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Diversity gain measurements for body-centric communication systems

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***Abstract-* In this paper, the implementation of diversity schemes for on-body communication systems at 2.4GHz, 5.8 GHz and 10GHz is investigated. In these systems both the transmitter and the receiver are placed on the body and at a distance that depends on the application in use. Monopole antennas on square ground planes are used as a transmitting element and two monopoles on a common ground plane as a two-branch receiver. Measurements have been carried out in an anechoic chamber in order to verify the scattering and fading effects of the body itself on the radio communication channel. The acquired data have been post-processed by resorting to different signal combining techniques, in order to evaluate the diversity performance. Measurement results in terms of diversity gain are shown for a number of typical on-body radio links, when different body postures are considered. Repeatability has been verified and proved for all considered radio links.**

***Index terms* –diversity, body area networks, on-body communication systems**

I. INTRODUCTION

On-body communications represent one of the most attractive research field of the latest years as resulting from the increased demand and diffusion of miniaturized electronic devices that can be worn or carried out by the user.

Preliminary reports about this manuscript appeared in [2]-[5]

Propagation models, parametric studies and performance measurements, suitable for on-body communication systems are being carried out [1] -[5] in order to provide simple rules for system designers. Recent new implementations apply to more complicated activities which the body is involved in and they require a larger quantity of data to be transferred with higher bit-rate. Military and sport equipments for communications between wearable transceivers and sensors give an example of this [6]. 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 separate antennas and properly combined. This process results in improved signal to noise ratio (SNR) and an increase in the signal reliability. At present, diversity is widely applied in receiving at base stations for mobile cellular systems and recent studies have been conducted on portable devices [7], where the multi-path effect is mostly determined by the environment 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 modules are placed on the same moving holder.

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In this work, an experimental investigation on the application of a diversity scheme in on-body high-rate communication systems is presented. Diversity scheme performances are evaluated in terms of the diversity gain and all measurements have been carried out at 2.45GHz, 5.8GHz (ISM frequency band) and 10GHz. Spatial diversity is investigated. The Cumulative Distribution Function (CDF) versus the relative power level has been calculated on collected transmitted power samples. These samples are combined through the Selection (SC), Equal Gain (EGC) and Maximum Ratio (MRC) combining techniques [7]-[8]. Comparisons with results shown in [3] are discussed.

II. EXPERIMENTAL SETUP

As noted above, in traditional mobile communication applications both the base station and the mobile antenna systems, whether or not in a diversity configuration, are always fixed or moving in the propagation environment, respectively. Similarly to traditional mobile communication systems where distinctions among indoor and outdoor, urban and rural propagation environments have been identified, a classification for body postures can be developed, depending on the activity. In addition to this and for each of the classified postures, the relative position of the transmitting and receiving antennas is relevant to the system performance, and it mainly depends on the application in use. According to previous considerations about the time-dependent propagation environment, the attention has been focused on some typical body postures that can be considered the most representative of a normal body activity. Some antenna placements have been identified, relatively to the application and the device in use, to estimate the performance improvement that diversity can provide. A number of different postures have been studied and roughly classified as sitting and standing postures. During measurements, free movements were allowed for some parts of the body, like leaning down, turning the trunk, walking, kneeling, and moving arms pretending to handle objects like in real situations. A wooden footstool has been used for sitting postures.

The antenna placements analysed in this work are shown in Fig. 1. They are intended to be used for devices like wireless earphones or visors in a helmet for the head position (pl. 1), music or video players for the head and the wrist positions (pl. 1,5), temperature sensors or step counters for the chest and the ankle positions (pl. 2, 3, 5), media players or mobile phones in a backpack for the back position (pl. 4). In this measurement set-up, the transmitting antenna was always mounted in the waist position (Tx).

Antennas used for measurements are monopoles on a copper ground plane. The transmitting one is mounted on a square 8cmx8cm ground plane while the two receiving monopoles are on a common rectangular ground plane and separated by a distance d.

