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TRANSMIT AND RECEIVE DIVERSITY IN BODY-CENTRIC WIRELESS COMMUNICATIONS

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Abstract

Two antenna diversity schemes are evaluated for use with the 2.45 GHz wireless off-body communication between a receiver worn at the ear and a stationary transmitter. A receive diversity scheme is compared to a transmit diversity scheme in an indoor environment. It is found that the two diversity schemes can provide the same improvement of the channel fading. Therefore the transmit diversity scheme may be a viable option for systems such as Hearing Instruments (HI) that are subjected to strict space requirements at the receiver end.

Keywords: BAN, Diversity, Diversity Gain, Motes, Off-body, Receive diversity, Transmit diversity.

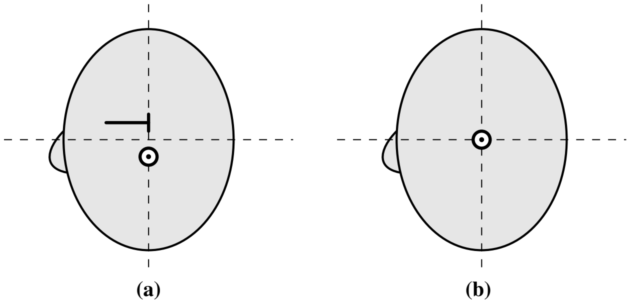

Figure 1: Configuration of the monopole antennas used for the receive diversity scheme (a) and the transmit diversity scheme (b).

1 Introduction

Body-Centric Wireless communications at 2.45 GHz have become an important research topic in recent years. The possibility to provide many different tasks like mobile conversations, remote control, medical, or military applications by the use of wireless technology have attracted the interest of several companies. The Hearing Instrument (HI) sector has also applied this technology to its applications with the objective to get improvements of the quality of life for hearing impaired people, e.g., the possibility to stream an audio signal from stationary or mobiles transmitters directly to HIs. Many studies of on-body communications have been carried out in relation to diversity schemes, e.g. [1–7]. A general improvement in the signal reliability in terms of on-body Diversity Gain [3,4] and channel performance [4] is reported. A statistical analysis is performed in [5–7]. Off-body communications also is a topic of research that has been investigated intensively in recent years, e.g. [8–12]. Some works employ a spatial reception diversity scheme to obtain an improvement in the received signal, such as [10–12]. It is reported that the results are heavily influenced by Line of Sight (LOS) and Non Line of Sight (NLOS) conditions [8, 10]. Space diversity is the most used scheme in body-centric communications and its principle is the use of more than one antenna in reception, transmission or on both sides, being in this last case a Multiple input multiple output (MIMO) system. Space reception diversity (RD) is a widely used scheme in body-centric communications. The combining techniques: Selection Combining (SC), equal gain combining (EGC) and maximal ration combining (MRC) [2, 4–6, 8, 10, 12] are used to improve the quality of the received signal. These techniques are based on the combination of uncorrelated branches to reduce channel fading. Space transmit diversity (TD) related with off-body wireless communications is much less used due to the increased complexity. Space-time codes should be used in order to obtain different branches in reception and combine them correctly to avoid fading and obtain a high signal strength [12]. However, a TD scheme that provides comparable performance to a RD scheme would be an optimal solution for systems with high space limitations at the reception part. An example is HIs, where it may not be practically feasible to include two uncorrelated antennas within the small package. In this study we present an off-body communication link based on a TD scheme. The TD scheme is compared to the widely studied RD scheme. Our TD scheme consists of two antennas as the stationary transmitter and one receiving antenna worn at the ear. The system is located in an indoor environment with high multipath conditions. The measurement results are obtained by the use of ZigBee wireless modules operating at 2.45 GHz. The diversity gains are found from post-processing the data and the results are presented in order to make a thorough comparison between the performance of the RD and TD scheme. Section 2 covers the measurement campaign in which RD and TD scheme are described as well as the measurement scenario. Section 3 is related with data analysis and combining techniques. Section 4 presents and discusses the obtained results. The last section of this paper is the conclusion in Section 5.

