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Random Receiver Orientation Effect on Channel Gain in LiFi Systems

Mohammad Dehghani Soltani, Zihong Zeng, Iman Tavakkolnia, Harald Haas, Majid Safari
LiFi R&D Center, Institute for Digital Communications, School of Engineering, The University of Edinburgh, UK
Email: {m.dehghani, zihong.zeng, i.tavakkolnia, h.haas, majid.safari}@ed.ac.uk

Abstract—Light-Fidelity (LiFi) has been considered as a complementary technology to radio frequency (RF) communications. The reliability of a LiFi channel highly depends on the availability and alignment of line-of-sight (LOS) links. In this study, we investigate the effect of receiver orientation including both polar and azimuth angles on the LOS channel gain in a LiFi system. The optimum tilt angle is calculated, which depends on both the user’s location and direction. The probability density function (PDF) of signal-to-noise ratio (SNR) is derived for on-off keying (OOK) modulation. Using the derived PDF of SNR, the bit-error ratio (BER) of OOK in an additive-white Gaussian noise (AWGN) channel with random orientation of the receiver is evaluated. It is shown that the effect of random orientation is negligible if the optimum tilt angle is chosen. Finally, we assess the effect of random orientation on the Shannon-Hartley upper bound capacity.

Index Terms—Random orientation, bit-error ratio (BER), light-fidelity (LiFi).

I. INTRODUCTION

It is anticipated that mobile data traffic will generate about 49 exabyte per month and the average global mobile connection speed will surpass 20 Mbps by 2021 [1]. The total number of smartphones (including phablets) will be over 50% of global devices and they will generate more than 86% of mobile data traffic by 2021 [1]. Therefore, both academia and industry are looking for alternative solutions to offload heavy traffic loads from radio frequency (RF) wireless networks. Light-Fidelity (LiFi) is a novel bidirectional, high-speed and fully networked wireless communication system that utilizes visible light and infrared in the downlink and uplink transmission, respectively [2]. Compared to RF networks, LiFi offers notable benefits such as providing enhanced security, utilizing a very large and unregulated bandwidth and energy efficiency. These advantages have put LiFi in the scope of recent and future research.

Device orientation can remarkably affect the users’ throughput. The majority of studies on optical wireless communications assume that the device always faces vertically upwards. Although this may be for the purpose of analysis simplification or due to lack of a proper model for device orientation, in a real life scenario users hold their device in a way that feels most comfortable. This can mean that the device is not always facing upwards and can have any random orientation. However, some studies have considered the impact of random orientation in their analysis [3]–[15]. Device orientation can be measured by the gyroscope and accelerometer embedded in every smartphone. Then, this information can be fed back to the access point (AP) by a limited-feedback scheme to enhance the system performance [16]–[18].

An AP selection algorithm for randomly-orientated UEs in LiFi networks is proposed in [3]. The orientation of UEs is modeled based on the Euler’s rotation theorem and using the rotation about each axis. By employing the same modeling for UE’s orientation, the handover probability and rate is evaluated in a standalone LiFi network with the consideration of random orientation and mobility of UEs in [4]. In [5], the handover probability is evaluated in a hybrid LiFi/RF-based network. The impact of the receiver tilt angle on channel capacity in visible light communication systems is shown in [6]. It is expressed that by properly tilting the receiver plane the channel capacity can be improved dramatically. The same approach is used in [7] to enhance the bit-error ratio (BER) of the on-off keying (OOK) modulation. In [8], the Newton method is employed to find the optimum tilt angle. By properly tilting the PD plane according to this optimum tilt angle, the signal-to-noise ratio (SNR) and spectral efficiency of M-QAM orthogonal frequency division multiplexing (OFDM) are enhanced. The optimum tilt angle of each PD for a single user multiple-input multiple output (MIMO) is obtained in [9]. It is shown that the cross-correlation of line-of-sight (LOS) channel gains at each PD is reduced. The impact of random orientation on LOS channel gain for randomly located users is investigated in [10].