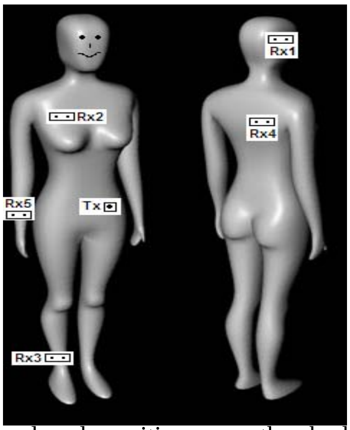

Fig. 1: Analysed positions on the body for the transmitting/receiving antenna system.

Although monopoles are apparently not suitable for integration on wearable systems, they are the most appropriate for this analysis because of their polarization features and omni-directional radiation pattern in the azimuth plane.

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 as in a two-branch diversity system. The RF output of the signal generator is connected to the transmitting antenna while the two receiving antennas are connected to the two ports of the VNA which is set up in a tuned received mode.

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Measurements have been carried out in a 6mx2.5mx3m fully anechoic chamber and in a typical office environment at the AAEL (Antenna and Applied Electromagnetic Lab) of the Electric and Electronic Department of the University of Birmingham. For the walking postures absorbers were removed to free a 50 cm wide path on the wooden floor. The measurement procedure consisted in collecting amplitude and phase samples for each channel that have been used to calculate the statistics of both channels and the diversity gain as shown in [3].

III. MEASUREMENT RESULTS AT 2.4GHz

A sample of measured results is presented in this section. Figures 2-4 show the received signals at the two antennas for three representative cases: back placement/sitting posture, wrist placement/standing posture, ankle posture/standing posture, respectively. Two receiving monopoles are at a distance of 5cm. For the back position one of the two signals is almost always stronger than the other and diversity is not useful. For the wrist position, both the signals have deep fading and sometimes it happens at different times, suggesting that diversity can be efficiently applied. In the ankle position, the two signals have deep fading at different times and they appear uncorrelated, suggesting that diversity can improve the system performance.

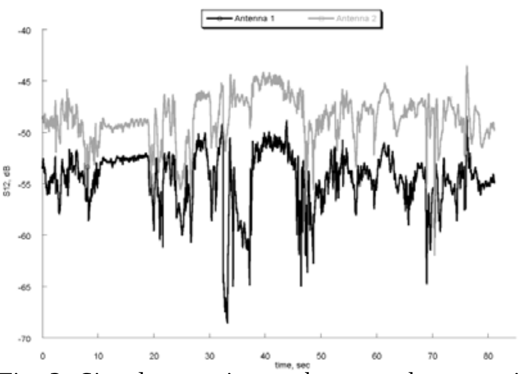

Fig. 2: Signal transmittance between the transmitting monopole and the receiving diversity system when the latter is mounted in the back position (RX4) for a sitting posture at 2.45GHz.

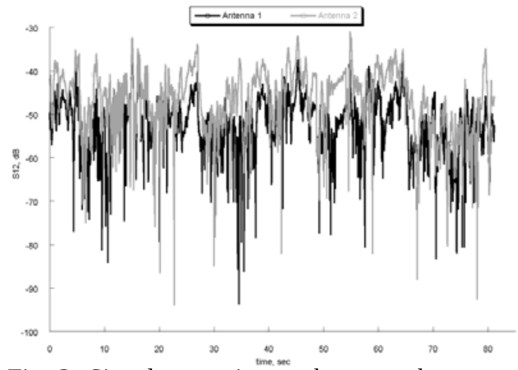

Fig. 3: Signal transmittance between the transmitting monopole and the receiving diversity system when the latter is mounted in the wrist position (RX5) for a standing posture at 2.45GHz.

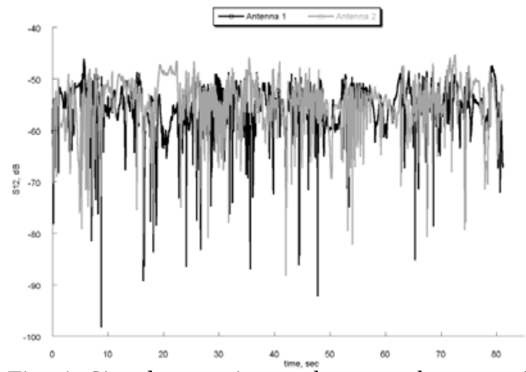

Fig. 4: Signal transmittance between the transmitting monopole and the receiving diversity system when the latter is mounted in the ankle position (RX3) for a standing posture at 2.45GHz.

