Performance evaluation of optical attocells configuration in an indoor visible light communication

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Article Info	ABSTRACT
	Visible light communication VLC is deemed as futuristic technology applied for both illumination and data communication due to the low-cost energy consumption, long life expectancy, huge bandwidth, and high security compared to radio frequency RF. Uncovered area, minimum signal-to-noise ratio (SNR) and received power results from the non-uniform distribution of small base stations (i.e. Optical attocells) in the room. In this paper, the researchers propose a new LEDs distribution of five optical attocells configuration model in order to optimize the received power distribution and SNR at the center of the room for indoor VLC system. The optical attocells configuration in terms of received power to fill the uncovered area at the center of the room has been investigated. The simulation results showed that the proposed attocells configuration saved 24.9% of the transmitted power. Besides that, the whole room was covered uniformly. As a result, the received power and SNR are improved.

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1. INTRODUCTION

The evolution of solid-state lighting technologies open doors for researchers in both academia and industry fields to apply the LEDs devices in several valuable applications due to the unlimited free spectrum, low cost of energy consumption, long life expectancy, and security issue features. The current advances and technical challenges of LEDs were investigated in order to improve the performance of illumination [1]. The optical band was proposed as a supplementary technology to RF in the indoor application to transfer data with high rates through the LEDs. The optical band contains an infrared (IR), visible light (VL) and ultraviolet (UV) sub-bands. On February 11th of 1800, W. Herschel discovered the Infrared light, he discussed the spectrum of sunlight with the prism and determined the temperature of all colors [2]. The IR is used in short-range applications to transfer information with standard data rates ranged between 9.6 Kbps and 16 Mbps [3]. The UV radiation and its properties were discovered earlier in phases by three fellow scientists gradually in 1614, 1777, 1801 named Sala, Scheele, and Ritter respectively [4]. Visible light is unique in nature than IR and UV as known previously. The first experiment was achieved by Graham Bell in 1880 through an advanced a photo phone system that transmitted speech wirelessly through the modulation of reflected sunlight [5], [6]. Besides that, VLC offers high data rate that goes up to Gigabit/second by applying multicarrier modulation systems such as OFDM. The VLC wavelength has a range of 400–700 nm as demonstrated on electromagnetic spectrum shown in Figure 1, different LEDs are used to create a secure zone in the physical layer of a VLC system in order to provide a higher transmission security [7], [8]. In addition, the white LEDs lighting system of high radiated power produces an excellent quality of services [9].
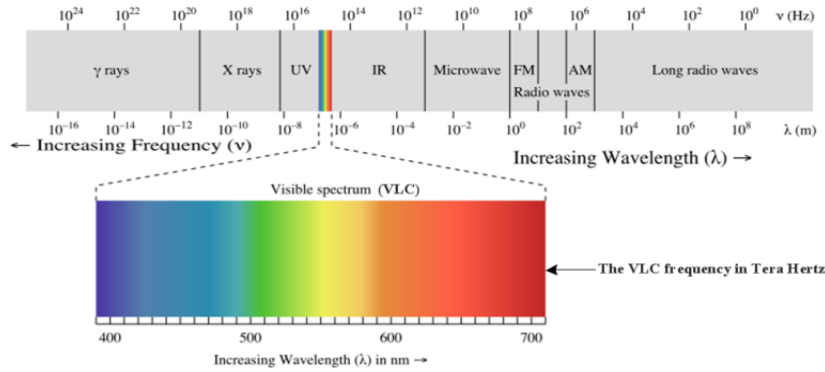
Figure 1. Frequency and wavelength of the electromagnetic spectrum [2]

