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Small-Scale Fading Characteristics of Diversity Combining Schemes used for Body-to-Body Communications within an Urban Environment at 2.45 GHz

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Abstract

In this paper, an analysis of spatial diversity and small-scale fading characteristics for body-to-body communications is presented. The measurements were made at 2.45 GHz in an urban environment with uncontrolled pedestrian and vehicular traffic. The virtual array of four distributed receive antennas where situated on the central chest, central waist, left waist and left wrist of the user's body. Combining of the received signal measured at each of the antennas in the virtual array has shown that an average diversity gain of up to 11.8 dB can be achieved when using four distributed antennas and a maximal ratio combining scheme. To model the small-scale fading characteristics obtained at the output of the virtual combiners, we use diversity specific, theoretical probability density functions for multi-branch receivers operating in Nakagami-*m* fading channels. It is shown that these equations provide an excellent fit to the measured channel data.

1. Introduction

Within the last decade, considerable research has been carried out to investigate signal propagation and channel characteristics in wireless body area networks (WBANs) [1, 2]. Body-to-body (B2B) communications, such as those found in B2B networks occur when a wireless device situated on one person communicates with wireless devices situated on other persons in the local vicinity. The wireless devices in body centric systems are prone to antenna-body interaction effects such as near-field coupling, radiation pattern distortion, and shifts in antenna impedance due to their close proximity to the human body [3]. Moreover, shadowing and scattering of the signal caused by the body and surrounding environment can also cause the variations in the received signal [4]. The net effect of these factors may lead to a degradation in the quality of the radio link and a reduction in the overall signal reliability.

Using a spatial diversity configuration at the receiver is one possible method to mitigate these deleterious effects. The key concept of spatial diversity is to combine multiple signals transmitted over different propagation paths with the aim of reducing the impact of deep fades. If diversity branches are suitably uncorrelated and have comparable mean signal levels, then it is expected that the combination of these signals will have a higher signal-to-noise ratio (SNR) compared to the case when only one branch is used [5]. To date, there have been relatively few studies which have investigated the benefits of spatial diversity techniques for B2B communications [6, 7]. In [6], it was shown that using multiple distributed antennas for B2B communications between emergency first responders improved the signal reliability for B2B channels during an indoor sweep-and-search-type operation. Selection diversity with multiple distributed antennas at both ends has also been used to mitigate the body shadowing in indoor B2B communications [7]. Here, it was shown that by using shoulder, front-chest, back-right-belt, and left-ankle position antennas it was possible to mitigate the effects of shadowing caused by the human body.

A probability density function (PDF) that has recently been used to model fading in channels that incorporate the human body is the Nakagami-*m* PDF [8, 9]. It has also been used in the analysis of diversity reception techniques [10] and for multiple antenna body centric applications [11]. In [12], Yacoub has provided the analytical first-order expressions for selection combining (SC) and maximal ratio combining (MRC) techniques under the assumption of identical Nakagami-*m* fading conditions, equal noise power and independence between diversity branches. In this paper, a fading characterization of B2B communications with multiple antennas within urban environment is presented using these analytical expressions for SC and MRC schemes.

2. Measurement System and Experiments

Four bespoke wireless nodes were distributed across the surface of the body of an adult male of height 1.83 m and mass 74 kg (person A) in the virtual receive array. These positions were: the central chest and waist, the left wrist, and the left waist. The purposely developed wireless nodes consisted of an ML2730 transceiver manufactured by RFMD and a Microchip PIC32MX which acted as a baseband controller. This configuration allowed the analog received signal strength output by the ML2730 to be sampled with a 10-bit resolution. The sample rate used in this study was 2 KHz and the shortest signal envelope considered for the analysis performed here was 14 seconds long. The transmitter node was mounted parallel to the body surface of an adult male of height 1.70 m and mass 75 kg (person B). It was configured to generate a continuous wave signal at 2.45 GHz with an output power of +21 dBm. During the measurements, the transmitter was alternated between four different body locations namely: the central chest region, the central waist region, the right wrist, and the right waist. The antennas used by both the transmitter and the receiver were +2.3 dBi, sleeve dipole antennas (Mobile Mark PSKN3-24/55S). The measurements were performed during the day in an urban environment within the city of Belfast in the United Kingdom. They were therefore subject to pedestrian and vehicular traffic. As illustrated in Fig. 1, five individual scenarios likely to be encountered in everyday life were considered. These were: (1) both person A and B stationary on opposite sides of the road; (2) person B walking away from and then (3) towards person A in a line parallel to the direction person A is facing; (4) both person A and B walking in parallel and in the same direction and then again in the (5) persons A and B walking in opposite directions.

