Effect of antenna type on the capacity of body-to-body capacity when using uniform power allocation

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***Abstract*—Body-area networks are led to target multimedia applications where high-data rate is involved. In this paper, the characterization of the measured body-to-body channels and the ergodic capacity with uniform power allocation is discussed when using multiple-input multiple-output (MIMO) PIFA and IFA antenna systems. This capacity is compared to the measured belt-head and belt-chest on-body channels using PIFA antennas in the same environment. It is shown that body channels reach less ergodic capacity than the equivalent Rayleigh channel because of the presence of a LOS component. The capacity is the same for the body-to-body case regardless of the antenna and the on-body channels reach better capacity values compared to these former.**

Keywords-component: Body area networks, body-to-body channels, on-body channels, MIMO antennas, channel capacity.

I. INTRODUCTION

Body area networks are becoming a new paradigm for wireless communications where the transmitter and the receiver are no longer on the conventional base station and the mobile terminal, respectively, but both carried on the human body. In the on-body network, the transmitter and the receiver are on the same body, while in the body-to-body case, they are on different bodies [1]-[4]. The in-body networks which are beyond the scope of this paper are the ones where either the transmitter or the receiver is within the body. Obviously, it implies that the structure of the devices should be low-profile, comfortable when held on the body and low power consuming such that the SAR is low. Many applications are intended for such devices, such as military, sports, entertainment, and patient monitoring systems, to cite just few. A broad range of future applications is expected provided that the technology will be in phase with the plans.

Future body-worn multimedia applications will certainly require high-data rate communications with a good signal quality. This goal is particularly challenging for systems that are power and complexity limited. One efficient mean to significantly increase the channel capacity is the use of multiple transmit and receive antennas (MIMO) [3], [6]. Early researches carried out by Foschini and Telatar [7], have predicted important spectral efficiencies for multiple antennas wireless channels in the presence of a rich scattering environment. These predictions have ignited the research towards the investigation of theoretical and practical aspects related to MIMO channels. It has been shown that, if the scattering environment is such rich that the MIMO matrix of channel gains has full rank and independent entries, then the capacity of the corresponding MIMO system scales linearly with min (M, N) relative to a system with a single transmit and a single receive antenna (SISO), with M being the number of transmit antennas and N the number of receive antennas.

In this paper, the channel capacity of the belt-belt and the belt-head body-to-body channels when using PIFA and IFA antennas are compared to the belt-head and belt-chest on-body channels when using the same PIFA antennas in the same indoor environment. Slow and fast fading statistical parameters, namely the path loss, the shadowing deviation and the Ricean K-factor are used in order to characterize the body-to-body channel. In [12, 13] the system performance when adopting the diversity at the reception has been investigated but according to the authors knowledge, no work has been reported comparing the capacity of the body-to-body channels with on-body channels when using MIMO antennas.
The measurements have been carried out in the 2.45 GHz ISM band at the University of Birmingham, using a MIMO channel measurement system.

II. MEASUREMENT AND CHANNEL CHARACTERIZATION

The measurements were performed in an indoor environment which was a 7.5 m × 9 m sized laboratory containing equipment, tables, and computers thus providing a rich multipath propagation environment. In the body-to-body measurements, an array of either microstrip-fed planar inverted-F (PIFA) or printed-IFA antennas have been placed on one human body, while the same type of antennas have been placed on a different body. The antennas in the array, as shown

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in Fig. 1, were 10mm-spaced with a radiating plate of 1-mm thickness, 3-mm distance between the short-circuit pin and the feeding pin and 0.8-mm thickness for the FR4 substrate The ground plane size was the same as the substrate size, which was 45 mm × 40 mm , which is believed to be small enough to fit into comfortable body-worn sensor devices [12,13]. Once mounted on the body, these antennas exhibit a return loss of less than 10 dB, a mutual coupling of -12.5 dB and a low detuning. The printed-IFA diversity antenna array was designed such that the substrate size was 40 mm ×40 mm and the ground plane size was 30 mm ×40 mm. In each case, the length of the longer arm of the inverted-F is 22 mm and the length of the shorter arm is 3 mm. The mutual coupling between the IFAs was -16 dB which is believed to be a low value for body applications [1]. Different configurations were used for the printed-IFA at the transmitter and the receiver as shown in Figure 2 such as the shorter arm is in the upper side on the transmitter and in the lower side for the receiver.