The statistical channel gain is derived under the assumption of a Gaussian model for the polar angle. It is noted that none of these studies are supported by any experimental data. A more realistic model for the polar angle based on the experimental measurements is considered in [14]. Using this model, the impact of random orientation on BER of a DC biased optical OFDM (DCO-OFDM) as a use case is evaluated. Measurements and modeling of random orientations of cellphones are reported in [11]–[13]. It is shown that the probability density function (PDF) of the polar angle can be modeled as a Laplace distribution for sitting activities and a Gaussian distribution for walking activities [13]. All these works signify the importance of incorporating device orientation. In [15], the impact of random orientation on a multi-directional receiver using spatial modulation is studied.

In this study, we evaluate the impact of device orientation on the LOS channel gain. Then, we provide a closed form solution for the optimum tilt angle. The effect of narrow and wide field-of-view (FOV) on the LOS performance is assessed. It should be noted that both [6] and [7] study the...
effect of the tilt angle without considering the impact of the random orientation on BER and link capacity. Furthermore, an optimization problem is formulated in their studies to find the optimum tilt angle. We also derive the PDF of SNR for OOK modulation with the consideration of random orientation. Using the derived PDF of SNR, the BER of OOK is obtained as [19]:

\[
\cos \psi = \lambda_1 \sin \theta + \lambda_2 \cos \theta
\]

where \(\lambda_1\) and \(\lambda_2\) are given as:

\[
\lambda_1 = \frac{r}{d} \cos \left( \Omega - \tan^{-1} \left( \frac{y_a - y_b}{x_a - x_b} \right) \right),
\]

and

\[
\lambda_2 = \frac{h}{d}.
\]

where \(r = \sqrt{(x_a - x_c)^2 + (y_a - y_c)^2}\) is the horizontal distance between the AP and the UE.

It is reported in [13] and [20] that the polar angle can be modeled as a Laplace distribution, \(\theta \sim L(\mu_\theta, \sigma_\theta)\), where \(\mu_\theta\) and \(\sigma_\theta = \sqrt{2} \theta\) denote the mean value and scale parameter, respectively. These values are reported in [13] for static and mobile users. Moreover, it is shown that the azimuth angle can be modeled as a uniform distribution, \(\omega \sim U[0, 2\pi]\). The angle of the direction that the user is facing is defined as \(\Omega = \omega + \pi\). In fact, \(\Omega\) gives a better physical concept (compared to \(\omega\)), as it denotes the angle between the user’s facing direction and the X-axis.

III. ORIENTATION ANALYSIS AND ITS IMPACT ON THE LOS LINK

In this section, we evaluate the effect of \(\theta\) and \(\Omega\) on the LOS channel gain. According to [12], [13], [20], we assume that \(\theta \in [0^\circ, 90^\circ]\). Referring to (2), for a given location of UE, the LOS DC gain is maximum when \(\cos \psi\) is maximum. It takes its highest value when \(\Omega = \tan^{-1} \left( \frac{y_a - y_b}{x_a - x_b} \right) \pm \Omega_{ot}\) and

\[
\theta = \cos^{-1} \left( \frac{h}{d} \right) \pm \theta_{ot},
\]

where \(\theta_{ot}\) is the optimum tilt angle. In fact, the optimum tilt angle is the polar angle for which \(\psi = 0\) (or the LOS channel gain is maximum) as shown in Fig. 2. For any arbitrary location of the UE and a given \(\Omega \in R_\Omega\), the optimum tilt angle can be obtained as:

\[
\theta_{ot, \Omega} = \arg \max_{\theta} \cos \psi
\]

\[
= \arg \max_{\theta} \sqrt{\lambda_1^2 + \lambda_2^2} \cos \left( \theta - \tan^{-1} \left( \frac{\lambda_1}{\lambda_2} \right) \right)
\]

