly with an anechoic chamber or significantly using an open area such as football field with a few scatterers. With reference to the measurements in open areas the authors of [7] mention a ground reflected component that would be present in received signal strength in on-body propagation. However, they also mention that for on-body measurements over the chest, the component of the field due to the ground reflection is not significant and therefore we choose to discount this factor in this paper. From literature such as [13, 18-21], it is reasonable to make the following points. At 0.9 to 2.45GHz and with regard to the skin reflecting wave, a vertical dipole/monopole exciting a TM wave supported by the inductive properties of skin will suffer less attenuation than a parallel dipole exciting a TE wave supported by the conductive nature of the skin. Based on the cited work in this paper, there is currently no standard reference distance for OBC and no method is available for the isolation of the surface wave from the skin reflected wave.

In [22], Mohamed Maalej presented cooperative communication routing protocol based on both energy consumption and QoS; measured by absolute Received Signal Strength Indicator (RSSI). Proposed algorithm confirmed better performance in terms of end-to-end delay and packet loss rate, taking into account the consumed energy by the network. In [23], the authors formulated the optimization issue of cooperative diversity technique using Linear Programming (LP). They attained optimized network lifetime of sensor networks using logic of cooperative routing. The performance and lifetime of existing routing schemes were than compared with developed ones. In [24], the researchers proposed routing algorithm called Minimum Power Cooperative Routing (MPCR) which utilized cooperative diversity. This algorithm constructed minimum power route, ensuring certain delivery ratio. Researchers in [25], proposed Residual-Energy-Activated Cooperative Transmission (REACT) and presented the concept of range extension using less burdened sensors as next hop for reduction of load on highly occupied ones. Remaining energy of the network will be used for extension of network lifetime. In [26], the author has explored the benefits of cooperative diversity for a linear arrangement of WSN, at the relay sensor node and a lightweight combining strategy at the receiver. In [27], researchers used a comprehensive measurement of path-loss and fading features for surface-level nodes in band of 400 MHz band for both flat and irregular outdoor terrain. They also presented a new mathematical path-loss SLIT model. In [28], a wireless sensor scheme utilizing cooperative diversity and relay deployment is presented for improving network lifetime.

The goal of our experiments is to isolate changes due to the skin reflected contribution of the space waves for situations with dry and fresh water wet clothing and to measure the effect on the on-body channel. The objective of our experiment is to statistically isolate the effect and provide a power model exponent for freshwater wet clothing. Our hypothesis is that wet clothing consistently provides a better on-body channel.

3 DETAILS OF EXPERIMENT, ANTENNAS AND EQUIPMENT

The main purpose of these experiments was to find out the effect of wet local environment in between the transceivers when they were placed on the human chest. The volunteer for the experiments was wearing a cotton T-shirt in different body orientations, the T-shirt was dry first and then was made wet by pouring water on the chest area. The antennas used are $\lambda/4$ monopoles, shown in Figure 2, located over a square ground plane on a 20mm thick polystyrene tile. The measured/modelled dimensions and characteristics of these antennas are shown in Table 1.

As mentioned earlier, these were TM antennas used to generate a skin reflected wave supported by the inductive properties of the body. The placement of the antennas with Line-of-Sight (LoS) conditions on the human chest is shown in Figure 3.

A flexible coaxial cable was used to connect network analyser with quarter-wave monopoles shown in the figure 2. The surface currents were seized to exist by placing a balun at quarter wave distance from the SMA connector.

