The Effect of Natural Light on the Performance of Visible Light Communication Systems

Mahmoud Beshr, Ivan Andonovic, and Moustafa H. Aly

Abstract—Visible Light Communication (VLC) offers advantages of low energy consumption, licence free and RF interference free operation. One application area for VLC is in the provision of health centred services circumventing issues of interference with any biomedical device within the environment. VLC performance is affected by natural light restricting system availability and reliability. The paper presents an analysis of the performance of VLC systems under different meteorological conditions. The evaluation considered the impact of natural light as a function of different reflection surfaces in different room sizes.

Keywords—Impulse response, Visible light communication, Natural light, Performance analysis.

I. INTRODUCTION

Concerns about energy consumption are leading to the phasing out of incandescent sources stimulating rapid growth in the use and development of solid-state sources [4], [6]. Visible Light Communication (VLC) overlays harness these light emitting diodes (LEDs) for communication purposes at the same time. VLC has the potential to provide high data rate, low energy consumption, license free and interference less operation especially in environments where issues with RF interference are a fundamental barrier.

VLC systems are affected by natural light (weather conditions). The performance of VLC systems has been evaluated but without rigorous consideration of the impairments owing to natural light [1], [2], [4]. In previous research, natural light has been treated as Gaussian noise; this research takes into consideration the variation of natural light intensity over the year under different meteorological conditions. Moreover the VLC impulse response has to date been determined solely for single reflection for standard room sizes [1], [4].

Here an evaluation of the impulse response for different room sizes for both line-of-sight (LOS) and non-line of sight (NLOS) components up to the fifth reflection is presented.

The paper is organized as follows. Section I presents the VLC system architecture and its mathematical representation. Section II presents the impulse response of the system for LOS and NLOS components. Section III summarizes the foundation to treating natural light and simulation conditions.

Section IV presents VLC system performance considering natural light. Section V contains the conclusions.

II. SYSTEM MODEL

It is assumed that the optical path is subject to multiple reflections [2] (Fig. 1). It is also assumed that the transmitter is positioned on the ceiling of the room with the receiver on the floor. The transmitter radiated light is characterised by $\Phi_1$, equal to the viewing angle of the LED. The beam is incident with angle $\theta_1$ after distance $d$ from source to reflection point.

![Fig. 1 Geometry of the analysis environment comprising n transmitter LEDs and a receiver photodiode (PD)](image)

The link geometry shown in Fig. 1 is considered in order to calculate the impulse response for the case of multiple reflections and multiple sources. The impulse response is given by Equation (1), where $N_{LED}$ is the total number of LEDs. It was assumed that each LED in the transmitter emits equal power. The response after $k$-bounces of the $n^{th}$ LED source is [2], [3], and [7]:

$$h(t) = \sum_{n=1}^{N_{LED}} \sum_{k=0}^{\infty} h^{(k)}(t; \Phi_n)$$

(1)

$$h^{(k)}(t; \Phi_n) = \int_{0}^{\infty} \left[ L_1 L_2 \ldots L_{K+1} f_n^{(k)} \left( \frac{\theta_{K+1}}{\Phi_{GVD}} \right) \right] \delta(t - \frac{d_1 + d_2 + \ldots + d_k}{c}) d A_{ref}, \quad k \geq 1$$

(2)

where

$$L_1 = \frac{A_{ref} (m + 1) \cos \phi_1 \cos \theta_1}{2\pi d_1^2}$$

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\[ L_2 = \frac{A_{\text{ref}} \cos \phi_2 \cos \theta_2}{\pi d_2^2} \]

\[ L_{k+1} = \frac{A_{\text{ref}} \cos \phi_{k+1} \cos \theta_{k+1}}{\pi d_{k+1}^2} \]

where \( L_{k+1} \) is the pass loss for each reflection, the directivity of the light beam is controlled by the mode number of radiation, \( m = -1/\log_2(\cos \phi_{k+2}) \) and it is governed by the LED viewing angle \((2\phi_{k+2})\). It is noted that the more distance \((dk)\) between transmitter and receiver the less power received. \( \theta k \) and \( \phi k \) are the angles of incidence and irradiance respectively. The field of view is the critical design parameter photodiode can only detects light beam with angle less than FOV. Hence it is considered as acceptance angle. The rectangular function \( \text{rect}(x) \) is given by \([2],[5]\).

