A Design for Wireless Communication System for Smart Ports

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ABSTRACT

Communication systems and infrastructures are considered main enabler for smart ports. The Light Fidelity (LIFI) communication system can provide cost effective, easy to install, fast, and secure communication system as it can make use of already installed lighting systems in the ports to provide communication link. Thus, LIFI ensures interference free with other radio frequency communication systems. Given the privileges of LIFI communication systems, this paper aims to test and evaluate the adoption of LIFI communication systems in ports and how LED layout can affect the system. A design tool for system planning is developed to determine optimum LED placement that provides a specified system performance, conforms to illumination standards and minimizes the variation of the Signal-to-Noise Ratio (SNR) across the communication link thereby maintaining a good quality of service (QoS). The evaluation of SNR, BIT Error rate (BER), data rate and illumination level are conducted for representative metrological conditions over the year to ensure smart port system performance and efficiency.

Keywords: Light Fidelity (LIFI) Performance, LED Layout, Smart Ports, Metrological Conditions

I. INTRODUCTION

Although the industry of ports and container shipping is often regarded as being conservative and resistant to change due to its nature and processes, the utilization of recent communication system technologies can lead to major enhancements in port system efficiency [1],[37]. One of the main pillars that are promising in this regard is smart ports. Despite being promising, smart ports face many challenges, one of these key challenges is to have a well-established wireless communication system.
that provides connections between different units, facilities, containers and moving trucks[1], [2],[36]. To have such a system, a total infrastructure renovation is required and this is considered the main barrier that faces smart ports from both economic and operational perspectives. Economically, infrastructure renovation requires very high cost which may not be feasible given the economic challenges currently facing the whole world. Operationally, maintaining this infrastructure to ensure its sustainability is also challenging given the advanced technologies required. One of the ways to overcome these challenges is the Light Fidelity (LIFI) communication system as it ensures different competitive advantages that make LIFI system preferred among different communication system technologies[31-37].

LIFI system is used to help address the mismatch, presenting an interesting set of characteristics; low power consumption, license free and RF interference free operation whilst offering the option to create and isolate a wireless cell by direct control of the light signal. Of the recent generations of wireless technologies, the Long-Term Evolution (LTE) depends on extensive spectrum reuse and well-designed cells. The range of techniques under the LTE umbrella increases system capacity but at a cost of a complex interference management overhead [1], [2]. The market for wireless networks is extending to be applied to have reliable, secure and economic communication system. Ultimately, it harnesses the unrelenting growth in the deployment of solid-state lighting based on LEDs [1], [3-5], [34].

LED layout is defined as the distribution of transmitters across the ceiling of a room (indoor environment for smart port), a key factor that modulates system performance. The location of the transmitters and, in turn, the relative positions of the transmitters with respect to receivers, limits system availability and network coverage across a room or in outdoor port operation. In addition, it is also important to optimize LED layout in order to mitigate the impact of sunlight on the system performance [1-3],[29].

The impact owing to LED layout has been reported [6-11] but a limited number of configurations have been considered; circular or square shapes for a standard room office only without consideration of the impact of sunlight irradiance. Also, the arrangement of LEDs has also been considered [12] from a statistical perspective, specifically the variance of the SNR over the room. One constellation is proposed and analyzed but a wider optimization of the layout to maximize system performance has yet not been addressed.
Although the path loss of the system has been characterized in [13], only Line of Sight (LOS) path components are considered in the analysis and sunlight is treated as Additive White Gaussian (AWG) noise. The level of sunlight irradiance is measured in the room under consideration; however, that represents a point evaluation as sunlight irradiance varies dramatically according to the time of day, the location, day of year and metrological conditions. Also, different room sizes and shapes are not considered [2], [31-33].

The state-of-the-art in terms of layout optimization is thus limited viz. two LED constellations, restricted to LOS components only with the impact of sunlight irradiance treated as AWG noise. A LED layout design has been considered without consideration of its impact on communication system performance [6] for specific room geometries without meeting lighting standards [14]. The variation of received signal strength to minimize SNR variations over the room has also been investigated but again without consideration of Non-Line of Sight (NLOS) paths and sunlight irradiance. The goal here is to provide an in-depth analysis of LIFI system performance designs under an extended range of environmental conditions. The analysis methodology developed can be applied to treat any room size, any surface reflectivity and any location, over different metrological conditions and with different LED panel specifications. It provides a base for an extensive design tool that aids the estimation of system reliability, availability planning and assessment. System planning must draw on design guidelines that treat different room shapes and sizes which include NLOS effects and sunlight irradiance over the year to enhance the quality of service provided. Finding the optimum LED layout that provides an acceptable system performance with minimum energy consumed is a key challenge for LIFI systems.

The remainder of the paper is organized as follows. Section II presents the detailed system architecture. Section III shows the proposed LED layout, followed by evaluation concerning SNR, BER and data rate performance. Finally, Section IV is devoted to the main conclusions.