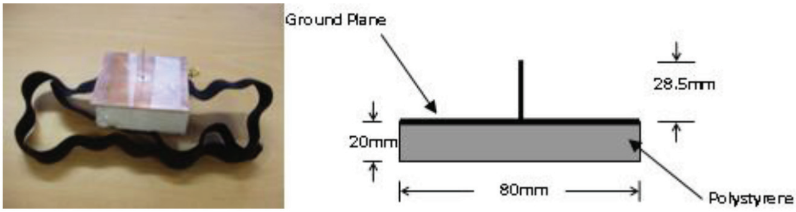

FIGURE 2
Antenna Layout and Line diagram of Quarter Wave Monopole at (2.5GHz)

TABLE 1
Characteristics of Thin Wire Monopole Antennas

Frequency (GHz)	2.45	1.8	0.9
Efficiency %	91	94	90
Gain (dBi)	1.36	1.91	1.1
Ground plane (mm2)	80x80	120x120	120x120
Probe length (mm)	28.5	40	80

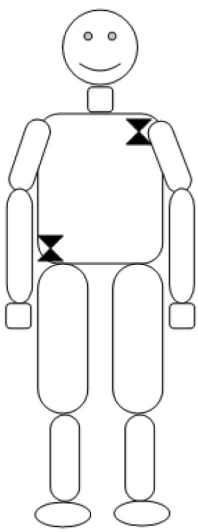

FIGURE 3
Placement of Monopoles on the chest and waist.

Over intervals of 30 sec, response of S_{21}(dB) response was computed with a volunteer wearing antennas on a T-shirt. Types of indicative positions used were four with different postures as shown in Figure 4. To avoid errors due to

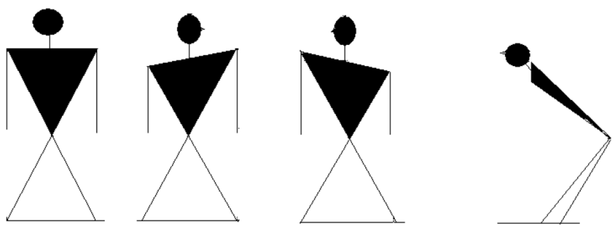

FIGURE 4
Different body postures during the experiment (a) Standing, (b) Twisting Left, (c) Twisting Right and (d) Bending forward

the observer, readings from the VNA were collected using a portable video camera with the data being transcribed from a time indexed recording. The distance between antenna centres, when the person was positioned at approx. 55cm. For twisting left and right, it was 45cm and 65cm respectively. Experiments at 2.45 GHz took place in an open environment with few close scatters. Experiments at 0.9GHz and 1.8GHz took place in an anechoic chamber.

The uncertainty in the measurements due to cable movements were not more than 0.01%. Recollect that these were static positions in which the volunteer was asked to remain still. Respiration was detectable in the results, however flexing of the cables was very low. Previously, samples of rainwater were collected at the site and measured to have permittivity of 73 and the conductivity of 2.3 S/cm. Thereafter, it was considered reasonable to use tap water as its properties were found to be essentially the same and consistent. The procedure in each case for the wet measurement was to throw a liberal amount of water onto the chest of the volunteer such that the T-shirt and the skin underneath were wet. No attempt was made to smooth or stretch the cloth and on the chest area only a T-shirt was worn.

The maximum achieved mismatch orientation for the monopoles in dry and wet experiments was approximately +5 to +10 degrees. Mismatch for the Polarization Loss Factor (PLF) of orientation was recorded to be 0.96, which contributed to an error of around 0.13 dB to the net results. The T-Shirts which were used in the experiment were 99.9% cotton with dielectric permittivity of 1.54 having a Loss Tangent of 0.06.

4 SIMULATED HUMAN TORSO MODEL AND MEASUREMENT SETUP

A 4-layer human phantom was created in CST Microstripes that was used to support our measurement data; as available in practice [20, 29-31]. Model for simulation contained layers of Muscle, Wet skin, Dry skin and Cotton T-shirt. The dimensions of the cylindrical model were taken so as to simulate the

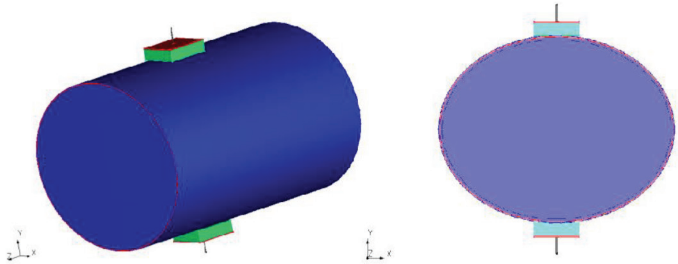

FIGURE 5
Layout of the 4-layer Human Torso Model (Front and Side view) with antennas at front and back for 2.5GHz

human torso i.e. 290mm for back to stomach, 418mm for one shoulder to other and 450mm vertically from waist to shoulder. A model having monopole antennas at front and back is shown in Figure 5.

