Characteristics of Shadowed Fading in Off-Body Communications Channels at 2.45 GHz

***Simon L. Cotton*[1]**

[1]Institute of Electronics, Communication & IT (ECIT), Queen's University Belfast, BT3 9DT, UK
simon.cotton@qub.ac.uk

Abstract

In this paper, a number of off-body channels which are susceptible to shadowing caused by the human body are investigated. In particular, the recently proposed shadowed κ–μ fading model is fitted to data obtained from field trials performed in low multipath conditions at 2.45 GHz. It is shown that this model provides a significantly improved fit to off-body channels which are subject to shadowing when compared to other fading models such as lognormal, Nakagami-*m* and Rice which are commonly applied to model fading in body centric communications channels.

1. Introduction

In off-body communications [1-7], shadowing of the direct line of sight (LOS) signal path can occur for a number reasons. Firstly it may be the result of the user's body intersecting the direct signal path between the transmitter and receiver [1]. Additional to this, shadowing may also be caused by other persons and obstacles situated in the local environment. For off-body communications in low multipath environments using directive antennas, shadowing caused by the body can be significant. In [2] it was observed that for a chest worn patch antenna the received signal dropped by 50 dB when the user's body turned to obstruct the main LOS path even at a very short separation distances of 1 m. Body induced shadowing has also been found to have a significant effect on the performance of multiple antenna systems [3]. Here, a dedicated channel model that captures the effects of correlated small-scale Rayleigh fading and correlated lognormal (body) shadowing was proposed and used to simulate the bit error characteristics and channel capacity curves for multiple-input multiple-output (MIMO) off-body communications.

A new statistical fading model for shadowed body centric communications channels was recently proposed in [1]. In this model, clusters of multipath are assumed to have scattered waves with identical powers, alongside the presence of elective dominant signal components – a scenario which is identical to that observed in κ–μ fading [8]. The difference between the model proposed in [1] and that of κ–μ fading is that the resultant dominant component, formed by phasor addition of the individual dominant components is assumed to be log-normally distributed. In this paper, the off-body channels presented in [1] are characterized using an alternative fading model, namely the shadowed κ–μ model, in which the lognormal distribution is superseded by the Nakagami-*m* distribution. This method of modeling shadowed fading has recently and independently been proposed in [9] and [10]. Unlike [1], it has the attractive feature that its probability density function (PDF) can be expressed in closed-form. In this paper, the fit of the shadowed fading model presented in [9] is compared with other popular fading models such as lognormal, Nakagami-*m* and Rice which are often used to characterize the fading observed in off-body channels.

2. Data Analysis

A statistical characterization of the off-body channels utilized in [1] was performed using the shadowed κ–μ model presented in [5]. The PDF of the fading signal in this model is given in equation (1), where κ is related to δ, σ and μ through the relationship $\kappa = \delta^2 / 2\mu\sigma^2$, which is simply ratio of the total power of the dominant components (δ^2) to the total power of the scattered waves ($2\mu\sigma^2$) where μ is related to the multipath clustering and the mean power is given by $\hat{r}^2$. In (1), $\Gamma(\bullet)$ is the gamma function, $m = E^2\left[\Delta^2\right] / \mathrm{var}\left[\Delta^2\right]$ is the Nakagami parameter where $\mathrm{var}\left[\Delta^2\right]$ is the variance. In this instance, $\Omega = E\left[\Delta^2\right]$ is the average power of the resultant dominant component. For convenience, the *rms* signal level, $\hat{r} = \sqrt{E\left[R^2\right]}$, or in the case of the non-LOS (NLOS) mobile measurements, the free space path loss, was removed from the fading envelopes. All parameter estimates for the PDF of the shadowed κ–μ model were then obtained using a non-linear optimization algorithm written in MATLAB. Parameter estimates for the lognormal,

978-1-4673-5225-3/14/$31.00 ©2014 IEEE

Nakagami-*m* and Rice PDFs were obtained using the `mle` function also available in the Statistics Toolbox of MATLAB.