**II. SYSTEM MODEL**

LED panels are placed on the ceiling and photodiodes on horizontal surfaces at distance 0.85 m from the floor as shown in Figure 1. Light rays are subjected to many reflections in their path from transmitter to receivers. LOS and NLOS components are considered in the analysis up to the fifth reflection. A range of surface reflectivity is considered in the analysis (plaster and plastic walls) and all surfaces are considered...
as pure Lambertian reflectors as most of the surfaces within the indoor environments that are approximated accurately as Lambertian reflectors [15]. The impulse response of multiple sources emitting equal power subjected to multiples reflections is given by [16].

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

\[ h^{(k)}(t; \Phi_n) = \int_0^1 \left[ L_1 L_2 \ldots L_{K+1} \Gamma^{(k)}(\theta) \right] rect(\theta_{FOV}) \times \delta(t - \frac{d + d_2 + \ldots + d_{K+1}}{c}) \, dA_{ref}, k \geq 1 \]

\[ L_1 = A_{ref}(m+1) \cos^m \Phi \cos \theta_1 2 \pi d_1^2 \]

\[ L_2 = A_{ref} \cos \Phi \cos \theta_2 \pi d_2^2 \]

\[ L_{K+1} = A_P \cos \Phi_{K+1} \cos \theta_{K+1} \pi d_{K+1}^2 \]

where \( k \) is the number of reflections, \( N \) is the total number of LEDs, \( L_{K+1} \) is the path loss, \( I^{(k)}_n \) is the reflected power, \( \Phi_1 \), is the viewing angle of the LED. The beam is incident at angle \( \theta_1 \) after distance \( d \) from
source to reflection point and the mode number \( m \) is a function of transmitter viewing angle given by \( m = -\frac{1}{\log_2 (\cos \phi_{1/2})} \). \( c \) is the speed of light, \( A_{PD} \) is the photodiode physical area, \( A_{ref} \) is the reflecting area of the light ray and \( \text{rect}(x) \) is given by [16-18]:

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

As the spectrum of sunlight irradiance falls in the same band of operation of the system, the impact of sunlight is considered in the layout optimization process to emulate more realistic operational scenarios. Sunlight irradiance has been modelled over the year using the model in [19]. The impact of sunlight irradiance is considered hourly over different metrological conditions for two different representative locations Cairo–Egypt and Berlin–Germany over the year (a total of 8760hrs). The cloud coverage over the representative locations is also considered in the analysis. Table 1 summarizes the simulation parameters.

Table 1: System simulation parameters

<table>
<thead>
<tr>
<th>System Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photodiode Responsivity</td>
<td>0.54 A/W</td>
</tr>
<tr>
<td>Data Rate (( R_b ))</td>
<td>1 Mbit/s</td>
</tr>
<tr>
<td>Photodiode area ( A_{pd} )</td>
<td>0.5*10^{-4}</td>
</tr>
<tr>
<td>( \phi_k ) irradiance angle</td>
<td>80</td>
</tr>
<tr>
<td>Receiver field of view (FOV)</td>
<td>45</td>
</tr>
<tr>
<td>Transmitter full width half maximum (FWHM) angle</td>
<td>9</td>
</tr>
<tr>
<td>Plastic wall surface reflectivity</td>
<td>~ 0.2</td>
</tr>
<tr>
<td>Plaster wall surface reflectivity</td>
<td>~ 0.8</td>
</tr>
<tr>
<td>Number of LED panels</td>
<td>4</td>
</tr>
<tr>
<td>Number of LED chips</td>
<td>900</td>
</tr>
<tr>
<td>LED Panels dimensions</td>
<td>2m*2m</td>
</tr>
<tr>
<td>LED transmitted power</td>
<td>0.452 W</td>
</tr>
<tr>
<td>Neighbouring LED chips spacing</td>
<td>4 Cm</td>
</tr>
</tbody>
</table>
III. LED LAYOUT OPTIMIZATION

Performance is analyzed over four seasons in representative environments using Monte Carlo simulations. The methodology is seeking to find the optimum placement of the LED panel in the indoor port operation environment that provides high system availability and efficiency. The optimization is constrained by two main requirements; maximizing the average SNR across the room at an acceptable lighting illumination according to EN12464-1 standard [14].

The characterization considers a range of LED panel placements across a room of any size. A MATLAB routine provides the SNR variation across the room within the illumination constraint. However, the global optimum provided by this route is not sufficiently robust and results from these nonlinear equations are tested and confirmed [21] through Monte Carlo simulations which consume significant computational time of up to 72 hours/simulation accomplished by using a high performance computer facility.

It is worth noting that a number of optimization approaches exist. For example, genetic algorithms and pattern search [22], [23] may provide a global optimum for the nonlinear optimization problem considering the stated constrains; however those algorithms are sensitive to initial conditions. Further, results from those algorithms yield a global optimum and need extensive verification to ensure that the results are the optimum for the spectrum of conditions and constrains [21], [24], [25]. Although the methodology considered for the present analysis is specifically developed to treat a number of design aspects for systems that emulate real scenarios, results have been tested for different constrains to validate the methodology.

