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Constituent of Symbiosis International (Deemed University), Pune

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Department of Electronics and Telecommunication Engineering

Subject: Wireless Communication

Report

Non-orthogonal multiple access (NOMA) for Indoor Visible Light Communications

SUBMITTED BY

GROUP NO. 9

Name of the students	PRN
RUDANSH MALHOTRA	19070123095
SAMIKSHA SHUKLA	19070123099
TUSHAR YADAV	19070123126
VARUN SARATHY	19070123131

॥वसुधैव कुटुम्बकम्॥

Under the Guidance of

Prof. Prabhat Thakur

DEPARTMENT OF ELECTRONICS & TELECOMMUNICATION ENGINEERING

SYMBIOSIS INSTITUTE OF TECHNOLOGY, PUNE– 412115

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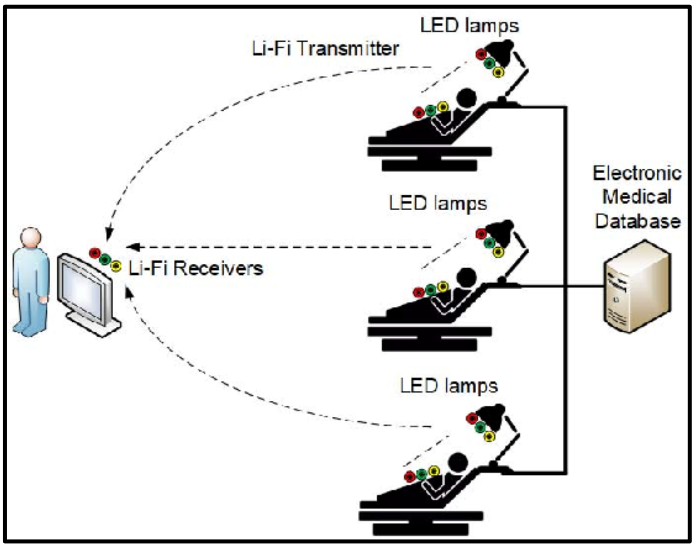
NOMA for VLC Systems

Abstract

Visible light communication (VLC) has emerged as a viable technique for high data rate communications, as well as an appealing supplement to traditional radio frequency (RF) communication. VLC is a secure, energy-efficient, and cost-effective technology that uses existing infrastructure for wireless data transmission, particularly in indoor contexts. Nonetheless, the small modulation bandwidth of light-emitting diodes (LEDs), which is in the megahertz region, remains the fundamental obstacle of producing high data rate VLC systems. We offer a complete review of PD-NOMA-based VLC systems in this study. In addition, we discuss aspects of the PD-NOMA VLC system restrictions and challenges, such as power allocation, clipping effect, MIMO, and security. Finally, we present open research concerns as well as potential future research topics to pave the road for the deployment of PD-NOMA VLC systems.

Introduction



The exponential expansion of multimedia applications and wirelessly connected devices as a result of the growth of mobile applications and the introduction of the internet of things (IoT) creates an exceptional increase in traffic demand that necessitates high-data-rate wireless connectivity. In this regard, future wireless network generations (beyond 5G) are expected to provide high system capacity, high quality of service (QoS), huge device connection, low latency, and high energy efficiency. Unfortunately, radio frequency (RF) communication in wireless networks is hampered by restricted spectrum resources, with the majority of applications and services crowded in traditional RF bandwidth below 6.5 GHz. Many researchers recently consider optical wireless communication (OWC) including ultraviolet (UV), infrared (IR) and visible light (VL) as an attractive complementary and alternative technique of RF. Moreover, IR communication and visible light communication (VLC) systems are widely used indoor systems. This report focuses on VLC as an emergent wireless communication technology that has been proposed as a promising candidate for high-speed communications.