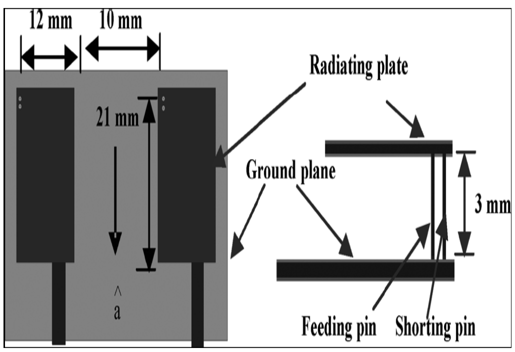
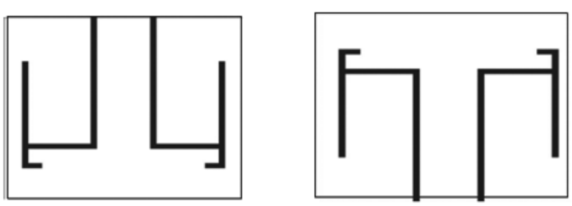


Figure .1 Configuration of the PIFA antenna used in the body measurements



a) On the receiver b) On the transmitter

Figure. 2 Configuration of the IFA antenna used in the body measurements

placed at the belt position at the left side of the first body, while the receiving array was placed at the left side of the belt position and at the right side of the head, respectively, thus forming the belt-belt and belt-head body-to-body channels. The two transmitting antennas were connected to a signal generator through an RF switch while the two receiving antennas on the other body were connected to the two ports of a HP8753ES vector network analyzer (VNA) calibrated in tuned receive mode. In the calibration preprocessing, the total power delivered to the transmitting antenna has been normalized to 0 dBm after connecting the signal generator to each port of the VNA through the same cables used afterwards in the

TABLE I. AVERAGE PATH LOSS, SHADOWING AND K VALUES FOR BODY-TO-BODY CHANNELS

Link	***Sub.***	***Path Loss (dB)***		***Shadow***		***K- Factor***	
		PIFA	***IFA***	***PIFA***	***IFA***	***PIFA***	***IFA***
Belt-head	h_{11}	58.12	72.38	4.41	4.70	0.38	0.41
	h_{12}	58.11	72.39	4.42	4.66	0.37	0.39
	h_{21}	57.84	71.73	5.02	4.52	0.63	0.73
	h_{22}	57.84	71.74	5.02	4.54	0.63	0.70
Belt-belt	h_{11}	59.34	68.01	6.03	6.78	0.48	0.70
	h_{12}	59.35	68	6.04	6.78	0.46	0.63
	h_{21}	59.57	67.90	6.41	5.64	0.47	0.80
	h_{22}	59.57	67.93	6.40	5.68	0.48	0.92

TABLE II. AVERAGE PATH LOSS, SHADOWING AND K VALUES FOR ON-BODY CHANNELS

Link	***Sub.***	***K-factor***	***path loss (dB)***	***Shadow***
belt-head	h11	6.38	52.65	0.61
	h12	7.33	55.81	0.919
	h21	1.052	62.10	1.467
	h22	0.82	63.43	1.019
belt-chest	h11	10.68	36.67	0.75
	h12	15.02	40.48	0.93
	h21	7.688	38.14	1.417
	h22	12.30	43.25	1.767

measurements. In order to ensure the synchronization of the two equipment, the 10 MHz reference output signal from the signal generator signal was fed to the VNA. The magnitude and the phase of the S21 parameter were measured between each pair of transmit-receive antenna. A total of ten sweeps were performed for ten different types of movements chosen as randomly as possible to reproduce naturalistic body movements. It is worthy to note here that, because of the random body movements performed during the sweeps and the naturalistic folding of the different body parts, the creeping waves may be collected. In some cases, the line of sight component may propagate in the form of these creeping waves and be attenuated. Thus the corresponding *K* factor will be reduced. In this paper the impact of these waves has not been studied. For further details on the measurement procedures, we refer the reader to [12,13]. Using these measurements, the channel is then characterized by separating the large and small-scale fading components. Usually, the long-term fading is removed from each spatial subchannel component by demeaning the signal received at this subchannel. The long-term fading envelope which results from the shadowing effect, represents the local average power of the received signal and is superimposed on the short-term fading corresponding to the contribution of the multipath components in the received signal. It is usually assumed that long-term fading is a multiplicative factor to the received signal envelope:

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

where x(t) is the received signal envelope, r(t) is the short-term fading envelope, and M(t) is the long-term fading

$$M(t) = \frac{1}{2w} \int_{t-w}^{t+w} x(\tau)\, d\tau \tag{2}$$

2w is the local averaging sliding window size. The window was selected such that there were sufficient short-term fading oscillations (approx. 4 to 6) inside the window and yet small enough compared to the time scale of the long-term variation.

