Dual Band Wearable Metallic Button Antennas and Transmission in Body Area Networks (BANs)

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Abstract— A dual band metallic antenna with the appearance of a button on a pair of jeans for use with wearable computer networks, emergency rescue scenarios and future wireless medical applications is presented. The design operates at 2.4GHz WLAN and the HiperLAN/2 bands and a parametric study is given to aid the design process together with measurement and simulation of the structure on a body. A study of transmission between pairs of on-body antennas is presented to give insight into on-body propagating Line of Sight and Non-Line of Sight channels. A term 'Body Gain' is defined to quantify how the body attenuates the channel.

1. Introduction

This paper describes a small antenna suitable for worn WLAN/Bluetooth and HiperLAN/2 Body Area Network (BAN), mobile computing applications, emergency rescue and wireless telemedicine.

Rapid progress in the area of wireless and mobile technologies has resulted in the development of many devices which are capable of being transported in pockets or otherwise worn on the body [1]. . For instance; safety glasses with integrated cameras, MP3 players sewn directly into clothing and wearable sensor systems [2]. These devices typically have the facility to communicate wirelessly to off-body networks and as their prevalence increases it will become a requirement for on-body wireless networks to be implemented offering non-physical connections between worn devices on a single user. With the continuing trend towards personal communications and mobile and pervasive computing, there is a need to create antennas suitable for mounting on the person for scenarios where, for instance, (i) medical sensors integrated into fabric may connect centrally to a transceiver mounted in clothing, or (ii) where separate wireless devices in pockets or worn on the body may communicate via wireless on-body channels to a central worn access point for communication off-body. Published work on worn antennas for integration into clothing includes [3-5] which present linearly polarized fabric based patch antennas and [6] which describes a circularly polarized design. Fabric antennas have also been combined with Electromagnetic Band Gap structures as reported in [7] for use at 2.4 and 5GHz bands. The subject of human body-antenna interaction has also been studied and the performance of a PIFA placed close to a human body is investigated in [8] while [9] presents a study to identify suitable antenna sites on a wearer using a simple monopole and coil antenna. Finally, on-body propagation channels are characterized in [10] and [11] for narrowband and Ultra Wide Band (UWB) channels respectively while body-worn channels have been characterized at 868MHz in [12] and a wearable communications network for use in fire rescue has been demonstrated in [13].

The unifying factor of much of the antenna design work described above is to make the antenna unobtrusive and conformal to the clothing surface. However, an alternative approach to that proposed in [3-7] is to disguise the antenna rather than hide it. The antenna described in this paper has a small ground plane and is a compact rigid metallic top loaded monopole with the appearance and size of a conventional waist button used in denim jeans. Monopoles have been shown to be efficient launchers of creeping waves on the body surface [9] and the rationale for designing an antenna of this structure is as follows: (a) clothing fabric is not used as an integral substrate which fills a resonant cavity as could be the case in a microstrip patch. This alleviates the performance consistency issues associated with substrate compression, poor electrical characterization of textile material and variable losses caused by moisture uptake which will be significant in a worn textile. (b) The small surface area of the antenna means that it is not required to be flexible so that surface distortion will not alter the input impedance and radiation patterns. (c) The antenna does not require a large flat ground plane and (d) the structure is relatively simple to incorporate into clothing by conventional construction methods, and it is even possible to fit retrospectively. A microstrip feed line on a flexible substrate is proposed as a method of excitation.

The paper is organized as follows. Section II describes the structure and performance of the Double Band Metallic Button Antenna (DBMBA) giving S11 curves simulated and measured on and off the human body, while section III describes the DBMBA design and operation. Section IV contains a parametric study of the DBMBA offering design insight and Section V presents the radiation patterns and on-body performance of the DBMBA. Section VI presents a study of point to point communication between DBMBAs mounted on a body and compared to a phantom with the electrical characteristics of free space. Section VII concludes the paper. Finally, a series of variations on the design of the DBMBA presented here has been reported in [14-18]. In [14] a PIFA structure is introduced with a polarisation orthoganol to the DBMBA; in [15] the antenna has been redesigned, is loaded with PTFE dielectric and contains a slot in the top disc; in [16 an altered design is given based on FR4 substrate and loaded with a via pin to reduce overall height; and in [17 & 18] totally different structures are presented which still have the appearance of buttons but are operational over the FCC defined UWB band.

2. Dual Band Metallic Button Antenna Structure and Performance

The structure of the Double Band Metallic Button Antenna (DBMBA) is shown in Fig.1 and the dimensions are tabulated in Table 1. The structure was introduced in [19&20] and consists of disc 1 and cylinder 2 which have diameters d1 and d2 respectively; cylinder 2 has height h_2. At the top of the button antenna are two air spaced discs (diameters d_3 and d_4) separated by honeycomb for rigidity. The central section of the antenna consists of an air filled cylinder (diameter d_2) containing a coaxially located conducting post which connects the upper disc 4 to the base disc 1. The antenna has similar dimensions and weight to a standard jeans button and is mounted on a flexible Velcro® substrate of height h_1 which is backed by a metallic ground plane of 5.0 cm × 5.0 cm. Feeding was via a side connected microstrip line (width 7mm) attached to the edge of disc 1. The Velcro® substrate offers good flexibility but strong resistance to compression and has a relative permittivity, ε_r, measured to be approximately 1.4.