$$f_R(r) = \frac{2r^{2\mu-1}}{\Gamma(\mu)}\left(\frac{\mu(1+\kappa)}{\hat{r}^2}\right)^{\mu}\left(\frac{m\hat{r}^2}{\mu(1+\kappa)\Omega + m\hat{r}^2}\right)^{m}\exp\left(-\frac{\mu(1+\kappa)r^2}{\hat{r}^2}\right){}_1F_1\left(m;\mu;\frac{\Omega(\mu(1+\kappa)r)^2}{\hat{r}^2\left(\mu(1+\kappa)\Omega + m\hat{r}^2\right)}\right) \quad (1)$$

3. Experimental Setup

The off-body measurements used for the model fitting performed here were obtained from the field trials conducted in [2]. They were performed in the anechoic chamber facilities at Queen's University Belfast in the United Kingdom. The chamber had a floor area of 54 m^2 and was housed in conductive shielding and lined with pyramidal RF absorbers. The measurement hardware consisted of a NovaSource G6 RF source combined with a Hittite HMC-455LP3 low noise amplifier configured to transmit a continuous wave signal with a power level of +22 dBm at 2.42 GHz. The transmit antenna used in this study was a flexible +6.2 dBi patch antenna (Fig. 1, [2]) designed to be resonant on the human body. The antenna had a –10 dB bandwidth of approximately 55 MHz (2.398-2.453 GHz) and was mounted with its ground plane parallel to the body surface of an adult male of height 1.95 m and mass 105 kg, at a height of 1.4 m. The antenna was positioned at the test subject's central chest region and placed directly on his clothing using a small strip of Velcro® and without the use of a dielectric spacer.

The receiver section of the measurement system consisted of an identical patch antenna connected to port 1 of a Rhode & Schwarz ZVB-8 VNA using a calibrated low-loss coaxial cable. The non-bodyworn antenna was mounted vertically on a non-conductive height adjustable stand at an elevation of 1.4 m above the floor level, corresponding to the height of the transmitter antenna. The VNA was then configured as a sampling receiver, recording the b_1 wave quantity incident on port 1 at a rate of 1 kHz for all experiments.

4. Results

Two off-body channels which were anticipated to suffer greatly from body shadowing were investigated. The first scenario considered the rotation of a user in front of the receiver. In this set of measurements, the user rotated 360° (with his hands by his sides) in an anti-clockwise direction from direct LOS between the transmit and receive antennas, through to the maximum shadowing condition where the user's body directly obstructed the main LOS path, before returning to LOS. The normalized received signal envelopes as the user performed a rotation at a distance of 1.5 m and 4 m from the receive antenna are illustrated in Fig. 9 of [1]. As noted in [1], the general shape of the received signal envelope was observed to be comparable irrespective of distance.

Figs. 1(a) and (b) show the shadowed κ–μ, lognormal, Nakagami-*m* and Rice PDFs fitted to the empirical probability density of the normalized signal envelope for the rotation data obtained at the 1.5 m and 4 m positions respectively. It should be noted that all parameter estimates for the shadowed κ–μ fading model are provided in Table I. As we can see in both cases the shadowed fading PDF of (1) significantly outperforms the lognormal, Nakagami-*m* and Rice PDFs.

Of the lognormal, Nakagami-*m* and Rice PDFs, the lognormal PDF was found to perform best although its fit was still poor compared to the shadowed κ–μ PDF. For example, in both cases it is unable to match the 'heavy tailed' behavior of the empirical PDFs at higher signal levels. For the measurements made at the 1.5 m separation distance, the PDF of the normalized received signal indicates that this type of channel is subject to heavy body shadowing as the received signal is most frequently observed to be at low levels caused by the strong fading. This is also confirmed by the low *m* parameters obtained for this scenario (Table I) which indicate significant fading of the resultant dominant component.

