Abstract—In this paper, the downlink signal-to-interference-plus-noise ratio (SINR) statistics are analysed in a direct current-biased optical orthogonal frequency division multiplexing (DCO-OFDM) based optical attocell network with a Poisson point process (PPP) cell deployment. An optical attocell system utilises existing lighting fixtures in an indoor environment to function as a small-cell cellular network. It uses each luminary as a base station (BS) to serve multiple nearby mobile users. Similar to a conventional radio frequency (RF) cellular system, the grid cell deployment is restricted by many practical issues in an optical attocell network. Therefore the performance of the system with PPP cell deployment is considered in this study in order to identify a lower bound for practical attocell networks with irregular cell deployment. An analytical framework is presented and compared with the computer simulations. Also the SINR statistics with different cell deployments are compared and discussed.

Index Terms—cellular network, optical attocell network, Poisson point process, visible light communication.

I. INTRODUCTION

With the development of wireless communication technology and emergence of advanced mobile devices, there is a significant increase in data traffic in wireless networks. The radio frequency (RF) spectral resources is becoming insufficient to meet the future demand. Researchers aim to solve this ‘spectral crisis’ in two ways. One of the methods is to explore new spectral resources for wireless transmission. The commonly considered frequency ranges are at the 60 GHz and optical region. In particular, visible light communication (VLC) has been researched because of three main characteristics [1]: i) using visible light for wireless transmission is licence-free; ii) it reuses the energy for lighting to provide an extra data transmission function, which means it is energy-efficient. iii) visible light cannot penetrate opaque objects. This property means that VLC offers security benefits. Also it intuitively avoids co-channel interference (CCI) between VLC systems in adjacent rooms. In this study, light emitting diodes (LEDs) and photodiodes (PDs) are used as the core components of the VLC transceivers, and intensity modulation/direct detection (IM/DD) techniques are used. The other method to deal with the challenge of the limited spectrum is to improve the usage efficiency of the existing spectral resource, such as adaptive resource allocation and cognitive radio. In particular, reducing the reuse distance of the spectrum resource offers significant improvements in terms of area spectral efficiency [2].

The concept of optical attocell network combines the methods mentioned above. It uses the licence-free visible light frequency band as the data transmission medium and an extremely small spatial reuse distance [3]. In a large indoor environment, typically many lighting devices are installed. This gives a unique opportunity to set up a cellular system in a single room, and this is termed an optical attocell network. An optical attocell network uses each luminary as a base station (BS) to serve multiple nearby users. This cellular system achieves bi-directional communication links and supports handover for moving users. The main limiting factors for the performance of an optical attocell network are the modulation bandwidth and the CCI between users in adjacent cells. To solve the bandwidth issue, wide-band LEDs have been researched and manufactured. A gallium nitride micro LED with a much wider bandwidth than typical commercially available white LED was considered in [4]. In addition, bandwidth-efficient modulation schemes were proposed to maximise the achievable throughput. In [5], [6], a data rate of 513 Mbps and 1 Gbps were achieved experimentally by using rate-adaptive discrete multi-tone modulation with white LEDs, respectively. In [4], a data rate of 3 Gbps was achieved by using a similar modulation scheme with a micro LED. Another energy efficient orthogonal frequency-division multiplexing (OFDM) scheme was proposed in [7], termed enhanced unipolar OFDM (eU-OFDM). It can enable energy and spectrum efficient communication in scenarios where lighting is not required. CCI degrades the signal quality received by users, especially for cell edge users. Several interference mitigation techniques were considered in optical attocell networks such as busy-burst signalling [8] and fractional frequency reuse [9].

In a previous study, a semi-analytical approach was carried out to evaluate the downlink transmission performance in an optical attocell network with hexagonal cell deployment [10]. Such a hexagonal grid cell deployment is highly idealised in RF cellular systems, which is considered to be obsoleted in [11]. Instead, uneven cell deployment is more common due to...
the difference in transmission power, mobile user density and some geometric constraints such as obstacles for placing BSs in an ideal position. Therefore, Poisson point process (PPP) cell deployment was introduced to analyse the performance of cellular networks. The results show that the performance of PPP model is a lower bound for a practical cellular system. In addition, by considering the PPP cell deployment allows tools from stochastic geometry to be used, which makes the performance of the cellular network more tractable. The same issue is also true for an optical attocell system. In an optical attocell network, the hexagonal grid cell deployment is possible, but unlikely due to wiring complexity, uneven lighting requirements and aesthetic quality. Therefore, in this study, a worst case random cell deployment with PPP is considered in an optical attocell network. An analytical framework for the downlink signal-to-interference-plus-noise ratio (SINR) statistics with PPP cell deployment is presented. In addition, the results of the systems with different cell deployments are compared to show the significance of the results with PPP cell deployment.