2. RELATED WORKS

The VLC is in demand to realize the optical attocells network and become a new path towards the smaller cells [10]. Besides, the VLC system of multiple LED lighting was presented in an indoor ecosystem to connect several devices in short-range distances [11]. The visible light of the indoor transceiver system was investigated extensively. It gives the Li-Fi concept when the devices use IR or RF for uplink connection and light emitting diodes for the downlink connection. A new device allocation system of Li-Fi was suggested for multi-user in the transceiver system, the results of this suggestion produced a high performance and minimum interference in the VLC physical link [12]. The discussion of LEDs characteristics as illumination tools is required to control the emitted optical power in the room that participates in providing a minimum SNR to guarantee the data transmission between devices, besides, the enhancement of the quality of VLC system [13]. Until now the regularity of SNR in every location inside the indoor VL environment is obstructed by the multipath dispersion in the channel. The evolutionary algorithm (EA) was designed to optimize the dynamic SNR allocation in the room with dimensions same as [14] by using three light configuration design A, B and C of 6×6, 7×7 and 5×5 LEDs arrays respectively, for the room, this approach was authenticated using tools with the ability to adjust the emitted power from each LED. The spectral efficiency of the cellular network increase when the cell sites are reduced, small cell notion of cellular system can be readily extended to VLC beating the high interference resulted from the proximate reuse of RF spectrum. Besides that, the optical attocell does not produce any extra interference, while improving indoor coverage. The light signal does not penetrate the walls due to the limited coverage zone of every single attocell that prevent the communication system from adjacent interference between neighbor rooms. These features facilitate applying manifold attocell to cover the whole room space. Figure 2 illustrated several cellular coverage zones, which included attocells configuration. The light distribution inside the room is imagined to work as tiny optical Base Station (BS), otherwise called the optical attocells. It is similar to the femtocell in the cellular communication system [15]. Besides that, the authors investigated the requirements of the 5G cellular system in terms of several parameters and various technologies to meet up to the expected performance demands.
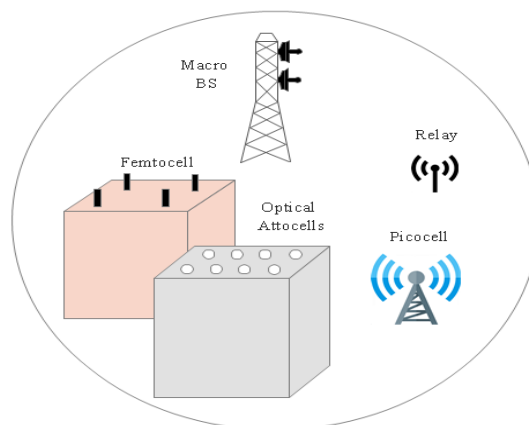

Figure 2. The attocell in the context of the heterogeneous network

The LEDs distribution on the indoor environment was investigated to improve the average area spectral efficiency [16], the optimization was studied for two attocell on the room of 2.5 m×5 m×3 m dimension. MATLAB was used for simulation and the result shows that the average coverage area is maximized at high FOV.

In this paper, the authors study the performance of attocells configuration based on the coverage area. To the best of the researcher's knowledge, the proposed design is a novel solution for an optimal coverage area by applying a new LEDs distribution in five attocells configuration model. This new configuration model increases the coverage area, enhances the SNR and optical power distribution. The rest of this paper is organized as follows: Section 2 presents related works of VLC system. Section 3 is the system model, it involves two subsections, light propagation model of LOS channel, mathematical equations of the received power and SNR analysis. Section 4 presents the results analysis and discussion. The conclusion of this work is illustrated in Section 5.

3. SYSTEM MODEL
3.1. Light Propagation Model

In this paper, only the LOS propagation model for optimizing the indoor VLC environment as depicted in Figure 3 was considered. The light is distributed from the ceiling to the whole room and the Lambertian radiation pattern is considered for the source of emission [17]. The illumination intensity of angle ϕ is defined by:

$$I(\phi) = I(0)cos^m(\phi) \tag{1}$$

Where I (0) represent the center luminous intensity from a group of LEDs, ϕ, and m represents the angle of irradiance and order of Lambertian emission respectively. In [18], The Lambertian radiant intensity is given by:

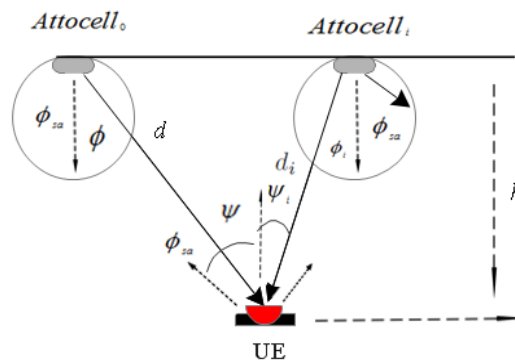$$R(\phi) = \frac{(m+1)}{2\pi} cos^m(\phi) \tag{2}$$

Figure 3. Geometry of LOS propagation model

The Lambertian coefficient is defined by semi-angle of half illumination from LEDs $\phi_{sa_{\frac{1}{2}}}$ such as:

$$m = \frac{-\ln 2}{\ln\left(\cos \phi_{sa_{\frac{1}{2}}}\right)} \tag{3}$$

The total transmitted power generated from the LEDs emission is given by:

$$P = P_{LED} * R(\phi) \tag{4}$$

The VLC channel is described by LOS link and characterized by DC gain as illustrated in (5)

$$H_{LOS} = \begin{cases} \frac{A_{rx}}{h^2} R(\phi) \cos(\varphi) & 0 \le \varphi \le \varphi_c \\ 0 & \varphi > \varphi_c \end{cases} \tag{5}$$

Where $R(\phi)$ is defined in (2), A_{rx} is the detector physical area of a photodiode (PD), h^2 is the distance between transmitter and receiver, φ refers to the incident angle of the receiver, φ_c is the field of view angle of PD. The whole power of LOS link can be computed using (6).

$$P_{LOS} = \sum_{i=1}^{LEDnum} P * H_{LOS} \tag{6}$$

The proposed optical attocells configuration is displayed in Figure 4. It is mounted on the ceiling, and the semi-angle at half power was controlled to avoid the co-channel interference.
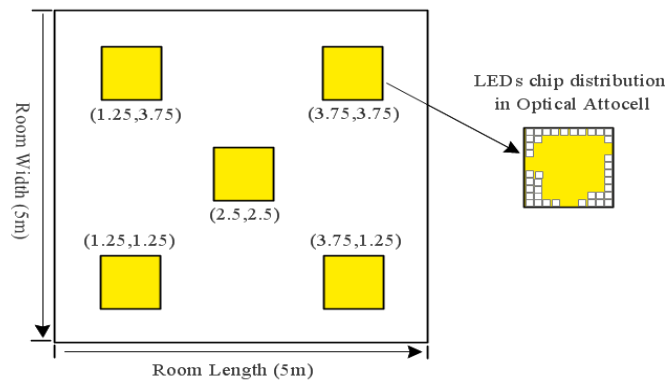

Figure 4. LEDs distribution in the proposed optical attocells network

3.2. SNR Analysis

Every communication system contains three basic parts transmitter, channel, and receiver. The channel of each communication system suffered from both internal and external random noise and distortion of the environment. The internal noise is difficult to remove in comparison to external noise which could be reduced and mitigated through various methods and mechanisms [19], [20]. In the source of the communication system, the transmitted intensity signal is sinusoid signal x (t) defined by an expression:

$$x(t) = P_t (1 + m \sin wt) \tag{7}$$

Where P_t represents the average transmitted power, and m define the amplitude of a sinusoidal signal. The received optical signal at the detector is represented by r (t), and it is defined by:

$$r(t) = P_r (1 + m \sin wt) + P_{amb} \tag{8}$$

Where P_r represents the average power at the receiver, and P_{amb} represents the power of ambient light incident in the photodiode detector. The photodiode transforms the received optical intensity of the incident signal into photocurrent in accordance with the law of responsivity given below:

$$R_p = \frac{I_P}{P_P} = \frac{q\eta_i}{hv} \tag{9}$$

The responsivity R_P is measured in amperes per watt, and it's defined as optoelectronic conversion factor that applied to convert the optical signal to the electrical domain. The received signal and DC measures of photocurrent can be separated in the following expression:

$$\begin{aligned} i_{photo}(t) &= R_p . r(t) \\ &= R_p(P_r + P_{amb}) + (R_p P_r m \sin wt) \end{aligned} \tag{10}$$

