On-Body Antennas and Propagation: Recent Development

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SUMMARY   The paper reviews recent advances in on-body antennas and propagation under a joint UK EPSRC research project between Queen Mary College, University of London and University of Birmingham. The study of on-body radio propagation has been extended by using various small antennas. The effect of antenna size, gain and radiation patterns on on-body channel characteristics has been studied. A practical wearable sensor antenna design is presented and it is demonstrated that a global simulation including sensor environment and human body is needed for accurate antenna characterisation. A 3D animation design software, POSER 6 has been used together with XFDTD to predict the on-body path loss variation due to changes in human postures and human motion. Finally, a preliminary study on the feasibility of a diversity scheme in an on-body environment has been carried out.

key words: *on-body communications, antennas and propagation, wireless sensors, diversity, numerical modelling*

1. Introduction

There have been growing interests in body-centric wireless communications [1] due to their abundance applications, for example, in personal healthcare, smart home, personal entertainment and identification systems, space exploration and military etc. A generic concept of body-centric wireless communications may include scenarios which RF sensor nodes are placed in/on body. Antennas and propagation is the central part of body-centric wireless systems and plays an important role in the implementation of miniaturised, spectrum and power efficient RF sensor nodes and the integrity of in/on/off body communications. Of the aforementioned aspects, on-body antennas and propagation has its distinct properties due to the presence of human body. It has been found [2], [14] that wearable antennas can suffer from reduced efficiency, radiation pattern fragmentation and variations in impedance at the feed. For on-body radio channels, main features such as shadowing effects, dynamic variation in path loss and time delay components make it different to characterise the channel behaviour. Previous studies [3], [4] demonstrated preliminary measurement results based on classic antennas such as microstrip patch, monopole, wideband bowtie *etc.* It is noted that the on-body radio propagation is predominantly based on space waves, creeping waves and a combination of both. In this paper, we shall present recent development in on-body antennas and propagation research, specifically, the analysis of antenna diversity for on-body communication systems; the design of small antennas within ISM frequency bands for wireless wearable sensors and their on-body performance evaluation. Numerical and system modelling are essential for understanding and optimising on-body communications. Further to [4], [5], a dynamic on-body channel modelling tool has been developed to enable the description of dynamic events and ultimately characterised the on-body channel statistically.

2. Wearable Antennas and On-Body Radio Propagation

For the on-body environment, antennas are required to be conformal to the body and immune from frequency and polarisation detuning. Hence it is vital to understand how best to specify an antenna radiation pattern, when part of it is space and part in the lossy body; how to specify coupling into the propagation mode which may be a surface wave or free space wave or a combination of both. Such work would be based on efficient numerical simulation plus verification by measurements on real bodies or phantoms. So far, it is still unknown how close to the surface the antenna can be mounted. If it is too close, it will have low efficiency due to body loss but good coupling to the surface wave and vice versa.

We have conducted a parametric study of six different antennas (as shown in Fig. 1) for on-body applications in order to evaluate the effect of body presence on general antenna parameters, including impedance matching, radiation patterns, gain and efficiency. The unique on-body propagation channel between various antenna pairs is also investigated as it is essential for the design of wearable wireless devices. The antennas include a half-wave dipole and quarter-wave monopole aligned vertically and parallel to a standing human, as a printed circuit board (PCB) trace upon FR4 substrate material; a printed circular loop implemented; an inverted L-shape antenna; a 'wiggle' antenna from Cypress Semiconductor and an L shape antenna with parasitic elements [6]. All antennas are printed on an FR4 board with $\epsilon_r = 4.6$, conductivity $\sigma = 0.002$ S/m and thickness of 1.6 mm (except for the wiggle antenna, thickness of 0.7 mm is applied). All antennas demonstrate excellent free space performance across the ISM band with omni-directional patterns and excellent gain and efficiency.