A DBMBA was constructed using the dimensions in Table 1 and the measured S11 is compared to simulation by CST Microwave Studio in Fig.2. The matched band at 5GHz is primarily due to the capacitance between discs 1 and 3 and the inductance associated with current flow on cylinder 2. The capacitance between the discs reduces the resonant size of the structure which bears a resemblance to a top hat monopole [21&22]. However the antenna differs from a simple top hat monopole in respect of the disc with diameter d_1. The lower resonance frequency at 2.45GHz is determined by the capacitance between the two top discs 3 and 4 which are loaded by a short circuited coaxial line of length, h_2. The mode at 5GHz due to the capacitance between discs 1 and 3 is largely unaffected by the addition of disc 4 and the inner via. All simulations were carried out by CST Microwave Studio.

Figure 2 gives measured and simulated S11 for the DBMBA mounted both in isolation and on a human body. A 3 layer skin tissue model [23] represented the body in CST with the skin surface directly against the antenna ground plane. Microstrip feeding was used for both on and off-body measurements and simulations. The layers used in the body model were: (i) skin: 1mm thick; (ii) fat: 3mm thick; and (iii) muscle: 44mm thick. A block of tissue of 120×120×40mm^3 was simulated in total and was limited by available RAM. Following [23] it was assumed that the tissue materials were non-dispersive [23] and electrical parameters were taken for 4GHz, the centre of the operating bands. Tissue parameters were taken from [24] as follows: skin: relative permittivity, $\varepsilon_r = 38$, conductivity, $\sigma = 2.34$S/m; fat: $\varepsilon_r = 5.1$, $\sigma = 0.18$S/m; muscle: $\varepsilon_r = 50.8$, $\sigma = 3$S/m. The on-body S11 measurements were taken with the ground plane attached directly to the skin (0mm gap). The antenna was sited on the lower abdomen of the user. Mounting the antenna on the body was observed to cause the upper bandwidth to decrease from 27% to

20% which still covers the HiperLAN2 band meaning that attaching that attachment to a human body has not significantly altered its response at the lower band.

3. Design and Operation

The surface currents of the DBMBA with the dimensions of Table 1 have been given in [19] at 2.5GHz and 5GHz respectively. Analysis of the surface currents showed a strong capacitance between the top plates (3 and 4) at the 2.4GHz band with a significant current flow down the central post to disc 1. The distance between discs 3 and 4 significantly affects the frequency of the lower band without detuning the upper band. The inductance of the central post also affects the lower band noticeably. Conversely, the upper band is influenced by the electric fields between discs 1 and 3, and both the upper and lower bands are influenced by the cylinder height, h_2. The next section contains a parametric study to inform the design process.

An equivalent lumped element circuit model of the DBMBA has been developed to help understand the behaviour of the antenna. The circuit topology and simulated results are given in [25] where excellent agreement is achieved between the equivalent circuit and measured results. In [25] a radiation resistance of about 80Ω is identified allowing the radiated power to be calculated across the bands and for a voltage transfer function for the antenna to be derived. This work paves the way for system level modelling of the antenna in body worn networks.

To be practically integrated into clothing, the antenna would need to be mounted on a small ground plane and to investigate this; a DBMBA was simulated over a rectangular ground plane with dimensions 30mm×40mm, Fig.3. At this size the ground plane is strongly resonant at the lower band, and the position of the antenna is critical to achieve a good match at the correct frequencies. Moving the antenna from position X_{20} at the centre point of the ground plane to X_0 at the shorter edge caused a 13% and a -18% change in the lower and upper band frequencies respectively. Using the antenna dimensions given in Table 1, the correct matched bands were obtained at X_{10} with the antenna offset 10mm from the shorter edge of the ground plane.

4. Parametric Design Study

A simulated parametric variation study was carried out on the principal DBMBA dimensions using CST to establish how they alter matched frequency. Bounded parameter ranges were defined in the simulator and varied individually. All parameters except that one being varied had the dimensions of Table 1. The dimensions studied were: d_1, d_2, d_3, d_4, d_5, h_2 and h_3. Table 2 gives the maximum percentage frequency variation and difference in fractional bandwidth observed. Maximum frequency or bandwidth variations are shown in the Table, though they do not necessarily occur at either end of the swept parameter ranges.

An overview of the tuning process should be aided by the summary presented in Table 3 which uses ranges of change: 5% ≤ not significant ('-'); 5% < moderate ≤ 25%; 25% < significant. The table indicates that the upper band is tuned by d_3 and the lower band by d_4 with relatively little coupling between the two. Second order tuning of the upper band can be achieved by adjusting the base disc diameter d_1 and middle cylinder diameter d_2 which moderately affect the band centre frequency and significantly affect on the bandwidth. The lower band can be tuned by the diameter of the inner post d_5 which significantly affects the band centre and moderately affects the bandwidth. As mentioned in the previous section, the cylinder height, h_2 affects both bands significantly. Where a band has become matched as a result of a parametric variation, a * appears in Table 3. Finally, it should be noted that the lower band match is sensitive to all dimensions and is the most easily detuned.