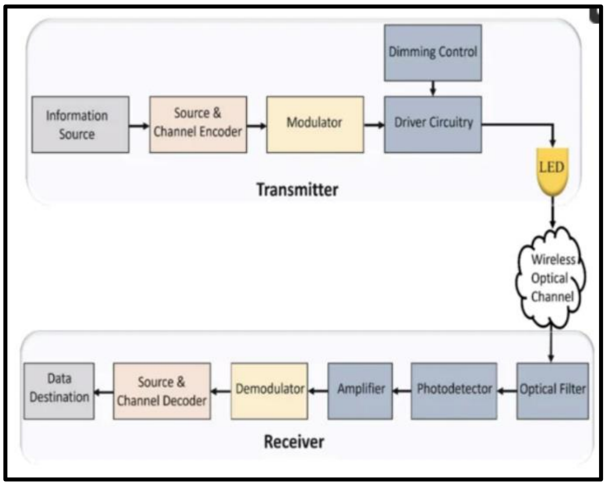
VLC Technology

Exploring the possibilities of the electromagnetic spectrum's license-free visible light band (380-750 nm, i.e., 400-789 THz), which offers significant bandwidth (400 THz), can overcome RF spectrum congestion and scarcity challenges. Furthermore, VLC technology has several distinct advantages, which are as follows:

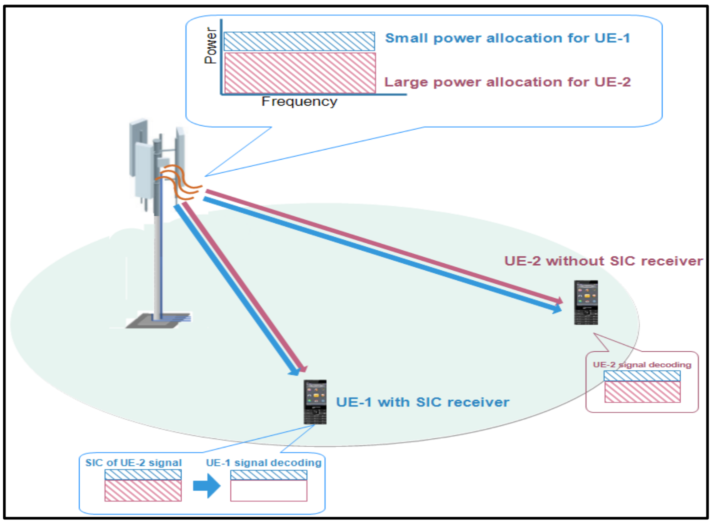
1. Health and safety: Wavelengths corresponding to VL frequencies are safe for the human body, allowing for high power transmission in various applications, as opposed to RF and IR, which have power restrictions for the body and eyes.

2. EMI (electromagnetic interference): VLC's immunity to RF interference makes it suited for EMI-prone environments such as hospitals, aircrafts, mines, and petrochemical industries.
3. Quality of Service (QoS) and security: VLC communication is primarily based on line of sight (LOS); the nature of VL does not penetrate walls that give small cells with high spatial reuse, good QoS, and a secure system that conceals data from potential eavesdroppers.
4. Compatibility with other technologies: VLC is not supposed to replace RF, but rather complement it where VLC networks can be connected to the existing optical fiber networks and integrated as part of 5G wireless communication systems.

VLC is a green and energy-efficient technique that takes advantage of the widespread use of light-emitting diode (LED) lighting infrastructure to provide illumination while also transmitting data even when the illuminating light is dimmed or turned off. Typical VLC systems employ relatively simple and off-the-shelf components, such as an LED as a transmitter and a photodetector (PD) as a receiver, to create low-cost systems. Figure below depicts the block diagram of the end-to-end VLC system. LEDs may communicate data by altering the light intensity at a very high frequency in a process known as intensity modulation (IM) without being seen by the human eye. At the receiver end, photodetectors or image sensors are employed in a process known as direct detection (DD) to generate an electrical current proportional to the fluctuation in the received optical power.