Antenna return loss, radiation patterns and gain and ef-
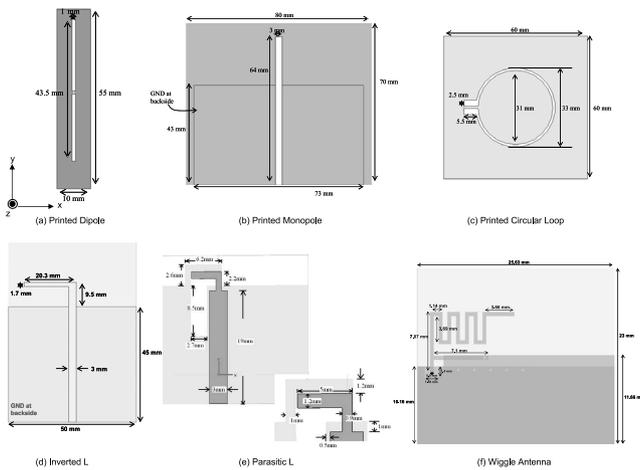
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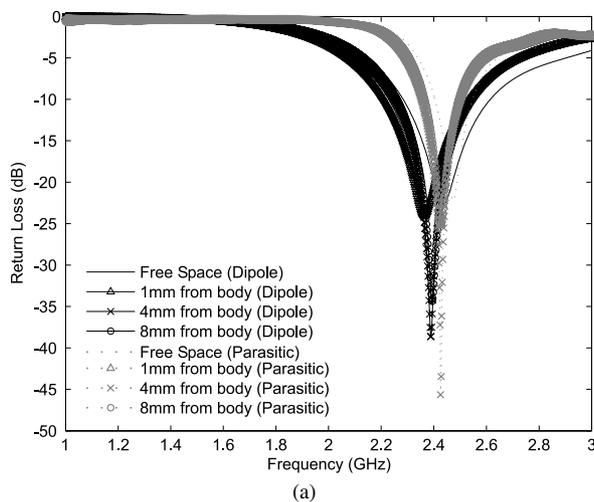
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Fig. 1 Schematics of antenna designs applied in the study (a) Dipole, (b) Monopole, (c) Circular Loop, (d) Inverted L, (e) Parasitic L and (f) Wiggle Antenna.

Table 1 Antenna types used in study and their dimensions and free space characteristics at 2.4/2.44/2.48 GHz.

Antenna	Size (mm^2)	Gain (dB)	Radiation Efficiency (%)
Printed dipole	10×55	1.8/1/9/2.0	95/97/99
Printed monopole	80×70	3.3/3.2/3.3	100/99/100
Circular loop	60×60	2.9/2.9/3.0	97/98/99
Inverted L	50×45	3.3/3.2/3.3	100/100/99
Parasitic L-shaped	30×20	1.5/1.6/1.9	81/83/87
Wiggle antennas	25.6×23	−4.8/−5.7/−6.7	18/17/14

Table 2 Path loss for various on-body antenna pairs.

Left Waist (Tx)	Right Chest (Rx1)	Right Thigh (Rx2)
Distance	34 cm	38 cm
Friis' loss in free space	30.85 dB	31.6 dB
Friis' loss on-body	48.63 dB	49.4 dB
Dipole antenna pair	51 dB	60.6 dB
Monopole antenna pair	51 dB	54.8 dB
Circular loop antenna pair	55.75 dB	55.51 dB
Inverted L antenna pair	55.8 dB	55.83 dB
Parasitic L antenna pair	51.38 dB	54.12 dB
Wiggle antenna pair	73.4 dB	77.5 dB

(a)

(b)

Fig. 2 (a) Return loss of the proposed dipole and parasitic L antennas when placed on the left side of the chest at various distances from the body (1, 4 and 8 mm) and (b) on-body radiation patterns of the dipole when placed on the left chest and left ear [18].

ficiency within the ISM band are presented with respect to distance from human body (1, 4 and 8 mm) and also on antenna location on the body which includes left chest, right chest, left ear and left waist. Figure 2 presents the return loss of the printed dipole antenna when placed on the left side of the chest at various distances from the body. The results show detuning from free space resonance caused by changes in antenna effective length due to changes in effective permittivity as seen to the radiator. The resonance frequency detunes the most when the antenna is closer to the body. The return loss results of parasitic L antennas show slight detuning from free space resonance in comparison to the dipole case and this is due to the presence of the ground plane which partially shields the antenna from the human tissue. Figure 2(b) shows the radiation patterns of the dipole antenna when placed on the left side of the chest and also on the left ear at 2.44 GHz. The patterns illustrate the loss caused by the presence of the human body specifically the backward radiation and also the increased directivity at specific angles due to the body curvature. Table 1 lists the applied antenna types and their main parameters at 2.4, 2.44 and 2.48 GHz when operating in free space. As expected, the conventional antennas demonstrate excellent performance. However, when size reduction is applied (as the case for parasitic L and wiggle antennas), antenna bandwidth (impedance bandwidth and hence radiation bandwidth) and radiation efficiency decrease due to the coupling between elements and the introduction of vias. This causes the radiated power to decrease rapidly therefore affecting efficiency due to additional loading impedance. All antennas suffer from reduced efficiency when placed on-body.