5. Measured DBMBA Radiation Patterns

The radiation patterns of the DBMBA were measured in a far field anechoic chamber. Feeding was via a microstrip line connected to the bottom disc, shown as in Fig.1. The antenna was mounted as shown in Fig.4, using adhesive paper tape, at waist height on an adult male in the position of the button on a pair of trousers. A coaxial cable was connected from an SMA connector at the edge of the ground plane where the microstrip line terminated. The ground plane size was 30mm×34mm and was mounted on to the skin of the human subject. The DBMBA was 10mm from the shorter edge of the substrate. A rotating wooden table was constructed for the human subject to lie on during measurement of the *x-z* and *y-z* planes. The measured radiation patterns of the DBMBA on a live adult male are shown in Fig.5 with a comparison to off-body measurement. The antenna is proposed for use in Personal Area Networks (PANs) where communication is necessary both to devices on-body and to external, off-body, network access nodes. With the DBMBA mounted as a waist height front trouser button there is good coverage at the front of the user's body providing connection to other worn devices. The *x-z* and *y-z* planes show there to be reasonable forwards coverage at both bands with a centre null of around 20dB and there is a deep null in the rear direction. As a live subject was used for mounting the antenna, it was necessary to disconnect between measurements in different planes and this led to some slight misalignment. The measured gains at each band for the antenna not mounted on a body ranged between 1.2 and 2.9dBi. Mounting on a body caused the gains to increase by roughly 1dB. The microstrip feed caused some asymmetry in the measured patterns due to feed radiation.

6. Point to Point On-Body Transmission

Fig. 6 shows a set of locations that were identified as possible sites for the button antenna. Positions 1 and 2 are on the shoulders as may be present on a uniform; 3 and 4 are in breast pocket positions and 5-8 represent jacket buttons. Positions 9, 10 and 11 were selected to assess coupling around the torso. A study was made of the channel gain between pairs of these points. The measured results are given in Tables 4 and 5 for 2.45 and 5GHz respectively. The channel gain is the S21 transmission between two identical button antennas mounted at the positions indicated. The body gain is defined as the difference between the channel gain measured on a human phantom of expanded polystyrene (ε_r = 1.01) and the channel gain measured for the same locations on a human body.

In all cases the ground plane of the DBMBA was mounted parallel to and about 3mm from the surface of the body. The antennas were fed by coaxial cables connected to an Anritsu ME7808A vector network analyzer. A set of 10 measurements were taken and the values are averaged for each link with the standard deviation shown.

Variance is small for LOS measurements taken on the torso, [26] though, standard deviations are typically higher for the non-Line of Sight (non-LOS) channels and this is probably due to fading caused by multipath ray combination. It is known that movements in the body, including breathing can cause significant variation in channel path and affect received signal strength for non-LOS channels, [27&28].

At 2.45GHz the body causes losses in received power ranging from 0.9 to 18.3dB. For LOS paths on the front of the torso all the body losses are less than 3dB. Shoulder to shoulder transmission (position 1 to 2) is subject to blockage caused by the neck of about 9.5dB. Transmission from front to back of the torso (position 5 to 11) has a loss of 18.3dB where creeping waves are the propagation mechanism and multipath fading is experienced. The two primary propagation paths between points 5 and 11 were up and around the neck or around the torso under the arms. Interference between these two path lengths caused fading, leading to the large standard deviation observed in the measurements. Side to side transmission (position 9 to 10) around the torso is subject to only 7.4dB body loss and there is some coupling between rear lobes of the antennas situated on the major axis of the elliptical cross section torso; the human volunteer was of slim build and multipath rays around the torso would have similar path lengths. Transmission loss from the chest (position 3) to the opposite side of the torso (position 9) was 7.7dB, similar to side to side transmission and again dominant multipath rays around the torso would have almost the same path length.

At 5GHz the LOS channels show a positive body gain meaning that the body is guiding the waves over the front surface of the torso. Interference between the direct space and the surface reflected rays caused the body gain to be relatively high across the chest positions 3 and 4 (8cm separation), and also from positions 5 to 7 (18cm). Conversely, there is relatively low gain between positions 5 to 6 (9cm) and 5 to 8 (27cm). This is consistent with single space and surface reflected wave interference where the frequency is 5GHz and the antenna heights are 14mm. With the exception of chest to torso side transmission (position 3 to 9), all the body gains are higher at 5GHz than 2.45GHz.

This study has indicated that the human body does not introduce losses greater than about 20dB and at 5GHz it can actually enhance received power over that of free space. The non-LOS channels suffer from high variance due to multipath fading while the LOS links can experience ray interference at 5GHz. The work implies that implementing spatial diversity into on-body systems would improve outage as suggested in [29].

7. Conclusions

A new antenna proposed for use in Personal Area Networks (PANs) has been reported with the appearance and dimensions of a standard jeans button. The antenna has been realized in both single and double band versions covering the WLAN and HiperLAN/2 bands. The antenna tuning is strongly determined by the capacitance between the various discs that make up the structure and frequencies can be controlled by varying the disc diameters or separations according to the parametric study presented. The radiation currents mainly flow axially along the central post of the structure giving it the radiation characteristics of a monopole on a small ground plane. The measured scattering parameters of the antenna are captured and used to create an equivalent circuit of lumped elements which accurately describes the frequency response as reported in [2]. This model will be developed to allow closed form design of the DBMBA in the future. A study of point to point transmission has been compared for on-body and free space situations using a phantom with a relative permittivity of 1.01. This has demonstrated that LOS transmission on the torso suffers from direct and surface reflected ray interference at 5GHz and it is therefore necessary to place antennas away from nulls if no diversity is used. Creeping waves provide reception for non-LOS paths, but multipath causes the received power to vary significantly. Again, a diversity system would compensate for low power levels. At both 2.45and 5GHz the human body is a relatively good guider of waves with most transmission loss better than 10dB when referred to free space. Siting the antennas on each shoulder offers good possibilities for off-body communication owing to the orientation of the antenna. Additionally, the blockage caused by the head and neck could offer could diversity potential.

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8. References

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Figure Captions:

Fig.1. Cross section and plan of Dual Band Metallic Button Antenna, DBMBA.

