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Cotton, S, Yoo, SK & Sofotasios, P
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Characterizing Fading in Wearable Communications Channels using Composite Models

Simon L. Cotton and Seong Ki Yoo
Institute of Electronics, Communications and IT (ECIT)
Queen’s University Belfast
Belfast, United Kingdom
{simon.cotton, syoo02}@qub.ac.uk

Paschalis C. Sofotasios
Dept. of Electronics and Communications Engineering
Tampere University of Technology
Tampere, Finland
p.sofotasios@ieee.org

Abstract—Characterizing and modeling the behavior of fading channels is critical for robust wireless systems design. This is especially the case for wireless devices designed to be positioned on the human body. So-called wearable communications are not only impacted by signal fluctuations caused by the propagation environment but also shadowed and envelope fading generated by the human body. In this paper we statistically characterize fading channels observed in wearable communications using a range of very general line of sight and multiplicative composite fading models such as \( \kappa-\mu / \lognormal \) line of sight (LOS)阴影化 and \( \kappa-\mu / \Gamma \) Gamma. In particular we investigate off-body wearable channels operating at 5.8 GHz for a series of experiments which are designed to be representative of everyday scenarios likely to be encountered by wearable device users. Using the Kullback-Leibler divergence, we then perform a quantitative analysis of the fits of these models to the measured composite fading data obtained for the wearable channels considered here.

Keywords—Body centric communications; fading; \( \kappa-\mu \) distribution; wearables

I. INTRODUCTION

The last decade has seen a significant rise in the adoption of so-called wearable devices which are designed to carried or worn by the user. For many of these devices, wireless communications are necessary in order to transfer or receive data from external networks. As the constituent nodes are operated in close proximity to the human body, they are particularly prone to shadowing [1-5] induced by the user’s body as well as perturbations in the signal power caused by the local surroundings [6, 7].

Body shadowing for wearable systems is a particular problem in low multipath environments. For example, for outdoor channel measurements made 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. Both body induced shadowing and multipath fading have also been found to have a significant effect on the performance of multiple antenna systems [6]. Here, a dedicated channel model that captured 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.

As both shadowing and multipath fading co-exist and can impact wearable communications channels simultaneously it seems a natural approach to consider the use of composite fading models to characterize and model their fading behavior. Over the last few decades, composite fading models have been proposed which combine shadowed and small-scale fading. These can be generally categorized into line of sight (LOS) and multiplicative shadowed fading models. In this case, LOS shadowed models correspond to fading scenarios in which there is random variation of the amplitude of the dominant signal component only e.g. caused by complete or partial obstruction of the direct signal path. This includes the Rice / lognormal [8], \( \kappa-\mu / \lognormal \) [1], Rice / Nakagami-m [9] and \( \kappa-\mu / \text{Nakagami-m} \) [10, 11] LOS shadowed fading models. On the other hand, the multiplicative shadowed fading models cause random fluctuations of the total power of the multipath components, i.e. both the dominant and scattered signal components. Examples of this category include Rayleigh / lognormal [12, 13], Rice / lognormal [14], Rayleigh / gamma [15], also known as the \( K \)-distribution, and Nakagami-m / gamma [16], also known as the \( \text{generalized } K \)-distribution, composite fading models.

The LOS shadowed fading model which appeared in [1] was first proposed in the context of body centric communications. 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 \( \kappa-\mu \) fading [17]. The difference between the model proposed in [1] and that of \( \kappa-\mu \) fading is that the resultant dominant component, formed by phasor addition of the individual dominant components is assumed to be log-normally distributed.

While the model proposed in [1] is useful for characterizing composite fading in which the LOS or dominant component undergoes shadowing, it cannot account for shadowing of the scattered multipath signal contribution. To this end, in this paper we make use of another \( \kappa-\mu \) fading related model. In this instance it is the \( \kappa-\mu / \Gamma \) Gamma composite fading model

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1 Also referred to as the \( \kappa-\mu \) shadowed fading model [10].
proposed in [18]. Here, the mean signal power of a $\kappa$–$\mu$ fading envelope is assumed to follow the Gamma distribution. Put more precisely, both the dominant and scattered signal components jointly undergo shadowed fading.