Coupling between the on-body antenna pair is investigated by examining the communication link loss and the electric field distribution along the body surface in free space environment. Table 2 presents the variation on path

loss for various antenna types, approximate free space and on-body path losses based on the calculation using Friis' formula. The path loss is dependent on the on-body link as well as the antenna types. The worst performance is noticed for the wiggle antenna pair as predicted due to its inefficiency.

3. Antenna Design for Wireless On-Body Sensors

Wearable antennas are likely to be integrated with RF transceivers in the design of wireless sensors. It is often required that a maximum achievable coverage range is to be delivered by the sensor with respect to the transceiver sensitivity level. The sensor antenna design is restricted by many factors including the sensor size, radio chip placement, and lumped component locations etc. Figure 3 shows photographs of the sensor transceiver layer and the prototype module fabricated at the Group of Healthcare Devices and Instrumentation, Philips Research. The current antenna deployed in the sensor design is a printed quarter wavelength monopole, etched on the edge of the circular PCB board. Hence the antenna is designed with the printed wire wrapping the transceiver chip and other components. The antenna is derived from a circumference monopole or an inverted L antenna [6], [7]. The sensor antenna performance is sensitive to lumped components, pins and copper routings presence in the package. The surrounding and adjacent components are modelled as a perfect conductor block in proximity of antenna. The PCB board includes the ground plane and supply voltage copper sheets.

The antenna design deployed in the proposed sensor is numerically analysed using the High Frequency Structure Simulator (HFSS), AnsoftTM. The antenna is modeled on FR4 substrate ($\epsilon_r = 4.6$ and thickness of 0.3 mm). The printed antenna thickness is $35\,\mu$m and the width of the line is $150\,\mu$m. The ground and supply voltage layers added have a diameter of 5.5 mm, thickness of $17.5\,\mu$m each and separation between the layers of $80\,\mu$m. The actual antenna length is 31.5 mm (approximately quarter wavelength of the required frequency, 2.4 GHz). The complex impedance at the RF transceiver differential output is $115+j180\,\Omega$, therefore a matching circuit is applied in order to match the output to the single-ended monopole (matching to $50\,\Omega$) [8]. Figure 4 presents the return loss of the sensor antenna when only one layer is modelled in comparison with the full sensor modelling. The one layer model includes the printed antenna, the transceiver chip and PCB board. The figure illustrates the significance of considering full structure modelling in characterising small antenna integrated with wireless sensors. The antenna may be detuned due to an increase in its electrical length caused by surrounding connectors. The calculated antenna gain is -1.2 dB with radiation efficiency of 48%. The antenna gain can be further improved to 1.6 dB with efficiency of 77% by impedance matching and antenna geometrical optimization in the sensor. This illustrates the potential extended coverage area served by the sensor with simple and reliable performance enhancement techniques.
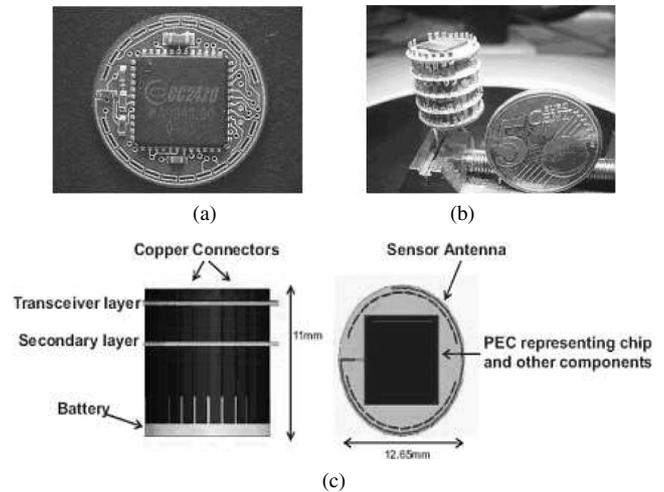
Fig. 3 (a) Photograph of the transceiver layer with a printed monopole antenna (top view), (b) Photograph of a prototype wireless sensor, and (c) CST Models of wireless sensors for antenna characterisation [9].
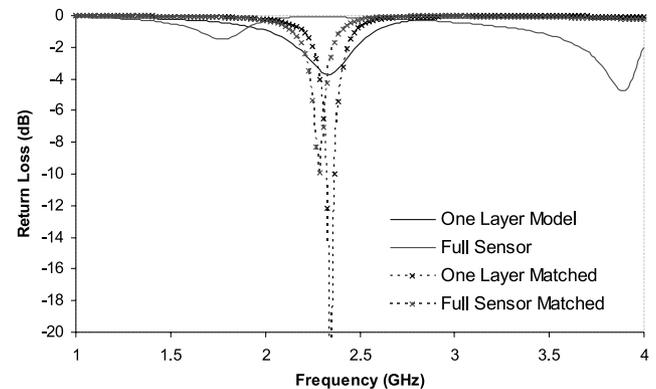