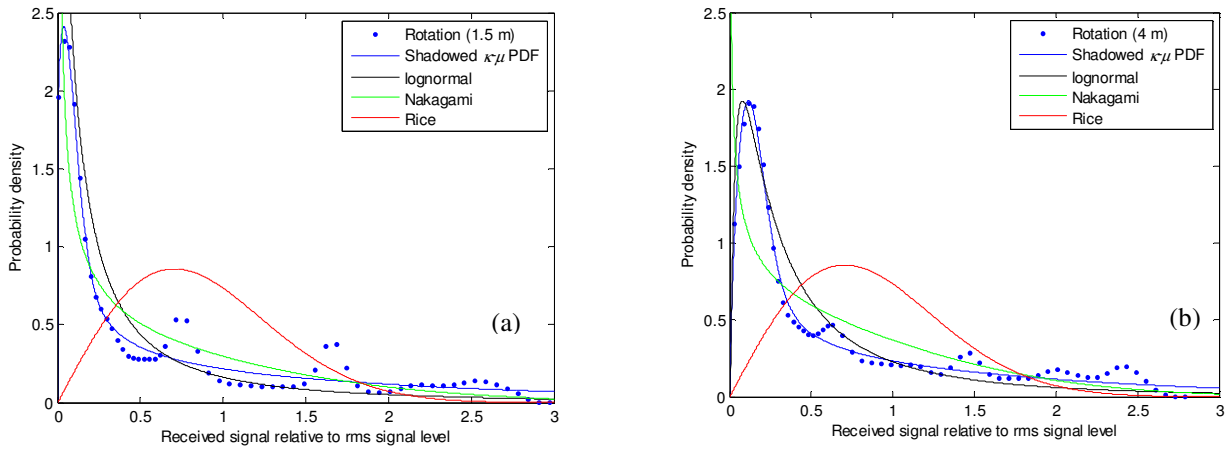

Fig. 1 Shadowed *κ–μ*, lognormal, Nakagami-*m* and Rice PDFs fitted to the empirical PDF for off-body channels while the user rotated at distances of (a) 1.5 m and (b) 4 m from the receiver.

The second shadowing scenario considered for the off-body channels was the situation encountered when the user simply walks so that their body obstructs the main LOS signal path. To study this, the user oriented themselves such that the chest worn antenna was now in direct NLOS to the receive antenna. The user then walked the maximum permissible distance (6.5 meters) away from the receive antenna. Fig. 2 shows the shadowed *κ–μ*, lognormal, Nakagami-*m* and Rice PDFs compared with the empirical PDF obtained by removing the estimated path loss based on the elapsed time and average velocity using the model given in [2]. Again we can see that the shadowed *κ–μ* PDF provides an enhanced fit to the measured data. However, unlike the rotational measurements, in this scenario the Nakagami-*m* and Rice PDFs provide an improved fit compared to the lognormal PDF. As noted in [1], it is observed that even under NLOS conditions and in the absence of multipath generated by the local environment a weak resultant dominant signal component still exists ($\kappa = 0.56$, Table I).

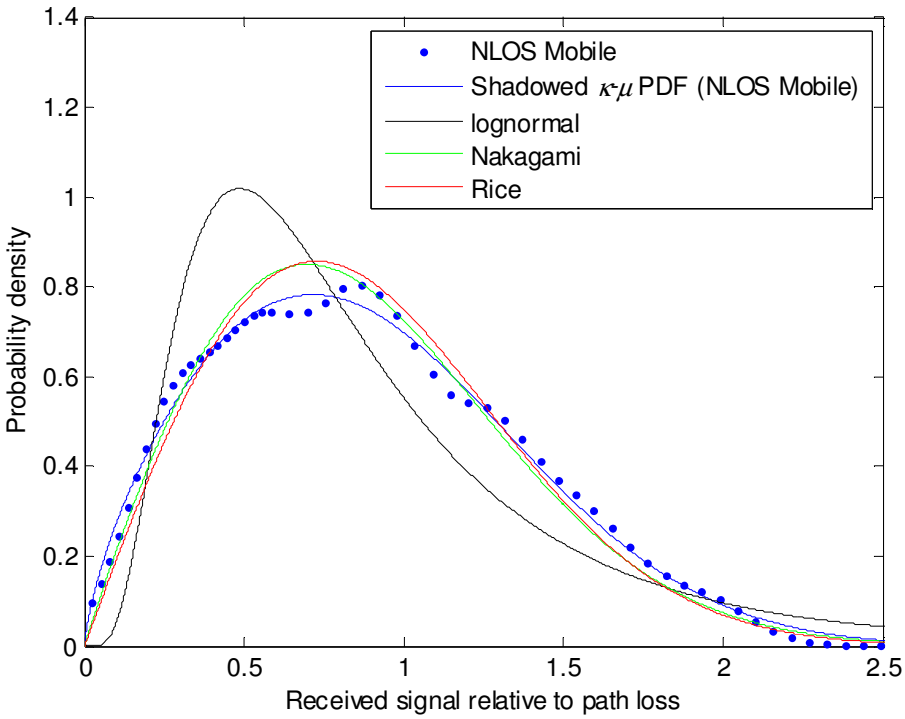

Fig. 2 Shadowed *κ–μ*, lognormal, Nakagami-*m* and Rice PDFs compared to the empirical PDF for off-body channel obtained for the user walking in NLOS in the anechoic chamber.

