INVESTIGATION ON CHANNEL CAPACITY OF IRS-AIDED OWC NETWORK

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ABSTRACT.

Optical wireless communication (OWC) is envisioned as one of the main enabling technologies of 6G networks, complementing radio frequency (RF) systems to provide high data rates. One of the crucial issues in indoor OWC is service interruptions due to blockages that obstruct the line of sight (LoS) between users and their access points (APs). In this paper we have studied the SINR and data rates of Intelligent Reflecting Surface (IRS)-aided OWC Network using simulations and effect of different parameters on it. It has been found that Signal to Noise plus Interference ratio and data rate should be high and user interference with other users, preamplifier noise and shot noise should be low.

KEYWORDS: Spectral efficiency, Energy efficiency , Data rate, MIMO

I. INTRODUCTION

The rapid evolution of communication technologies has set the stage for 6G networks to revolutionize data transmission by offering ultra-high speeds, low latency, and massive connectivity. Among the technologies underpinning 6G, Optical Wireless Communication (OWC) has emerged as a viable alternative and complement to traditional Radio Frequency (RF) systems. OWC operates in the visible, infrared, and ultraviolet light spectrum, providing an unlicensed, interference-free communication medium [1]. This makes OWC particularly attractive for indoor environments, where it can support high-capacity networks with minimal interference.

II. LITERATURE REVIEW

Despite its potential, OWC systems face critical challenges, particularly line-of-sight (LoS) blockages caused by physical obstructions that can severely disrupt connectivity. Such interruptions limit the practicality of OWC systems, especially in dynamic environments. To address this issue, researchers have proposed the integration of Intelligent Reflecting Surfaces (IRSs) into OWC networks. IRSs are passive devices capable of dynamically reflecting signals to redirect light paths, thereby mitigating the effects of blockages and enhancing overall system performance. Recent studies have demonstrated the potential of IRSs to improve the robustness, coverage, and spectrum efficiency of wireless communication systems [2].

Hamad et al. (2024) explored the application of IRSs in laser-based OWC networks, showing significant improvements in data rates under practical deployment constraints [2]. Similarly, Sun et al. (2023) investigated capacity enhancement in Multiple-Input Multiple-Output (MIMO) OWC systems assisted by Optical Intelligent Reflecting Surfaces (OIRS), emphasizing the importance of optimizing IRS configurations for capacity gains [3].

In this study, we examine the spectrum efficiency of IRS-aided OWC networks through simulations, analyzing the interplay of various parameters, including Signal-to-Noise plus Interference Ratio (SINR), user interference, network load, and channel bandwidth. Our findings have underscored the need for careful parameter optimization to achieve high spectrum efficiency. Specifically, reducing preamplifier noise, shot noise, and user interference while maintaining high SINR levels is critical.

The foundations of VLC were laid with early research demonstrating the feasibility of using LEDs for data transmission, achieving data rates in the megabits-per-second range [4]. Over the years, advancements in modulation techniques, such as Orthogonal Frequency Division Multiplexing (OFDM), have significantly enhanced VLC capabilities. For instance the study [5], reported data rates exceeding 100 Gbps, showcasing VLC as a viable contender for next-generation communication networks. One of the key advantages of VLC is its security. Since visible light cannot penetrate opaque objects, communication remains confined within physical boundaries, reducing the risk of unauthorized interception [6]. Moreover, the visible light spectrum, which is unregulated and significantly larger than the RF spectrum, allows for higher data throughput and minimizes interference, as highlighted in [7].

Despite its benefits, VLC faces challenges, such as susceptibility to ambient light interference, shadowing, and the line-of-sight requirement. Researchers have proposed various solutions to overcome these issues. For example, introduction of Multiple Input Multiple Output (MIMO) techniques to improve system robustness as discussed in [8]. Hybrid systems that integrate VLC with RF technologies have also been explored to enhance reliability and coverage, as discussed in [9].