where \(\lambda_1 = r/d \cos \left( \Omega - \tan^{-1} \left( \frac{y_a - y_b}{x_a - x_b} \right) \right)\), and for \(\Omega \not\in R_\Omega\), \(\theta_{ot} = 0\); where \(R_\Omega\) defines the range of \(\Omega\) for which the AP is in the FOV of the UE.
For the given location of $L_4$ (shown in the subset of Fig. 2) and with $\Psi_c = 90^\circ$, Fig. 3 shows the curves of the LOS channel gain versus $\theta$ for various values of $\Omega$. Other simulation parameters are given in Table I. It can be seen that for the given location based on the angle $\Omega$, we have different values for the optimum tilt angle that can be determined according to (6). For instance, for $\Omega = 180^\circ$, we have $\theta_{\text{opt},\Omega} = 56^\circ$ and for $\Omega = 225^\circ$, we have $\theta_{\text{opt}} = 65^\circ$. For directions of $0^\circ$, $45^\circ$ and $315^\circ$ the optimum tilt angle is $0^\circ$ (or vertically upward). For any $\Omega \in \mathcal{R}_\Omega = [135^\circ, 315^\circ]$, the optimum tilt angle can be obtained by (6). While for $\Omega$ out of $\mathcal{R}_\Omega$, the optimum tilt angle is $\theta_{\text{opt}} = 0^\circ$. It should be noted that under the condition of $\Omega = \Omega_{\text{opt}}$ and $\theta = \theta_{\text{opt}}$ given in (5), the maximum LOS channel gain can be achieved.

The optimum tilt angles for the locations of $L_1$ and $L_2$ with $\Omega = 45^\circ$ equal to $64.76^\circ$ and $60.5^\circ$, respectively. However, for the locations of $L_4$ and $L_5$ with $\Omega = 45^\circ$, the optimum tilt angle is zero. It is also intuitive that when the UE faces toward the AP, there exists an optimum $\theta$ that results in the maximum LOS channel gain. However, if the UE faces in the opposite direction of the AP, then, $\theta = 0^\circ$ leads to the maximum value for the channel gain. As can be noticed from (6), the optimum tilt angle depends on the UE’s location and its direction and is independent of the FOV. In the following, we investigate the effect of FOV on the LOS channel gain.

For a given $\Omega$ and UE’s position, let’s define $\Psi_{\Omega,\text{min}}$ as the minimum FOV for which if $\Psi_c \leq \Psi_{\Omega,\text{min}}$, then the LOS channel gain is zero for any $\theta \in [0^\circ, 90^\circ]$. This minimum FOV is given as:

$$
\Psi_{\Omega,\text{min}} = \cos^{-1} \left( \sqrt{\lambda_1^2 + \lambda_2^2} \right).
$$

From (3), we have $\cos \Psi = \sqrt{\lambda_1^2 + \lambda_2^2} \cos (\theta - \tan^{-1} (\lambda_1 / \lambda_2))$. For a given UE’s location and $\Omega$, for any $\theta \in [0^\circ, 90^\circ]$, $\cos \Psi \leq \sqrt{\lambda_1^2 + \lambda_2^2}$. On the other hand, if $\cos \Psi \leq \cos \Psi_c$, the LOS channel gain is zero. Consequently, for $\Psi_c \leq \cos^{-1} \left( \sqrt{\lambda_1^2 + \lambda_2^2} \right)$, the LOS channel gain is always zero. The physical concept of $\Psi_{\Omega,\text{min}}$ is that for a given UE’s location and $\Omega$, with $\Psi_c \leq \Psi_{\Omega,\text{min}}$, the AP is always out of the UE’s FOV for all $\theta \in [0^\circ, 90^\circ]$.

