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Channel Characteristics of Dynamic Off-Body Communications at 60 GHz Under Line-of-Sight (LOS) and Non-LOS Conditions

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Abstract—This letter investigates the first-order characteristics of dynamic off-body communications channels at 60 GHz. In particular, we have studied signal propagation from a chest-worn millimeter-wave transmitter as an adult male walked toward and then away from a hypothetical base station. The mobile line-of-sight (LOS) and non-LOS (NLOS) channel measurements have been conducted in a diverse range of environments, including a hallway, an open office, an anechoic chamber, and an outdoor car park. In this study, we have decomposed the received signal into its path loss, large-scale, and small-scale fading components. The large-scale fading has been modeled using the gamma distribution, while the Rice and Nakagami-m distributions have been employed to describe the small-scale fading observed in the LOS and NLOS channel conditions, respectively. The results have shown that the estimated path loss exponents for the anechoic chamber and car park environments were greater than those obtained for the hallway and open office environments for both the LOS and NLOS walking scenarios. Across all environments, it was found that the gamma distribution provided an adequate fit to the large-scale fading. Additionally, the Rice and Nakagami-m distributions were found to well describe the small-scale fading for the LOS and NLOS walking scenarios, respectively.

Index Terms—Large-scale fading, millimeter-wave (mm-wave) communications, off-body communications, path loss, small-scale fading.

I. INTRODUCTION

RECENTLY, much interest has been generated toward the use of millimeter-wave (mm-wave) technologies for body-centric and wearable systems [1]–[6]. Advancements in this area mean that it will soon be feasible to use operating frequencies in the 59–66-GHz range to provide high bandwidth capabilities for these applications. Operating wearable systems within this part of the mm-wave spectrum will be attractive for many reasons, not least due to the small size of antenna that can be used [2], the lower interference, and much greater frequency reuse that can be achieved over smaller areas [5] compared to competing microwave technologies.

The characteristics of the on-body channel at 60 GHz have been studied in [2] and [3]. In [2], it was shown that the choice of antenna polarization is of great importance, and its impact is significantly influenced by the separation distance between the antenna and the body. In [3], the path loss and temporal fading were studied for differing polarizations. The authors found that the received signal often deviated significantly from its fitted path loss model irrespective of polarization. They also adopted a Gaussian distribution to characterize the temporal fading observed in on-body links at 60 GHz and subsequently derived a model for the standard deviation. Similarly, an off-body propagation model at 60 GHz was developed using theory in [6] and validated using empirical measurements. In [6], the path gain was considered for varying angular orientations of a human subject while maintaining a fixed separation distance between the transmitter (TX) and receiver (RX). Although these studies have made important contributions to our understanding of the mm-wave on- and off-body communications channels, they have only considered scenarios where the person has been stationary or made dynamic movements at a particular location.

Against this background, the contributions of this letter may now be highlighted as follows. For the first time, we investigate the first-order statistical characteristics of off-body communication channels operating at 60 GHz when a hypothetical user walks toward and away from a base station. These truly mobile measurements allow us to simultaneously record the path loss, large-scale, and small-scale fading to provide a detailed description of the channel. Furthermore, we perform our measurements over a diverse range of operating environments (both indoor and outdoor) to ensure the generality and applicability of our analysis. Finally, we employ well-known fading models to characterize the signal fluctuation in line-of-sight (LOS) and non-LOS (NLOS) conditions that allow the channels presented here to be readily reproduced.

II. MEASUREMENT SYSTEM AND EXPERIMENTS

The experiments conducted in this study were all carried out in the European (59–66 GHz) unlicensed Industrial, Scientific and Medical band at an operating frequency of 60 GHz. The measurement system consisted of a Hittite HMC6000L-P711E mm-wave TX module and Hittite HMC6001L-P711E mm-wave RX module, both containing on-chip, low-profile antennas. The in-package antennas offer +7.5 dB gain with a maximum...
The gamma distribution has been widely used to describe large-scale fading because of its excellent fit to empirical data.
and its mathematical tractability [9]. Letting $Z$ represent a gamma random variable that is used to model the large-scale fading, the corresponding cumulative distribution function (CDF) can be expressed with the shape parameter $\alpha$ and scale parameter $\beta$ as follows:

$$F_Z(z) = \frac{1}{\Gamma(\alpha)} \gamma(\alpha, \frac{z}{\beta})$$  \hspace{1cm} (2)

where $\Gamma(\cdot)$ is the gamma function and $\gamma(\cdot, \cdot)$ is the lower incomplete gamma function.

