Indoor Off-Body Communications at 5.8 GHz with Multiple Antennas at the Base Station: A Statistical Characterization using the Nakagami-*m* Fading Model

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Abstract

In this paper we investigate the first and second order characteristics of the received signal at the output of hypothetical selection, equal gain and maximal ratio combiners which utilize spatially separated antennas at the base station. Considering a range of human body movements, we model the model the small-scale fading characteristics of the signal using diversity specific analytical equations which take into account the number of available signal branches at the receiver. It is shown that these equations provide an excellent fit to the measured channel data. Furthermore, for many hypothetical diversity receiver configurations, the Nakagami-*m* parameter was found to be close to 1.

1. Introduction

Fading caused by multipath signal propagation can cause significant fluctuation of the received signal in wireless communications systems. This is particularly the case for off-body communications [1, 2] in which one or more wireless devices are typically positioned on the human body. Physiological and biomechanical movements of the human body can act to further excite additional signal paths which increase fading when compared to non-bodyworn systems. The small scale attributes of this signal variation are often reported using a combination of first- and second-order statistics such as probability density functions (PDFs) and level crossing rates (LCRs).

The Nakagami-*m* distribution has recently been used to model fading in channels that incorporate the human body [3]. Moreover, it has been used in the analysis of diversity reception techniques [4, 5] and for body centric applications [2]. In [6], Yacoub has provided the analytical first- and second-order expressions for selection combining (SC), equal gain combining (EGC), 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 statistical characterization of indoor off-body communications using with multiple antennas at the base station is presented using these analytical expressions.

2. Experiments and Measurement Setup

All of the experiments conducted in this study were carried out in Wireless Communication Laboratory (WCL) situated on the second floor of the ECIT building at Queen's University Belfast in the United Kingdom. The lab (dimensions – 7 m × 10 m × 2.7 m) contained a number of chairs, boxes, lab equipment and also desks constructed from medium density fiberboard. The transmitter section of the radio channel measurement system consisted of an ML5805 transceiver, manufactured by RFMD, which was configured to transmit a continuous wave signal with a power level of +21 dBm at 5.8 GHz. The antennas used by both the transmitter and the hypothetical base station were +2.3 dBi, sleeve dipole antennas (Mobile Mark model PSKN3-24/55S). The transmit antenna was mounted parallel to the body surface of an adult male of height 1.83 m and mass 80 kg. The antenna was then alternated between three different body locations on the test subject: (a) the central chest region, at a height of 1.42 m, (b) the central waist region, at a height of 1.15 m, and (c) the right wrist region at a height of 0.98 m.

The receiver section (i.e. the hypothetical base station) of the radio-channel measurement system consisted of four identical sleeve dipole antennas and a Rohde & Schwarz ZVB-8 Vector Network Analyzer (VNA). The four antennas were connected to ports 1, 2, 3, and 4 of the VNA using calibrated low-loss coaxial cables. The antennas were aligned along a straight line with an equal spacing of either a half or full wavelength, i.e. a uniform linear array. The receiver array was mounted vertically on a non-conductive height adjustable stand at an elevation of 0.83 m above the floor level. Both the transmitter antenna and receiver antenna array were vertically polarized.

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The VNA was configured as a sampling receiver, recording the b_1 wave quantity incident on ports 1, 2, 3, and 4 at a rate of 56 Hz. A number of different scenarios were considered in the experiments, these were: (1) mobile LOS and (2) NLOS where the test subject walked towards and then away from the receiver antenna array in a straight line, respectively, and finally (3) random movement in LOS and (4) NLOS where the test subject walked randomly towards and then away from the receiver antenna array, respectively. All measurement trials were repeated five times.

