Coverage analysis of Multiuser VLC networks

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PROBLEM STATEMENT

In this paper, a new mathematical framework for the coverage probability analysis of multiuser visible light communication (VLC) networks is presented. It takes into account the idle probability of access points (APs) that are not associated with any users and hence do not function as the source of interference. The goal of this paper is to evaluate the coverage probability of a typical user in the network, which is equivalent to evaluating the complementary cumulative distribution function (CCDF) of the SINR.

MOTIVATION

When we came to know that a project was required to be implemented, we started searching for various research papers. We came across the term “Visible light communication”. This sparked our curiosity because in OCS we studied Optical communication through guided media i.e. an optical fiber, but Visible light communication talks about optical communication without any guided media, instead, Light Emitting Diodes (LEDs) are used. Light-emitting diodes (LEDs) are changing indoor wireless communications. Problems that motivated researchers to research more about this topic is that current wireless networks are experiencing difficulties in keeping pace with the exponential growth of wireless devices that require higher data rate and seamless service coverage Visible light communications (VLC) that use LEDs as transmitters is an emerging research area and have significant commercial potential. This light serves two purposes: illumination and information carrier. Due to the intrinsic characteristics of light, VLC is more secure, more power-efficient, and can provide higher network data transmission rates than radio frequency communications. Going through numerous papers on VLC, we came across our current paper, “Coverage analysis of Multiuser VLC network”. In today’s world, there’s mostly more than one device in a room and it is important that each device is able to receive the required information efficiently, on time, securely and without any loss of data. We also wanted to understand how much coverage each LED can provide with reliable information output which can thus help in calculating how much LEDs are required per room.

BACKGROUND

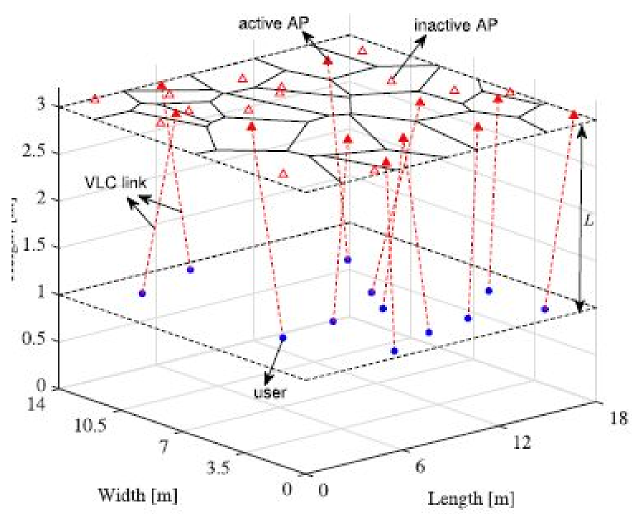
We have chosen this project to see how the future optical network can look like and how efficient it would be. We have implemented the paper using the MATLAB tool and obtained the results according to the paper.

System-level performance of multiuser VLC networks is typically evaluated with the aid of computer simulations. They are often complicated, time-consuming, and unable to provide many insights into how the performance is affected by various parameters in the network. The analytical evaluation, on the other hand, is generally not straightforward due to the lack of accurate and at the same time analytically tractable models. The most common approach for modeling the location of optical APs is based on the grid model, where LED lights are installed in the ceiling with a regular pattern The evaluation of the grid-based network is recognized to be analytically difficult and hence is normally done with computer simulation, which has also motivated the authors to use stochastic Models for the performance evaluation. Compared to the grid model, stochastic models are more mathematically tractable. More importantly, the following observations indicate that in some scenarios a stochastic model is required in order to accurately characterize the performance of VLC networks. Firstly, modern LED lights with built-in motion detection sensors are widely deployed in public spaces to reduce energy consumption. In this scenario, some of the LED lights are temporarily switched off when they are not required to provide illumination. Also, even when switched on, some of the LEDs can turn off their wireless communication functionality when no data traffic is demanded from them, for example, relying on an AP sleep strategy. In these scenarios, the distribution of APs cannot be accurately modeled by the grid model. Instead, a stochastic thinning process built upon the grid-like deployment of LEDs is more accurate. However, modeling this stochastic thinning process requires full knowledge of the users' movement and handover characteristics, which is not analytically tractable. Secondly, the distribution of active APs in a VLC network is generally variable, and it changes dynamically due to the random movement of users. Thirdly, the grid model is not applicable in scenarios where not only ceiling lights but also LED screens, reading lamps, and other "smart" lights are an integral part of the network architecture, in which the deployment of VLC APs appears to be more stochastic. For these reasons and in order to obtain analytically tractable results, the PPP model is of our focus in this paper.