The potential applications of VLC are extensive. In indoor environments, VLC can provide high-speed data transmission while maintaining lighting functionality [10]. In vehicular communication systems, VLC facilitates communication between vehicles and infrastructure, enhancing traffic management and safety [11]. Underwater, where RF signals are ineffective, VLC offers a viable alternative for short-range communication [12]. Furthermore, VLC is being explored for Internet of Things (IoT) applications, particularly in scenarios requiring secure and high-speed data links [13].

III. SYSTEM MODEL

We consider a downlink VLC system where L optical APs are mounted on the ceiling to offer both illumination and communication for K users, who are randomly distributed across the communication plane, as illustrated in Fig. 1.

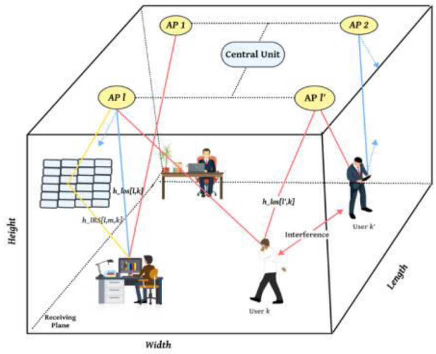

Fig. 1: IRS-aided OWC system model [15]

Each optical AP, l ∈ L, consists of multiple LEDs to provide a wider coverage area while maintaining eye safety regulations. Each user, k ∈ K, is equipped with an optical receiver also known as angle diversity receiver (ADR) with multiple branch photodiodes which are oriented in different directions to provide independent channel responses. The directions of the ADR photodiodes are specified by their elevation (E_l) angles and azimuth (A_z). Further details on channel response calculations can be found in [14]. A mirror array, which plays the role of IRS with reflective elements, is mounted on the wall to improve the gain of the reflective channel. The mirror array consists of M, identical, passive, and smooth reflective mirrors. Each mirror, m ∈ M, is rectangular with specific width × height dimensions and oriented according to two independent angles: the roll angle around the y-axis, ϵ_y, and the yaw angle, ϑ_z, around the z-axis. Given the large number of mirrors in the indoor environment, mirror orientations are determined to achieve better coverage in the room. Therefore, each user is expected to find at least one mirror available at its location that can improve its received signal.

In the following, the LoS link between a pair of an optical AP and a user, the specular NLoS link established through an IRS mirror.

A. The LoS channel gain

The LoS component of the optical channel is the largest contributor to the power received by the user. The received channel gain by user k ∈ K from AP l ∈ L considering the LoS component is given as

$h_{k,l}^{LoS}=$

$$\left\{\begin{array}{ll}\frac{(n+1)A_r\cos^n(\alpha_{k,l})\cos(\delta_{k,l})}{2\pi D_{k,l}^2}, & 0\le\delta_{(k,l)}\le\psi_c\\ 0 & \delta_{(k,l)}>\psi_c\end{array}\right. \quad \text{………………(1)}$$

where n is the order of Lambertian emission, which is based on the half-power semi-angle of the LED $\phi_{1/2}$ and can be expressed as $n = -\ln(2)/\ln(\cos(\phi_{1/2}))$. Moreover, A_r is the detector area, /alpha $\alpha_{(k,l)}$ is the incident ray angle between the normal to the AP l and the irradiance ray of the user k, $\delta_{(k,l)}$ is the angle between the normal of the photodetector and the incident ray, and $D_{(k,l)}$ is the distance between AP l and user k. Note that, the incidence angle $\delta_{(k,l)}$ must be within a range from 0 to the acceptance semi-angle of the concentrator (ψc), guaranteeing that the signal of the direct LoS is detected by the receiver; otherwise, no signal is received, i.e., $h_{k,l}^{LoS} = 0$.