3. Nakagami-*m* Model for Selection, Equal Gain and Maximal Ratio Combining

To characterize the small-scale fading experienced at the output of the hypothetical base station, the theoretical PDFs for SC, EGC and MRC combiners operating in Nakagami-*m* fading channels [6] were fitted to the data. The m and Ω parameters were estimated using a non-linear least squares routine programmed in MATLAB. It should be noted that the minimum data set size used for the parameter estimation consisted of 2100 channel realizations. Under the assumption of identical Nakagami-*m* fading conditions, equal noise power and independence between diversity branches Yacoub [6] has shown that the PDF, $p_{SC}(r)$, of the output of a selection combiner for M branches may be expressed as

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

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. For an equal gain combiner with M branches operating in a Nakagami-*m* fading channel, the PDF $p_{EGC}(r)$ may be written as [6]

$$p_{EGC}(r) = \sqrt{\frac{2M}{\Omega}} \int_0^a \int_0^{a-u_M} \cdots \int_0^{a-\sum_{i=3}^M u_i} g(u_2, \ldots, u_M) du_2 \ldots du_M \tag{2}$$

where, $g(u_2,\ldots,u_M) = p(u_1 = a - \sum_{i=2}^M u_i)\prod_{i=2}^M p(u_i)$, $a = r\sqrt{2M/\Omega}$, and $p(u_i)$ is the density function of the normalized Nakagami-*m* envelope u_i, $u_i = r_i / \sqrt{\Omega/2}$ obtained as [6]

$$p(u_i) = \frac{m^m u_i^{2m-1}}{\Gamma(m)2^{m-1}} \exp\left(-\frac{mu_i^2}{2}\right) \tag{3}$$

Similarly the PDF, $p_{MRC}(r)$, of the fading observed at the output of an M branch maximal ratio combiner operating in Nakagami-*m* may be written as [6]

$$p_{MRC}(r) = \frac{2m^{mM}}{\Gamma(mM)\sqrt{\Omega}} \left(\frac{r}{\sqrt{\Omega}}\right)^{2mM-1} \exp\left(-m\frac{r^2}{\Omega}\right). \tag{4}$$

4. Results

4.1 First Order Statistics

Combining of the received signal for each of the three schemes (SC, EGC, and MRC) was performed using the procedure described in [2]. To estimate the m and Ω parameters of the small-scale fading at the output of the hypothetical combiners, the data was normalized to the local mean *rms* signal level. A smoothing window of 100 samples was used for this purpose. As an example of the results of the model fitting using equations (1), (2) and (4), Table 1 shows the estimated m and Ω parameters for all of the potential diversity combining configurations for the waist region in scenario 2. In Table 1, to improve the robustness of the parameter estimates, $\bar{m}$ and $\bar{\Omega}$ are the mean parameter estimates of m and Ω averaged over the five the five repeated trials. As we can see from Table 1, the m parameter estimates are quite close to 1. When the m parameter is equal to 1, the Nakagami-*m* PDF degenerates to the Rayleigh PDF. Therefore, this suggests that the small-scale fading conditions experienced in these experiments are similar to those for a diversity combiner operating in a Rayleigh fading environment.

Fig. 1 shows the empirical and theoretical PDFs for two- and four-branch diversity combined envelopes with half-wavelength antenna spacing at the receiver while the user was walking in straight line away from the receiver antenna array with the transmit antenna on the central waist region during trial 3 of scenario 2. 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 theoretical the PDFs for SC, EGC and MRC combiners operating in Nakagami-*m* fading conditions can be used to adequately describe first-order statistics for off-body systems operating at 5.8 GHz with multiple antennas at the base station.

Table 1 Estimated Model Parameters For Two-, Three- and Four-Branch Diversity Combiners with Half-Wavelength Antenna Spacing at the Base Station and the Transmitter at the Waist Region in Scenario 2.

Number of Branches	Selection Combining		Equal Gain Combining		Maximum Ratio	
	$\bar{m}$	$\bar{\Omega}$	$\bar{m}$	$\bar{\Omega}$	$\bar{m}$	$\bar{\Omega}$
Two-branch	1.03	0.67	1.02	0.63	1.02	0.50
Three-branch	0.93	0.54	0.97	0.43	0.94	0.33
Four-branch	0.90	0.47	0.95	0.32	0.92	0.25