We report in this paper a new and simpler method for the characterization of the density function of the SINR by exploring powerful mathematical tools from stochastic geometry.

IMPLEMENTATION

1. The paper has considered a downlink transmission scenario in a multi-user VLC network, with full-frequency reuse, over a three- dimensional indoor space. The VLC APs are vertically fixed since they are attached to the room ceiling while their horizontal locations are modeled by a 2D homogeneous PPP $\Phi_a = \{x_l, l \in N\} \subset R^2$, with node density λ_a, where x_i is the horizontal distance between AP i and the origin. Similarly, mobile users are also assumed to be at a fixed height. Their horizontal locations are modeled by another independent 2D homogeneous PPP $\Phi_u = \{y_j, j \in N\} \subset R^2$, with node density λ_u.
2. The basic scenario can be illustrated from the below picture.



3. The complete VLC channel between an AP and a user includes both the line-of-sight (LOS) link and non-line-of-sight (NLOS) links, that are caused by light reflections of interior surfaces in the indoor environment. However, in a typical indoor environment, the signal power of NLOS components is significantly lower than that of the LOS link. So, the paper focuses only on LOS.
4. For each VLC link, the direct current gain of the channel is given. The VLC channel gain from AP i to the typical user can be simplified to: $h_i(x_i) = \alpha(x_i^2 + L^2)^{-\frac{m+3}{2}}$
5. SINR at the typical user is given by - $$\text{SINR} = \frac{P_{tx}\alpha^2(x_0^2 + L^2)^{-(m+3)}}{\sum_{x_i \in \Phi_a \setminus \{x_0\}} P_{tx}\alpha^2(x_i^2 + L^2)^{-(m+3)} + \sigma^2},$$

For small scale VLCs, user performance is limited by interference by neighboring APs, so the SINR can be approximated as SIR as-

$$\mathsf{SIR} = \frac{(x_0^2 + L^2)^{-(m+3)}}{\sum_{x_i \in \tilde{\Phi}_a \setminus \{x_0\}} (x_i^2 + L^2)^{-(m+3)}}.$$

Idle probability

P (idle) can be given by

$$p_{\text{idle}} = \mathbb{P}\left[\sum_{y_i \in \Phi_u} 1_{\mathcal{A}}(y_i) = 0\right] = \left(\frac{\beta}{\beta + \frac{\lambda_u}{\lambda_a}}\right)^{\beta}.$$

The main interest is to find the probability that there exist k users inside the Voronoi cell generated from ɸ a. The idle probability of APs is determined by the ratio of user density to AP density, but not the exact value of user density or AP density.

Coverage probability analysis

➔ In the low SINR regime:

- For a low SINR regime, Coverage probability analysis is given as the function of the denominator of the Laplace of transform of P(SIR<T) where T is the threshold.
- The Laplace of transform can be given as below:

$$\mathcal{L}_{\mathsf{ISR}}(s) = \frac{1}{\frac{1}{m+3} E_{\frac{m+4}{m+3}}(s) + \Gamma\left(\frac{m+2}{m+3}\right) s^{\frac{1}{m+3}}} \exp\Bigg[- \pi \tilde{\lambda}_a L^2 \times \left(-1 + \frac{1}{m+3} E_{\frac{m+4}{m+3}}(s) + \Gamma\left(\frac{m+2}{m+3}\right) s^{\frac{1}{m+3}} \right) \Bigg], \quad (13)$$

- The coverage probability of a typical user in the low SIR regime, i.e., T < 1, can be approximated by $\mathbb{P}[\mathsf{SIR} > T] \approx 1 - \exp\left(\frac{s^*}{T}\right),$ where s* are the poles of the Laplace transform which are [-2.173,1.847,-1.658] upon setting m at semi-angles=[45,60,75].