The Rice and Nakagami-\(m\) fading models have gained widespread use to describe small-scale fading for the LOS and NLOS channel conditions, respectively [10]. The CDF of the signal envelope, $R$, in a Rice fading channel can be expressed as follows:

$$F_R(r) = 1 - Q_1\left(\frac{s}{\sigma}, \frac{r}{\sigma}\right)$$  \hspace{1cm} (3)

where $Q_1(\cdot)$ denotes the Marcum Q-function and $s$ and $\sigma$ are the noncentrality and scaling parameters, respectively. From the parameters $s$ and $\sigma$, we can obtain well-known K factor that is defined as the ratio between the power in the dominant component ($s^2$) and the power in the scattered component ($2\sigma^2$).

In a Nakagami-\(m\) fading channel, the CDF of the signal envelope, $R$, can be expressed as

$$F_R(r) = \frac{\Gamma(m, m^2 r/\Omega)}{\Gamma(m)}$$  \hspace{1cm} (4)

where $m$ is the fading severity parameter and $\Omega = E[\cdot]$ is the mean power with $E[\cdot]$ denoting the expectation operator.

IV. RESULTS

A. Path Loss

The parameter estimates for $P_0$ and $n$ over all of the considered environments are given in Table I along with the body shadowing factor (BSF) that is defined as the difference between $P_0$ for the LOS and NLOS scenarios. As an example, Fig. 3(a) and (b) shows the path loss model fits for the LOS and NLOS in the hallway environment, respectively. As anticipated, for all of the environments, $P_0$ for the NLOS case was greater than that for the LOS due to the shadowing effects caused by the test subject’s body. When comparing the corresponding BSF for all environments, the body shadowing effects were more predominant in the anechoic chamber and car park environments than those observed in the hallway and open office environments. For both the LOS and NLOS scenarios, the estimated path loss exponents for the anechoic chamber and car park environments were greater than those for the hallway and open office environments. This was presumably due to the additional multipath

<table>
<thead>
<tr>
<th>Environments</th>
<th>$D_{SN}$ (dB)</th>
<th>Path loss</th>
<th>BSF (dB)</th>
<th>Large-scale fading</th>
<th>Small-scale fading</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>LOS</td>
<td>NLOS</td>
<td>LOS</td>
<td>NLOS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$n$ $P_0$ (dB)</td>
<td>$n$ $P_0$ (dB)</td>
<td>$\alpha$ $\beta$</td>
<td>$\alpha$ $\beta$</td>
</tr>
<tr>
<td>Hallway</td>
<td>12.7</td>
<td>1.13</td>
<td>42.3</td>
<td>1.18</td>
<td>58.5</td>
</tr>
<tr>
<td>Office</td>
<td>20.0</td>
<td>1.18</td>
<td>45.1</td>
<td>1.07</td>
<td>57.4</td>
</tr>
<tr>
<td>Anechoic</td>
<td>2.2</td>
<td>1.41</td>
<td>43.0</td>
<td>1.86</td>
<td>75.5</td>
</tr>
<tr>
<td>Car park</td>
<td>2.6</td>
<td>1.53</td>
<td>48.7</td>
<td>1.98</td>
<td>88.8</td>
</tr>
</tbody>
</table>

Fig. 3. Received signal power with the superimposed path loss fit and large-scale fading for the (a) LOS and (b) NLOS in the hallway environment.