The power of an electrical signal at the receiver is given by:

$$P_{signal} = \frac{1}{2} m^2 R_p P_r^{\,2} \tag{11}$$

The photo-generated shot noise increases at the receiver due to the transmitted signal and the ambient light. Subsequently, the received photocurrent considers only a DC component at condition $P_{amb} \gg P_r$. Also, the noise power results from the pre-amplifier $\overline{\iota_{circ}^2}$ and shot noise $\overline{\iota_{shot}^2}$ are uncorrelated and the total noise power can be simply expressed by:

$$P_{noise} = \overline{\iota_{circ}^2} + \overline{\iota_{shot}^2}$$
$$= \overline{\iota_{circ}^2} + 2qR_p(P_r + P_{amb}).B_{eff} \tag{12}$$

The B_{eff} represents the equivalent noise bandwidth of the system, q is the electronic charge. From (11) and (12), the signal to noise ratio (SNR) is approximately expressed by:

$$SNR_{link} = \frac{P_{signal}}{P_{noise}} \tag{13}$$

The next section shows the simulations results and analysis; it was achieved based on the parameters illustrated in Table 1.

Table 1. Parameters of Simulation

Parameters	Value
Room dimension in meter	$5 \times 5 \times 3\ m$
Transmitted optical power by individual LED	20 mW
Total transmitted power (single attocell)	54 W
Detector physical area (PD)	$1\ cm^2$
Gain of an optical filter (Ts)	1
Refractive index	1.5
FOV of a receiver	$60°$
LED center luminous intensity	0.73
Semi-angle at half power	$12.5°, 20°, 30°, 40°, 50°, 60°, 70°, 80°$
Table height	0.85m
Transmitter position (Attocells)	4 Attocells: (1.25,1.25), (1.25,3.75), (3.75,1.25), (3.75,3.75)
	5 Attocells: (1.25,1.25), (1.25,3.75), (2.5,2.5), (3.75,1.25), (3.75,3.75)
Responsivity of PD	0.54 (A/W)
Bandwidth	30 Mb/s
Temperature	298 K

4. RESULTS AND ANALYSIS

The performance evaluation of multiple attocells configuration was measured as shown in Table 2. The amount of optical received power in five locations in the room as represented by (1.25, 1.25), (1.25, 3.75), (2.5, 2.5), (3.75, 1.25), (3.75, 3.75) were investigated. In a typical four attocells configuration, the maximum received power is concentrated at the corners of the room. The center of the room received low optical power and SNR distribution. Interestingly, the new LEDs distribution of optical attocells configuration has been producing a uniform power and SNR distribution in the whole room. In this manner, the proposed configuration model consumes less transmission power than that applied in four attocells configuration.

Table 2. Received Power of Different Attocells Configuration

Optical Attocells configuration with different semi-angle $\varphi_{\frac{1}{2}}$	Optical Received Power at different positions (dBm)				
	(1.25 , 3.75)	(1.25 ,1.25)	(2.5,2.5)	(3.75 ,1.25)	(3.75 ,3.75)
Four	12.76	12.76	-16.99	12.76	12.76
12.5					
Five	12.23	12.23	12.23	12.23	12.23
Four	1.966	1.966	2.101	1.966	1.966
70					
Five	2.429	2.429	3.718	2.429	2.429

Figure 5 to Figure 8 shows the received power and SNR distribution at semi-angle at half power 12.5° and 70° respectively. There is a trade between the received power and SNR distribution. At small semi-angle at half power, the received power is increased and SNR is decreased, and when the semi-angle at half power is increased, the SNR distribution increased and the received power will be decreased. Clearly, the results were improved as compared to [21] [22].
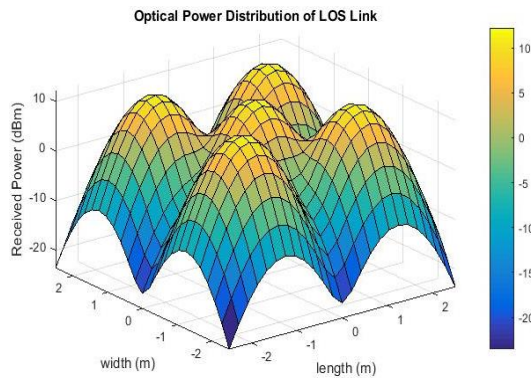