Fig. 4 Comparison of sensor antenna return loss for mismatched and matched designs and the effects of surrounding sensor components [9].

4. Numerical Simulation of Dynamic On-Body Channels

To help in the development of communication links is necessary to model the channel [5], [10]. However, to our knowledge, no attempts have been made to characterise electromagnetic (EM) propagation around the human body when it is in motion. This is due to the difficulty of defining the human body in the postures involved in various activities. The geometry of the human body has a complex shape and consists of different layers (e.g. tissues), each of them having its own permittivity and conductivity. We have overcome the latter problem by using a homogeneous body model. The body shape has been determined using animation software [11].

Two different channels have been investigated and measurements have been carried out. The transmit antenna Tx was placed on the left belt while two receive antenna positions were investigated. The right ankle and right wrist have been considered, because in these positions the chan-
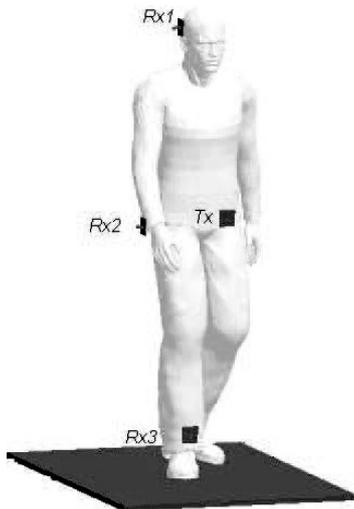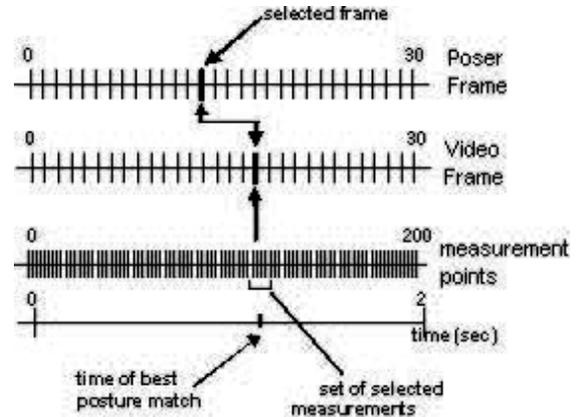
Fig. 5 Model of the avatar, 'James' in XFDTD (Model is one frame from 30 comprising a walking sequence in POSER6; monopole antennas are attached at various points on the body [11]).

Fig. 6 S21 for right wrist to left belt channel for frame 17 (solid line = measured points, dotted line = average of all measured values, dashed line = simulation result;measured values arranged in 5 groups, 1st group is 1st value used around best fit frame, 2nd group is 2nd value and so on) [11].