The analysis of VLC technology unitization at smart ports context had not been fully analyzed [31-37], using MATLAB software, system had been simulated to evaluated the technology unitization at smart ports environment. The analysis is carried out for a 1 Mbit/s data rate and 0.54 $A/W$ photodiode Responsivity. Simulation parameters are largely the same as stated in Table 1 except that LED chip Power 63 mW which is required to enable a meaningful comparison between the results from the adopted methodology and other research work [26]. The optimization methodology considers not only the LED position but also system performance over different metrological conditions over the year and level of illuminations at indoor environment and outdoor environment to ensure that good level of illumination at different locations.
A. SNR Performance

The evaluation is carried out over the year for two representative locations, Berlin and Cairo. Summer and winter seasons are considered only; results for the rest of the year are assumed to lie between these extremes. Indicative performance can be derived from the results for autumn and spring in [29].

B. Summer

Four LED panels provide the specified illumination level in the range 300 lx - 800 lx as stated by the European standards for indoor workplace lighting EN12464-1 [14]. Here, the LED panels provide illumination in the range from 300 lx - 800 lx over the room area. The average SNR (Figure. 2 and Figure. 3) over the room for a Cairo summer - clear sky where the noise owing to sunlight irradiance is at the maximum value - is in the range of ~ 86 dB -53 dB, ~81 dB - 50 dB for plaster and plastic walls respectively.

Figure 2. Average SNR for a Cairo Summer, Clear Sky and Plaster Wall

Figure 3. Average SNR for a Cairo Summer, Clear Sky and Plastic Wall
The average SNR increases by 15% when the proposed LED layout is compared to the results of [26] under the same simulation conditions. The maximum average SNR for both LED layouts in [26] is 73 dB and under the same scenario the SNR is enhanced by ~15% and ~10% for plaster and plastic walls respectively. The minimum average SNR is 53 dB in a corner of the room.

Moreover, the luminance level for office environments is stipulated to be 400 lx on average (equal to ~60 dB SNR) over 50% of the room while the rest of the room should not fall below 100 lx on average; the lighting constraint is thus also fulfilled by the proposed LED layout. Hence the LED layout provides optimized system performance in the presence of sunlight and fulfils the relevant lighting illumination standard.

C. Winter

In winter, sunlight irradiance is at a minimum, especially in Berlin owing to a high percentage of cloud cover. The average SNR for a Berlin winter lies in the range of ~87 dB - 63 dB and ~82 dB - 54 dB for plaster and plastic walls respectively (Figure 4 and Figure 5). The SNR improves by ~17% compared to the results of [26]. As expected, the SNR decreases to ~53 dB for plastic walls due to the poorer surface reflectivity. The SNR within the room varies as a function of sunlight irradiance and cloud cover over the year.
A comparison of performance as a function of metrological conditions - as represented by Cairo and Berlin - is presented in Figure 6 (plaster walls) and Figure 7 (plastic walls). Figure 6 and Figure 7 summarize the maximum and minimum average SNR for the proposed LED layout. The layout provides an enhancement of system performance compared to the results in [26]; the maximum SNR lies in the range of ~ 96 dB – 68 dB achieved as expected in Germany for a winter day with significant cloud coverage and plaster walls. SNR in Cairo are in the range of ~ 87 dB - 52 dB, 89 dB - 54 dB, 95 dB - 61 dB for summer clear sky, summer cloudy sky and winter clear sky respectively. For Berlin, the SNR is in the range of ~ 94 dB - 64 dB and ~92 dB - 62 dB for winter clear sky and summer clear sky respectively. Again, the lighting illumination standard [14] is fulfilled under all metrological conditions.

The proposed LED layout provides better system performance for the same room size with a lower number of LEDs than Komine et.al [27] viz. the former used 1400 LED chips as opposed to the 900 chips in the present study.
The same system performance is achieved with ~ 35% reduction in the number of LED chips illuminating the same size of room attributed to an optimized layout and the higher intensity of chips employed compared to [27]. The central luminous intensity of chip employed in [27] was 0.73 cd (20 mW transmitted power) and the employed chip (63 mW transmitted power) has maximum luminous intensity of 9.5 cd.

IV. CONCLUSIONS

LED layout is investigated in order to optimize LIFI system performance and fulfil the lighting requirement governed by standards. Research to date has reported on LED layout design in indoor environments; however, few analyses consider the optimization from a mathematical perspective and they do not consider fulfilling the lighting standards and commercially available LED panels. Moreover, evaluations are confined to a specific room size, do not consider the impact of sunlight irradiance and cloud cover and are limited to LOS components only.
The framework developed aims to provide design guidelines for system developers applicable to any room size, wall reflectivity, and illumination level, location worldwide with consideration of both LOS and NLOS components and the impact owing to sunlight irradiance over the year. Figures 6 and 7 summarize the performance of the indoor LIFI system at indoor smart port environment. The developed framework for LED layout design in LIFI system shows that LIFI system can provide smart and economic solution in smart ports operation and shows the availability of system as function of SNR in different real operation and metrological indoor environment that can be applied in smart port design.
REFERENCES