Figure 5. Received optical power (12.5°)
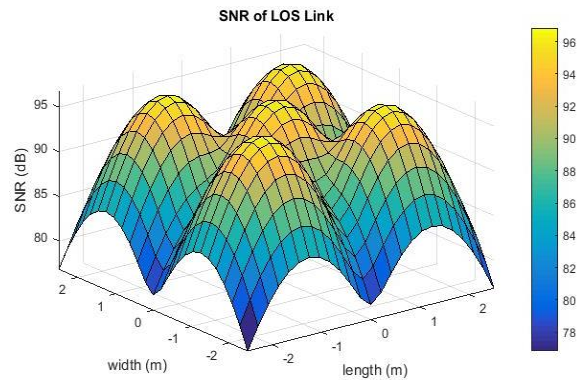
Figure 6: SNR distribution (12.5°)
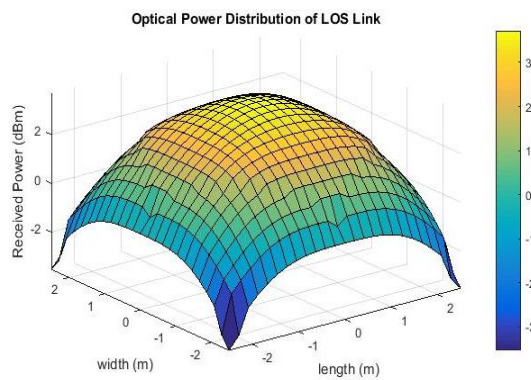
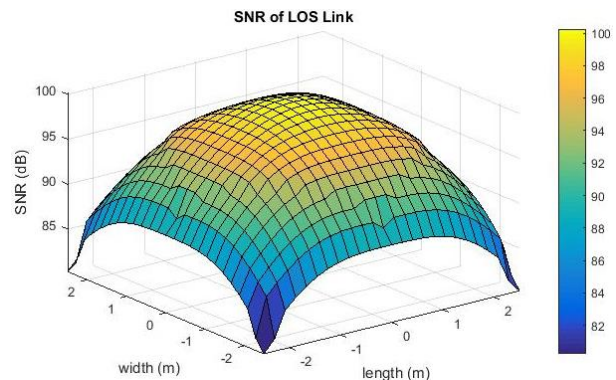Figure 7. Received optical power (70°)

Figure 8: SNR distribution (70°)

Figure 9 shows the coverage area of the room in terms of optical received power for the four attocells configurations; the authors observed a small power distribution at the center of the room. To avoid this problem, the five attocells configuration with less radiated power has been proposed as demonstrated in Figure 10.
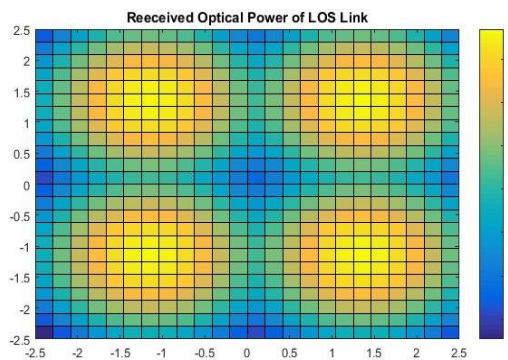

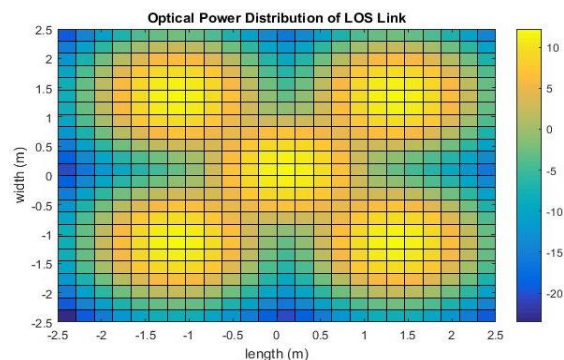Figure 9. Coverage area of four attocells (12.5°)