Fig. 4-(a) illustrates the impact of different FOVs on the LOS channel gain versus $\Omega$ for $L_1$ and $L_5$ with $\Omega = 45^\circ$. It can be observed that the UE’s FOV affects the LOS channel gain remarkably. As it can be seen, narrower FOV results in a smaller range of $\theta$ for which the LOS channel gain is non-zero. In other words, the user is able to tilt the device more without missing the LOS link. Furthermore, it can be noticed that if the UE is located at $L_5$, it is more greatly affected by the reduction of the FOV compared to the position $L_1$. Based on (7), the minimum FOV that ensures the visibility of LOS link for these two locations, $L_5$ and $L_1$, are $\Psi_{\Omega,\text{min}} = 64.12^\circ$ and $\Psi_{\Omega,\text{min}} = 1^\circ$, respectively. This means that for the location of $L_5$ and $\Omega = 45^\circ$, with $\Psi_c \leq 64.12^\circ$, the LOS channel gain is out of the UE’s FOV for all $\theta \in [0^\circ, 90^\circ]$. Therefore, in order to guarantee the visibility of the AP in the UE’s FOV, the condition $\Psi_c \geq \Psi_{\Omega,\text{min}}$ should be fulfilled. However, for the location of $L_1$ and $\Omega = 45^\circ$, a narrow FOV can guarantee the visibility of AP for all polar angles of $\theta \in [0^\circ, 90^\circ]$. This can be considered as one important metric in design of FOV to mitigate co-channel interference.

For a given $\theta$ and UE’s position, let’s define $\Psi_{\theta,\text{min}}$ as the minimum FOV for which if $\Psi_c \leq \Psi_{\theta,\text{min}}$ then LOS channel gain is zero. This $\Psi_{\theta,\text{min}}$ is given as:

$$
\Psi_{\theta,\text{min}} = \cos^{-1} (\kappa_1 + \kappa_2) = | \tan^{-1} \left( \frac{\lambda_2}{\lambda_1} \right) - \theta |. \tag{8}
$$

Detailed proof of (8) is provided in Appendix A. To better understand the physical concept of $\Psi_{\theta,\text{min}}$, consider the case with $\theta = 0^\circ$ (vertically upward device), the minimum FOV that ensures non-zero LOS channel gain at any arbitrary location is $\Psi_{\theta,\text{min}} = \tan^{-1} (\lambda_2 / \lambda_1)$. In other words, if $\Psi_c$ is less than $\Psi_{\theta,\text{min}}$, the LOS channel gain is zero. The effect of different FOV on the LOS channel gain versus $\Omega$ for $L_1$ and $L_5$ with $\theta = 41^\circ$ (this value is reported in [13] as the mean of experimental data for sitting users) are shown in Fig. 4-(b). According to (8), the smallest FOV for which the LOS channel gain is still non-zero would be $\Psi_{\theta,\text{min}} = 23.1^\circ$ for $L_5$ and $\Psi_{\theta,\text{min}} = 23.76^\circ$ for $L_1$. This can be confirmed from the results shown in Fig. 4-(b) where for $\Psi_c = 24^\circ$, the LOS channel gain is almost zero for all values of $\Omega$.

**TABLE I: Simulation Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver FOV</td>
<td>$\Psi_c$</td>
<td>$90^\circ$</td>
</tr>
<tr>
<td>LED half-intensity angle</td>
<td>$\Phi_{1/2}$</td>
<td>60$^\circ$</td>
</tr>
<tr>
<td>PD responsivity</td>
<td>$R_{PD}$</td>
<td>1 A/W</td>
</tr>
<tr>
<td>Physical area of a PD</td>
<td>$A$</td>
<td>1 cm$^2$</td>
</tr>
<tr>
<td>Transmitted electrical power</td>
<td>$P_{\text{trans}}$</td>
<td>1 W</td>
</tr>
<tr>
<td>Downlink bandwidth</td>
<td>$f$</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Noise power spectral density</td>
<td>$N_0$</td>
<td>$10^{-21}$ A$^2$/Hz</td>
</tr>
<tr>
<td>Vertical distance of UE and AP</td>
<td>$h$</td>
<td>2 m</td>
</tr>
</tbody>
</table>
IV. ANALYSIS OF BER AND LINK CAPACITY