Fig.2. Measured and simulated S11 for Microstrip fed DBMBA on and off-body.

Figure 3. Reduced size ground plane with offset button positions X_0 to X_{20} indicated. Position X_{10} (10mm from edge) offers correct tuning. The circle on the right hand side shows the relative DBMBA size.

Fig.4. Mounting of microstrip fed DBMBA on human test subject, (antenna profile enlarged for clarity).

Fig.5. Microstrip fed DBMBA Radiation patterns. (a) 2.45GHz, (b) 5.2GHz, (c) 5.5GHz. LHS: *x-y* plane, Center: *y-z*, RHS: plane *x-z*. In all cases DBMBA is mounted as a front trouser button at waist height. Solid line shows on-body measurement and broken line represents isolated antenna. Heavy line: co-polarization, thin line: cross polarization.

Fig.6. On body DBMBA locations for point to point transmission study.

	Dimension	Electrical length, lower band	Electrical length, upper band
Disc 1 diameter, d_1	10.0mm	0.081λ	0.198 λ
Cylinder 2 diameter, d_2	7.0mm	0.056λ	0.137 λ
Disc 3 diameter, d_3	16mm	0.129λ	0.315 λ
Disc 4 diameter, d_4	16mm	0.129λ	0.315 λ
Inner via diameter, d_5	2mm		
Substrate height, h_1	1.8mm		
Cylinder height, h_2	8.3mm	0.064λ	0.154 λ
Gap height, h_3	3.0mm		
Substrate relative permittivity	1.4	-	-
Ground plane size	50mm×50mm	$(0.40\ \lambda)^2$	$(0.98\ \lambda)^2$

TABLE 1
Dimensions of DBMBA (Fig.1)

	Parameter range, mm	Lower Freq-uency change	Lower Bandwidth Range	Upper Freq-uency Change	Upper Band-width Range
d_1	10.0mm	+2%	0%-8%	-25%	57%-0%
d_2	7.0mm	-12%	0%-3%	+15%	22%-34%
d_3	16mm	-3%	0%-5%	-35%	0%-38%
d_4	16mm	-49%	18%-0%	-4%	27%-33%
d_5	2mm	+37%	0%-11%	+5%	38%-29%
h_2	1.8mm	-49%	9%-0%	-64%	0%-34%
h_3	8.3mm	-4%	0%-10%	+14%	45%-28%

TABLE 2
DBMBA Parametric Variation

	Effect on			
	Lower Frequency	Lower Bandwidth	Upper Frequency	Upper Bandwidth
d_1	-	Moderate*	Moderate	Significant*
d_2	Moderate	-*	Moderate	Moderate
d_3	-	-*	Significant	Significant*
d_4	Significant	Moderate*	-	Moderate
d_5	Significant	Moderate*	-	Moderate
h_2	Significant	Moderate*	Significant	Significant*
h_3	-	Moderate*	Moderate	Moderate

TABLE 3
DBMBA Parametric Study Summary. * indicates that band becomes matched (S11 < -10dB) over the parametric variation.

DBMBA locations	Shortest surface route between antennas (m)	Phantom Channel Gain (free space) (dB)	Standard Deviation	On-body channel gain (dB)	Standard Deviation	Body gain (dB)	Channel type (LOS = Line of Sight)
1 to 2	0.3	-30.7	0.30	-40.0	1.23	-9.4	Non-LOS (neck blockage)
3 to 4	0.08	-26.9	0.25	-29.2	0.76	-2.3	LOS
5 to 6	0.09	-17.1	0.42	-18.9	1.08	-1.7	LOS
5 to 7	0.18	-23.3	0.35	-24.2	0.84	-0.9	LOS
5 to 8	0.27	-26.9	0.82	-29.7	0.67	-2.9	LOS
9 to 10	0.48	-38.8	1.69	-46.1	3.59	-7.4	Non-LOS (torso blockage)
3 to 9	0.43	-45.8	3.70	-53.5	2.98	-7.7	Non-LOS (torso blockage)
5 to 11	0.44*	-35.6	0.69	-53.8	3.75	-18.3	Non-LOS (neck/torso blockage)

TABLE 4
2.45GHz Measured on-body channel gain and body gain Between DBMBA locations Defined in Figure 6.
*route upwards and around neck

DBMBA locations	Shortest surface route between antennas (m)	Phantom Channel Gain (free space) (dB)	Standard Deviation	On-body channel gain (dB)	Standard Deviation	Body gain (dB)	Channel type (LOS = Line of Sight)
1 to 2	0.3	-40.1	0.85	-43.4	0.99	-3.32	Non-LOS (neck blockage)
3 to 4	0.08	-40.2	0.50	-37.0	1.13	3.18	LOS
5 to 6	0.09	-23.8	0.40	-23.6	2.23	0.22	LOS
5 to 7	0.18	-30.1	0.26	-27.6	2.05	2.48	LOS
5 to 8	0.27	-33.9	0.90	-33.2	1.66	0.62	LOS
9 to 10	0.48	-50.5	1.58	-55.6	3.30	-5.19	Non-LOS (torso blockage)
3 to 9	0.43	-47.3	1.59	-56.5	2.23	-9.19	Non-LOS (torso blockage)
5 to 11	0.44*	-40.8	0.70	-58.6	3.21	-17.8	Non-LOS (neck/torso blockage)

TABLE 5

5GHz Measured on-body channel gain and body gain Between DBMBA locations defined in Figure 6. *route upwards and around neck