Table I Estimated Parameters for Off-Body Channels using the Shadowed κ–μ PDF

Position	$\hat{\kappa}$	$\hat{\mu}$	$\hat{r}$	$\hat{m}$	$\hat{\Omega}$
Rotation (1.5 m)	134	0.56	1.03	0.18	3.40
Rotation (4 m)	47.1	0.84	1.08	0.18	2.08
Mobile NLOS	0.56	0.85	1.04	491	0.36

5. Conclusion

A statistical characterization of shadowed off-body fading channels has been presented using the shadowed κ–μ fading model. Rather than being deterministic, this recently proposed model incorporates a resultant dominant that is described by a random process, in particular it is considered to follow a Nakagami-*m* distribution. This new shadowed fading model has been shown to provide an excellent fit to measured data when compared to many of the popular fading models currently used to model fading in body centric communications channels.

6. Acknowledgments

This work was supported by the U.K. Royal Academy of Engineering and the Engineering and Physical Research Council (EPSRC) under Grant Reference EP/H044191/1 and by the Leverhulme Trust, UK through a Philip Leverhulme Prize.

7. References

1. S. L. Cotton "A statistical model for shadowed body centric communications channels: theory and validation," *to appear*, *IEEE Transactions and Propagation*, March 2014.

2. S. L. Cotton, A. McKernan, A. J. Ali and W. G. Scanlon, "An experimental study on the impact of human body shadowing in off-body communications channels at 2.45 GHz," *5th European Conf. Antennas and Propagation* (*EUCAP*), pp. 3133–3137, Rome, Italy, Apr. 2011.

3. P. Van Torre, L. Vallozzi, L. Jacobs, H. Rogier, M. Moeneclaey and J. Verhaevert, "Characterization of measured indoor off-body MIMO channels with correlated fading, correlated shadowing and constant path loss," *IEEE Transactions on Wireless Communications*, vol. 11, no. 2, pp. 712–721, February 2012.

4. M. Mackowiak, and L.M. Correia, "A statistical model for the influence of body dynamics on the gain pattern of wearable antennas in off-body radio channels," *Wireless Personal Communications*, vol. 73, pp. 381-399, May 2013.

5. M. Mackowiak, R. Rosini, R. D'Errico, L. M. Correia, "Comparing off-body dynamic channel model with real-time measurements," *2013 7th International Symposium on Medical Information and Communication Technology* (*ISMICT*), pp. 121-125, March 2013.

6. D. Smith, L. Hanlen, J. Zhang, D. Miniutti, D. Rodda and B. Gilbert, "Characterization of the Dynamic Narrowband On-Body to Off-Body Area Channel," *IEEE International Conference on Communications*, pp.1-6, June 2009.

7. S. L. Cotton and W. G. Scanlon, "Measurements, modeling and simulation of the off-body radio channel for the implementation of bodyworn antenna diversity at 868 MHz," *IEEE Transactions on Antennas and Propagation*, vol. 57, no. 12, pp. 3951–3961, Dec. 2009.

8. M. D. Yacoub, "The κ-μ and the η-μ distribution," *IEEE Antennas Propagation Magazine*, vol. 49, no. 1, pp. 68–81, Feb. 2007.

9. S. L. Cotton, "Human Body Shadowing in cellular device-to-device communications: channel modeling using the shadowed κ–μ fading model," *under revision*, *IEEE Journal on Selected Areas in Communications Special Issue on Device-to-Device Communications in Cellular Networks*, 2013.

10. J. F. Paris, "Statistical characterization of κ–μ shadowed fading," *to appear*, *IEEE Transactions on Vehicular Technology*, 2013.