5 RESULTS

Initially the effect of a water layer over the skin of the voxel on transmission and return loss was measured through simulations. These simulated results are shown in Figure 6.

The top two traces of the simulation in Figure 6 show that the S_{11}(dB) is the same for wet and dry and that both wet and dry have the best match at about 2.5GHz. For S_{21}(dB), the simulation shows that the transmitted wave is severely attenuated but wet propagation is generally better.

Next the measured results S_{21}(dB) at 0.9 GHz for wet and dry clothing in four stances is shown in Figure 7. Each 30 second window consisted of 15 measurements (one every two seconds) and each of those was averaged 256 times by the VNA to produce a mean. The results show that for all stances the wet channel is better.

The experiments were then repeated for 1.8GHz and the results are shown in Figure 8.

Here in figure 8 again the wet OBC channel is shown to improve propagation. In general the results are more dynamic than at 0.9GHz but the attenuation is increased at 1.8GHz as predicted by all of the on-body communication models in the literature.

At 2.45 GHz the experiment was then repeated on the outside site for wet and dry clothing and in the chamber for dry clothing only. The results for this set are shown in Figure 9. Inspection of the results show that the attenuation has again increased and that the wet channel is generally better than the dry channel. Also these results show that although the channel is not totally repeatable there is reasonable agreement between the chamber and open site results for the dry channel.

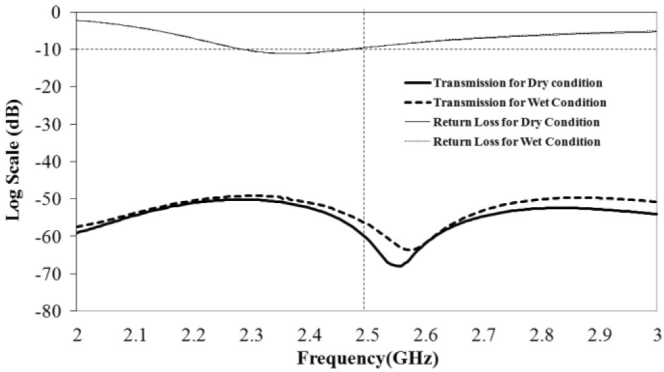

FIGURE 6
Simulated S_{21} (dB) and S_{11} (dB) results for the 4-layered Human torso model with antennas at front and back at 2.5 GHz

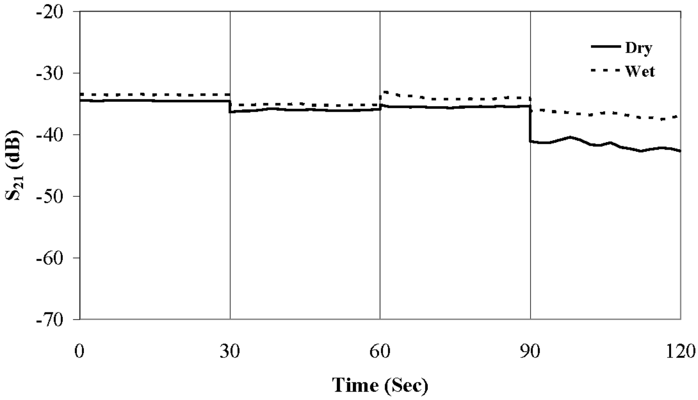

FIGURE 7
Measured S_{21}(dB) Between Waist-to-Chest worn antennas on the body with changes in posture (Frequency f=0.9GHz, 0-30s Standing Straight, 30-60s Torso Left, 60-90s Torso Right, 90-120s Bending Forward)

The next set of results relates to an experiment that was slightly different. Here we were interested in the improvement in the channel of single and double T-shirts compared to no clothing on the torso at all. These measurements that were for the standing posture only were taken at 1.8GHz and are shown in Figure 10. These results show that the channel is improved similarly by one and two layers of clothing. Note that both of these layers were dry and that a further improvement in the channel would have been seen had they been wet.