In particular, Fig. 5 shows the Cumulative Distribution Function (CDF) versus the relative power level for the waist/ankle and the waist/wrist links, when the two receiving antennas are placed at a distance d=5cm. In sitting postures, the body is sat on the wooden footstool and only arms, trunk and head are moved pretending to handle objects while sitting on a desk.

Standing postures also include walking, knee bending and rotation. The CDF curve relevant to the power samples of the two channels are plotted in the left part of each figure (lines with white markers). These samples are collected and combined through the Selection (SC), Equal Gain (EGC) and Maximum Ratio (MRC) technique [5]. The CDF traces relevant to the combined signals are plotted in the same figure (lines with black markers).

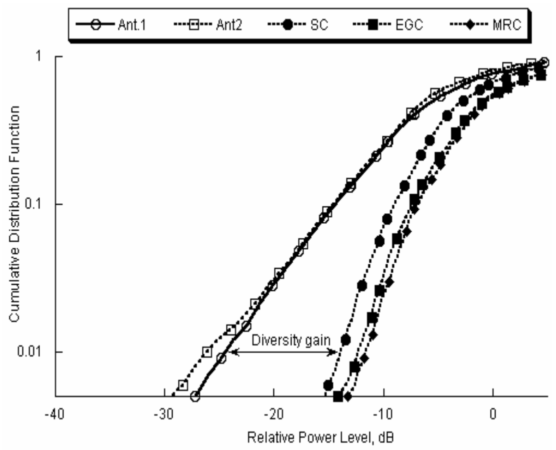

Fig. 5: Cumulative distribution function for the waist/ankle link in a sitting posture with receivers placed at a distance d=5cm at 2.45GHz.

For a given CDF value, the difference between the strongest channel trace and each one of the combined signals represents the Diversity Gain for the relative combining technique [5]. In the following we always consider diversity gain at 99% reliability level (CDF=0.01).

On the basis of an extensive measurement campaign on the above cited links (Fig. 1), it results that the performance of each diversity scheme is seriously affected by the two-branch antenna placement and relative distance d, as well as the body activity. Moreover, it appears that the signal combining does not improve the performances of line-of-sight links, like the waist/chest one, for any posture or distance between antennas. In these cases, the diversity gain for the SC scheme is close to zero since one of the two channels is characterized by a stronger signal level. For the same link, the diversity gain for EGC and MRC techniques does not increase more than 2-3 dB. Similarly, almost static links, like the waist/centre back link, and shadowed links, like the waist/ankle link in the sitting posture, show relative small values of diversity gain: around 3-4dB for the SC and 6-7dB for EG and MRC techniques. Better performance is obtained for non-line-of-sight links like the waist/wrist and the waist/head links, and diversity gain is between 8-9dB and 11-12dB for SC and EGC/MRC, respectively.

Tables I-II summarize some measured results when the receiving antennas are placed in other positions on the body for sitting and standing postures for a distance d equal to 5 cm. As can be seen from the table results, better diversity gain can be obtained for some postures and not for others. Performance of such a system depends on various factors and they increase in non-line of sight conditions between the transmitter and receiver, for a high mobility of the body, and for the presence of objects along the direct path between antennas.

Table 1: Diversity Gain (CDF=0.01) for some placements of the receiving antennas for standing postures, d=5cm

DG (dB) vs antenna placement	SC	EGC	MRC
Head	5.44	6.6	7.16
Chest	0.66	1.93	2.18
Back	3.84	5.21	5.77
Wrist	4.91	5.96	6.49
Ankle	9.76	10.5	11.29

Table 2: Diversity Gain (CDF=0.01) for some placements of the receiving antennas for sitting postures, d=5cm

DG (dB) vs antenna placement	SC	EGC	MRC
Head	8.5	8.74	9.8
Chest	0.1	0.57	1.07
Back	3.38	5.08	5.31
Wrist	3.22	3.71	4.34
Ankle	8.94	9.25	10.15

In order to check the reliability of the previous diversity gain results, the repeatability of the above described measurements has been tested. In the following only the results for the walking body posture are shown; the receiving antennas are at a distance of 6 cm and results are shown only for MRC diversity technique. For five radio links in Fig. 1, each measurement (walking activity) has been repeated 5 times. From each one of the 5x5 data results the dependence of the diversity gain on the signal correlation and the power unbalance has been analysed and it is plotted in Fig. 6 and Fig. 7. In the figures, the 5 measurements relevant to the same radio link are represented by the same marker .