The remainder of this paper is organised as follows: the downlink system model in an optical attocell network is presented in Section II. The PPP cell deployment and the analytical SINR statistical results are introduced in Section III. The performance of the systems with different cell deployments are compared in Section IV. Conclusions are given in Section V.

II. DOWNLINK SYSTEM MODEL

A. Propagation Model

In this study, a room with large number of luminaries are considered. Each luminary is treated as a point source. It is assumed that the PD detector installed on the user mobile device is facing upward. A full receiver FOV of 180° is considered. Each luminary is treated as a point source. It is assumed that the optical attocell cellular system is not just a LOS system. Considering the i-th BS and a user of interest, the channel DC gain between them is calculated as:

$$G_i = \frac{(m+1)A_{pd}}{2\pi d_i^2} \cos^m(\phi_i) \cos(\psi_i),$$

(1)

where $i = 0, 1, \cdots$; $A_{pd}$ is the physical area of the PD; $d_i$ represents the Euclidean distance between the i-th BS and the user; $\phi_i$ is the angle of incidence from the i-th BS; $\psi_i$ is the angle of radiance to the user; and $m$ denotes the Lambertian emission order, which is related to the LED half-power semi-angle by $m = -\ln(2)/\ln(\cos(\Phi_{1/2}))$. The LED half-power semi-angle $\Phi_{1/2}$ indicates the angle of radiance at which the emitted optical power is half of that emitted with $\phi_i = 0$. In this study, a fixed vertical separation $h$ between BSs and the user mobile device is assumed. The geometry of the above model is illustrated in Fig. 1, which also shows the following relationships: $\cos(\phi) = \cos(\psi) = \frac{h}{d_i}$ and $d_i = \sqrt{r_i^2 + h^2}$, where $r_i$ is the horizontal separation between the i-th BS and the user. Therefore, expression (1) can be converted to a function of $r_i$ as follows:

$$G_i(r_i) = \frac{(m+1)A_{pd}h^{m+1}}{2\pi (r_i^2 + h^2)^{m+3/2}}.$$  

Since the detector area is much larger than the wavelength, small scale fading does not exist in an IM/DD VLC system. Shadowing and the blockage issues are not considered in the channel model in this study.

B. DCO-OFDM Transmission

In an optical attocell system, a strong LOS connection between a BS and a user is likely to be established as each BS only covers the users close to it. Consequently, the multi-path effect due to wall reflection is minor [14]. In addition, OFDM is used in this system, which can eliminate the inter-symbol interference (ISI) caused by the multi-path effect. This offers a near-flat frequency response of the wireless channel. Therefore, the multi-path effect due to wall reflection is omitted in this study and the magnitude response over the whole frequency band is assumed to be unity. Among several optical OFDM schemes, DC-biased optical (DCO)-OFDM achieves a high spectral efficiency. Therefore, it is used in the optical attocell system to maximise the achievable data rate. Typically, in order to overcome the distortion of the clipping noise, a high optical power is required in a DCO-OFDM system. In this study, it is assumed that both illumination and communication functions are provided by the optical attocell system, which means the optical power for downlink communication is high [3]. It has been shown that a signal-to-noise ratio (SNR) up to 70 dB is achievable in a single cell deployment with such high output optical power [15]. At the transmitter side of an OFDM system, a frequency domain symbol sequence with K quadrature amplitude modulation (QAM) data symbols are defined as: $X = [X_0 X_1 X_2 \cdots X_{K-1}]$. An IM/DD
system requires the time-domain OFDM signal to be real and unipolar. In a DCO-OFDM system, \( X_k = X_{K-k}^* \) and \( X_0 = X_{K/2} = 0 \) are required to ensure that the transmitted signal is real [16], which is termed as Hermitian symmetry. Here \([\cdot]^*\) is the complex conjugate operation. Consequently, only \( K = K/2 - 1 \) symbols carry information bits. On the other hand, an unipolar signal is achieved by adding a DC-bias. After the \( K \)-point inverse discrete Fourier transform (IDFT) operation and the addition of the DC-bias, the time domain OFDM symbol at time slot \( t \) can be calculated as:

\[
x(t) = x_{\text{DC}} + \sum_{k=0}^{K-1} X_k \frac{\sqrt{2} \pi / K}{\sqrt{K}} e^{j2\pi k t / K}, \quad t = 0, 1, \ldots, K - 1
\]  

where \( x_{\text{DC}} \) denotes the DC-bias component; and \( j \) represents the imaginary unit. After the addition of DC-bias, the remaining negative samples are set to zero. Since it is assumed that the ISI caused by reflection is negligible, the required cyclic-prefix (CP) length would in turn be short in an optical attocell network. Therefore, the penalty of adding a CP is also omitted in this study. Assume that the sampling and the synchronization are perfect, the time-domain signal received by the user device at time slot \( t \) can be expressed as:

\[
y(t) = x_0(t)G_0R_{\text{pd}} + \sum_{i \in I} x_i(t)G_iR_{\text{pd}} + n(t),
\]

where \( x_i(t) \) denotes the transmitted signal from the \( i \)-th BS at time slot \( t \). In the case of \( i = 0 \), \( x_0 \) represents the desired transmitted signal for the user of interest; \( R_{\text{pd}} \) denotes the responsivity of the PD; and \( n(t) \) represents the receiver noise sample at time slot \( t \). The second term of \( y(t) \) denotes the received interference signal, where \( I \) is the set of all the interfering BSs. The receiver noise is modelled as an Additive White Gaussian Noise (AWGN) with a noise power spectral density (PSD) of \( N_0 \). Since the 0-th subcarrier and the \( K/2 \)-th subcarrier are not used, \( n(t) \) is drawn from a Gaussian distribution with zero mean and variance of \( \sigma^2 = \frac{K-2}{2} N_0 W \), where \( W \) is the total available intensity modulation bandwidth. By using appropriate DC-bias level, clipping noise can be minimised to a level that causes negligible distortion in the transmission [17]. Non-linearity effects of the LED can be effectively mitigated by using pre-distortion techniques [18]. Therefore, it is trivial to consider these minor effects in this study.

C. Signal-to-Interference-plus-Noise Ratio

SINR is an important metric to evaluate the connection quality and the transmission capacity in a cellular system. Based on the user received signal (4), the downlink SINR can be calculated by:

\[
\gamma = \frac{P_{\text{elec},0} G_0^2 R_{\text{pd}}^2}{\sum_{i \in I} P_{\text{elec},i} G_i^2 R_{\text{pd}}^2 + \sigma^2},
\]

where \( P_{\text{elec},i} \) denotes the electrical signal power transmitted by BS\( i \) excluding the DC component, which is calculated by \( P_{\text{elec},i} = \mathbb{E}[x_i^2(t)] \), where \( \mathbb{E}[\cdot] \) represents the expectation operation. In this study, no power control is considered, and a fixed electrical power for each BS is considered, which means \( P_{\text{elec},0} = P_{\text{elec},1} = \cdots = P_{\text{elec}} \). The cases with different electrical power for each BS can also be handled by the analysis described in this paper, but it is omitted here for simplicity. The relationship between the average electrical power and the average optical power in a DCO-OFDM system can be given as [16]:

\[
P_{\text{opt}}^2 = \frac{\eta^2}{\epsilon + \eta^2},
\]

\[
\eta = x_{\text{DC}}/\sqrt{P_{\text{elec}}},
\]

where \( \eta \) represents a DC-bias factor, which determines the level of DC-bias depth. Increasing \( \eta \) would decrease the clipping noise, but also decrease the amount of available electrical power for a certain amount of average optical power. After rearranging (6), it can be found that:

\[
P_{\text{elec}} = P_{\text{opt}}^2/\eta^2.
\]