NOMA



Non-Orthogonal Multiple Access (NOMA) enables numerous users to share the same frequency band at the same time, boosting the system's spectral efficiency. NOMA is divided into two types: PD-NOMA and code domain NOMA (CD-NOMA). CD-NOMA operates on the same basic principle as CDMA, with several users sharing the same resources (frequency, time). Nonetheless, for more users, CD-NOMA uses sparse spreading or nonorthogonal low cross-correlation sequences. CD-NOMA is divided into numerous classes, including sparse code multiple access (SCMA), low-density spreading CDMA (LDS-CDMA), and LDS with OFDM (LDS-OFDM). However, the commonly used PD-NOMA-based system, which is less complex than the CD-NOMA-based system, is a possible contender for beyond 5G networks, where various users transmit and receive varying power levels throughout the full available frequency and time resources. As a result, the focus of this review is on PD-NOMA as an appealing approach for developing RF and VLC technologies with the potential to deliver ubiquitous connection and high system throughput.

Multiple Access Techniques in VLC Systems

The various access mechanisms used on VLC are primarily RF-based. Several OMA approaches, including optical TDMA (OTDMA), optical CDMA (OCDMA), wavelength division multiple access (WDMA), and OFDMA, are being investigated in VLC systems. OTDMA in VLC systems necessitates precise synchronization between LEDs serving as access points (APs) and user receivers. In multicell settings, OTDMA suffers from inter-cell interference (ICI) at overlapping areas between the cells, resulting in considerable reduction of VLC system performance. The fundamental disadvantage of OCDMA is that it cannot accommodate a high number of users without generating long optical orthogonal codes (OOC), which increases the system's complexity and reduces the achievable data throughput. Multicolor LEDs are utilized in WDMA to assign non-interfering wavelengths to users to transmit simultaneously, resulting in relative difficulty in implementing such dense WDMA systems utilizing off-the-shelf LEDs. Researchers have focused on OFDMA as an efficient strategy for VLC networks due to distinct characteristics such as low implementation complexity and excellent spectral efficiency.

In addition to OMA, many NOMA approaches are used in VLC systems. Optical SDMA (OSDMA) is a NOMA approach that separates users in the space domain by using several directional optical beams at the transmitter. However, OSDMA increases the system's implementation complexity due to the design changes required in LEDs and optics. Furthermore, optical PD-NOMA has lately acquired prominence as a promising technology capable of addressing fundamental difficulties in VLC systems while outperforming conventional multiple access techniques.

PD-NOMA in VLC System

The PD-NOMA method has various advantages, including user fairness, increased cell-edge throughput, improved spectrum efficiency, and low transmission latency (no scheduling request from users to base station is required). Furthermore, the distinct properties of VLC networks improve PD-NOMA performance over RF for the following reasons:

1. PD-NOMA performance improves when the signal to noise ratio (SNR) is high, like in VLC networks with small cells that provide short propagation distance and strong LOS. PD-NOMA is good at multiplexing a limited number of users, which is useful in indoor VLC systems.
2. Accurate channel status information (CSI) at the transmitter can improve each user's power allocation in PD-NOMA. Because of the low mobility of the channel in indoor VLC systems, the quasi static character of the channel leads to a more reliable assessment of the CSI.
3. By managing the channel gain difference between users, tuning the semiangles of the LEDs and the fields of vision (FOVs) of PD can improve PD-NOMA performance in VLC.

NOMA vs OMA

PD-NOMA and OFDMA are the most relevant NOMA and OMA schemes for a high data rate in VLC systems, respectively. The performance of PD-NOMA outperforms OFDMA in terms of the achievable data rate, under perfect interference cancellation, in an indoor downlink VLC system with illumination constraints. On the contrary, when the interference cancellation becomes imperfect the PD-NOMA performance degrades based on the cancellation error percentage. From a large-space indoor scenario standpoint, the sum rate of the multicell VLC network was investigated for both PD-NOMA and OFDMA. Results showed that PD-NOMA outperforms OFDMA in terms of the total network sum rate for three different complexity scenarios. Comparing NOMA with TDMA shows the ability of NOMA to increase the system capacity by 125% when the semi angle of the LED is 30°. PD-NOMA not only outperforms OFDMA in terms of achievable data rate and system capacity but also system fairness. Consequently, it is evident that PD-NOMA has a superior performance that is able to outperform other multiple access techniques. These distinct advantages offered by PD-NOMA led many researchers to further investigate the performance of PD-NOMA in VLC networks.