The remainder of this paper is organized as follows. Section II introduces the $\kappa$–$\mu$ / gamma and $\kappa$–$\mu$ / lognormal LOS shadowed composite fading models. In Section III, the channel measurements are described including the measurement system, environments and scenarios. Section IV, evaluates the goodness-of-fit of both the $\kappa$–$\mu$ / gamma composite fading model and $\kappa$–$\mu$ / lognormal LOS shadowed fading model to the empirical data as well as presenting some examples of the model fits. Finally, Section V concludes the paper with some closing remarks.

II. COMPOSITE FADING MODELS

A. $\kappa$–$\mu$ / lognormal LOS Shadowed Fading Model

The probability density function (PDF) of the composite signal envelope, $R$, in a $\kappa$–$\mu$ / lognormal LOS shadowed fading channel [1] is given in (1) where $I_v(\bullet)$ is the modified Bessel function of the order v. In this model, as with the $\kappa$–$\mu$ fading model proposed in [17], $\kappa$ simply ratio of the total power of the dominant components ($\tilde{\sigma}$) to the total power of the scattered waves ($2\mu\sigma^2$) and $\mu$ is related to the multipath clustering and $\Omega$ is the mean signal power which is given by

$$E[R^2] = \Omega = \delta^2 + 2\mu\sigma^2.$$  

The intensity of shadowing of the LOS or dominant component is controlled by the $a$ and $b$ parameters which are the location and scale parameters respectively inherited from the lognormal distribution.

B. $\kappa$–$\mu$ / Gamma Multiplicative Shadowed Fading Model

The PDF of the composite signal envelope, $R$, in a $\kappa$–$\mu$ / Gamma shadowed fading channel [18] is given in (3). As with the $\kappa$–$\mu$ / lognormal LOS shadowed fading model above, $\kappa$ and $\mu$ have their usual meanings [17] whereas $a$ and $b$ relate to the shape and scale parameters of the Gamma distribution used to control the variation of mean signal power. It is worth highlighting that the $\kappa$–$\mu$ / Gamma composite fading model inherits all of the generality of the $\kappa$–$\mu$ distribution and therefore includes as special cases the one-sided Gaussian, Rice (Nakagami-$m$), Nakagami-$m$ and Rayleigh distributions. For example, as $a \rightarrow \infty$, there is no shadowing of the mean signal power, and in this case, the $\kappa$–$\mu$ / Gamma composite fading model coincides with the $\kappa$–$\mu$ fading model. Likewise, by setting $\mu = 1$ and again letting $a \rightarrow \infty$, the Rice PDF can be obtained, where $\kappa$ becomes equivalent to the Rice $K$ factor. The Rayleigh distribution can be readily deduced by setting $\kappa = K = 0$. Similarly, the Nakagami-$m$ distribution can be obtained by letting $\kappa \rightarrow 0$ with the $\mu$ parameter becoming equivalent to the $m$ parameter of the Nakagami-$m$ distribution. Moreover, the PDF of the $\kappa$–$\mu$ / Gamma composite fading model also includes as special cases other shadowed fading models such as the Rayleigh / gamma [15] and Nakagami-$m$ / gamma [16] composite fading models.

III. CHANNEL MEASUREMENTS

The channel measurements conducted in this paper considered a hypothetical wearable device positioned at three locations on the human body, namely the chest, waist and right wrist as shown in Fig. 1(a). These locations were chosen as they were representative of real-life wearable applications e.g. the chest region is suitable location for electrocardiogram monitors, the waist region is a possible mounting point for a gate node in a body area network (BAN) and the wrist is will be used for smart watches.