The following set of experiments were also performed when the probe antennas were replaced with a set of square loop antennas on the same size ground

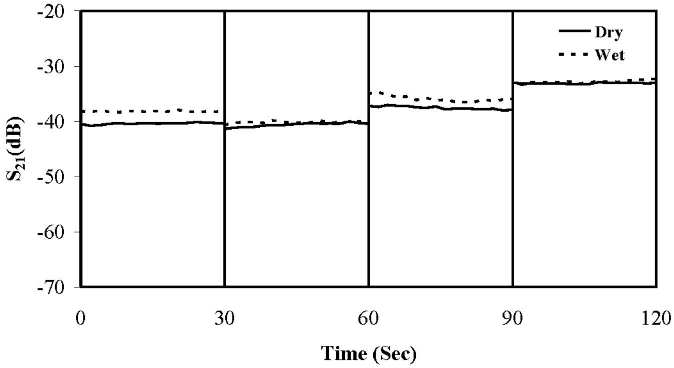

FIGURE 8
S_{21} (dB) measurements with same parameters as in Figure 7 but f = *1.8GHz*

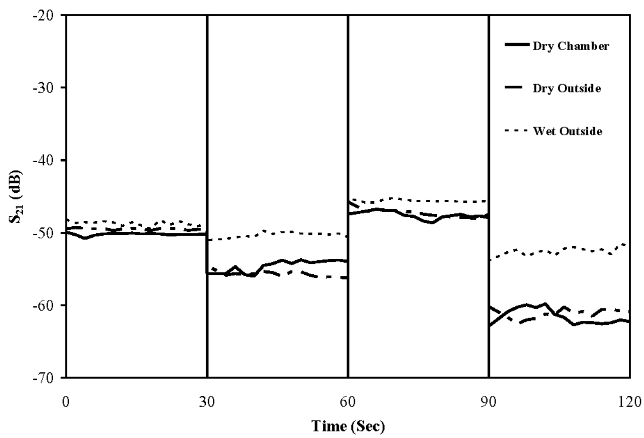

FIGURE 9
S_{21} (dB) measurements with same parameters as in Figure 7 but f = 2.45*GHz*

planes as before, but results are not included as these also provided a TM wave supported by the inductive property of the body. Very similar results were seen with these antennas and therefore we feel we can reasonably state that the wet dry behaviour of on-body channel is not antenna specific. The S_{11}(dB) was measured for the monopole antenna at 2.45GHz wet and dry on the body and in free space and is shown in Figure 11. Results for wet and dry were very similar (-12dB at 2.45GHz) and results for free space showed a better S_{11}(dB) @ 2.45GHz -14dB.

Note that detuning and reduction in Q is normal for most on-body antennas. These results in Figure 11 confirmed that the antennas were isolated from the channel results and that the size of the ground planes tiles used was sufficient to avoid significant mutual coupling. For the antennas themselves

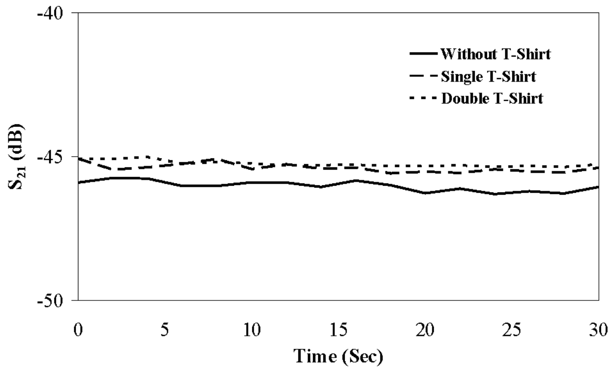

FIGURE 10
Comparison of S_{21}(dB) Measurements for different numbers of T-shirts (none, one and two) inside the Chamber at 1800MHz, standing upright.