Challenges in PD-NOMA VLC

1. Power Allocation
2. Clipping Effect
3. MIMO
4. Security
5. Hybrid VLC/RF Systems

MATLAB Implementation & Simulation

Let us consider a wireless network consisting of three NOMA users, numbered U1, U2 and U3. Let $d1$, $d2$ and $d3$ denote their respective distances from the base station (BS) such that, $d1>d2>d3$. Based on their distances, U1 is the weakest/farthest user and U3 is the strongest/nearest user to the BS. Let $h1$, $h2$, and h_3 denote their corresponding Rayleigh fading coefficients such that, $|h1|^2 < |h2|^2 < |h3|^2$. (The channels are ordered this way because $h_i \propto \frac{1}{d_i}$). Let α_1 , α_2 and α_3 denote their respective power allocation coefficients. According to the principles of NOMA, the weakest user must be allocated the most power and the strongest user must be allocated the least power. Therefore, the power allocation coefficients must be ordered as $\alpha_1>\alpha_2>\alpha_3$.

Algorithm -

1. Set simulation parameters: Distances are set as $d_1=500m$, $d_2=200m$, $d_3=70m$. The power allocation coefficients are set as $\alpha_1=0.8$, $\alpha_2=0.15$, $\alpha_3=0.05$. These values satisfy the conditions $\alpha_1>\alpha_2>\alpha_3$ and, $\alpha_1>\alpha_2+\alpha_3$. Set path loss exponent.
2. Set the transmit power range (here, we have used 0 to 40 dBm). Convert the transmit power from dBm to linear scale for future calculations.
3. Generate Rayleigh fading coefficients h_1 , h_2 , h_3 for each user using the command.
4. Define the amount of noise power. For that, let's consider a bandwidth of 1 MHz. As we know, the thermal noise power is given by, kTB. For a bandwidth of 1 Hz, the noise power is $\log10(kT)=-174$ dBm. So, for 1 MHz bandwidth, the noise power will be $-174+\log10(1MHz)$.
5. Using the noise power calculated in step 3, let's generate noise samples for all the three users n1, n2 and n3 have mean zero and variance no, This no is the σ^2 that we used in the equations.
6. Generate random message bits for users.
7. Do QPSK modulation for each user's message. For this, we are going to use MATLAB's in-built QPSKModulator object. This will greatly simplify our modulation and demodulation part. First, we have to create the QPSKModulator and QPSKDemodulator.
8. Do superposition coding to create the NOMA transmit signal.
9. Iterate over every value of transmit power.
   (i) Write received signal equation for all the three users
   (ii) Perform equalization by dividing each received signal with the respective user's fading coefficient.
   (iii) First, let’s do the processing at the receiver side of U1. Directly demodulate eq1 to get x1. To do this, we use the QPSKDemodulator object
   (iv) Moving on to U2. First, directly decode x1 from eq2.
   Now, we can perform SIC to remove our estimate of U1's data (i.e., dec12_remod) from eq2 Do direct QPSK demodulation on rem2 as before, to get U2's data.
   (v) Moving on to U3. First direct decode x1 from eq3. Remodulate the estimate of x1 that is obtained and subtract it from eq3.
   Again, demodulate rem31 to get x2. Remodulate the estimate of x2 and subtract it from rem31.
   (vi) BER calculation. For this, we use MATLAB's inbuilt biterr() function.
10. Plot the BER vs transmit power graphs of all the three users.