\[ \text{rect}(x) = \begin{cases} 1 & \text{for } |x| \leq 1 \\ 0 & \text{for } |x| > 1 \end{cases} \]

The constant term, \( c \), is the speed of light. Let \( \Gamma_n^{(k)} \) in Equation (2) denotes the power of the reflected ray after \( k \)-bounces from the \( n \)-th LED. The reflected power can be calculated as:

\[ \Gamma_n^{(k)} = \int \Phi_n(\lambda) \rho_1(\lambda) \rho_2(\lambda) \ldots \rho_k(\lambda) d\lambda \]

The reduced form of Equation (4) with lower accuracy is described by:

\[ \overline{\Gamma}_n^{(k)} = \bar{P}_n \bar{p}_{n,1} \bar{p}_{n,2} \ldots \ldots \bar{p}_{n,k} \]

where \( \bar{p}_{n,k} = \frac{1}{n} \int \Phi_n(\lambda) \rho_k(\lambda) d\lambda \) is the average reflectance, and \( P_n = \int \Phi_n(\lambda) d\lambda \) is the radiant power from the \( n \)-th LED source for \( k=1 \). Equations (4) and Equation (5) have the same value \([2]\):

\[ \Gamma_n^{(1)} = \Gamma_n^{(1)} = \int \Phi_n(\lambda) \rho_1(\lambda) d\lambda \]

(6)

However, the differences are more obvious for the case of higher order reflections; the photodiode position for LOS is given as \([2],[7]\):

\[ h^{(0)}(t; \Phi_0) = L_0 \text{rect}(\frac{\theta_0}{\text{FOV}}) \delta(t - \frac{d_0}{c}) \]

(7)

where

\[ L_0 = \frac{A_{\text{ref}}(m+1)\cos^m \phi_0 \cos \theta_0}{2\pi d_0^2} \]

A. Signal to Noise Ratio (SNR)

In order to compute the SNR and concomitant Bit Error Rate (BER), it was assumed that the transmitter sends data at a bit rate \( R_b \) using ON-OFF keying (OOK) with NRZ pulses. The transmitted average power is \( P_t \), the received average power is \( P_r = H(0)P_t \), where the channel DC gain is determined as detailed in the previous section. The channel is assumed to be distortion free with gain \( H (f) = H (0) \) for all frequencies. The receiver pre-amplifier is followed by an equalizer. Each sample of the equalizer output contains noise with a total variance given by \([2],[3],[7],[8]\):

\[ \sigma_{\text{total}}^2 = \sigma_{\text{shot}}^2 + \sigma_{\text{thermal}}^2 \]

(8)

The shot noise is;

\[ \sigma_{\text{shot}}^2 = 2qR_{p_n} I_2 R_b \]

(9)

while the thermal noise variance is given by:

\[ \sigma_{\text{thermal}}^2 = \frac{4kT R_b}{R_{p_n}} I_2 + \frac{16n^2kT}{\theta_m} \left( \Gamma + \frac{1}{\theta_m R_b} \right) C_n^2 I_2 R_b^3 + \frac{4n^2kT R_b}{\theta_m} \]

(10)

The SNR is expressed using Equation (8), Equation (9), Equation (10);

\[ SNR = \frac{(R_b)^2}{\sigma_{\text{total}}} \]

and the BER is given by;

\[ BER = Q\left(\sqrt{SNR}\right) \]

(12)

where

\[ Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-y^2/2} dy \]

(13)