By inserting (8) and (2) into (5), the downlink SINR received by the user can be rewritten as:

\[
\gamma = \frac{(r_0^2 + h^2)^{-m-3}}{\sum_{i \in I} (r_i^2 + h^2)^{-m-3} + \Omega} = \frac{S}{\Upsilon + \Omega},
\]

\[
\Omega = \frac{4\pi^2 (K - 2) N_0 W \eta^2}{KP_{\text{opt}}^2 (m + 1)^2 A_{\text{pd}}^2 R_{\text{pd}}^2 h^{2m+2}},
\]
where \( S = (r_0^2 + h^2)^{-m-3} \) denotes the effect of desired signal power; \( \Upsilon = \sum_{i \in \Omega} (r_i^2 + h^2)^{-m-3} \) denotes the effect of interfering signal power; and \( \Omega \) denotes the effect of receiver noise variance.

III. POISSON POINT PROCESS NETWORK MODEL AND SINR STATISTICS

The optical attocell cellular network model considered in this study is similar to that presented in [11]. The two-dimensional (2-D) positions of both the BS and the mobile user are arranged according to a stationary homogeneous Poisson point process with a fixed density. Each user is associated with the closest BS to it. This results in coverage areas of BSs following a Voronoi tessellation on the 2-D plane. The cell deployment is shown in Fig. 2 (b).

Without loss of generality, the network model is simplified as follows. The desired user is assumed to be located at the origin. BSs are randomly distributed around the user based on a PPP of density \( \Lambda \). The network extends to infinity in all directions. Note that CCI is the main concern of this study. Thus, it is important to consider the users experiencing the worst case CCI. Since interference is higher with an increase of the neighbouring BSs, an infinite network offers this worst case CCI condition. The first closest BS to the user (\( r_0 \) away from the user) serves the user. A cellular system with a reuse factor of \( \Delta \) divides the available transmission resource into \( \Delta \) equal blocks. In a grid network, these resource blocks are assigned to cells with a reuse pattern that avoids adjacent cells using the same resource, thereby mitigating the CCI. However, such a reuse pattern cannot be used in a PPP network as the BS locations are independent from each other. Therefore, each cell randomly selects one of the \( \Delta \) resource blocks for transmission regardless of the location of these cells. This is equivalent to amending the density of the interfering BSs to be \( \frac{\Lambda}{\Delta} \). The simplified cellular network model is shown in Fig. 3.

Next, the main results of the SINR statistics achieved by the system with PPP cell deployment is presented. Firstly, the calculation of the probability density function (PDF) of interference \( \Upsilon \) conditioning on \( r_0 \), \( f_{\Upsilon}(\nu|r_0) \), is considered. However, the exact expression of \( f_{\Upsilon}(\nu|r_0) \) is difficult to calculate due to the mathematical complexity. Alternatively, an expansion based on the Gram-Charlier series and Laguerre polynomials proposed in [19] is used to approximate the distribution. In this approximation, the PDF is expanded as a sum of gamma densities, which can be calculated if the row moments of the distribution are known. Therefore, the characteristic function \( \varphi_\Upsilon(r_0, \omega) = \mathbb{E} \left[ e^{j\omega r_0} \right] \) is evaluated.

Based on the relationship between the characteristic function and the cumulant generating function, the expression of the \( n^{th} \) cumulant of \( \Upsilon \) conditioning on \( r_0 \) can be calculated as:

\[
\kappa_n(\Upsilon|r_0) = \frac{\Delta \pi (r_0^2 + h^2)^{1-n(m+3)}}{\Delta(n(m+3)-1)}. \tag{11}
\]

Then the corresponding \( n^{th} \) row moment can be calculated recursively by the following relationship as:

\[
\mu_n = \begin{cases} 
1 & : n = 0 \\
\kappa_1 & : n = 1 \\
\kappa_n + \sum_{l=1}^{n-1} \binom{n-1}{l-1} \kappa_l \mu_{n-l} & : n \geq 2 
\end{cases} \tag{12}
\]

Since the row moments are known, the approximated expression for \( f_{\Upsilon}(\nu|r_0) \) can be calculated. Then the SINR CDF can be calculated using the following equation:

\[
P[\gamma < T] = P[\Upsilon > S/T - \Omega] = \int_{\Omega}^{\infty} \int_{-\infty}^{\infty} f_{\Upsilon}(b)^{1/T} f_T(b|r_0) \mathrm{d}v \mathrm{d}b, \tag{13}
\]

where \( f_{\Upsilon}(b) = 2\pi \Lambda b e^{-\Delta \pi b^2} \) is the PDF of the distance between the origin and the nearest node [20]. The final result of \( P[\gamma < T] \) is concluded in (14). The detailed derivation will be presented in a future publication.