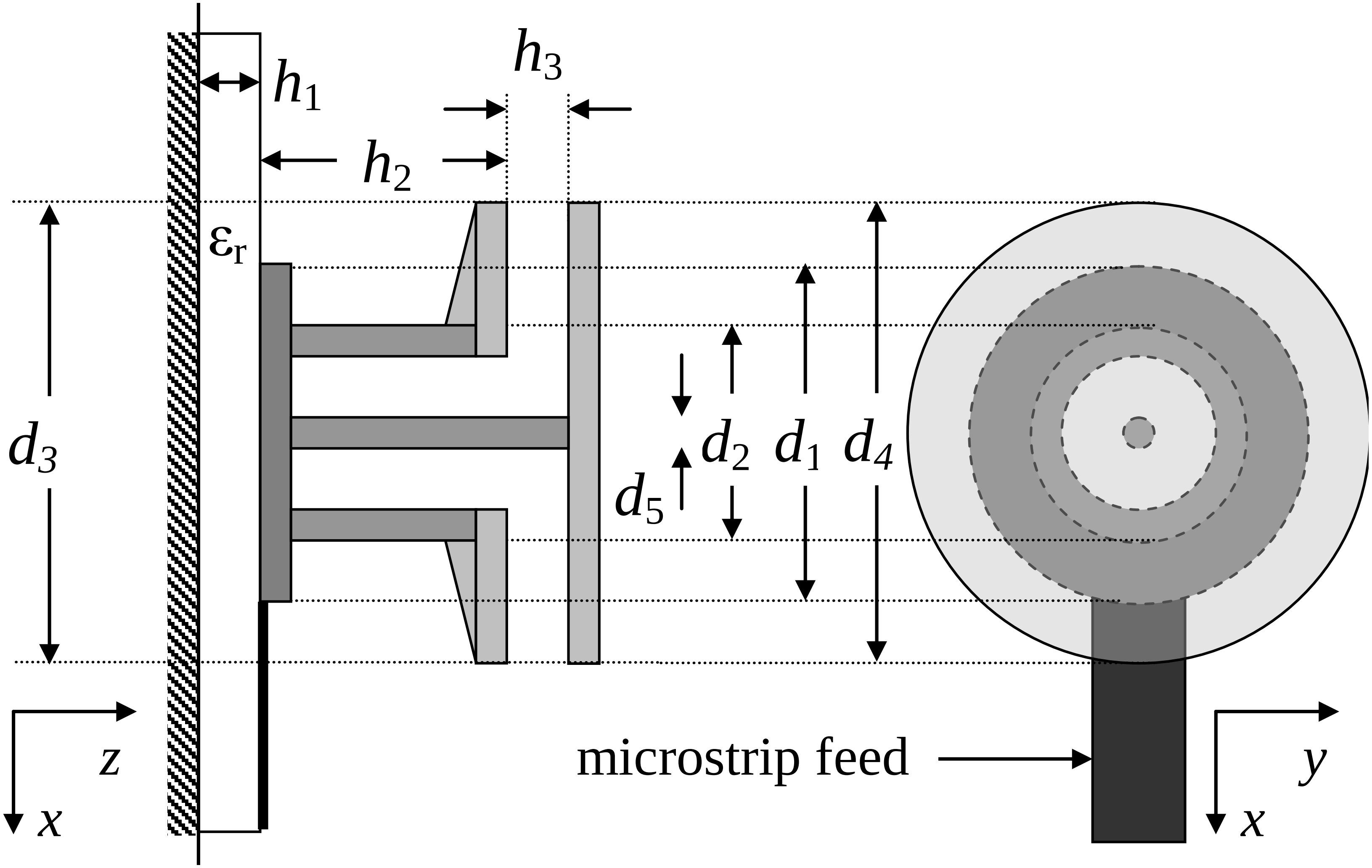

Fig.1. Cross section and plan of Dual Band Metallic Button Antenna, DBMBA.