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Code -

```
clc; clear variables; close all;

N = 5*10^5;

Pt = 0:2:40;            %Transmit power (dBm)
pt = (10^-3)*db2pow(Pt);    %Transmit power (linear scale)

BW = 10^6;          %Bandwidth = 1 MHz
No = -174 + 10*log10(BW);   %Noise power (dBm)
no = (10^-3)*db2pow(No);    %Noise power (linear scale)

d1 = 500; d2 = 200; d3 = 70;    %Distances
a1 = 0.8; a2 = 0.15; a3 = 0.05; %Power allocation coefficients

eta = 4;    %Path loss exponent

%Generate Rayleigh fading channel for the three users
h1 = sqrt(d1^-eta)*(randn(N/2,1) + 1i*randn(N/2,1))/sqrt(2);
h2 = sqrt(d2^-eta)*(randn(N/2,1) + 1i*randn(N/2,1))/sqrt(2);
h3 = sqrt(d3^-eta)*(randn(N/2,1) + 1i*randn(N/2,1))/sqrt(2);

%Generate noise samples for the three users
n1 = sqrt(no)*(randn(N/2,1) + 1i*randn(N/2,1))/sqrt(2);
n2 = sqrt(no)*(randn(N/2,1) + 1i*randn(N/2,1))/sqrt(2);
n3 = sqrt(no)*(randn(N/2,1) + 1i*randn(N/2,1))/sqrt(2);

%Generate random binary message data for the three users
x1 = randi([0 1],N,1);
x2 = randi([0 1],N,1);
x3 = randi([0 1],N,1);
```

```
%Create QPSKModulator and QPSKDemodulator objects
QPSKmod = comm.QPSKModulator('BitInput',true);
QPSKdemod = comm.QPSKDemodulator('BitOutput',true);

%Perform QPSK modulation
xmod1 = step(QPSKmod, x1);
xmod2 = step(QPSKmod, x2);
xmod3 = step(QPSKmod, x3);

%Do super position coding
x = sqrt(a1)*xmod1 + sqrt(a2)*xmod2 + sqrt(a3)*xmod3;

for u = 1:length(Pt)

%Received signals
   y1 = sqrt(pt(u))*x.*h1 + n1; %At user 1
   y2 = sqrt(pt(u))*x.*h2 + n2; %At user 2
   y3 = sqrt(pt(u))*x.*h3 + n3; %At user 3

%Perform equalization
   eq1 = y1./h1;
   eq2 = y2./h2;
   eq3 = y3./h3;

%Decode at user 1 (Direct decoding)
   dec1 = step(QPSKdemod, eq1);

%Decode at user 2
   dec12 = step(QPSKdemod, eq2);        %Direct demodulation to get U1's data
   dec12_remod = step(QPSKmod, dec12);      %Remodulation of U1's data
   rem2 = eq2 - sqrt(a1*pt(u))*dec12_remod; %SIC to remove U1's data
   dec2 = step(QPSKdemod, rem2);        %Direct demodulation of remaining signal
```