2 Measurement Campaign

All of the measurements in this study were carried out at 2.45 GHz by the use of the commercially available wireless ZigBee modules XM2110 IRIS from Crossbow. IRIS motes are made up by the Atmel RF230 (AT86RF230), IEEE 802.15.4 compliant, ZigBee ready radio frequency transceiver integrated with an Atmega1281 micro-controller, a MMCX connector in which an external antenna is attached and a 512 KB flash memory. Due to its small size (57 mm × 32 mm × 25 mm) it is easily used in Body Area Networks (BAN) experiments. The MIB520 mote interface board was used to connect the motes to a laptop. MIB520 provides a serial/USB interface for both data communication and programming procedures. The motes were used to obtain the Received Signal Strength Indicator (RSSI) which is a measurement of the power present in a received radio signal. The value can be directly read from the AT86RF230 Radio. The RSSI obtained value should be correctly calibrated and converted to relate it with the received power that is used in this study. A 50 ms sampling time was used. This sampling time is sufficient to obtain the instantaneous levels of the normalized fast fading signals necessary for the characterization of the channel. In order to evaluate the signal correlation between the two branches of both the transmit and the receive diversity schemes, it is necessary to obtain time-synchronized measurements of the signal gain of the two branches. For the purpose of this work, the transmitter is considered to be the stationary device, and the receiver is considered to be the mobile device. However, since $|S_{21}| = |S_{12}|$ the data logging can in practice be done at either end of the wireless channel. Therefore, the RSSI was in all cases logged by the laptop computer at the off-body base-station to simplify the data-logging procedure, and thus the receiving antenna at the ear was in fact transmitting, while the stationary transmit antenna was in fact receiving. This has no impact on the result and therefore the mobile antenna at the ear will be referred to as the receiver, while the stationary antenna will be referred to as the transmitter. The measurements were obtained by the use of monopole antennas at both the transmitter and the receiver.

2.1 Receive Diversity Scheme

For the RD scheme the transmit antenna is placed at a table next to the laptop PC, while the receive antennas are located at the ear of a person, defining an off-body communication link. The two receive antennas were oriented so that they are mutually orthogonal in order to reduce the signal correlation as indicated in Figure 1a. One antenna was oriented normal to the surface of the head while the other was oriented tangential to the surface of the head. The receive antennas are connected to separate IRIS motes programmed with different node IDs. The transmit antenna is connected to a IRIS mote that is programmed to communicate with both IDs such that the two channels can be distinguished. Both reception antenna and transmitters are paired with a group ID such they only receive package from motes programmed with the same group ID in order to avoid interferences from other communications of the environment. Thus, for the reception scheme were used:

- Three XM2110 IRIS 2.45 GHz.
- One MIB520CB mote interface board.

2.2 Transmit Diversity Scheme

For the TD scheme the transmit antennas are placed at a table next to the laptop PC, while the receive antenna is located at the ear of a person. The receive antenna was a monopole antenna that is oriented normal to the surface of the head as indicated in Figure 1b. The two transmit antennas are oriented such that they are mutually orthogonal in order to reduce signal correlation. The two IRIS motes that are connected to the transmit antennas were programmed with different mote IDs. The mote that is connected to the receive antenna is programmed to communicate with both IDs, such that the two signal branches can be distinguished. Again all motes are programmed with the same group ID in order to avoid interferences. The equipment used for the transmit scheme was:

- Three XM2110 IRIS 2.45 GHz.
- Two MIB520CB mote interface boards.

2.3 Measurement Scenario

The measurements were done in an office environment. This office is an open room by one side and is closed by the other with three windows, it contains a number of PC, chairs, desk and some electronic devices. The test person was positioned two meters away from the stationary antenna(s). The measurements were divided in three groups, LOS, NLOS and a combination of LOS and NLOS, for the three cases the person was not static, some random movements were done during the measurements. For LOS conditions, the user is placed such that the side of the head where the antenna(s) is mounted is directly facing the stationaty antenna(s), with no obstacles between them. For NLOS conditions, the user was placed in the opposite position as for LOS so the head is positioned between the antennas. For the NLOS/LOS measurements the user is placed head directly facing the stationary antenna(s) and some movements are done in order to combine LOS and NLOS situations.