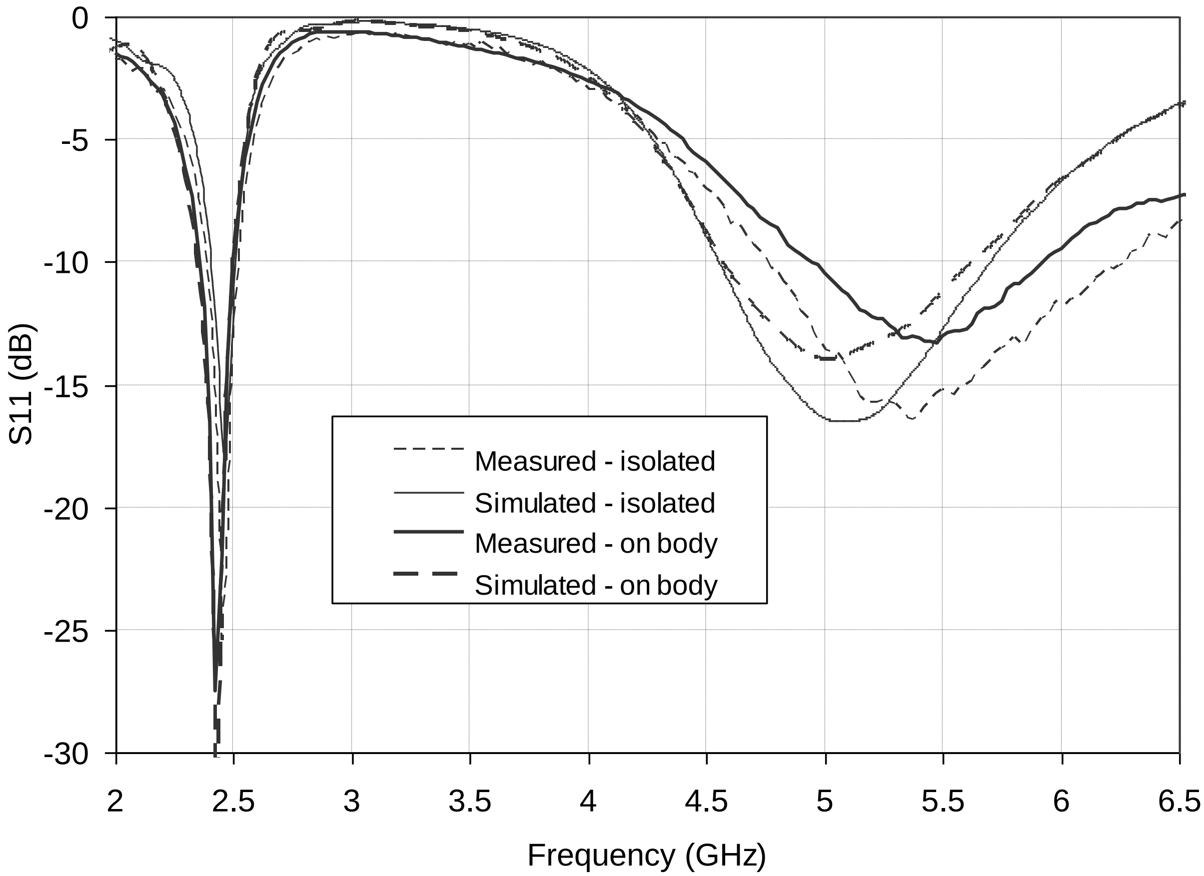

Fig.2. Measured and simulated S11 for Microstrip fed DBMBA on and off-body.

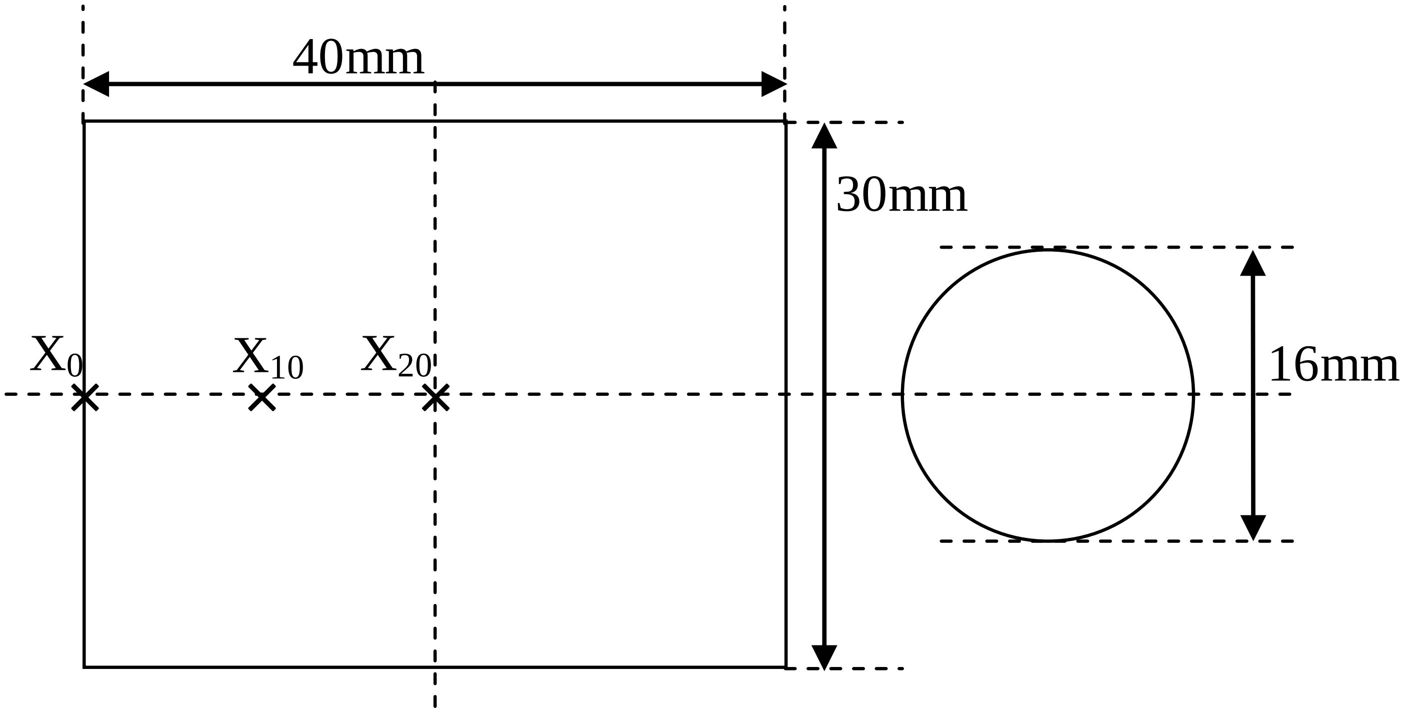

Figure 3. Reduced size ground plane with offset button positions X_0 to X_{20} indicated. Position X_{10} (10mm from edge) offers correct tuning. The circle on the right hand side shows the relative DBMBA size.