III. SYSTEM IMPULSE RESPONSE

### TABEL 1

<table>
<thead>
<tr>
<th>LIGHT REFLECTION FOR SINGLE SOURCE IN 15M<em>15M</em>3M ROOM SIZE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plaster Wall (W)</td>
</tr>
<tr>
<td>------------------</td>
</tr>
<tr>
<td>First Reflection</td>
</tr>
<tr>
<td>Second Reflection</td>
</tr>
<tr>
<td>Third Reflection</td>
</tr>
<tr>
<td>Fourth Reflection</td>
</tr>
<tr>
<td>Fifth Reflection</td>
</tr>
<tr>
<td>Transmitter</td>
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<tr>
<td>Receiver location (10,15,3)</td>
</tr>
</tbody>
</table>

The performance of the system was evaluated both for a big room (Table I) and standard office room (Table II) with the transmitter positioned on the ceiling and the receiver on the floor. The rooms are empty and unfurnished. Light diffusely reflected on plastic wall, plaster wall, floor and ceiling surfaces are considered. The room is equipped with five
identical transmitters at different locations and all transmit the same data in phase. The system was evaluated using a Matlab program and results were validated with [2]. The transmitter emitting 1W power was deployed in empty rooms of size 15m*15m*3m and 5m*5m*3m respectively. Light reflections were considered until the fifth reflection. LOS and NLOS components were simulated for different surfaces and summarized in Table I and Table II.

| TABLE II | LIGHT REFLECTION FOR SINGLE SOURCE AT 5M*5M*3M ROOM SIZE |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Plaster Wall (W) | Floor (W) | Ceiling (W) | Plastic Wall (W) | Time Delay (s) |
| First Reflection | 0.0159 | 0.0123 | 0.0080 | 0.0159 | 1.0000 |
| Second Reflection | 2.8547 | 2.2124 | 1.4273 | 2.8547 | 2.0000 |
| Third Reflection | 7.5382 | 5.8421 | 3.7691 | 7.5382 | 4.0000 |
| Fourth Reflection | 4.9239 | 3.8161 | 2.4620 | 4.9239 | 5.0000 |
| Fifth Reflection | 1.2567 | 0.7394 | 0.6285 | 9.7394 | 8.0000 |
| LOS component | = 0.0159 W |

Receiver location (3,2.5,3)

IV. NATURAL LIGHT

The performance of VLC systems is impaired by shot noise from natural light, illumination light and thermal noise due to receiver load resistor at photodiode. Natural light intensity varies year round depending on factors such as time of day, meteorological conditions, communication path direction relative to the sun, receiver FOV and receiver optical system parameters e.g. photodiode sensitivity. For example, during summer periods when natural light intensity is highest, the system may suffer catastrophic failure due to high intensity noise, especially if the detector is subject to direct incidence of natural light [8], [9], [10].

Two classes of natural light affect systems performance: direct and indirect. On average, indirect is between 10%-20% of the direct natural light [9]. Since Shot Noise is highly dependent on the sunlight level captured within the receiver FOV, and its intensity depends on whether it is direct or reflected, it is important to characterize the likelihood and the frequency of direct against indirect sunlight to better define system availability and reliability [9], [10].

According to [1], natural light has been categorized to five main levels,

- clear night with full moon,
- summer's day with clear sky,
- summer's day with overcast sky,
- winter's day with clear sky,
- Winter's day with overcast sky

These categories were characterised using a cosine corrected light sensor [2]; light can enter the sensor within a 180 degrees hemisphere. Natural light can thus be categorised in Table III.

| TABLE III | NATURAL LIGHT LEVELS [2] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Natural light | Intensity (LUX) |
| Clear night, Full moon | 0.3 |
| Winter's day, Overcast sky | 900-2000 |
| Summer's day, Overcast sky | 4000-20000 |
| Winter's day, Clear Sky | Up to 9000 |
| Summer's day, Clear Sky | Up to 100,000 |

According to [1], [9], no fixed conversion factors exist to convert light intensity from LUX to W/m². For the analysis here, LUX is converted to watts/m² for day light by multiplying with 0.00402, only appropriate for the visible light band of interest [2].