3 Data Processing

The data processing method in this study is based on the three well-known signal combining techniques:

- Selection combining (SC)
- Equal gain combining (EGC)
- Maximal ration combining (MRC)

The same data processing procedures are applied for both the transmit and the receive diversity schemes, in order to compare the performance of the two schemes as it is done in [13]. As shown in [11] the expressions used to obtain the combining techniques are as follow:

$$SC(t) \; = \; MAX(r_1(t) \; , \; r_2(t)) \tag{1}$$

$$EGC(t) \; = \; \frac{r_1(t) \; + \; r_2(t)}{\sqrt{2}} \tag{2}$$

$$MRC(t) \; = \; \sqrt{r_1^2(t) \; + \; r_2^2(t)}\,, \tag{3}$$

where $r_1(t)$ and $r_2(t)$ are the envelopes of the two signals. In SC the highest quality samples from all branches are taken by comparison between the available received signals candidates. In EGC all branches are weighted by the same factor and added coherently. The most interesting combining algorithm however, is the MRC due to its better results. In MRC, branches with higher quality are amplified while weak branches are attenuated. In this algorithm all branches are weighted by a proportional factor. The two branches should have the same average power level and noise power mean to achieve better results once the combining is applied. The Diversity Gain (DG) is defined as the improvement of the signal level from the combined signals relative to the best single branch value. It is calculated at some outage probability level, which is commonly chosen to be 1 %. It this work the DG is compared at the 0.1 %, 1 % and 10 % outage probability levels. The envelope correlation coefficient (ρ_e) was also part of this study, as is introduced in [9, 13], the ρ_e follows the next expression:

$$\rho_\mathrm{e} = \frac{\Sigma_{i=1}^{N}\,[r_{\mathrm{i}1}(t) - \bar{r}_1(t)]\,[r_{\mathrm{i}2}(t) - \bar{r}_2(t)]}{\sqrt{\Sigma\,[r_{\mathrm{i}1}(t) - \bar{r}_1(t)]^2}\,\sqrt{\Sigma\,[r_{\mathrm{i}2}(t) - \bar{r}_2(t)]^2}}\,, \tag{4}$$

where $r_{i1}(t)$, $r_{i2}(t)$ represents the instantaneous levels of the normalized fast fading signals for the two receivers and $r_{i1}(t)$ and $r_{i2}(t)$ are their respective means. The envelope correlation coefficient gives a measure of how independent are the received branches, in order to obtain a significant improvement in DG, ρ_e should be less than 0.7, the lower ρ_e the higher DG is achieved. The combined signal obtained from the combining techniques were processed to obtain the Cumulative Distribution Function (CDF) for visual comparison. The DG and the envelope correlation coefficient (ρ_e) are the parameters used to compare the schemes in this work. They were selected in order the show a clear comparison between the results.

Table 1: Envelope correlation coefficient (ρ_e) for the received branches.

	TD (dB) $\rho_\mathrm{e}(R1, R2)$	RD (dB) $\rho_\mathrm{e}(R1, R2)$
LOS	0.38	0.83
NLOS	0.12	0.05
NLOS / LOS	0.049	−0.03

4 Results and Discussion

A comparison between the transmit and receive schemes is presented in this section. Each of the schemes are compared to the raw data such that the signal improvement from the schemes can be identified. Next, the two schemes will be compared directly. The envelope correlation coefficient for the received branches is listed for both schemes in Table 1.

Table 2: The obtained MRC diversity gain at different outage probability levels.

	LOS		NLOS		NLOS/LOS	
	TD (dB)	RD (dB)	TD (dB)	RD (dB)	TD (dB)	RD (dB)
0.1%	10	5	12	4.1	3	9
1%	6.1	2.8	7.26	7.6	9.8	8.1
10%	2.9	3.75	2.8	2.8	4.3	3

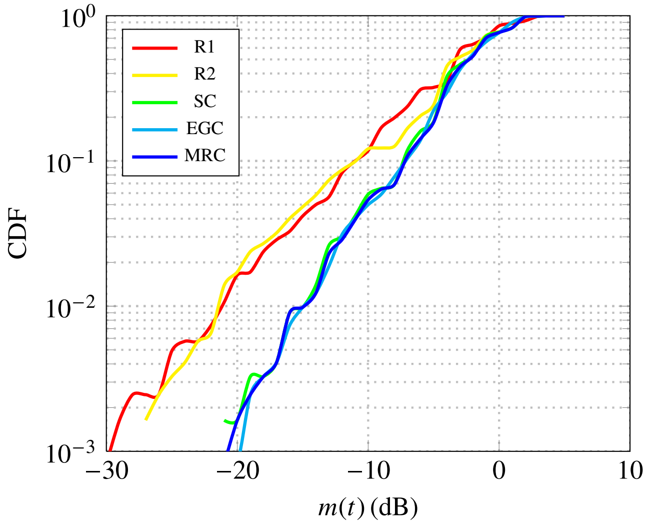

Figure 2: CDF of the raw branches and the diversity combined signals for the TD scheme under LOS conditions