➔ In the High SINR regime:

- Coverage analysis in the interference limited scenario for the high SINR regime can be given as

$$\mathbb{P}[\mathsf{SINR} > T] = \frac{1}{\Gamma\left(\frac{m+2}{m+3}\right)\Gamma\left(\frac{m+4}{m+3}\right)} T^{-\frac{1}{m+3}}.$$

➔ Upper bound on the coverage analysis:

- The obtained result serves as an upper bound on the coverage probability since it ignores the effect of receiver noise and underestimates the interference level and hence overestimates the SINR. This result is stated below:

Proposition 1: An upper bound on the coverage probability of a typical user is:

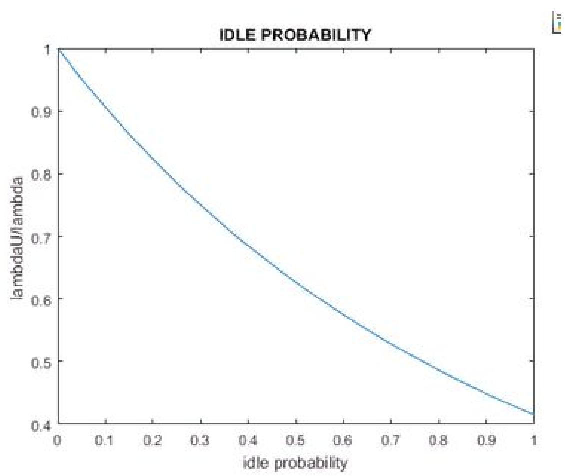
$$\mathbb{P}\left[\mathrm{SINR} > T\right] \leq T^{-\frac{1}{m+3}} \exp\left(-\pi \tilde{\lambda}_a L^2 \left(T^{\frac{1}{m+3}} - 1\right)\right). \quad (25)$$

RESULTS

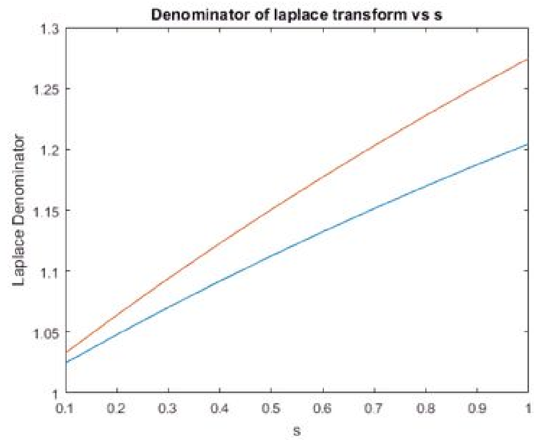
Based on the highest channel gain association of the user with the corresponding AP's, the dependence of the idle probability on the ratio of node density of users and ap's were derived and similarly a graph was plotted which clearly demonstrates the relationship:

<u>Inference 1</u>

As the user density increases, the probability of AP's being idle decreases. Without efficient interference mitigation techniques, the coverage probability reduces as the density of APs increases.



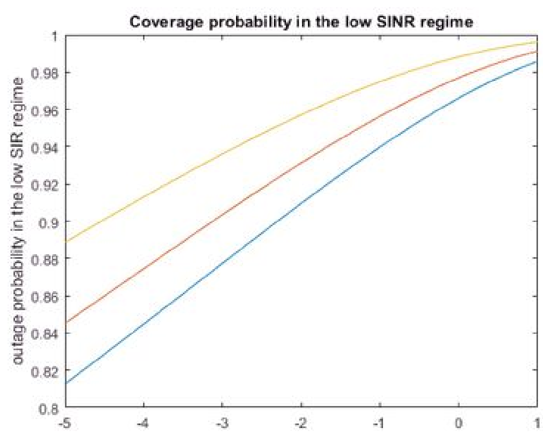
1. The Laplace transform as a function of s derived is given below:



2. Outage probability in the low SINR regime at semi-angles = [45,60 and 75] is given below:

Inference 2

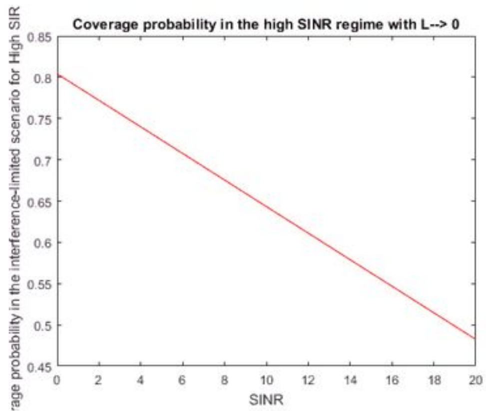
AP's with smaller semi angle had more directional light beams, hence less light coverage per AP.