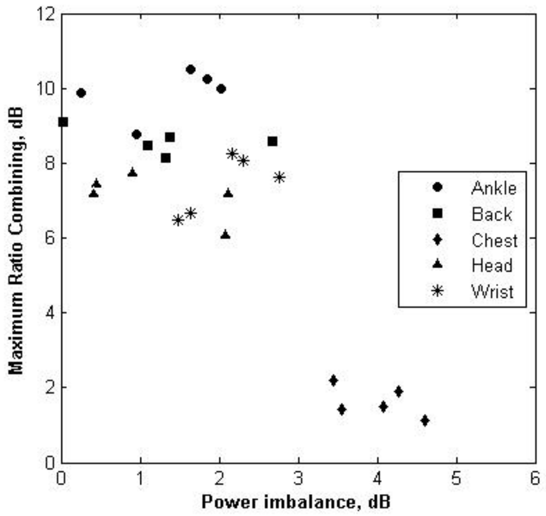

Fig. 6 Repeatability test for the Diversity Gain versus power unbalance.

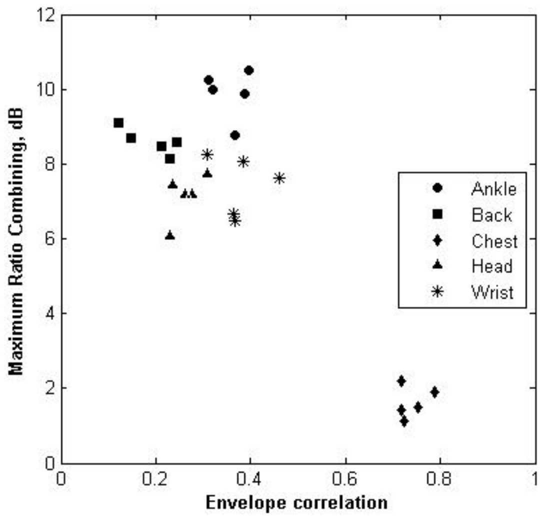

Fig. 7 Repeatability test for the Diversity Gain versus the envelope correlation coefficient

As it can be seen from the plots, data points corresponding to the same radio link are clustered, so confirming the repeatability of the performed measurements.

IV. MEASUREMENT RESULTS AT HIGHER FREQUENCIES

A similar setup and the corresponding measurement campaign has been conducted at different frequencies including two different orientation of the two branch receiving system and the analysis of demeaning. Demeaning of the data is usually used to remove the slow fading and extract the fast fading. Various demeaning window sizes were used for different channels to ensure that sufficient number of fast fading oscillations are present in the window and yet small enough to remove the slow variations caused by shadowing. It was observed that slow fading was correlated for both diversity branches. The data was demeaned and the slow and fast fading envelopes extracted. The correlation between the slow fading envelopes of the two diversity branch signals was higher than 0.7. This high correlation suggests that the slow fading has effectively no part in the diversity performance and should be removed, as is done for mobile communications. It is usually assumed that slow fading is multiplicative factor to the received signal envelope [9], i.e.

$$r(t) = m(t)M(t) \tag{1}$$

where r(t) is the received signal envelope, m(t) is the fast fading envelope, and M(t) is the local mean envelope representing the slow fading [6]:

$$M(t) = \frac{1}{2w}\int_{x-w}^{x+w} r(t)dt. \tag{2}$$

The length *2w* of the averaging window is considered as critical for the indoor mobile scenario. For on-body channels, it was observed that the choice of the window size does not affect the diversity gain and the envelope correlation between the diversity branches for some cases. It was noted that the diversity gain and correlation coefficients are insensitive to a certain range of window size and a noticeable change occurs outside this range. For this reason, different window sizes were selected for different channels within the range for each channel. The selection of the demeaning window size was done by carefully analyzing each data set and then looking for a proper window size that was chosen to be equal to 60 samples for the chest and head link and 50 samples for the wrist link. A second new aspect that has been considered in the analysis at higher frequencies with respect to [3] regards the orientation of the two branch receiving systems. Two cases were analyzed: in the first one the two antennas are vertically lined while in the second one they are horizontally lined with respect to the ground.