Figure 10. Coverage area of five attocells (12.5°)

The results showed that the SNR and the received power at the center of the room were improved. Besides that, the four optical attocells configuration in previous studies was used 14400 LEDs chip while the proposed optical attocells configuration has used 13520 LEDs chip. Figure 11 and Figure 12 shows maximum optical received power at the center of ceiling for the various semi-angle at half power and field of view respectively. Figure 13 showed the total SNR distribution at the center of the room for all-optical attocells network. It was improved with an average difference ratio of 9.12%. The simulation results showed that both total SNR and the optical received power were improved. Subsequently, the coverage area of the whole room was increased uniformly as compared to [23], [24].
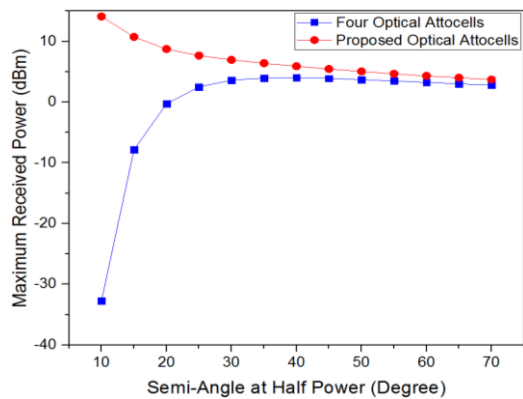

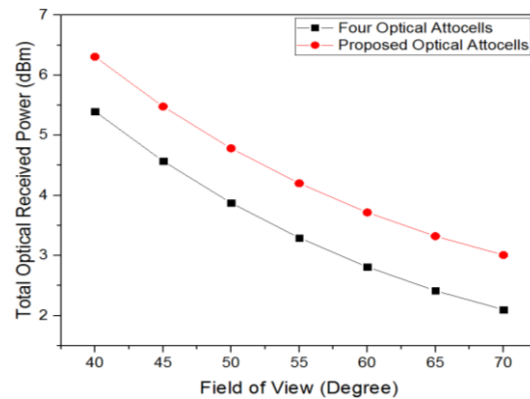Figure 11. Maximum optical received power distribution at the center of the room

Figure 12. Total received power at the center of the room under various FOV
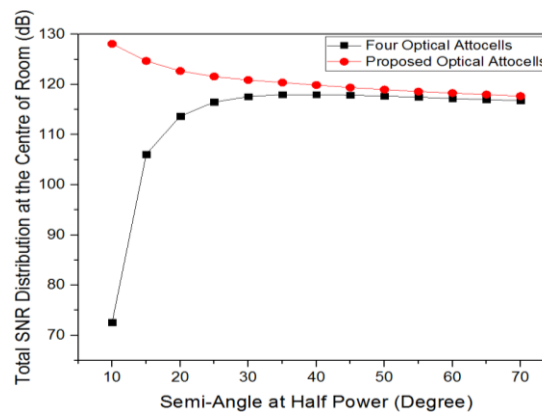

Figure 13. Total SNR distribution of all optical attocells network

5.   CONCLUSION

Visible light communication is a new emerging technology alternative to radio frequency in the indoor communication systems. It's proposed as a promising and a powerful technology for 5G networks. In this paper, the authors investigated the optical attocells configuration in the room under the LOS condition to fill the uncovered area. Besides that, the SNR and optical received power were optimized by developing a new LEDs distribution of five attocells configuration. The simulation results of the proposed attocells configuration displayed that the optical received power against FOV has increased with an average difference ratio of 28%. Also, the total SNR has improved with average difference ratio of 9.12%. Subsequently, the coverage area was increased uniformly. In coming future work, the same attocells configuration will be applied to non-LOS propagation link, towards enhancing the link quality and performance of visible light communication systems.

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