Fig. 7 Simulated and measured S21 for left belt to right wrist channel at 2.45 GHz for walking human [11].

nel movement is large and involve combinations of line of sight (LOS) and non-LOS radiowave propagation.

The human body used in the simulations has been derived from a 3D animation design software, POSER 6 from e-frontier [12], and a realistic walk has been obtained using the walk designer in POSER. This software creates a movie of the walking avatar, 'James.' Frames from this movie are then exported from POSER and input to XFDTD, a finite-difference time-domain EM simulator, from REM-COM [13]. At this point the 2.45 GHz antennas and connection ports are added to the body, as shown in Fig. 5 and the object dielectric properties are specified. Thus the body is a homogeneous one, composed of, in this case, skin tissue. Overall dimensions of the body were 171 cm of height and 60 cm of width and the skin parameters used were relative permittivity = 37.5708, conductivity = 1.31 S/m and SAR Density = 1125 kg/m^3. The duration of the walk is one second and 30 frames from POSER are simulated in XFDTD.

Figure 6 illustrates how this comparison between measurements and simulation was made. The top line represents the POSER movie with 30 frames in one pace, composed of two steps, starting with the right foot and the left hand forward. The total measurement period was 120 s with the network analyser taking one measurement each 10 ms, all at 2.45 GHz. During this period the subject wearing the antennas, continued to pace up and down the anechoic chamber. Continued pacing was considered to be a more reliable way of maintaining a walking style that matched the walk of the avatar in POSER 6. Within the 120 s, 60 walks were performed and recorded using the video camera. The second line in Fig. 6 represents 2 s of video frames. Continued walking meant that it was not always possible to maintain synchronism between the walks of the subject and the avatar. Matching the simulated frames to the measured data was then achieved by a visual comparison of the video recording and the frame under consideration to determine the time of
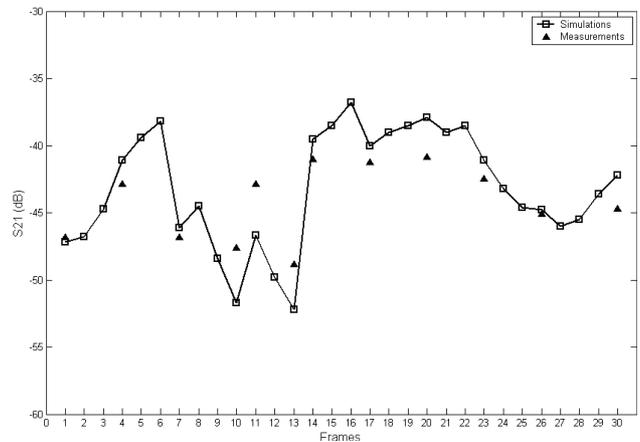
the video frames that matched the frame. As suggested in the first two lines of Fig. 6, due to the difficulty of getting similar walks between the subject and the avatar, the postures of the POSER frame and of the video recording did not always occur at the same point in time. This is not a problem because the comparison was made frame by frame and not continuously in the time. This means that the systematic error due to the lack of synchronism was always corrected. Although POSER and the video recorder both had a frame rate of 30 fps, the network analyzer had a sample rate of 100 samples/s, in order to get more samples for each frame and to decrease misalignment errors. Furthermore, five points of the S21 data centered on the instance when the video frames matched the simulated frames were taken for each walk. On average, 40 such instances were found in the 60 walks for each simulated frame. Finally these 40 × 5 values were averaged to give the triangle point S in Figs. 7 and 8.