B. Large-Scale Fading

To abstract the large-scale fading from the received signal power, the estimated path loss was first removed from the measurement data using the path loss parameters given in Table I. Then, the local mean was calculated by averaging over a distance of ten wavelengths (or equivalently seven samples). The parameter estimates for the gamma fading model were obtained using maximum likelihood estimation (MLE) performed in MATLAB. Fig. 3(a) and (b) shows the large-scale fading overlaid on the received signal power for the LOS and NLOS in the hallway environment, respectively. As an example of the model fitting obtained for the large-scale fading, Fig. 4 shows the CDFs of the gamma distribution fitted to the empirical data for the LOS and NLOS walking scenarios in each environment. It is clear that this probability model provides an adequate agreement with the measured data for all of the considered cases. To allow the reader to reproduce their own simulated large-scale fading data based on the empirical data reported here, Table I provides the parameter estimates for the gamma distribution over all four environments. Reviewing Table I, it is clear that the $\alpha$ parameter for the LOS large-scale data was greater than that for the NLOS, suggesting that the off-body channel for the LOS walking scenario was less susceptible to variations caused by large-scale fading compared to the NLOS case.

\(^2\) A Kolmogorov–Smirnov (K-S) test was performed at the 1% significance level for all large-scale fades above the 0.01 cumulative probability level. It failed to reject the null hypothesis that the data followed the specified distribution for 50% and 75% of all LOS and NLOS cases, respectively.
Fig. 4. Empirical CDFs of the large-scale fading with corresponding gamma CDF fit: (a) Hallway, (b) Open office, (c) Anechoic chamber, and (d) Car park.

C. Small-Scale Fading

The small-scale fading was extracted by removing both the path loss and large-scale fading from the measurement data as detailed above before transforming the data to its linear amplitude. Similar to the large-scale fading, the parameter estimates for the Rice and Nakagami-\(m\) fading models were obtained using MLE. Table I shows the parameter estimates for the Rice and Nakagami-\(m\) fading models for the LOS and NLOS walking scenarios, respectively. As expected, the \(K\) factor for the LOS case was greater than unity for all of the considered environments indicating that a strong dominant signal component existed. When comparing the \(K\) factors across all four environments, the \(K\) factors for the anechoic chamber and car park environments were larger than those for the hallway and open office environments. This was most likely due to the varying levels of scattered signals found in each environment. As shown in Table I, the scattered signal power \((2\sigma^2)\) for the hallway and open office environments was greater than the anechoic chamber and outdoor car park environments, while the dominant signal power \(s^2\) was almost the same for all of the environments. As shown in Table I, the \(m\) parameter estimates were greater than unity for all of the environments. This indicates that the fluctuations of the signal envelope observed in NLOS scenarios were less severe than those experienced in Rayleigh fading channels \((m = 1)\).

As an example of the model fitting for the small-scale fading, Fig. 5 shows the excellent fits of the Rice and Nakagami-\(m\) fading models to the measurement data for the LOS and NLOS cases, respectively.3 Interestingly, the shape of the CDFs for the anechoic chamber and car park environments (less multipath) were significantly different between the LOS and NLOS orientations. Specifically, the shape of the CDF for the LOS case was much more constricted (in fact, the small-scale fading becomes increasingly deterministic) than that observed for the NLOS condition. This suggests that LOS channels in sparse environments will not suffer from significant fluctuations due to small-scale fading.

3Similarly, the K-S test performed at the 1\% significance level for all small-scale fades above the 0.01 cumulative probability level failed to reject the null hypothesis for 50\% and 75\% of all LOS and NLOS cases, respectively.

V. Conclusion

The first-order characteristics of dynamic off-body communication channels at 60 GHz within indoor and outdoor environments have been investigated in terms of path loss, large-scale, and small-scale fading when the bodyworn node was positioned on the front-central chest region. From the estimated path loss at the reference distance, it was found that the impact of body shadowing on the off-body link was more pronounced in the anechoic chamber and car park environments, where there existed less opportunities for multipath signal propagation compared to the hallway and open office environments. Over all of the measurement scenarios considered in this study, the gamma distribution was found to well describe the large-scale fading. Furthermore, the Rice and Nakagami-\(m\) distributions provided a good fit to small-scale fading observed in the LOS and NLOS off-body links, respectively.

REFERENCES