B. The IRS-reflected channel gain

Assuming complete specular reflection by the mirrors of the IRS, the received channel m,l gain by user k ∈ K from mirror m ∈ M reflecting the signal from AP l ∈ L is given as

$$h_{k,m,l}^{IRS}=\left\{\begin{array}{ll}\frac{(n+1)\rho_m A_r\, dA_m \cos^n(\alpha_{m,l})\cos(\beta_{k,m})}{2\pi(D_{m,l}+D_{k,m})^2}, & 0\le\beta_{k,m}\le\psi_c\\ 0, & \beta_{k,m}>\psi_c\end{array}\right. \quad ..(2)$$

where ρ_m and dA_m are the reflection coefficient and the area of mirror m, respectively, $\alpha_{m,l}$ is the irradiance angle from AP l to mirror m, $\beta_{k,m}$ is the incidence angle of the signal reflected from mirror m to user k, $D_{m,l}$ is the distance between AP l and mirror m and $D_{k,m}$ is the distance between mirror m and user k. Moreover, the irradiance and incidence angles can be calculated as

$$\cos(\alpha_{m,l}) = \frac{D_{m,l}\cdot n_l}{\|D_{m,l}\|}, \quad (3)$$

$$\cos(\beta_{k,m}) = \frac{D_{k,m}\cdot n_k}{\|D_{k,m}\|}, \quad (4)$$

Where n_l represents the normal vector to the AP plane, n_k denotes the normal vector at the receiver plane, · is the inner product and ‖·‖ denotes the Euclidean norm operators.

C. User Data Rate

In the system model considered, the signal received by user k, k ∈ K, can be expressed as

$$y_k = [h_{k,l}^{LoS} + h_{k,m,l}^{IRS}]P_k x_k + [h_{k,l}^{LoS} + h_{k,m,l}^{IRS}]P_{k'} x_{k'} + z_k, \quad (5)$$

where x_t and P_t, t ∈ {k, k′}, are the transmitted signal and power intended to a certain user. Note that multi-user interference can be avoided through serving users over exclusive frequencies or time slots. Moreover, z_k is the real-valued additive white Gaussian noise (AWGN) with zero mean and a certain variance. From equation(5), the signal-to-interference plus-noise ratio $SINR_k$ of user k can be expressed as

$$SINR_k = \frac{\left[R_0^2 P_k^2 (h_{k,l}^{LoS}+h_{k,m,l}^{IRS})^2\right]}{(I_k^2+\sigma_t^2)}, \quad (6)$$

Where R_0 is the receiver responsivity, I_k represents the interference received by user k from optical APs other than its corresponding optical AP, and $\sigma^2{}_t$ is the summation of preamplifier noise, shot noise associated with the received signal and background shot noise. Considering a tight lower bound of the achievable data rate for the dimmable VLC system derived in [16] , the data rate of user k ∈ K is given by

$$R_k = \frac{B}{K_{in}}\log_2\left(1 + \frac{e}{2\pi} SINR_k\right), \quad (7)$$

Where B is the modulation bandwidth, K_{in} denotes users interfering with each other, i.e., users served by the same optical APs, and $\frac{e}{2\pi}$ is for IM/DD.

IV. ANALYSIS AND RESULTS

This section presents the results of simulations exploring how transmitted power, distance between access point and mirror in IRS reflected channel , distance between access point and user in LOS channel affect SINR , data rate i.e. spectral efficiency (SE) of next-generation wireless system. Spectral efficiency is a critical metric for measuring how efficiently a wireless network utilizes its available bandwidth to transfer data.

The simulations are conducted with parameters as data available in literature [17] as follows :

R_0 =0.4 A/w, P_k =1 to 10 w, A_r =20 mm^2 , $\varphi_{1/2}$ = 60°, ρ_m= 0.95= mirror reflectivity,dAm=25x10 cm^2 area of each mirror,σ_t^2=10^{-12} w , m= 0.5 m to 5m , B= 20MHz and explore their effects on spectral efficiency of the system.