The transmitter section of the channel measurement system consisted of an ML58051, single chip fully integrated Frequency Shift Keyed (FSK) transceiver, manufactured by RFMD. It was configured to transmit a continuous wave signal with a power level of +17.6 dBm at 5.8 GHz. The transmit antenna was mounted tangentially with respect to the body surface of an adult male of height 1.83 m and mass 73 kg using a small strip of Velcro. During the measurements, the transmitter was alternated between the three aforementioned body locations on the test subject.

The receiver section of the channel measurement system, consisted of an antenna which was mounted vertically on a non-conductive polyvinyl chloride (PVC) stand at an elevation of 1.10 m above the floor level so that the antenna was parallel to the body worn nodes while the user was stationary. The antenna was connected to port 1 of a Rohde & Schwarz ZVB-8 vector network analyzer (VNA) using a low-loss coaxial cable. A pre-measurement calibration was performed to reduce the effects of known system based errors using a Rohde & Schwarz ZVZ51 calibration unit. This also enabled the elimination of the effects of the power amplifier and cable loss.

The VNA was configured as a sampling receiver, recording the magnitude of the $b_1$ wave quantity incident on port 1 with a bandwidth of 10 kHz, which was centered at the operation frequency. The magnitude of the $b_1$ measurements were automatically collected and stored on a laptop through a local area network (LAN) connection, providing an effective channel sampling frequency of 425.6 Hz (or equivalently a channel sample period of 2.3 ms). The average walking speed estimated from the channel data was 1.19 m/s. The antennas used by both the transmitter and receiver were omnidirectional sleeve dipole antennas with +2.3 dBi gain (Mobile Mark model PSKN3-24/55S4) in free space. The measured radiation patterns at each of the body locations utilized in this study are indicated in Fig. 1(b).

To perform a robust characterization of the indoor off-body wearable channel at 5.8 GHz, we conducted our experiments in a number of different indoor environments, in order to fully encapsulate variations in room size, materials and furniture. These locations were situated within the Institute of Electronics, Communications and Information Technology (ECIT) at Queen’s University Belfast in the United Kingdom. They were: (1) an indoor laboratory environment with dimensions of 4.75 m x 9.14 m. The laboratory is situated on the 2nd floor of the ECIT building and contained a number of
Taking the derivative of \( f_{\kappa}(r) \) with respect to \( r \) gives:

\[
f_{\kappa}(r) = \frac{\mu}{\beta \sqrt{2\pi \Omega}} \left( \frac{r}{\sqrt{\Omega}} \right)^{\mu-1} \frac{(1+2\kappa)(1+\kappa)^{\frac{\alpha}{\beta}}}{\kappa^\alpha \Gamma(\alpha) b^{\frac{\alpha}{\beta}}} \exp \left( \frac{-\mu(1+\kappa)}{\beta} \right) I_{\mu-1}\left(2\mu\sqrt{\kappa(1+\kappa)}\left(\frac{r}{\sqrt{\Omega}}\right)\right) d\kappa
\]

and

\[
f_{\kappa}(r) = \frac{2\mu(\kappa+1)^{\frac{\mu-1}{\kappa}}}{\kappa^2} \frac{r^{\mu-1}}{\Gamma(\alpha) b^{\frac{\alpha}{\beta}}} \exp \left( \frac{-\mu(\kappa+1)}{\omega} \right) \exp \left( -\frac{\omega}{b} \right) I_{\mu-1}\left(2\mu\kappa(\kappa+1)\left(\frac{r}{\sqrt{\omega}}\right)\right) d\omega
\]

Fig. 1 (a) Three different body worn node locations and (b) measured azimuthal radiation patterns for the sleeve dipole antenna in free space (black dashed lines) and situated on the chest (red continuous lines), waist (blue continuous lines) and wrist (green continuous lines) regions. It should be noted that the black arrow in (b) represents the direction that the test subject was facing.