V. SYSTEM PERFORMANCE

Signal to Noise Ratio (SNR) was calculated for each natural light category listed in Table III. Monte Carlo simulation together with a Matlab routine were used to model the system, simulate and evaluate the average SNR for each light category. The analysis was carried out for a 100 Kbit/s data rate and 0.54 A/W photodiode responsivity.

Clear Night Full Moon

Fig. 2 Average SNR in clear night, full moon

Fig. 2 shows that average SNR for plaster wall, ceiling, floor and plastic surfaces; the effect of natural light was weak since the SNR is relatively high. The Average SNR for plastic wall (lowest surface reflectivity) was ~30 dB; ~46 dB for plaster walls (highest surface reflectivity); ~42dB and ~45dB for ceiling and floor respectively. The system can provide a 10⁻¹¹ BER in this case of natural light and data rate.
Winter's Day, Overcast Sky

For this case, the average SNR for plastic walls reduces to ~28 dB compared (Fig. 3) to the clear night full moon case. For plaster walls, a slight decrease to ~44 dB is observed; for ceiling and floor surfaces it decreased to ~39 dB and ~42 dB respectively.

Winter Day Clear Sky

A clear sky condition further degrades the SNR. The SNR reduces to ~27 dB for plastic walls and ~43 dB for plaster walls. The SNR for floor and ceiling surfaces was lower, but the required level of BER was still attainable.

Summer's Day, Overcast Sky

In the summer when the sunlight intensity is highest - in the 4000 to 20000 LUX range - the shot noise increases reducing the SNR from ~40 dB to ~24 dB for plastic walls (Fig. 4) compared to clear night full moon case. Moreover the SNR decreases to ~35 dB, ~39 dB and ~41 dB for ceiling, floor and plaster wall surfaces respectively. A slight degradation was evident on comparison of winter to summer for the overcast sky cases.

Summer's Day, Clear Sky

During a sunny day and the sky is clear, sunlight intensity may reach up to 100,000 LUX. As a consequence, the SNR decreases to ~20 dB for plastic walls. In the case of plaster walls, the SNR did not degrade by the same percentage due to high reflectivity, being ~40 dB (Fig. 6). Moreover the SNR decreases to ~34 dB and ~37 dB for ceiling and floor surfaces respectively.
VI. CONCLUSION

The impact of natural light on VLC system performance was evaluated for a number of conditions; clear night-full moon, summer's day - clear sky, winter's day - clear sky, summer's day - overcast sky and winter's day - overcast sky (Table IV). The evaluation also considered a range of surfaces; plaster walls provided the best SNR performance when compared to floor, plastic walls and ceiling surfaces. NLOS component decreases for every reflection considered, especially in relatively spacious environments (15m*15m*3m). The fourth and fifth reflections can be neglected due to the negligible effect on system performance. As expected, the lowest SNR (and BER) occurred for summer's day, clear sky since the natural light intensity reaches its maximum.

<table>
<thead>
<tr>
<th>Natural light level/ SNR (dB)</th>
<th>Plastic wall</th>
<th>Plaster wall</th>
<th>Floor</th>
<th>Ceiling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear night full moon</td>
<td>30</td>
<td>46</td>
<td>45</td>
<td>42</td>
</tr>
<tr>
<td>Summer's day with clear sky</td>
<td>20</td>
<td>40</td>
<td>37</td>
<td>34</td>
</tr>
<tr>
<td>Summer's day with overcast sky</td>
<td>24</td>
<td>41</td>
<td>39</td>
<td>35</td>
</tr>
<tr>
<td>Winter's day with clear sky</td>
<td>27</td>
<td>43</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>Winter's day with overcast sky</td>
<td>28</td>
<td>44</td>
<td>42</td>
<td>39</td>
</tr>
</tbody>
</table>

In summary, the availability of VLC systems is a strong function of the level of natural sunlight and indeed may be compromised under high intensity scenarios such as encountered during the summer.

REFERENCES