A. SNR Statistics

The received electrical SNR of OOK modulation in LiFi systems can be obtained as follows:

\[ S = \frac{R_{PD}^2 H^2 P_{elec}^2}{N_0 B}, \]  

(9)

where \( R_{PD} \) represents the PD responsivity. The single sided noise spectral density is \( N_0 \) and \( B \) is the modulation bandwidth. The channel gain, \( H \), can be obtained by (1). Based on the experimental measurement of the device orientation reported in [13], the polar angle, \( \theta \), follows a truncated Laplace distribution between 0 and \( \pi/2 \) for sitting activities. For walking activities, the Gaussian distribution matches the experimental measurements more closely. The distribution of the LOS channel gain is reported to follow a clipped Laplace distribution as [13], [14]:

\[ f_{H}(h) = \frac{\exp \left( -\frac{h - \mu_H}{b_H} \right)}{b_H \left( 2 - \exp \left( -\frac{\max - \mu_H}{b_H} \right) \right)} + c_H \delta(h), \]  

(10)

where the constant \( c_H \) is given as [14]:

\[ c_H = F_{\cos \theta}(\cos \Psi_c), \]

(11)

\[ \approx \begin{cases} 
1 - \frac{1}{2} \exp \left( -\frac{h_0 - \mu_H}{b_H} \right), & \theta_c < \mu_H \\
\frac{1}{2} \exp \left( -\frac{h_0 - \mu_H}{b_H} \right), & \theta_c \geq \mu_H 
\end{cases} \]

and \( h_0 = \cos^{-1} \left( \frac{\cos \Psi_c}{\sqrt{h_0^2 + \lambda^2}} \right) + \tan^{-1} \left( \frac{\lambda}{h_0} \right) \). The parameters \( \mu_H \) and \( b_H \) are the mean and scaling factor of the LOS channel gain, respectively, which are given as:

\[ \mu_H = \frac{H_0}{d_m + \frac{1}{2}} (\lambda_1 \sin \mu_H + \lambda_2 \cos \mu_H), \]  

(12)

\[ b_H = \frac{H_0}{d_m + \frac{1}{2}} |\lambda_1 \cos \mu_H - \lambda_2 \sin \mu_H|, \]  

(13)

where \( H_0 = \frac{(m+1)d_m^m}{b_0} \) and \( b_0 = \sqrt{\sigma^2/2} \). The factors, \( \lambda_1 \) and \( \lambda_2 \), are given in (4). The parameters \( \mu_H \) and \( \sigma_H \) are the mean and standard deviation of the polar angle, which are obtained based on the experimental measurements. For static users, they are reported as \( \mu_H = 45^\circ \) and \( \sigma_H = 7.3^\circ \). The support range of \( f_{H}(h) \), is \( h_{\min} \leq h \leq h_{\max} \) where \( h_{\min} \) and \( h_{\max} \) can be determined as:

\[ h_{\min} = \begin{cases} 
\frac{H_0}{d_m + \frac{1}{2}} \min \{\lambda_1, \lambda_2\}, & \text{o.w.} \\
\frac{H_0}{d_m + \frac{1}{2}} \sqrt{\lambda_1^2 + \lambda_2^2}, & \text{if } \lambda_1 \leq 0
\end{cases} \]  

(14)

\[ h_{\max} = \begin{cases} 
\frac{H_0}{d_m + \frac{1}{2}} \lambda_2, & \text{if } \lambda_1 > 0 \\
\frac{H_0}{d_m + \frac{1}{2}} \sqrt{\lambda_1^2 + \lambda_2^2}, & \text{if } \lambda_1 \leq 0
\end{cases} \]  