3. Coverage probability in the high SINR regime in an interference-limited scenario with L→ 0 is derived as:

Inference 3

When L = 0, the three-dimensional network model reduces to a two-dimensional planar model, and the coverage probability is found to follow a power-law decay profile. When the SINR target increases, the coverage probability in the high SINR regime decreases.



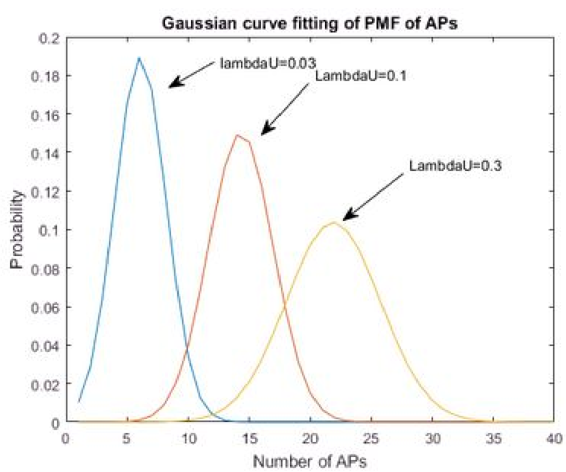
4. The derived idle probability of VLC APs is shown to be accurate. However, it does not confirm that the thinned process is a homogeneous PPP. Therefore the PMF of active AP's was derived as a function of user density which is given as:

$$\mathrm{P}\left[\sum_{x_i \in \bar{\Phi}_a} \mathbf{1}_{\mathcal{A}}(x_i) = n\right] = a_{\mathrm{G}} \exp\left(-\left(\frac{n - b_{\mathrm{G}}}{c_{\mathrm{G}}}\right)^2\right),$$

Where ag, bg, and cg are constants that depend on user density.

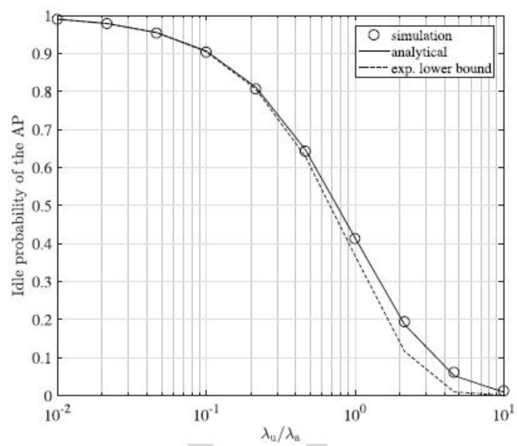
Inference 4

It can be seen from the results that the number of AP's can be well modeled by the discrete Gaussian function. This result follows directly from the fact that the Poisson approximation and the Gaussian approximation of the PMF of distribution have the same mean.