The accuracy of (14) is evaluated by comparing its results to the corresponding Monte Carlo simulations. The main system parameters are listed in Table I. In the results, three systems with different configurations are considered, as shown in Fig. 4. Although the cell does not have a regular coverage area for the system with the PPP cell deployment, it is important to make sure that systems with different cell deployments have the same BS density in order to achieve a fair comparison. Assuming the system with a hexagonal grid cellular model has a cell radius of \( R \), the corresponding PPP network should have a BS density of \( \Lambda = \frac{1}{\pi R^2} \frac{2\sqrt{3}}{9\pi^2} \). It can be found that the numerical results of the analysis calculated using (14) generally matches the corresponding Monte Carlo simulation, except for a minor mismatch at the high SINR region. This

**TABLE I**  
**SYSTEM PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS LED optical power</td>
<td>( P_{\text{opt}} )</td>
<td>10 W</td>
</tr>
<tr>
<td>vertical separation</td>
<td>( h )</td>
<td>2.25 m</td>
</tr>
<tr>
<td>Noise PSD</td>
<td>( N_0 )</td>
<td>( 1 \times 10^{-20} ) A^2/Hz</td>
</tr>
<tr>
<td>PD area</td>
<td>( A_{\text{pd}} )</td>
<td>1 cm^2</td>
</tr>
<tr>
<td>PD responsivity</td>
<td>( P_{\text{rd}} )</td>
<td>0.6 A/W</td>
</tr>
<tr>
<td>DC-bias factor</td>
<td>( \eta )</td>
<td>3</td>
</tr>
<tr>
<td>number of subcarriers</td>
<td>( K )</td>
<td>512</td>
</tr>
</tbody>
</table>
\[
P[\gamma < T] = \int_0^\infty 2\pi Ab \sum_{n=0}^\infty \frac{\beta^n \sum_{l=0}^n \frac{C_{l}^{n}}{n!} \mu_1(Y)}{\beta l + \alpha} \left( \begin{array}{c}
\sum_{l=0}^n \frac{C_{l}^{n}}{\beta l + \alpha} \left( \frac{1}{T} \left( b^2 + h^2 \right)^{m+3} - \Omega \right) \right) dB
\end{array}\right)
\]

\[
\beta = \frac{(2m + 5) (b^2 + h^2)^{m+3}}{m + 2}, \quad \alpha = \frac{\Lambda \pi (2m + 5) (b^2 + h^2)}{\Delta (m + 2)^2}, \quad C_{l}^{n} = \left( \frac{n}{l} \right) (-1)^{n-l}/\beta l, \quad S_{l}^{n} = \left\{ \frac{1}{\Pi_{l=1}^{n-1} (\alpha + l)} : l > n - 1 \right\}
\]

Fig. 4. The analytical and simulated results of the CDF of the downlink transmission SINR achieved by PPP networks.

mismatch is caused by the approximation for \(f_T(\gamma|\nu_0)\) which uses the expansion introduced in [19]. The mismatch becomes obvious when the overall interference level is very low. Therefore, the best match can be observed for the system with \(R = 1.5\ m, \phi_{1/2} = 40^\circ, \Delta = 1\) and noise distortion. This is because, the noise variance is much higher than the interference in the high SINR region. In another case with \(R = 2.5\ m, \phi_{1/2} = 60^\circ, \Delta = 1\) and without noise distortion, the differences between analysis and simulation in the high SINR region becomes significant due to the absence of noise distortion. In the case with \(R = 2.5\ m, \phi_{1/2} = 60^\circ, \Delta = 3\) and noise distortion, the interference level is lower relative to the cases with \(\Delta = 1\). Consequently, the differences become even greater despite the presence of noise. However, generally the distribution at low SINR region is of higher importance. Thus, it is still valid to consider (14) to be an accurate result.