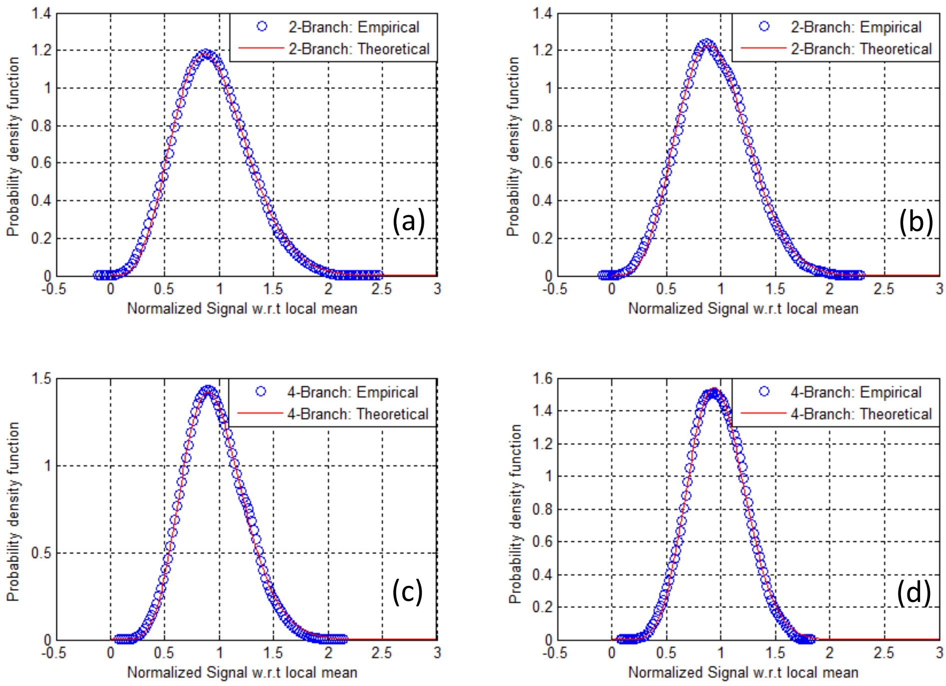

Fig. 1 Empirical and theoretical PDFs for (a) two-branch SC, (b) two-branch MRC, (c) four-branch SC and (d) four-branch MRC diversity combined envelopes during trial 3 of scenario 2.

4.2 Level Crossing Rates

As an example, Fig. 2 shows the theoretical LCR [equation (36), 6] for one- and four-branch MRC diversity combined envelopes with half-wavelength antenna spacing at the receiver fitted to the empirical LCRs while the user walked towards the receiver during trial 4 of scenario 1 with the transmitter positioned on their right wrist. It should be noted that the plots shown in Fig. 2 are not normalized to the maximum Doppler frequency as is the case with [equation (36), 6]. It can be seen quite clearly that the crossing rates for the combined signal envelopes are significantly reduced at lower signal levels compared to the signal envelope at the branch with the highest mean. In fact, when moving from a single- to four- branch receiver, all fades beyond 8 dB below the local mean signal level are completely eradicated. Although not shown due to space limitations, for all of the combined signals, including the results not shown here, the LCR equations provided an excellent fit to all of the combined envelopes.

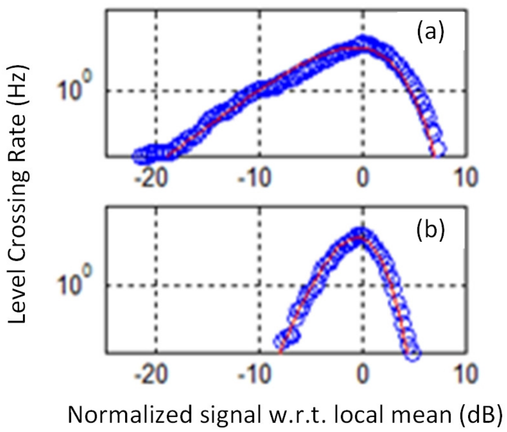

Fig. 2 Empirical (blue circle) and theoretical (red continuous line) level crossing rates for (a) one branch (highest mean signal) and (b) four-branch MRC during trial 4 of scenario 1.

5. Conclusion

A statistical characterization of diversity combining techniques used for indoor off-body fading channels at 5.8 GHz has been performed using the Nakagami-*m* fading model. Diversity specific theoretical equations previously derived by Yacoub [6] to model the PDF and LCR of selection, equal gain and maximal ratio combined fading envelopes have been shown to provide an excellent fit to the experimental data. This means that simulation techniques such as that proposed in [2] for multi-branch reception in Nakagami-*m* fading environments can be used to reproduce the fading envelopes observed in the channels presented in this study.

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