3. Data Analysis

Prior to the diversity analysis at the virtual receive array, the cross-correlation between the signal envelopes observed at each branch was calculated using the process described in [13]. The local mean here, as with the model fitting discussed below was calculated over 500 samples. For brevity, these results are not discussed here although it should be noted that the cross-correlation coefficient was always less than the 0.7 figure below which a diversity scheme is anticipated to be effective [14]. The diversity gain, which is defined as the difference in signal level of the branch with the highest mean and that of the output of the diversity combiner for a given probability of signal reliability, was employed to evaluate the performance of each combining technique [12]. All diversity gain calculations in this paper were made at a signal reliability of 90%. To characterize the small-scale fading experienced at the output of the virtual receive array, the theoretical PDFs for SC and MRC combiners operating in Nakagami-*m* fading channels were fitted to the measured data obtained at the output of the hypothetical combiners which was normalized to the local mean. A non-linear least squares routine programmed in MATLAB was used to estimate m and Ω parameters. The PDF of the output of a selection combiner with M signal branches operating in a Nakagami-*m* fading environment may be expressed in terms of the m and Ω as [12]

$$p_{SC}(r) = \frac{2Mm^{m}r^{2m-1}\Gamma^{M-1}(m, mr^{2}/\Omega)}{\Omega^{m}\Gamma^{M}(m)}\exp\left(-m\frac{r^{2}}{\Omega}\right) \tag{1}$$

where $\Gamma(m) = \int_0^\infty x^{m-1}\exp(-x)dx$ is the Gamma function and $\Gamma(a,b) = \int_0^b x^{a-1}\exp(-x)dx$ is the incomplete Gamma function. The PDF of the output of an M branch maximal ratio combiner operating in the same environment may be written as [12]

$$p_{MRC}(r) = \frac{2m^{mM}}{\Gamma(mM)\sqrt{\Omega}}\left(\frac{r}{\sqrt{\Omega}}\right)^{2mM-1}\exp\left(-m\frac{r^{2}}{\Omega}\right) \tag{2}$$

Please note that it was assumed that each branch has the identical Nakagami-*m* fading conditions, equal noise power and independence between diversity branches.

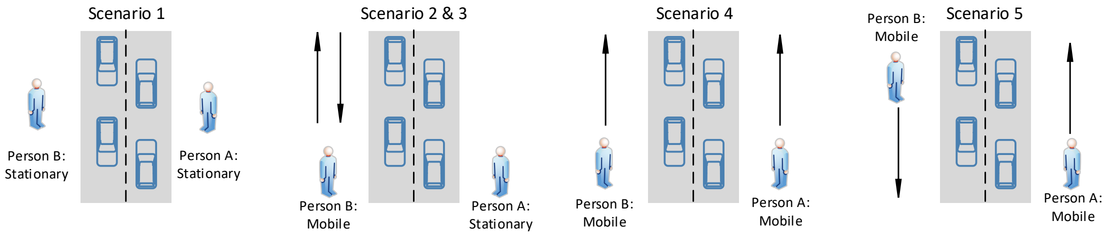

Fig. 1 Measurement scenarios considered in this study. It should be noted that the road was 5 m wide and the maximum displacement between persons A and B for scenarios 2, 3 and 5 was 20 m.