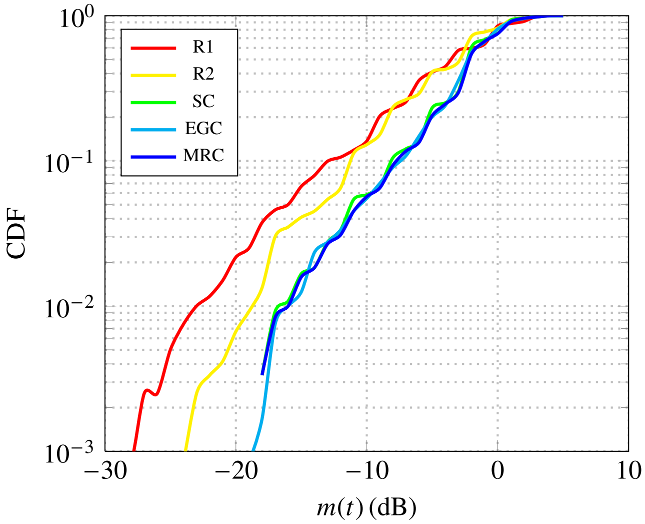

Figure 3: CDF of the raw branches and the diversity combined signals for the RD scheme under LOS conditions.

The envelope correlation coefficient is quite similar for the two branches, and varies primarily with the environment conditions. The envelope correlation is seen to quite low for both schemes, except for the LOS case. The CDF of the TD and the RD schemes are shown in Figures 2 and 3, respectively. It is observed that the two schemes offer a similar improvement of the combined signals over the raw branches, since the signals were relatively uncorrelated. It is also observed that the three combining techniques offer very similar gains.
The MRC diversity gain of the two schemes is calculated and listed in Table 2. It is seen that a significant DG of several dBs can be obtained, especially at low outage probabilities. At the 1 % outage probability level the diversity gains are at least 7 dB for both schemes under NLOS and mixed conditions. The DG is slightly lower in the LOS case, especially for the RD scheme. This is due to the relatively strong branch 2, as seen in Figure 3. The CDFs of the MRC combined signals are shown for each of the diversity schemes in Figure 4. Both LOS, NLOS and mixed conditions are displayed. It is seen that the characteristics of the CDFs are very similar. Therefore we can conclude that the TD and RD schemes can offer a similar improvement of the channel fading under both LOS and NLOS conditions. In relation with diversity combining techniques, as expected, MRC and EGC are the ones that provides better results. In some case SC was the technique with the best performance. In general, the TD scheme provides at least similar performance than RD. Even when TD does not provide better DG than RD, it still provides an improvement in relation with single received signals. This means that it can be taken in account as an attractive scheme for systems in which there exists high space restrictions in the receiver end as it is in HIs.

5 Conclusion

Two different diversity schemes were compared in order to demonstrate that a transmit diversity scheme can be used as an alternative to the reception one for off-body links in which reception devices have strong space restrictions. Diversity gains and envelope correlation coefficients were calculated form the measurement results in order to compare the

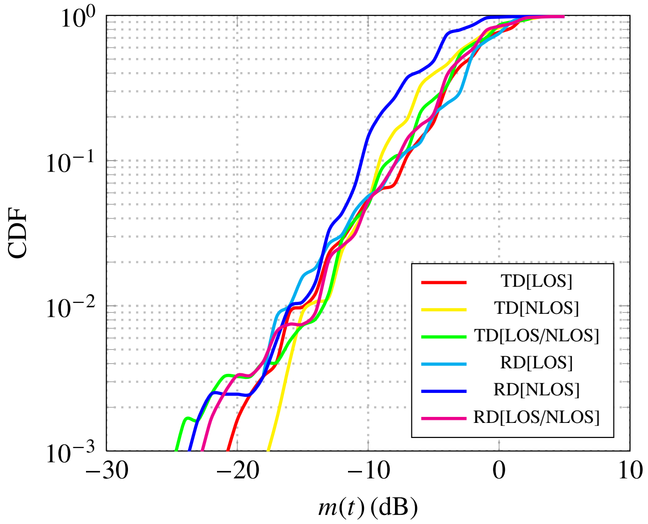

Figure 4: CDF of the MRC combined signals for the transmit and receive diversity schemes. LOS, NLOS and NLOS/LOS conditions are compared.

schemes. Looking to the results we can conclude that both schemes provide good performance in terms of DG for every condition, as it was expected. As a comparison between them, they provide a similar behaviour for almost all cases, and around 7 dB of DG can be expected at the 1 % outage probability level.

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