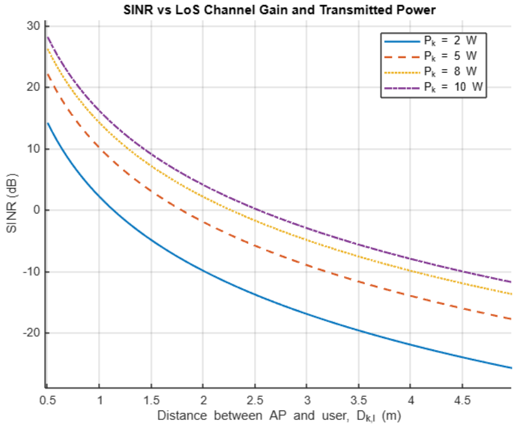

Fig.2 :SINR Vs Distance between AP and User for LOS channel

From fig.2 which has plotted for LoS Channel gain between SINR vs distance between Access Point (A.P) and user. It has found that when we have increased the distance the SINR decreases. The observation has been done taking five different power levels and it has found that higher power level gives better SINR till a certain level after that increasing power level will merely affect the SINR.

Table-1: SNIR at a distance of 0.7m between A.P and User for different transmitted power

S No.	Power	SINR
1.	2W	8.75 dB
2.	5W	16.71 dB
3.	8W	20.79 dB
4.	10W	22.73 dB

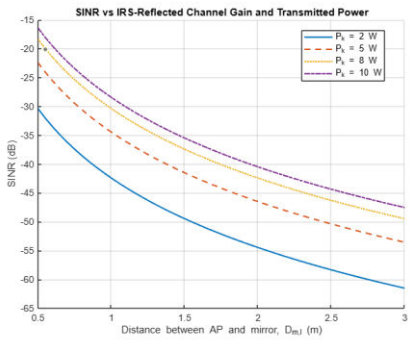

Fig.3 SINR Vs Distance Between A.P and Mirror for IRS channel

from the graph fig.3 which has plotted for IRS-reflected channel gain between SINR vs distance between Access Point (A.P) and mirror. It has found that when we have increased the distance the SINR decreases and this decrease is greater compare to last case of LOS channel gain i.e. Fig.2. The observation has been done taking five different transmitted powers and it has found that higher power level gives better SINR till a certain level after that increasing power level will slightly effect the SINR but this values of SINR are high as compare to LoS case.

Table-2: SNIR at a distance of 0.7m between A.P and mirror for different transmitted power

S No.	Power	SINR
1.	2W	-36.33dB
2.	5W	-28.38 dB
3.	8W	-24.29 dB
4.	10W	-22.36 dB

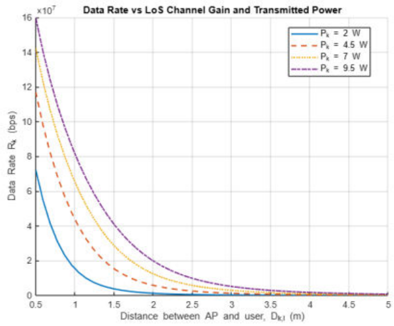

Fig.4 Data Rate Vs Distance Between A.P and User for Los channel

from the graph fig.4 which has plotted for LOS Channel gain between Data Rate vs distance between Access Point (A.P) and user. It has found that when we have increased the distance the data rate decreases. the observation has been done taking four different power levels and it has found that higher the power level the received data rate is high but with a higher steeper decrease in curve.