It is estimated that, in this matching process, the differences between the positions of the human body and the avatar were of the order of 5 cm, primarily due to the diffi-
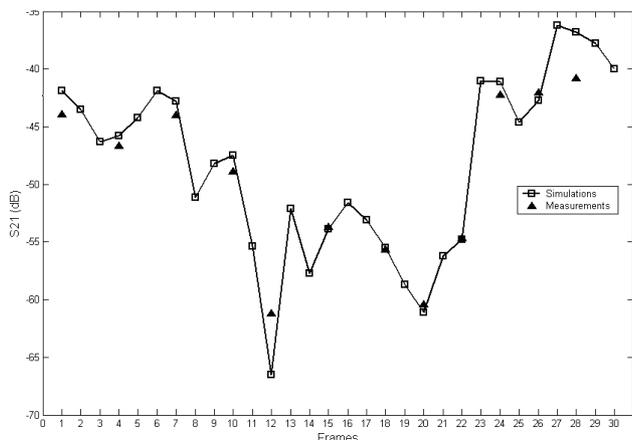
Fig. 8 Simulated and measured S_{21} for left belt to right ankle channel at 2.45 GHz for walking human [11].
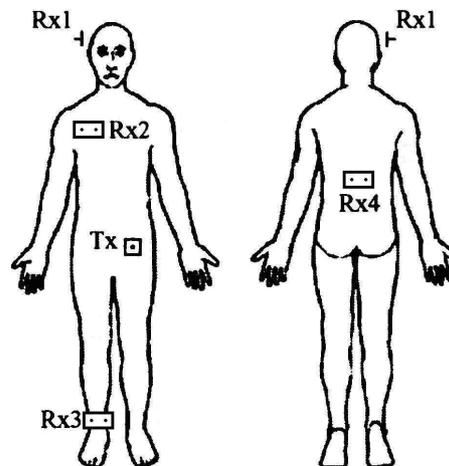

Fig. 9 Analysed positions on the body for the transmitting/receiving antenna system [15].

culty of controlling the posture of the subject.

Figures 7 and 8 show the simulated S21 values in dB (circles and solid lines) for every frame of the POSER walk and the measured values (triangles), averaged as noted above, for some frames. The solid line in Figs. 7 and 8 are the simulated S21 values versus the number of walk frames. It is first noted that there is a significant range between the maximum and minimum values in both the channels, indicating the importance of this study. The simulations and measurements agree within about 4 or 5 dB in both channels.

Path Loss results and statistical parameters derived from the data show that, especially when measurements campaign are difficult to carry out, the use of an animation and electromagnetic software is a promising technique for characterization of on-body communication channels.

5. Antenna Diversity for On-Body Communication Systems

Recent new implementations apply to more complicated activities which the body movement is involved in and they require a larger quantity of data to be transferred with higher speed. Military and sport equipment for communications between wearable instruments and sensors give an example of this. The need for higher performance systems also suggests the use of multiple antenna systems in an on-body environment. Diversity is a well known technique used to reduce the fading effect due to a multi-path propagation channel, by using a multiple antenna system at the receiver. Two or more uncorrelated signals are received by the separate antennas and combined using a number of different techniques. At present, diversity is widely applied in receiving at base stations for mobile cellular systems and recent studies have been conducted on portable devices. In both previous applications, the base station antenna system, whether or not in a diversity configuration, is always fixed and the mobile unit moves in the propagation environment. In this case, the multi-path effect is mostly determined by the en-

vironment that closely surrounds the receiving terminal. On the contrary, in an on-body propagation system, the performance is mostly determined by the body activity, as both the transmitting and the receiving systems are placed on the same moving environment.

A preliminary study on the feasibility of a diversity scheme in an on-body environment has been carried out [15]. Measurements have been conducted in an anechoic chamber and a monopole antenna has been used as a transmitter and two monopoles on a common ground plane as a receiver. In this analysis, postures with different levels of mobility have been studied and roughly classified in sitting and standing postures. During measurements, in both sitting and standing postures, free movements are allowed for each part of the body: leaning down, turning the trunk, walking, kneeling, and moving arms pretending to handle objects like in a real environment. A wooden footstool without any metallic parts, such as screws or bolts, has been used for sitting postures. All antennas are placed on the front of the body, whilst position 4 is centred in the middle of the dorsal area. They are intended to be used for devices like wireless earphone or visors in a helmet on the head (position 1), music and video players for the head (position.1 and right waist, Tx), temperature sensors or step counters, like in reference 3, for the chest and the ankle (positions 2, 3), media players or mobile phone in a backpack (position 4). The transmitting antenna was always mounted in the waist position (Tx), while the two receiving ones were placed in other positions as shown in Fig. 9.