4. Results

Table I shows the average diversity gain for each combining scheme considering different numbers of spatially distributed body-worn antennas for each scenario. As expected, the MRC scheme provided the highest overall diversity gains. The highest diversity gains for SC and MRC were obtained in scenario 5 when both persons walked in opposite directions. Fig. 2 shows the empirical cumulative distribution functions (CDFs) obtained for this scenario for each transmitter location with different numbers of spatially distributed antennas to illustrate the advantage over using a single branch receiver in B2B communications. In scenario 5, the best performing two branch receiver configuration for the chest and right waist transmitter locations was the chest / left waist combination, whereas the chest / central waist combination provide the highest diversity gain for central waist and right wrist transmitter locations.

For the three-branch diversity configurations, the chest / central waist / left waist combination provided the highest diversity gain for all transmitter locations. It can also be seen from Table I that the lowest average improvement in the diversity gain when moving from a two-branch receiver to a four-receiver was observed in the scenarios where both ends of the B2B link were stationary (i.e. scenario 1). However when the one or both ends of the B2B link become mobile a significant increase in the average diversity gain was found when moving from a two- to four-branch receiver. In particular, in scenario 5 an average improvement of approximately 6.4 dB was observed for a four-branch MRC receiver, compared to the equivalent two-branch case.

Table I Average diversity gains in dB of the two, three and four branch diversity configurations over all scenarios. It should be noted that the average value was calculated over all of the possible two-, three-, and four-branch combiners for each of the transmitter locations.

Scenario	Two-Branch		Three-Branch		Four-Branch	
	$\overline{SC}$	$\overline{MRC}$	$\overline{SC}$	$\overline{MRC}$	$\overline{SC}$	$\overline{MRC}$
1	1.39	2.83	1.62	2.86	1.79	3.79
2	3.28	4.89	4.89	7.43	5.67	8.98
3	2.98	4.44	4.19	6.59	4.90	7.94
4	3.10	4.65	4.78	7.26	5.70	8.90
5	3.97	5.41	7.14	9.32	9.14	11.76

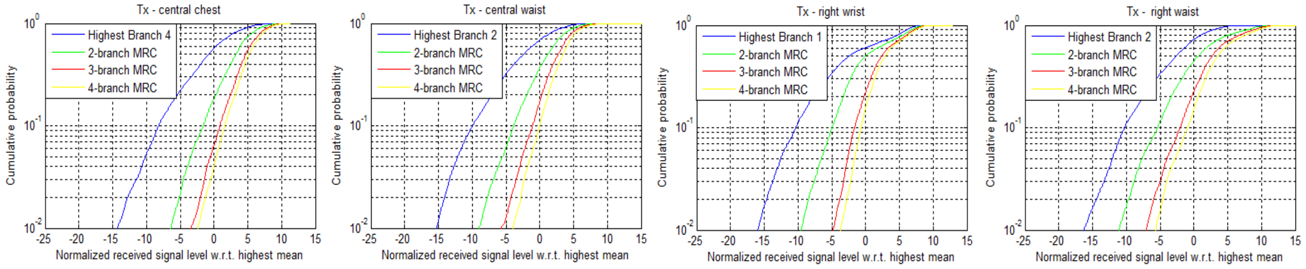

Fig. 2 Empirical CDFs of best performing two-, three- and four- branch MRC diversity scheme for each transmitter location in scenario 5.

As an example of the results of the model fitting performed in this study, Table II shows the estimated *m* and Ω parameters for all of the potential diversity combining configurations for the transmitter at the right waist region in scenarios 1, 4, and 5. As we can see from Table II, the *m* parameter estimates are greater than 1. This suggests that the small-scale fading conditions experienced at input of the virtual combiners considered in these experiments are less severe than similar combiners operating in a Rayleigh fading environment. Fig. 3 shows the empirical and theoretical PDFs for all four-branch SC and MRC diversity combined envelopes for each transmitter position during scenario 4. In all of the combined channels, the respective theoretical first-order equation provided an excellent fit to all of the combined envelopes analyzed in this study. This suggests that the theoretical PDFs for SC and MRC combiners operating in Nakagami-*m* fading conditions can be used to adequately describe the small-scale fading characteristics of B2B communications operating at 2.45 GHz with distributed antennas on the human body in an urban environment.