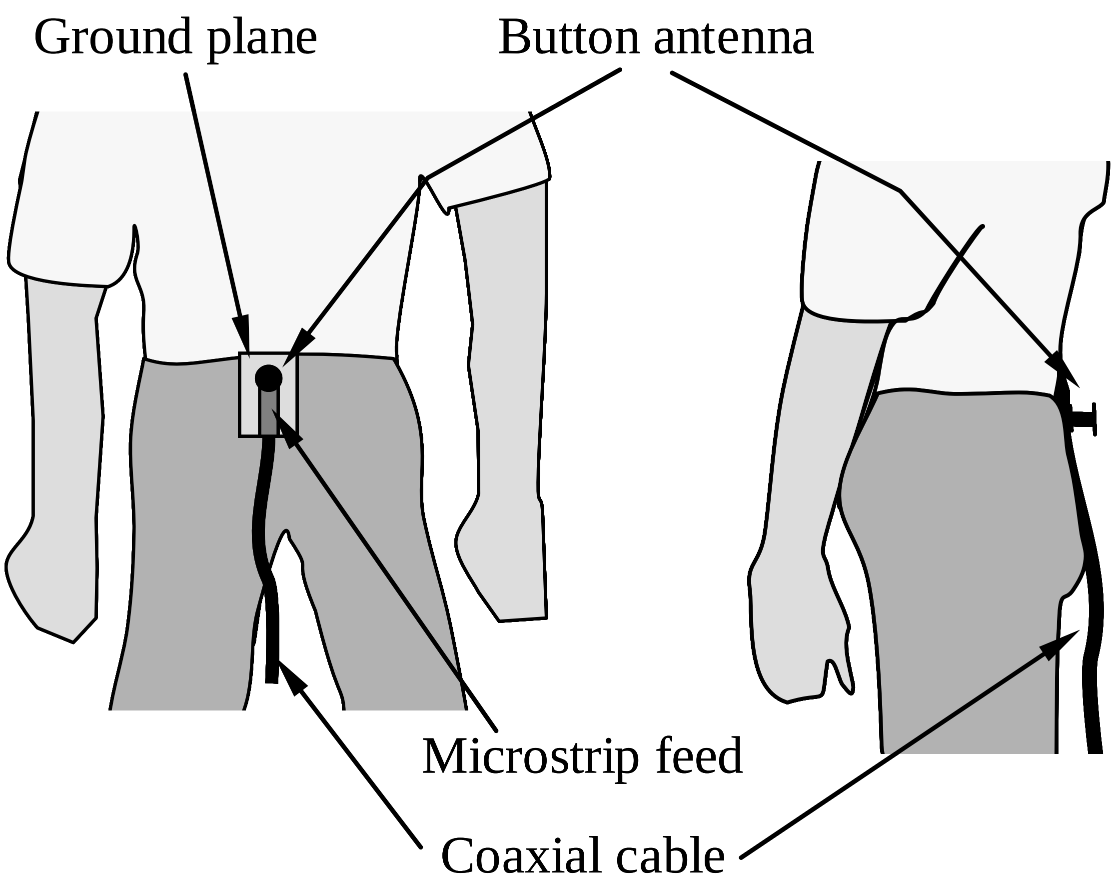

Fig.4. Mounting of microstrip fed DBMBA on human test subject, (antenna profile enlarged for clarity).