Table 3: Diversity Gain (CDF=0.01) for some placements of the receiving antennas for sitting postures, d=1,5cm and 2,5cm. Receiving antennas are horizontally lined, 5.8GHz.

DG (dB) vs antenna placement d=1.5cm	ρ	ΔP	SC	EGC	MRC
Head	0,439	0,63	8,4	9,2	10,0
Chest	0,257	2,29	4,4	5,3	5,7
Wrist	0,210	1,72	7,2	8,1	8,8
DG (dB) vs antenna placement d=2.5cm	ρ	ΔP	SC	EGC	MRC
Head	0,161	0,28	8,4	9,4	9,8
Chest	0,268	3,12	2,9	3,6	4,4
Wrist	0,338	2,99	7,0	8,0	8,6

Table 4: Diversity Gain (CDF=0.01) for some placements of the receiving antennas for sitting postures, d=1,5cm and 2,5cm. Receiving antennas are vertically lined, 5.8GHz.

DG (dB) vs antenna placement d=1.5cm	ρ	ΔP	SC	EGC	MRC
Head	0,442	0,86	7,1	7,9	8,2
Chest	0,548	0,91	3,0	4,4	4,8
Wrist	0,338	1,24	7,4	8,3	8,9
DG (dB) vs antenna placement d=2.5cm	ρ	ΔP	SC	EGC	MRC
Head	0,225	0,04	8,4	9,0	9,7
Chest	0,268	0,82	4,8	5,8	6,4
Wrist	0,269	0,13	6,6	7,9	8,4

Table 5: Diversity Gain (CDF=0.01) for some placements of the receiving antennas for sitting postures, d=1.5cm. Receiving antennas are horizontally lined, 10GHz.

DG (dB) vs antenna placement d=1.5cm	ρ	ΔP	SC	EGC	MRC
Head	0,032	0,17	8,3	9,4	9,9
Chest	0,137	2,31	3,8	4,9	5,5
Wrist	0,100	1,57	7,9	9,0	9,6

Table 6: Diversity Gain (CDF=0.01) for some placements of the receiving antennas for sitting postures, d=1.5cm. Receiving antennas are vertically lined, 10GHz.

DG (dB) vs antenna placement d=1.5cm	ρ	ΔP	SC	EGC	MRC
Head	0,022	0,25	7,6	8,6	9,3
Chest	0,011	0,17	5,6	6,7	7,2
Wrist	0,067	0,75	6,6	7,5	8,0

Data in the Tables 3-6 evidence that the diversity system has almost the same effect both at 2.4 GHz and at higher frequencies. Smaller values for the diversity gain are obtained when the receiving antennas are placed in positions where, due to the random activities of the body, the link channel is more static or the antennas are in line of sight. It follows that up to 10dB can be gained for the head position while the diversity gain is almost always less than 6dB when the antennas are placed in the middle of the chest. The effect of the receiving antennas orientation does not influence significantly the system performance and the different values obtained from the two set-up cannot be justified in this sense. More likely, just the body posture and its activities strongly affects the reachable values for diversity gain.

Correlation coefficients and power imbalance between branches are always less than 0.6 and 3dB, respectively, at 5.8 GHz and less than 0.15 and 2.5dB, respectively, at 10 GHz. These values clearly are in agreement with the high values of the diversity gain. The latest analysis at 5.8 GHz regards a repeatability test similar to the one conducted at 2.4 GHz. Five repeated measurements were carried out showing a maximum difference of 1.7dB in the diversity gain, 0.2 in the envelope correlation coefficient and 3 dB in the power imbalance. These results finally prove the reliability of the measurement campaign.

V. CONCLUSIONS

In this paper, a study on the feasibility of a diversity scheme at different frequencies in an on-body communication system has been carried out through experimental measurements. The diversity gain for the most relevant combination techniques and several positions of the receiving antennas on the body have been calculated and compared. Data demeaning has been applied and repeatability tests have been conducted to verify consistence of the measurement campaign. Measurement results show a general improvement in the signal reliability which suggests the applicability of a diversity scheme to body centric communication systems in the frequency range2.4-10GHz.

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