Table II Estimated model parameters for two-, three-, and four-branch diversity combiners at the receive array for the right waist region in scenarios 1, 4, and 5. It should be noted that the two- and three- branch were wrist / central waist and wrist / central waist / left waist.

Number of branches	Scenario 1				Scenario 4				Scenario 5			
	SC		MRC		SC		MRC		SC		MRC	
	m	Ω	***m***	Ω	***m***	Ω	***m***	Ω	***m***	Ω	***m***	Ω
Two-branch	1.57	0.71	1.68	0.49	1.68	0.72	1.81	0.49	1.57	0.71	1.68	0.49
Three-branch	1.35	0.59	1.54	0.33	1.43	0.60	1.59	0.33	1.35	0.59	1.54	0.33
Four-branch	1.19	0.51	1.35	0.25	1.27	0.52	1.39	0.25	1.19	0.51	1.35	0.25

5. Conclusion

The small-scale fading characteristics of multiple branch receivers used for B2B communications in a populated urban environment have been investigated. Using spatially distributed antennas positioned at the central chest and waist, the left wrist and left waist in conjunction with the popular SC and MRC combining schemes, it has been shown that worthwhile diversity gains can be obtained. Finally, the first-order statistics of the small-scale fading observed at the output of the hypothetical diversity combiners have been presented and shown to provide a good match to the theoretical expressions for combiners operating in Nakagami-*m* fading channels.

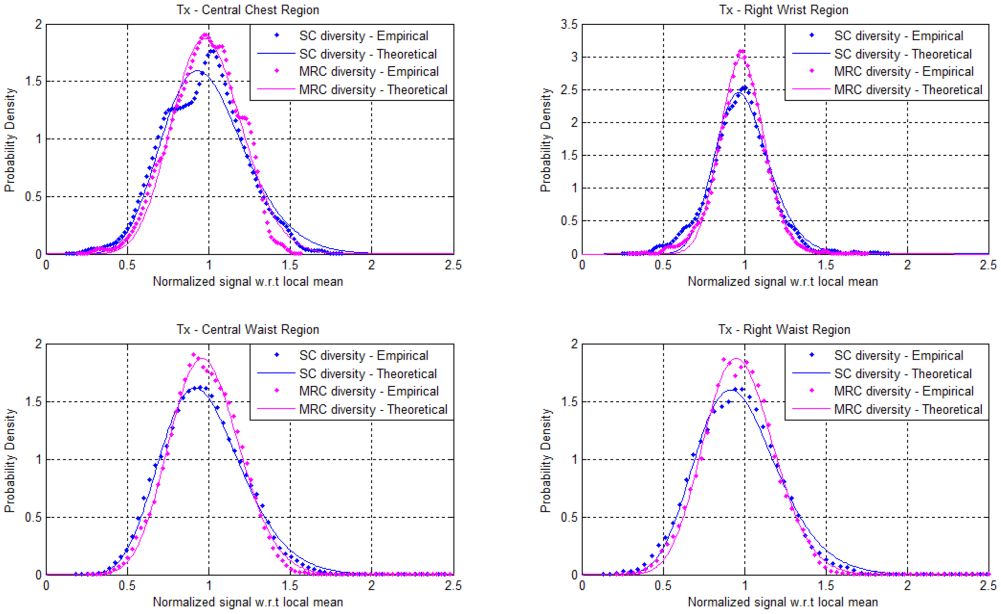

Fig. 3 Empirical and theoretical PDFs for four-branch SC and MRC combined envelopes for each transmitter location in scenario 4.

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