The window is a sliding window so that at each instant, the received signal envelope is normalized to its local average value, and hence the long-term variation is removed to achieve the short-term fading envelope r(t). The choice of the window size has been studied in our previous works and is beyond the scope of this paper. But most importantly, our previous works have shown that the fast fading component follows a Rician distribution, while the slow fading is log-normal-distributed [3,9,12,13]. Table 1 shows the statistical parameters of the belt-head and belt-belt body-to-body channels while Table 2 shows the same parameters for the belt-head and the belt-chest on-body channels when using PIFA antennas. Denoting H the $N\times M$ MIMO antenna system such that $\mathbf{H}=\begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix}$ where h_{ij} is the spatial subchannel between the i^{th} receive antenna and the j^{th} transmit antenna, it is shown from Table 2 that the on-body subchannels for both belt-chest and belt-head channels do not exhibit the same propagation characteristics.

For the belt-head on-body channel, h_{11} and h_{12} exhibit lower mean path loss and higher K values than the subchannels h_{21} and h_{22}, while less disparity is noted for the case of belt-chest channel. The belt-chest channel experiences low path loss and high Rician K-factor, thus tending to a strong Rice case. The belt-head channel, on the other hand, exhibits higher path loss and lower K values particularly with the subchannels h_{11} and h_{12}, which represents a Rice case tending to a Rayleigh channel. For the case of body-to-body channels using either PIFA or IFA antennas as shown in Table 1, the different spatial subchannels exhibit the same statistical parameters for a given body channel. The belt-head and the belt-belt channels using PIFA antennas show statistical parameters that are comparable to the belt-head on-body channel. The K-factor for all subchannels is less than 1 which shows that the direct path is weak compared to the on-body case. On the other hand, it is seen that the body-to-body channels are suffering from an important shadowing effect. This comes from the mutual effect of the presence of two bodies which parts contribute in blocking the signal. Comparing the body-to-body channels when using either printed-IFA or PIFA antennas, it is seen that when using IFA antennas, the channels are experiencing higher path loss compared to PIFA antennas while the shadowing and the K-factors remain comparable. We do believe that, in addition to the configuration shown in Fig.2 which has been shown to be viable in on-body channels, a study of the different configurations of printed IFA antennas should be undertaken. The statistical parameters of the belt-head and the belt-belt body-to-body channels are close when using the PIFA antennas except that the shadowing value is higher in the belt-belt channel. For the printed-IFA antennas, the path loss is less in the belt-belt channel than in the belt-head but the shadowing is still higher. The shadowing values are higher because of the more important effect of the floor at the receiver in the belt-belt channel and the higher path loss may be due to the polarization loss resulting from the difference in the direction of the antennas in the transmitter and the receiver at the belt positions.

III. SIMULATION RESULTS

The achievable equal power capacity using the on-body and the body-to-body measured channels are investigated and compared for the 2×2 MIMO channels taking the 2×2 Rayleigh channel as a reference.

At first, the MIMO channels for the Rayleigh, on-body and body-to-body cases are normalized such that to maintain the Frobenius norm of the channels at M×N. This corresponds to a tight power control process where the effect of path loss is alleviated and only the channel matrix structure effect is considered. Figure 3 depicts the ergodic capacity of the on-body and the body-to-body channels when using equal power allocation scheme and PIFA antennas and compares them to the ideal Rayleigh channel. The SNR is varied in the expression of the capacities after the channel normalization. It is seen that, at low SNR, the average achievable capacities for the belt-head and the belt-belt body-to-body channels are similar to Rayleigh case, while the on-body channels yield better capacity values.

This may be due to the low subchannel correlation in the on-body channels compared to body-to-body channels. The on-body belt-head and belt-chest channels give better capacity values than the rich scattering Rayleigh channel because of the high SNR value at the receiver resulting from the presence of a strong LOS component. Thus the effect of the received SNR is predominant at this range. When the SNR increases, Rayleigh channel is providing the highest capacity value , while the body-to-body channel are showing the highest capacity penalty. As previously mentioned, the matrix order is the most influencing factor at this range, therefore the on-body channels are still exhibiting better capacity values because of their low correlation of compared to the body-to-body channels.

Figure 4 represents the achievable capacity of the body-to-body channels when using different types of antennas at the transmission and the reception sides, namely PIFA and printed-IFA antennas. It is seen that when normalizing the MIMO channel such that the effect of power difference is removed , the belt-head and the belt-belt body-to-body channels achieve the same ergodic capacity regardless of the chosen antenna.