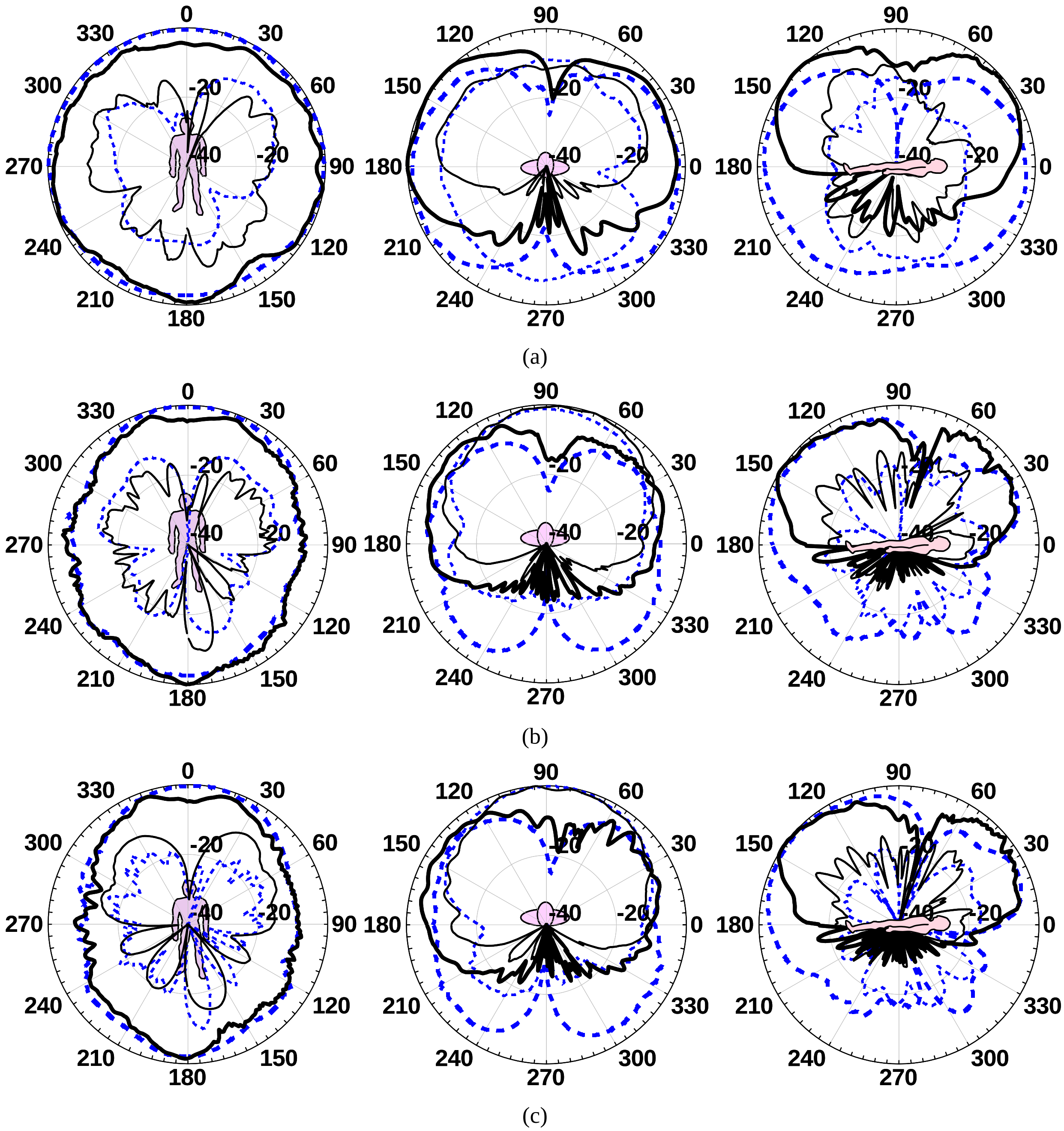

Fig.5. Microstrip fed DBMBA Radiation patterns. (a) 2.45GHz, (b) 5.2GHz, (c) 5.5GHz. LHS: *x*-*y* plane, Center: *y*-*z*, RHS: plane *x*-*z*. In all cases DBMBA is mounted as a front trouser button at waist height. Solid line shows on-body measurement and broken line represents isolated antenna. Heavy line: co-polarization, thin line: cross polarization.

Mode7

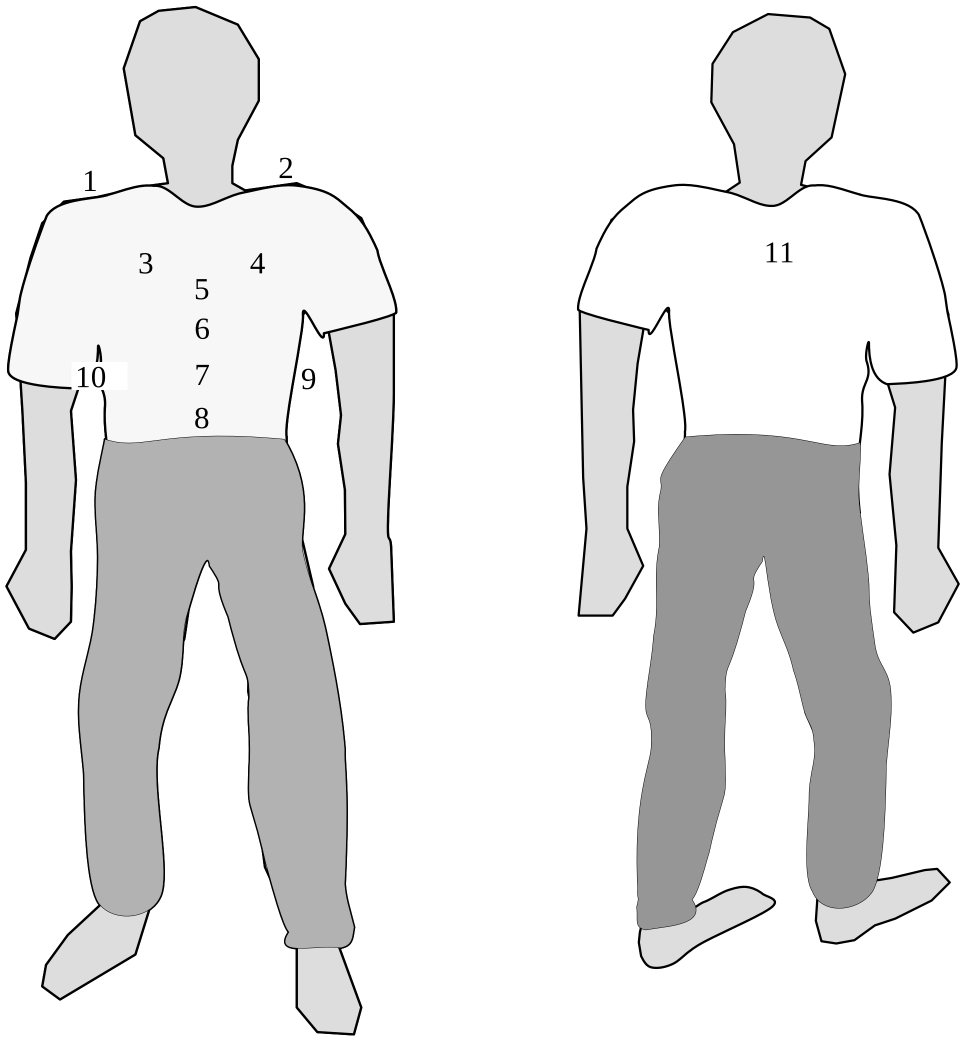

Fig.6. On body DBMBA locations for point to point transmission study.