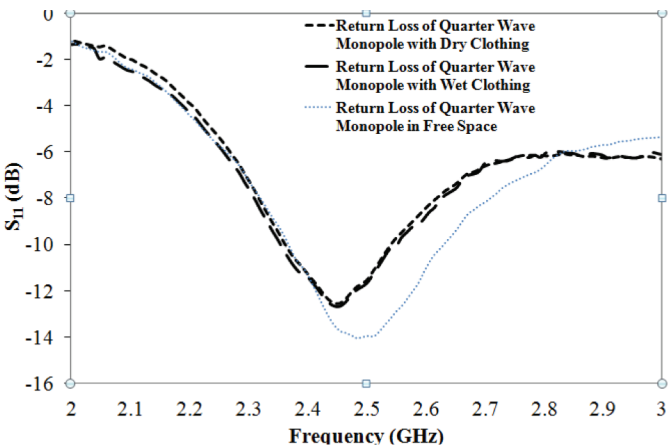

FIGURE 11
Return loss of quarter wave monopole antenna in free space and on-body with wet and dry clothing at 2.45GHz

all of our simulations agreed well with our measurements meaning that these antennas were generic.

The results in Figure 12 show the measurements of the author in the context of other work in the field. Note these are spot measurements rather than continuous and that they lie between the LoS and NLoS as predicted by [24] in for TM type antennas.

One measurement with volunteer standing inside the anechoic chamber with his arms stretching outwards was also performed. In this measurement both antennas were put on the hip of the human male but with NLoS condi-

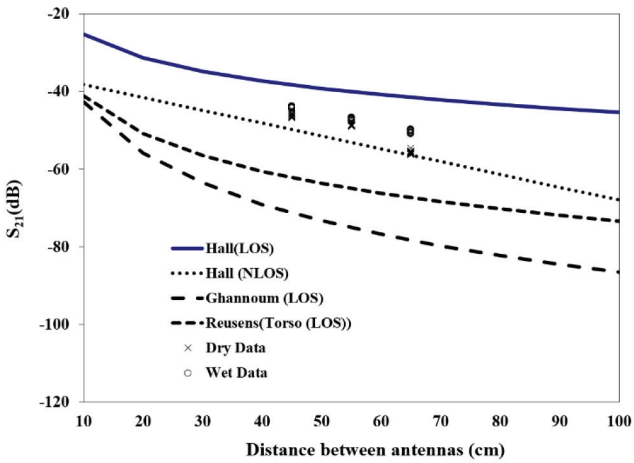

FIGURE 12
Comparison of on-body propagation models at 2.45GHz for human torso by [11, 17, 18] and location of our measured data (Dry and Wet)

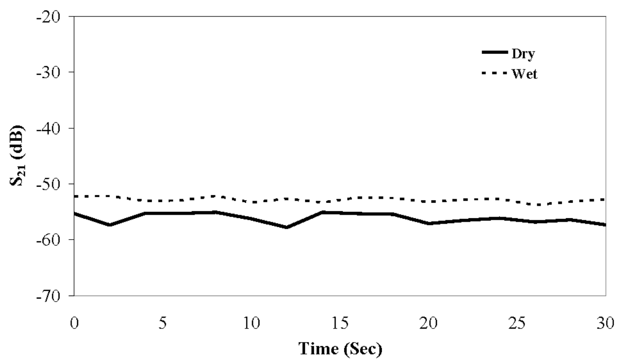

FIGURE 13
S_{21}(dB) Measurements for Antennas located on the waist of Human Body with wet and dry clothing and with arm stretching outwards in NLoS conditions

tions, results are shown in Figure 13 and the layout is shown in Figure 14. Here once again our hypothesis that wet clothing improves the propagation is well supported by the results shown in Figure 13.