chairs, boxes, lab equipment, metal cabinets and also desks constructed from medium density fiberboard. The lab was unoccupied for the duration of the experiments facilitating pedestrian free off-body wearable channel measurements; (2) a seminar room with dimensions of 7.92 m x 12.58 m which is located on the 1st floor of the ECIT building. The seminar room contained a large number of chairs, desks, a projector and a white board. It also featured an external facing boundary wall constructed entirely from glass with some metallic supporting pillars. Again, the seminar room was unoccupied for the duration of the experiments; (3) an open office area with dimensions of 10.62 m x 12.23 m situated on the 1st floor of the ECIT building as illustrated using the red rectangular outline. The open office area contained a number of soft partitions, cabinets, PCs, chairs and desks. It is worth noting that all three environments also consisted of metal studded dry walls with a metal tiled floor covered with polypropylene-fiber, rubber backed carpet tiles, and metal ceiling with mineral fiber tiles and recessed louvered luminaries suspended 2.70 m above floor level.

Two movement scenarios deemed likely to be encountered in everyday life and particularly susceptible to shadowed fading were considered. These were: (1) walking in LOS conditions and (2) walking in non-LOS (NLOS) where the test subject walked towards and then away from the receiver in a straight line (from a point 9 m away from the receiver to 1 m point directly in front of it and vice versa). Due to the limitation of space, for the indoor laboratory environment, the random movement measurements were conducted at the separation distances of 1 m, 5 m and 8 m. The smallest data sets considered for the statistical analysis presented here were: 2401 for the LOS walking, 2251 for NLOS walking. The mean recorded noise threshold in all three different indoor environments was observed to be approximately -98.6 dBm.

To improve the validity and robustness of the parameter estimates obtained in this study, measurements were repeated three times for all of the considered body worn node positions and movement scenarios within three different environments.

**IV. RESULTS**

The \( \kappa-\mu / \text{lognormal LOS shadowed fading model} \) was recently proposed in [1] and has been successfully used to model the fading observed in body centric communications channels. Unlike the \( \kappa-\mu / \text{gamma composite fading model} \), in a \( \kappa-\mu / \text{lognormal LOS shadowed fading channel} \) it is the LOS signal which only undergoes shadowed fading, with the scattered multipath contribution remaining unperturbed by the shadowing effect. Therefore, to better understand the modes of propagation and hence the underlying signal models for the wearable channels studied in this work we utilized the Kullback-Leibler divergence \( (D_{KL}) \) to measure the information loss between the empirical PDFs and the theoretical PDFs for the composite and LOS shadowed fading models.

The Kullback-Leibler divergence quantifies the difference between two distributions and is defined as [19]

\[
D_{KL} = \int_{-\infty}^{\infty} f_1(x) \ln \left( \frac{f_1(x)}{f_2(x)} \right) dx
\]

where, in general, \( f_1(x) \) represents the true PDF of the data and \( f_2(x) \) denotes the test PDF, i.e. the approximated PDF of \( f_1(x) \).

Table I shows the mean values of the \( D_{KL} \) averaged over the three repeated trials for all of the considered body worn node locations and movement scenarios within three different environments.
It was observed that the $\kappa$-$\mu$ / gamma composite fading model provided a better fit compared to the $\kappa$-$\mu$ / lognormal LOS shadowed fading model for the majority of all of the considered data sets. This observation suggests that in the majority of cases considered here, measurable shadowing of both the dominant and scattered signal components was found to exist. For instance, irrespective of the body worn node locations, the $\kappa$-$\mu$ / gamma composite fading model outperformed the $\kappa$-$\mu$ / lognormal LOS shadowed fading model for the LOS walking scenario in the seminar room. This result may suggest that there existed some shadowing effects even if the LOS signal path existed, i.e. the scattered signal contributions were shadowed by the human body and the surrounding obstacles.