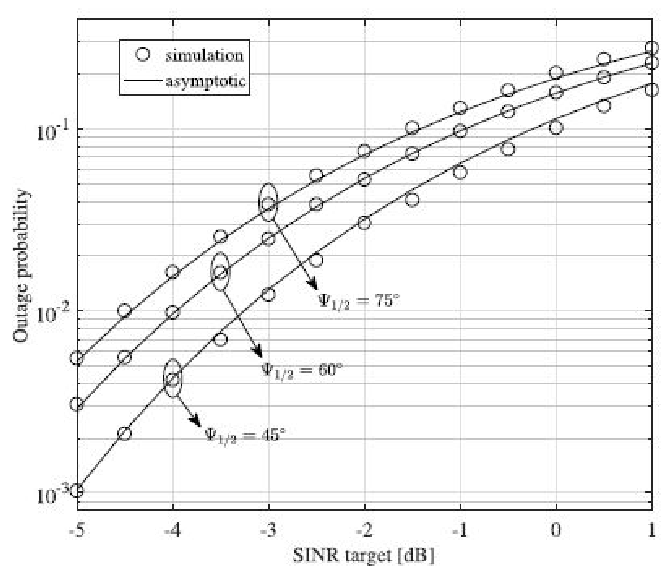


RESULTS OF THE ORIGINAL PAPER

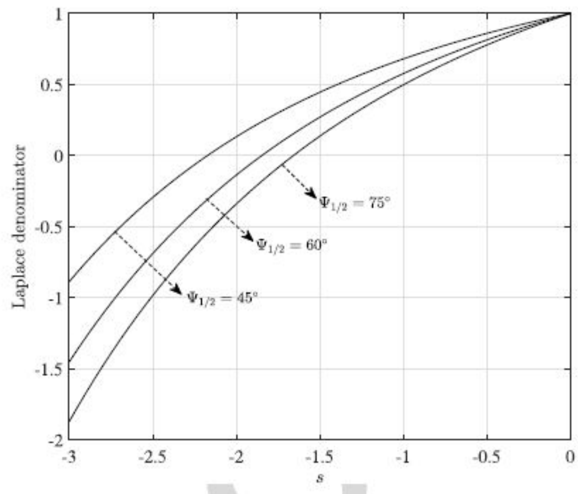
Idle probability



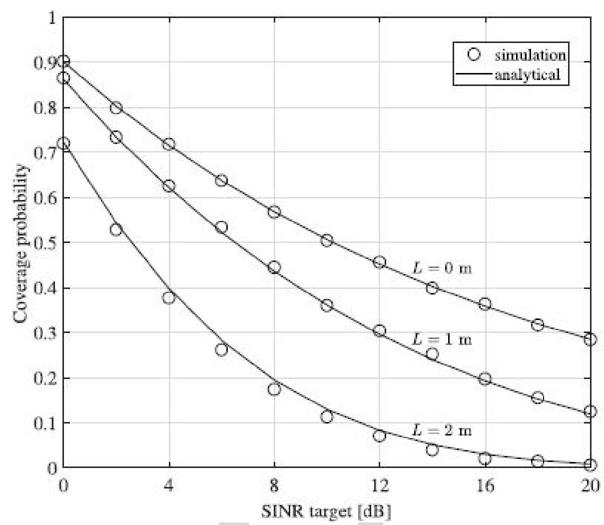
Coverage probability in the low SINR regime



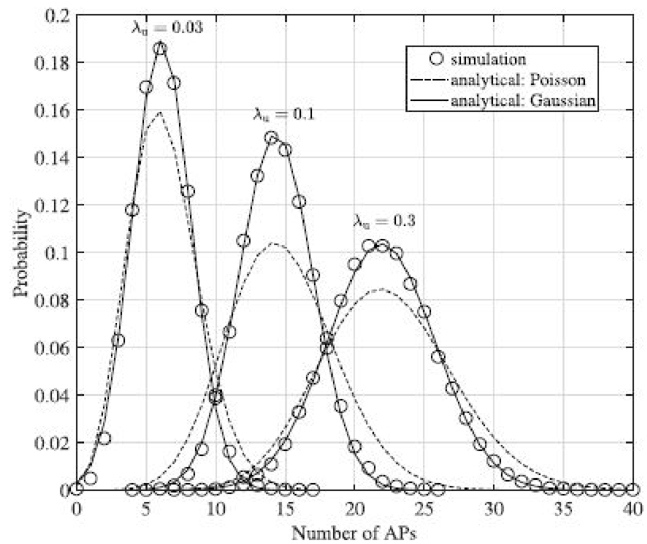
The denominator of Laplace as a function of s



Coverage probability in the high SINR regime with L=0



Gaussian curve fitting of a number of AP’s.



CONCLUSION

1. In this paper, we provide a new analytical framework for the coverage analysis of multiuser VLC networks, taking into account the idle probability of APs that is evident especially in underloaded networks as well as general networks that operate with an AP sleep strategy to save energy and/or minimize the co-channel interference.

2. By using mathematical tools from stochastic geometry and statistical-equivalent transformation, analytical expressions for the coverage probability are derived and given intractable forms. Based on the derived results, it is shown that not only the density of AP’s but also the density of users, has a significant impact on the coverage performance The homogeneous PPP assumption for active APs is shown to be valid in general and gives close coverage results to the exact ones when the density of users is no smaller than the density of APs.

3. A detailed evaluation of the applicability of the PPP model to VLC networks can be our future work. Further extensions of this work could include more realistic channel and blockage models. It is also of interest to generalize the proposed analytical framework to incorporate cell coordinations.

Group -14