6 STATISTICAL ANALYSIS OF MEASURED DATA

Following the analysis of Fort et al. [7], we assume that the path-loss in dB (i.e. $20log_{10}|S_{21}|$) is normally distributed N(μ, σ2), making the path-loss itself

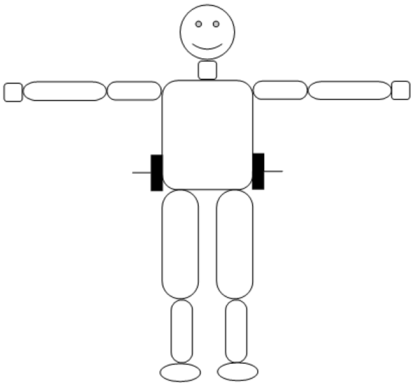

FIGURE 14
Dry and Wet measurements for monopole antennas on waist of human male inside anechoic chamber at 2.5GHz and with arms stretching outwards

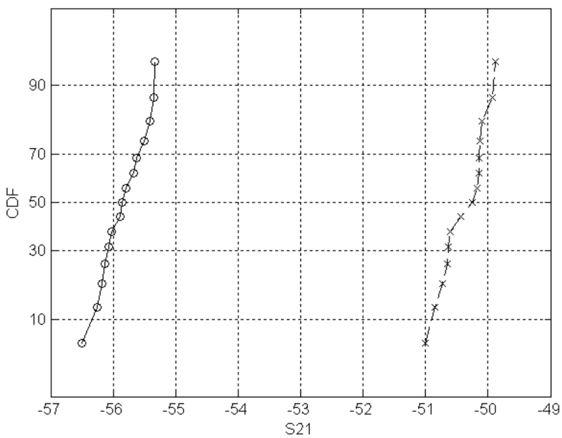

FIGURE 15
Typical Normal probability plot of path–loss in dB. The data shown is for $f = 0.9GHz$, left–twist.

a log-normal variate and this assumption can be confirmed through simple normal probability plots, e.g. Figure 15.

It must be admitted that any analysis is complicated by the possibility of different behaviours of wet and dry fabric and, potentially, the presence of postural tremors. Despite these, F-tests confirm that in the majority of cases the variances of wet and dry data can be considered to be equal. This agreement is improved by removing the first few seconds of data following a change in position. Although already clear from the data presented in Figures (7)-(9), both single and two sided t-test analysis confirms that in all cases the mean value (which corresponds to the large scale path-loss) is, statistically, significantly greater in wet than in dry conditions ($p = 0.00007$). It is also interesting to note that in wet conditions, at 1.8GHz and at 2.5 GHz, the reduction in path-loss obtained from changing from still to right-twist is around 3 -3.5dB, or more. A LoS channel (path loss exponent n=2) would generate only $20log_{10}(55/45dB_{,}$ which suggests that the channel has an n value much nearer to those values (n=4) which are typical for the OBC. Similarly, the change to left-twist increases the path-loss by a similar amount.

7 CONCLUSION

In this paper evidence has been provided for the existence of a guided wave between the skin surface and clothing, which can exist with reduced attenuation when wet. The effect is significant and repeatable. Results presented for our own measurements and the models of others suggest the need for models for both TE and TM mode stimulated skin reflecting waves. This paper has also highlighted the need for a reliable and robust on body reference distance for mobile communications frequencies between 0.9 and 2.5 GHz. The results show that the relative improvement of the wet body channel can be measured but that channels for postures are dynamic relative to each other. A protocol has been demonstrated that allows accurate open site measurements for on body antennas using portable equipment and video. Further work on this topic would be to extend to form an analytical model of the skin reflected wave. The authors are currently investigating on-body transmission lines using water.

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