Table-3: Data rate at a distance of 0.7m between A.P and User for different transmitted power

S No.	Power	Data Rate
1.	2W	$3.942*10^7$ bps
2.	4.75W	$7.962*10^7$ bps
3.	7W	$10.402*10^7$ bps
4.	9.5W	$12.128*10^7$ bps

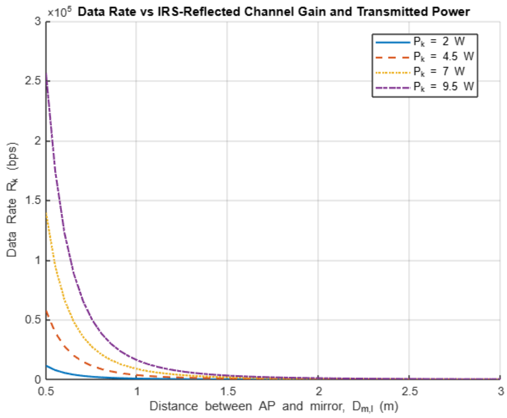

Fig.5 Data Rate Vs Distance Between A.P and Mirror for IRS reflected channel

from the fig.5 which has plotted for IRS-reflected channel gain between Data Rate vs distance between Access Point (A.P) and mirror. It has found that when we have increased the distance the data rate decreases. the observation has been done taking four different power levels and it has found that higher the power level the received data rate is high but with a higher exponential decrease in curve.

Table-4: Data rate at a distance of 0.7m between A.P and Mirror for different transmitted power

S No.	Power	Data Rate
1.	2W	$0.03 *10^5$ bps
2.	4.5W	$0.15 *10^5$bps
3.	7W	$0.36 *10^5$ bps
4.	9.5W	$0.66*10^5$ bps

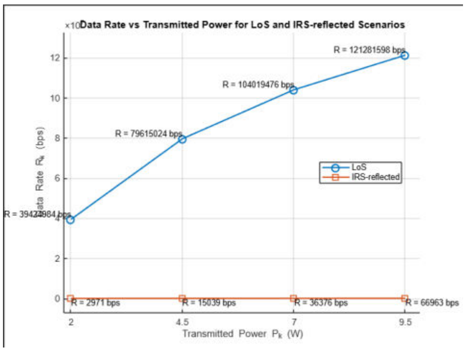

Fig.6 Data Rate Vs Transmitted Power for LoS and IRS-reflected Scenarios

from the graph fig.6 which has plotted for LoS and IRS-reflected Scenarios between Data Rate vs transmitted Power for a fixed distance between A.P and user & A.P and Mirror i.e 0.7m. It has found that LoS communication is superior in terms of data rate, making it the preferred option for OWC systems when a direct path is available while the IRS-reflected communication can extend coverage to non-LoS regions but comes at the cost of reduced performance. Improving IRS design can narrow the performance gap between IRS-reflected and LoS paths. Combining LoS and IRS-reflected paths in hybrid OWC systems can enhance overall coverage and reliability.

V. CONCLUSION

As the distance between the AP and the user increases, the LoS channel gain (h_(k,l)^LoS) decreases significantly, resulting in reduced SINR and, consequently, a lower data rate. This highlights the importance of maintaining optimal placement of access points (APs) in OWC systems to ensure a strong line-of-sight connection. The use of IRS improves signal quality by enhancing the channel gain for reflected paths. However, the IRS-reflected path introduces additional attenuation due to the longer propagation distances (Dm,l+Dk,m). For shorter distances, the IRS can effectively increase SINR and data rates, making it a valuable tool for improving coverage in obstructed or non-LoS scenarios. As data rate is high means channel capacity of the system is high and which makes spectral efficiency (channel capacity/ Bandwidth) of the system high .Hence higher transmitted power improves both SINR and data rates, as shown in all scenarios (LoS and IRS-reflected). However, increasing Pk indefinitely is not practical due to power constraints and safety regulations. LoS communication generally provides higher data rates due to stronger channel gains and fewer propagation losses. IRS-reflected communication is beneficial when LoS paths are unavailable or blocked, but its effectiveness depends on precise alignment and efficient design of the reflecting surfaces. For future prospect, data rate of the system may be optimized to get maximum value. For future prospect, SINR and Data rate may be enhanced by using any optimization technique.

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