(15)

Using the fundamental theorem of determining the distribution of a random variable [21], the probability density function (PDF) of SNR can be obtained as follows:

\[ f_S(s) = f_H \left( \sqrt{s/S_0} \right) \frac{2S_0}{\sqrt{S_0}} \frac{\exp \left( -\frac{|s - \sqrt{S_0}h_{\max}|}{\sqrt{2S_0}b_H} \right)}{\sqrt{2\pi b_H}} + c_H \delta(s), \]  

(16)

where \( S_0 = \frac{p_0^2 \sigma_{\text{opt}}^2}{N_0 B} \) and with the support range of \( s \in (s_{\min}, s_{\max}) \), where \( s_{\min} = S_0 h_{\min}^2 \) and \( s_{\max} = S_0 h_{\max}^2 \), with \( h_{\min} \) and \( h_{\max} \) given in (14) and (15), respectively.

B. BER Performance

In this subsection, we aim to evaluate the effect of UE orientation on the BER performance of a LiFi-enabled device as one use case. The BER is one of the common metrics to evaluate point-to-point communication performance. Assuming the OOK modulation, the average BER of the communication link can be obtained as [22]:

Fig. 4: The effect of different FOVs on the LOS channel gain.
where $Q(\cdot)$ is the Q-function. Substituting (16) into (17) and calculating the integral from $s_{\min}$ to $s_{\max}$, we get the average BER of the OOK modulation in an AWGN channel with random orientation.

The gap between these two scenarios becomes larger after a certain point, extra transmitting power does not reduce the BER of the random orientation scenario. However, the BER of the fixed scenario decreases as the transmission power increases. The other interesting observation is the remarkable improvement in BER of the vertically upward scenario outperforms the random orientation. As can be seen from these results, the fixed orientation scenario outperforms the random orientation one. The gap between these two scenarios becomes larger for higher SNRs. The reason for this is that in some cases with the random orientation the AP is out of the UE’s FOV and hence an error occurs (see [14]). Therefore, after a certain point, extra transmitting power does not reduce the BER of the random orientation scenario. However, the BER of the fixed scenario decreases as the transmission power increases. The other interesting observation is the remarkable gap between the vertically upward scenario and random orientation one. This confirms the significance of considering the fixed random orientation in the analysis and performance evaluation.

C. Upper Bound on Link Capacity

The upper bound of capacity in an additive white Gaussian noise (AWGN) channel is $C = B \log_2(1 + s)$ based on the Shannon-Hartley theorem. However, with consideration of random orientation, this upper bound is given as:

$$C = \int_{s_{\min}}^{s_{\max}} \left( \frac{\sqrt{S} - \sqrt{S_0} h_{\text{th}}} {\Delta \sqrt{s}} \right) \log_2(1 + s) ds.$$

where $\Delta = 2B^{-1} b_{\text{th}} \sqrt{S_0} \left( 2 - \exp \left( \frac{b_{\text{max}} - b_{\text{th}}}{b_{\text{th}}} \right) \right)$. Noting that $I = \int_{s_{\min}}^{s_{\max}} c_H \delta(s) \log_2(1 + s) ds = 0$ (since if $s_{\min} > 0$, due to the delta function $I = 0$ and if $s_{\min} = 0$, $I = c_H \log_2(1) = 0$). Therefore, the integral in (18) can be rewritten as (19) given at the top of next page. This integral does not have a closed form and can be obtained numerically.

Same scenarios described in previous subsection are considered here. As presented in Fig. 6, compared to the other scenarios, the optimum tilt angle scenario provides the maximum link capacity. This would be the upper bound on link capacity at the given location of $L_1$. As can be seen, the random orientation and fixed orientation scenarios have almost the same performance while the gap between them and vertically upward scenario is remarkable.