Moreover, for all cases of the NLOS walking scenario with the exception of the measurement for the waist positioned antenna in the seminar room environment, the $\kappa$-$\mu$ / gamma composite fading model provided a better agreement with the measurement data compared to the $\kappa$-$\mu$ / lognormal LOS shadowed fading model. In this case, the LOS signal path was obscured by the human body and therefore the received signal was contributed by the multipath components including both the dominant and scattered signal components. These multipath components were shadowed together by the human body and the surrounding obstacles while the test subject was walking away from the receiver. Nonetheless, for the scenarios considered here there were still a few cases for which the $\kappa$-$\mu$ / lognormal LOS shadowed fading model outperformed the $\kappa$-$\mu$ / gamma composite fading model (e.g. chest LOS in the laboratory and open office areas; waist NLOS in the seminar room). For these it can be deduced that the impact of shadowing on the scattered signal contribution in some cases will be less apparent.

To allow the reader to reproduce some of the first order statistics presented in this paper, in Table II, we present the average parameter estimates for the $\kappa$-$\mu$ / gamma composite fading model\(^2\). The parameter estimates were obtained using a non-linear least squares routine programmed in MATLAB to match the empirical PDF with the theoretical PDF. As an example of the model fitting, Figs. 2, 3 and 4 shows the empirical PDFs obtained for the wrist worn transmitter within all three indoor environments when the test subject performed LOS, NLOS walking movements. It can be seen that both two composite fading models provided a good fit to the measured data although their $D_{KL}$ values appeared different. As an example of the model fitting, Fig. 10 shows the empirical PDFs obtained for the wrist worn transmitter within all three indoor environments when the test subject performed LOS, NLOS walking movements, a rotational movement at 9 m and random movements around the 1 m location. It can be seen that both two composite fading models provided a good fit to the measured data although their $D_{KL}$ values appeared different.

\(^2\)As the $\kappa$-$\mu$ / gamma composite fading model was predominantly chosen by the Kullback-Leibler divergence as the best fitting model, we concentrate on the parameter estimates for this model. Prior to parameter estimation, we normalized our data to the estimated path loss to remove signal attenuation due to the transmitter-receiver separation. The path loss values were obtained by mapping time into distance, based upon an estimate of the test subject’s walking velocity.
TABLE I. AVERAGE VALUES OF THE KULLBACK-LEIBLER DIVERGENCE FOR THE TWO COMPOSITE FADING MODELS

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\kappa$–$\mu$ / gamma</th>
<th>$\kappa$–$\mu$ / lognormal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Laboratory</td>
<td>Seminar</td>
</tr>
<tr>
<td>LOS Walking</td>
<td>Chest</td>
<td>0.00496</td>
</tr>
<tr>
<td></td>
<td>Waist</td>
<td>0.00662</td>
</tr>
<tr>
<td></td>
<td>Wrist</td>
<td>0.00338</td>
</tr>
<tr>
<td>NLOS Walking</td>
<td>Chest</td>
<td>0.00316</td>
</tr>
<tr>
<td></td>
<td>Waist</td>
<td>0.00459</td>
</tr>
<tr>
<td></td>
<td>Wrist</td>
<td>0.00147</td>
</tr>
</tbody>
</table>

TABLE II. AVERAGE PARAMETER ESTIMATES FOR THE $\kappa$–$\mu$ / GAMMA COMPOSITE FADING MODEL DURING THE LOS AND NLOS WALKING SCENARIOS FOR THE CHEST POSITION IN EACH ENVIRONMENT

<table>
<thead>
<tr>
<th>LOS</th>
<th>NLOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa$</td>
<td>$\beta$</td>
</tr>
<tr>
<td>Lab</td>
<td>1.54</td>
</tr>
<tr>
<td>Sem</td>
<td>3.36</td>
</tr>
<tr>
<td>OQ</td>
<td>1.94</td>
</tr>
</tbody>
</table>

V. CONCLUSION

In this paper, the shadowed fading in indoor wearable communications channels at 5.8 GHz has been investigated. Using the Kullback-Leibler divergence, it has been shown that the $\kappa$–$\mu$ / gamma composite fading model provided a better fit compared to the $\kappa$–$\mu$ / lognormal LOS shadowed fading model for the majority of the wearable fading channels considered in this study.

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