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A Statistical Characterization of On-Body Fading using the Shadowed κ–μ Fading Model

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***Abstract*—In this paper we investigate the received signal characteristics of on-body communications channels at 2.45 GHz. The hypothetical body area network configuration considered a transmitter node situated on the person's left waist and receiving nodes positioned on the head, knee and wrist of the person's right side. The on-body channel measurements were performed in both anechoic and reverberant environments while the person was moving. It was found that the recently proposed shadowed κ–μ fading model provided an excellent fit to the measured data.**

I. INTRODUCTION

Shadowing of the received signal is known to be an inherent part of body centric communications [1]. So called *body shadowing* occurs when one or more parts of the human body obscure the direct line of sight (LOS) signal path between the transmitter and receiver, either or both of which may be body worn. On-body channels, such as those found in body area networks (BANs), are an example of a body centric communications system in which both end of the wireless link typically reside on the body. Here, shadowing caused by body parts obstructing the direct link between antennas can cause substantial attenuation of the received signal. Body shadowing has previously been observed in on-body channel measurements [1, 2] and simulations [3] conducted at 2.45 GHz. Moreover, it is postulated that body shadowing will make future non-LOS (NLOS) millimeter-wave on-body communications at 60 GHz [4] very difficult, if not impossible.

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 [5]. 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 a log-normally distributed. In this paper, we characterize the on-body channels presented in [1] using an alternative fading model, namely the shadowed κ–μ model, in which the lognormal distribution is superseded by the Nakagami-*m* distribution.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 [6] and [7]. Unlike [1], it has the attractive feature that its probability density function (PDF) can be expressed in closed-form.

II. MEASUREMENT SETUP AND EXPERIMENTS

The measurements were conducted at 2.45 GHz in the anechoic and reverberation chamber facilities at Queens University Belfast in the United Kingdom. The antennas used in this study were compact (5 mm height) higher mode microstrip patch antennas [1] designed specifically for on-body networking applications. The test subject was an adult male of height 1.82 m and mass 90 kg. In the experiments, the antennas were mounted so that the radiating patch element was parallel to the body surface. They were then connected to port 1 and 2 of a Rhode & Schwarz ZVB-8 vector network analyzer (VNA) using calibrated low-loss coaxial cables. The VNA was configured with an output power of 0 dBm and set to record measurements of S_{21} at 5 ms intervals for 30 seconds. For all of the measurements presented here, the user performed a walking motion at a set location at in both environments.

III. RESULTS

A statistical characterization of the three on-body channels utilized in [1] namely the front-left-waist to the right-head, right-knee and right-wrist was performed using the shadowed κ–μ model presented in [6]. 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 [7]. In this instance, $\Omega = E\left[\Delta^2\right]$ is the average power of the resultant dominant component. For convenience, the *rms* signal level, $\hat{r} = \sqrt{E\left[R^2\right]}$, was removed from the fading envelopes presented here to enable a direct comparison of the fading characteristics for each of the on-body links. All parameter estimates for the PDF of the shadowed κ–μ model were obtained using a non-linear optimization algorithm in MATLAB and are given in Table I.

Fig. 1 shows the PDF of the shadowed κ–μ model fitted to the empirical PDF for each of the three channels while the user was in the anechoic chamber. Firstly, it is worth remarking that the PDF given in (1) provides an excellent fit to these shadowed on-body fading channels. In this environment, multipath signals returned in the direction of the human body from the local surroundings will be minimised and hence the signal characteristics will be determined mostly by processes related to the body itself. This can be seen from the parameter estimates for the right head and right knee positioned antennas where the $\hat{\mu} < 1$ and $\hat{\kappa} > 1$ suggesting that these channels suffer less from multipath and that a dominant component exists. As expected, the right wrist positioned antenna exhibited the greatest amount of variation in the resultant dominant component ($\hat{m} = 0.39$). This was due to body shadowing caused by the oscillatory movement of the arm from the front to the back of the body.

Fig. 2 shows the PDF of the shadowed κ–μ model fitted to the empirical PDFs for same on-body channels while the user was in the reverberation chamber. Again, the PDF of the shadowed κ–μ model provided an excellent fit to the measured data. Interestingly, even for this extreme multipath environment, dominant signal components were still observed in the fading characteristics of each the on-body fading channels (Table I).

IV. CONCLUSION

A statistical characterization of on-body fading channels has been presented using the shadowed κ–μ fading model. This recently proposed model has been shown to provide an excellent fit to measured data. Finally even in a highly reverberant environment, a dominant component was still found to exist in all of the shadowed on-body channels considered in this study.

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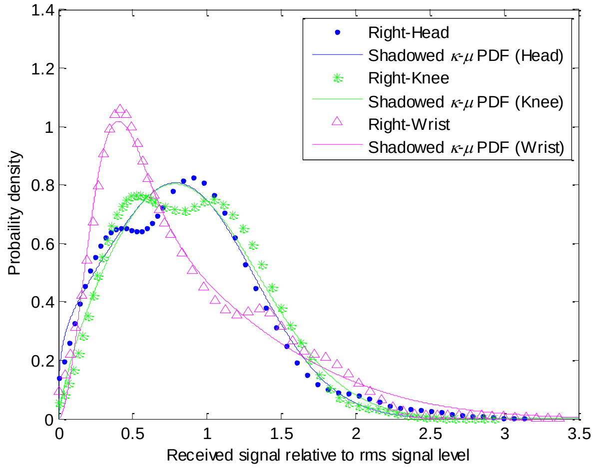

Fig. 1 PDF of the shadowed κ–μ model fitted to the empirical PDF for each of the three channels on-body channels in the anechoic chamber.

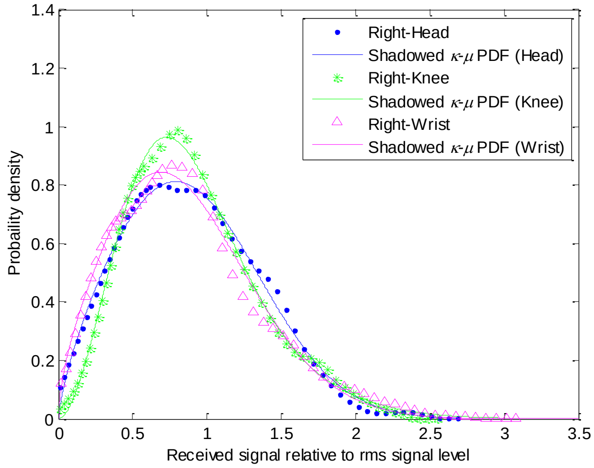

Fig. 2 PDF of the shadowed κ–μ model fitted to the empirical PDF for each of the three channels on-body channels in the reverberation chamber.

TABLE I. ESTIMATED PARAMETERS FOR ALL ON-BODY CHANNELS.

Environment	Position	$\hat{\mu}$	$\hat{\kappa}$	$\hat{r}$	$\hat{m}$	$\hat{\Omega}$
Anechoic Chamber	Right-Head	0.64	1.94	1.01	650	0.60
	Right-Knee	0.88	1.36	1.18	948	0.47
	Right-Wrist	1.38	3.95	0.87	0.39	1.02
Reverberation Chamber	Right-Head	0.87	0.96	1.04	445	0.49
	Right-Knee	1.39	1.02	1.13	0.36	0.42
	Right-Wrist	0.79	12.6	1.04	0.98	0.88

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