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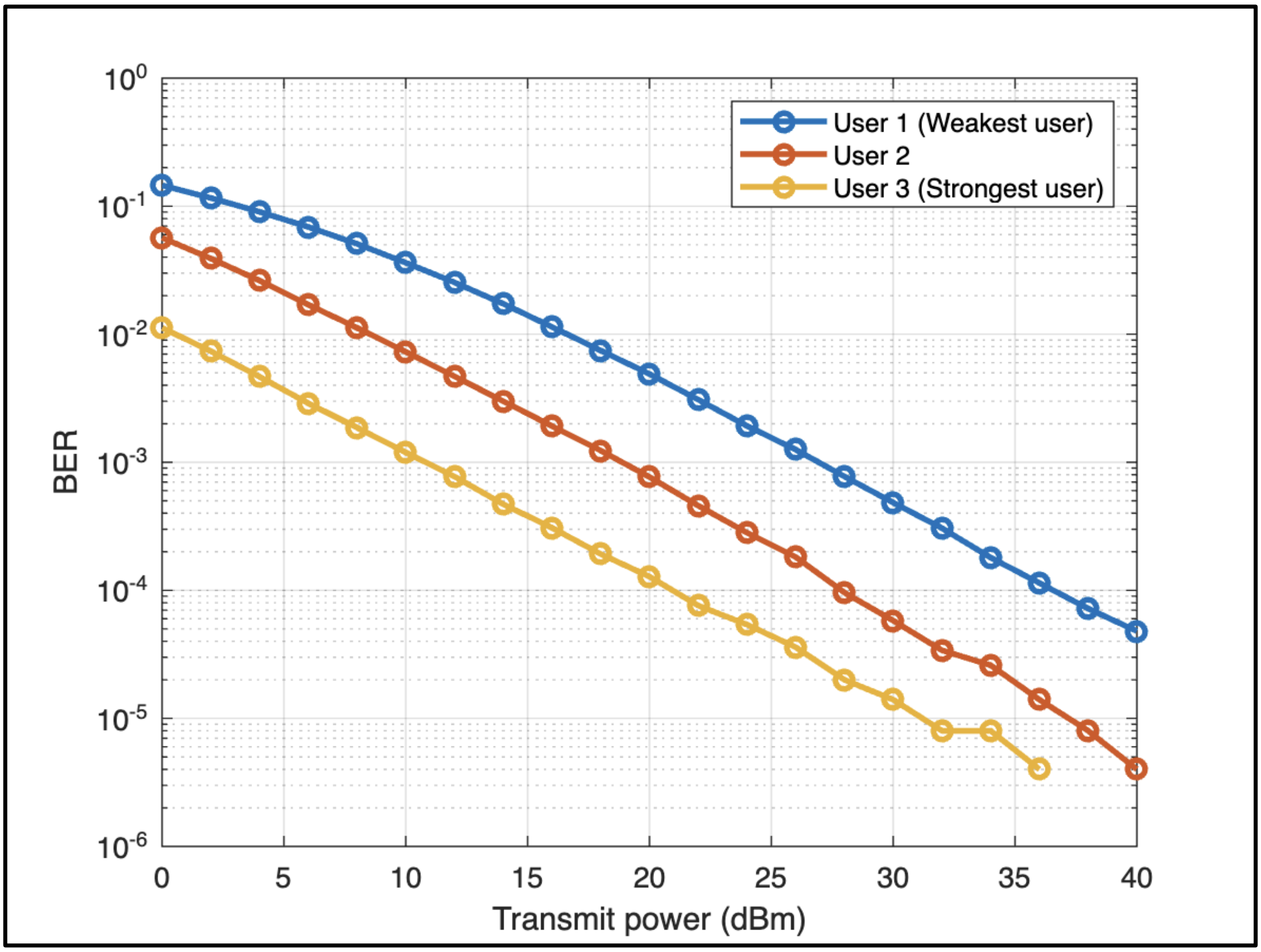
```
%Decode at user 3
   dec13 = step(QPSKdemod, eq3);          %Direct demodulation to get U1's data
   dec13_remod = step(QPSKmod, dec13);        %Remodulation of U1's data
   rem31 = eq3 - sqrt(a1*pt(u))*dec12_remod;     %SIC to remove U1's data
   dec23 = step(QPSKdemod, rem31);        %Direct demodulation of remaining signal to get U2's data
   dec23_remod = step(QPSKmod, dec23);        %Remodulation of U2's data
   rem3 = rem31 - sqrt(a2*pt(u))*dec23_remod;    %SIC to remove U2's data
   dec3 = step(QPSKdemod, rem3);          %Demodulate remaining signal to get U3's data

%BER calculation
   ber1(u) = biterr(dec1, x1)/N;
   ber2(u) = biterr(dec2, x2)/N;
   ber3(u) = biterr(dec3, x3)/N;
end

semilogy(Pt, ber1, '-o', 'linewidth', 2); hold on; grid on;
semilogy(Pt, ber2, '-o', 'linewidth', 2);
semilogy(Pt, ber3, '-o', 'linewidth', 2);

xlabel('Transmit power (dBm)');
ylabel('BER');
legend('User 1 (Weakest user)', 'User 2', 'User 3 (Strongest user)');
```

Output -



Conclusion

In this report, we presented VLC as a promising wireless technology for indoor communication. Several multiple access techniques in VLC systems including OTDMA, OCDMA, OFDMA, WDMA and OSDMA were reviewed. We discussed, in detail, PD-NOMA as a promising scheme that can overcome the VLC limitations. Furthermore, we reported PD-NOMA's challenges in VLC systems, such as power allocation, clipping effect, MIMO and security. We also applied this technology to an application in healthcare domain.

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