V. CONCLUSIONS AND FUTURE WORKS

In this paper, the effect of receiver orientation including both polar and azimuth angles on LOS channel gain in a LiFi system is studied. We derived the optimum tilt angle, which depends on both user’s location and direction. The PDF of SNR is derived for OOK modulation. Then, using the derived PDF of SNR, the BER of OOK in an AWGN channel with the random orientation of the receiver is evaluated. It is shown that the random orientation effect can be neglected when the optimum tilt angle is chosen. Finally, we assessed the effect of random orientation on the Shannon-Hartley upper bound capacity.
\[ C = \frac{1}{\Delta} \left\{ \begin{array}{ll}
\int_{\sqrt{S_0\mu H}}^{\sqrt{S_{min}}} \exp \left( - \frac{s - \sqrt{S_0\mu H}}{\sqrt{S_{0}b}} \right) \log_2 (1 + s^2) ds, & \sqrt{S_0\mu H} < \sqrt{S_{min}} \\
\int_{\sqrt{S_{min}}}^{\sqrt{S_{max}}} \exp \left( \frac{s - \sqrt{S_0\mu H}}{\sqrt{S_{0}b}} \right) \log_2 (1 + s^2) ds + \int_{\sqrt{S_{max}}}^{\sqrt{S_{min}}} \exp \left( - \frac{s - \sqrt{S_0\mu H}}{\sqrt{S_{0}b}} \right) \log_2 (1 + s^2) ds, & \sqrt{S_{min}} < \sqrt{S_0\mu H} < \sqrt{S_{max}}
\end{array} \right. \] (19)

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APPENDIX

PROOF OF (8)

For a given UE’s location, the \( \cos \psi \) can be expressed as:

\( \cos \psi = \kappa_1 \cos \left( \Omega - \tan^{-1} \left( \frac{y_u - y_a}{x_u - x_a} \right) \right) + \kappa_2, \) (20)

where \( \kappa_1 \) and \( \kappa_2 \) are given as:

\[ \kappa_1 = \frac{r}{d} \sin \theta, \quad \kappa_2 = \frac{h}{d} \cos \theta. \] (21)

Since \( \theta \in [0^\circ, 90^\circ] \), so \( \kappa_1 \geq 0 \) and \( \kappa_2 \geq 0 \). Thus, based on (20), we always have \( \cos \psi \leq \kappa_1 + \kappa_2 \) for any arbitrary value of \( \Omega \). Therefore, if \( \Psi_\epsilon \leq \cos^{-1} \left( \kappa_1 + \kappa_2 \right) = \Psi_{\theta, \text{min}} \), the LOS channel gain is zero for all \( \Omega \). On the other hand, we have:

\[ \kappa_1 + \kappa_2 = \frac{r}{d} \sin \theta + \frac{h}{d} \cos \theta. \] (22)

Let’s define the auxiliary angle, \( \beta = \sin^{-1} \left( \frac{r}{d} \right) \). Recalling that \( d = \sqrt{x^2 + y^2} \), it is clear that \( \frac{r}{d} = \cos \beta \). Replacing for \( \frac{r}{d} \) and \( \frac{h}{d} \) by \( \sin \beta \) and \( \cos \beta \), respectively, then, (22) can be expressed as:

\[ \kappa_1 + \kappa_2 = \sin \beta \sin \theta + \cos \beta \cos \theta = \cos \left( \theta - \beta \right). \] (23)

Hence, \( \Psi_{\theta, \text{min}} = \cos^{-1} \left( \kappa_1 + \kappa_2 \right) = |\beta - \theta| \). Using the triangle rules, \( \beta \) can be denoted as \( \beta = \tan^{-1} \left( \frac{r}{h} \right) \). Thus,

\[ \Psi_{\theta, \text{min}} = \cos^{-1} \left( \kappa_1 + \kappa_2 \right) = | \tan^{-1} \left( \frac{r}{h} \right) - \theta |. \]

This completes the proof of (20).

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