IV. SINR STATISTICS COMPARISON

For a system with a hexagonal cell deployment, the locations of BSs are fully correlated, which guarantees a minimum distance between the desired user and the interfering BSs, as shown in Fig. 2 (a). One of the fundamental characteristics of light propagation from an optical source is that the received signal power is constant along a circle centred at the source. The hexagon shape provides the best approximation to this circle compared to square or triangle. Therefore, CCI is minimised in a hexagonal network. In contrast, the locations of BSs are completely uncorrelated in a PPP network as shown in Fig. 2 (b). In the worst case, BSs are extremely close to each other, which causes significant CCI. Thus, similar to [11], we expect to use the performance of the system with the hexagonal (PPP) cell deployment as an upper (lower) bound of the practical system performance. In order to demonstrate this expectation, systems with these two cell deployments are compared to the systems with the cell deployments that are likely to be used in practice.

A. Square Network

The first potential cell deployment in practice considered here is the square lattice cellular model, in which BSs are placed on a square lattice as shown in Fig. 2 (c). This arrangement is common in indoor lighting network deployment due to several advantages, which include design simplicity, providing good illumination uniformity and compliance to the shape of a room.

In the square network, the cell size is controlled by a parameter \(L\) which is defined as the distance between the two closest BSs. In order to have a fair comparison, the density of the BSs should be the same as the case with hexagonal network and PPP network. This requires: \(L = \frac{\sqrt{A_{cell}}}{m} \approx 1.61R\).

B. Hard-Core Point Process Network

In some cases, the room may not need uniform illumination. For example, illumination is enhanced in the task areas\(^1\), while

\(^1\)Area within which the visual task is carried out.
less lighting is required in the remaining areas. This fact would introduce an uneven lighting network deployment. In this case, the position of BSs may be unregulated, but it is unlikely to place two luminaries extremely close to each other. Therefore, the Matérn type I hard-core point process (HCPP) is considered to model the BSs position, as shown in Fig. 2 (d).

The HCPP is based on a PPP with the condition that the shortest distance between any two nodes is greater than a specified threshold $c$. To generate a set of nodes according to a HCPP, a set of nodes following a PPP with a density of $\Lambda_0$ is necessary. Then each point is marked with a random number. A dependent thinning process is carried out for each marked node as follows: retain the marked node if there is no other node within the circle centred at the marked node with a radius of $c$. After the thinning, the HCPP nodes density would be reduced. Therefore, to generate a HCPP with density of $\Lambda$, the initial PPP density $\Lambda_0$ has to be [21]: $\Lambda_0 = -\ln(1 - \Lambda \pi c^2) / \pi c^2$.

C. Results and Discussions

Fig. 5 shows the SINR CDF results with four different cell deployments, namely hexagonal, PPP, square and HCPP cell deployments. The system parameters follow those listed in Table I. As expected, due to the dependence of BS placement, the PPP network shows the worst performance. It exhibits a median SINR of about 2.5 dB. In contrast, the strict control of BS location with hexagonal lattice mitigates the CCI, thereby providing the best SINR performance with a median SINR of about 6.9 dB. Due to the undesired approximation of a square to a circle, the system with a square network offers a slightly worse SINR than the the case of a hexagonal network. The achieved median SINR is 6.5 dB. For the case of the HCPP network, the achieved median SINR is about 4.6 dB, which is better than the case of the PPP network because of the minimum distance constraint. Therefore, it is concluded that the downlink SINR performance in an optical attocell network with a PPP (hexagonal) cell deployment can be considered as a lower (upper) bound for the case of practical systems.

V. CONCLUSION

This paper presents a new analytical framework for the system performance of an optical attocell network. The downlink SINR statistics in a DCO-OFDM based optical attocell network with PPP cell deployment have been considered. An analytical expression for the statistics of SINR in PPP network has been presented. The result shows the accuracy of the expression. In addition, the SINR statistics of the PPP network are compared to systems with hexagonal, square and HCPP cell deployments. The results have demonstrated that the system with PPP (hexagonal) cell deployment behaves as an upper (lower) bound for the systems with square and HCPP cell deployments. These results can be used to estimate the performance of a practical optical attocell system without using time-consuming computer simulations. Furthermore, they can be used as benchmarks for further research on optical attocell systems, and as a guideline for setting up a practical system.

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