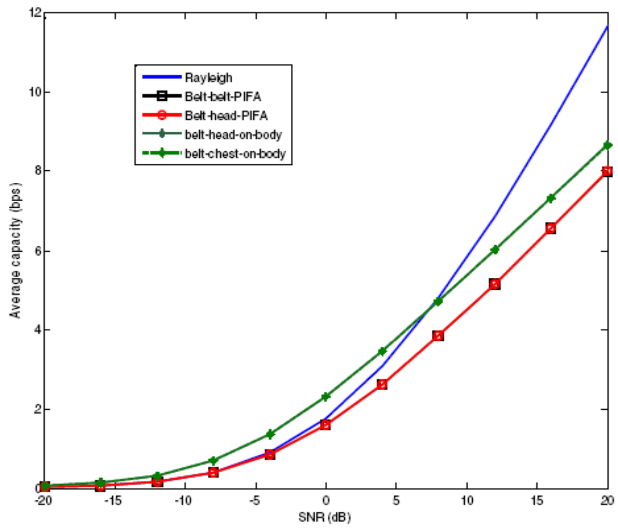


Figure 3. Comparison of the average capacity of the body-to-body and the on- body channels

Let us study the same ergodic capacity when the normalization is performed such that each channel realization is divided by the average Frobenius norm of all the realizations, thus encompassing the effect of path loss as well as the MIMO matrix structure.

Fig. 5 compares the ergodic capacity when adopting this normalization denoted normalization 2 in the figure to the one which fixes the square value of the Frobenius norm of each realization at $M \times N$. It is first seen from this figure that the average capacity with a given normalization scheme is the same for the belt-belt and the belt-head body-to-body channels. Furthermore, the ergodic capacity of a given channel with a given normalization is independent of the antenna type used in the arrays. However, when the path loss is considered, the achievable capacity loss is approximately 2.3 bps at an SNR value of 20 dB.

IV. Conclusion

In this paper, the ergodic capacity variation when using PIFA and printed-IFA antenna arrays in a MIMO body-to-body channel is studied and compared to the on-body channel using PIFA antennas. Two channels are of concern in the body-to-body case, namely the belt-belt and the belt-head channels while the belt-head and belt-chest are studied for the on-body case. It is shown that, because of the presence of a LOS component, all the body channels are exhibiting a capacity penalty as compared to Rayleigh channel.

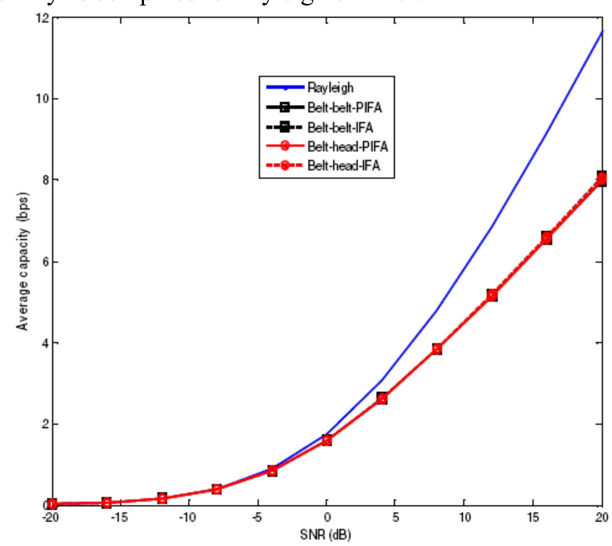


Figure 4. Average capacity of the body-to-body channels with different antennas

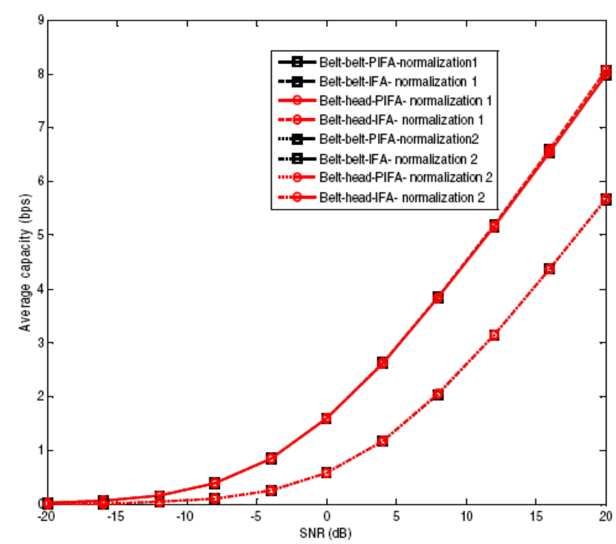


Figure 5. Average capacity of the body-to-body channels with different antennas with path loss effect

The achievable capacity with uniform power allocation is the same for the body-to-body case regardless of the antenna. The on-body channels reach better capacity values compared to the body-to-body channels with PIFA antennas. A capacity loss is noted when considering the effect of power difference by adopting the second scheme of channel normalization.

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