Antennas used for measurements are monopoles on a copper ground plane. The transmitting one is mounted on a square 8×8 cm^2 ground plane while the two receiving monopoles are on a common 6×12 cm^2 rectangular ground plane separated by a distance of 5.3 cm (0.4λ at 2.45 GHz in free space). An RF signal generator and the Agilent 8720ES vector network analyzer (VNA) have been used to measure the transmittance from the Tx monopole to both the receiving monopoles (two-branch diversity system). The RF out-

Table 3 Diversity Gain for some placements of the receiving antennas for standing postures (Selection Combining (SC). Equal Gain Combining (EGC), Maximum Ratio Combining (MRC)) [15].

Diversity Gain	Rx	Placement		
	Ankle	Right Ankle	Right Chest	Centre Back
SC	2.57	4.61	2.17	5.86
EGC	3.69	5.53	3.16	6.65
MRC	4.28	6	3.89	7.12

put of the signal generator is connected to the transmitting antenna while the two receiving antennas are connected to the two ports of the VNA set up in a tuned received mode. Measurements have been carried out in an anechoic chamber in the Antenna and Applied Electromagnetic Laboratory of the Electronic, Electrical and Computer Engineering Department at the University of Birmingham. The chamber is $4 \times 2.5 \times 2.5 \, \text{m}^3$ and fully anechoic, but for the walking postures, the absorbers were removed to free a 50 cm wide path on the wooden floor. The measurement procedure consisted in collecting 1601 amplitude and phase time samples for each channel with a time step of 0.225 seconds. (i.e. a 360 seconds time sweep). Collected samples have been used to calculate the statistics of both channels and the diversity gain. The two-branch normalized power samples have been combined through the selection combining (SC), equal gain combining (EGC), and maximum ratio combining (MRC) techniques.

Results in Table 3 show improvement in the signal reliability that prove the applicability of a diversity scheme to on-body communication systems. Recent measurements with printed inverted F antennas, PIFAs, dipoles and loops mounted very close to the surface of the body confirm these levels. It is clear that multipath due to the environment and the body both play a role. When the wave on the surface of the body is highly attenuated, as in the case of the printed-IFA, then low path gain and high diversity gain result. PIFAs, on the other hand, have a better path gain but less diversity gain. The uplink and downlink diversity and correlation is reciprocal suggesting that in most cases the local off-body scattering environment is dominant. Dynamic channels or channels with non-line-of-sight, such as from the belt to the wrist, give higher diversity gains.

6. Conclusion

In this paper, recent advances in on-body antennas and radio propagation have been reviewed. On-body radio channel characteristics have been studied for various electricaly small antennas and diversity antennas. Numerical investigations of the antenna performance proved the influence of the lossy human tissue presence on antenna parameters including impedance matching, gain, radiation patterns and efficiency and also the significance of antenna positions in determining the ultimate antenna gain and efficiency. It is revealed that on-body path losses are associated with the size, gain and polarisation of antennas and on-body posi-

tions. The calculated diversity gain values are often greater than a few dB, so proving the applicability of a spatial diversity scheme to on-body communication systems.

Recent research interests in on-body antennas also include the development of wearable antenna optimization and fabrication for VHF/UHF applications [16] and textile antennas [17]. It is needed to develop low-profile unobtrusive body worn antenna to replace large monopole whip antennas for UHF band for squad level communications. Such antennas are likely made out of textile materials and integrable into garments. Some of textile antennas are meant to be part of a "wearable intelligent textile system," which expands the classical concept of garments, adding new functionalities like monitoring of vital signs, as well as other physiological parameters of the human body. However, the human body is an uninviting and often hostile environment for a wireless signal. For developing wearable communication systems with optimised wireless data-path, long battery life, and effective control of field distribution, a thorough understanding of on-body radio propagation is critical to the future advancement of body-centric wireless communications. The use of animation software coupled to an electromagnetic simulator has been demonstrated. The effect of body dynamics during walking and the antenna position on channel path gain at 2.45 GHz has been investigated. Significant fading, in the order of 20 dB, is seen. The simulation software shows encouraging agreement with measurements. One of the primary difficulties has been making the body used in the measurements take the posture used in the simulation, and these difficulties are believed to account for much of the, up to 5 dB difference between the simulation and the measurements. Nevertheless the results show the promise offered by the use of such combined animation/electromagnetic software for characterisation of on-body communication channels.

Acknowledgment

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