Joint User Pairing and Subcarrier Allocation for NOMA-based Hybrid Power Line and Visible Light Communication Systems

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Abstract: With the rapid growth of the number of mobile communication users, the radio frequency bands occupied by traditional radio frequency (RF) communication are becoming more and more crowded, and visible light communication (VLC) based on light emitting diode (LED) has become a powerful candidate. However, visible light cannot be used directly as an information source, and power line communication (PLC) is needed to provide data to the VLC transmitter. In a hybrid power line and visible light communication (HPV) system, the PLC can transmit data to the VLC transmitter. In order to improve spectrum utilization, we introduce non-orthogonal multiple access (NOMA) technology, but allocating all users to a resource block will result in higher computational complexity and decoding delay. This paper proposes a joint user pairing and subcarrier allocation algorithm based on fairness (IGA-JUPSA). While ensuring the performance of the system, the algorithm can also reduce the complexity of calculation and improve user satisfaction. The simulation results show that the proposed IGA-JUPSA scheme can reduce the computational complexity while ensuring the performance of the HPV system, and can also take into account the fairness of the HPV system and user satisfaction.

1. INTRODUCTION

With the popularization of smart terminals and the rapid development of technologies such as the Internet of Things and cloud computing, large capacity and high transmission rate will become the basic characteristics of future wireless transmission networks. At present, the widely used wireless frequency bands are mainly concentrated below 10GHz, and have become more crowded and will gradually fail to meet the increasing bandwidth requirements of the market. Compared with traditional radio frequency (RF) communication, visible light communication (VLC) based on light emitting diode (LED) has become a potential high-speed wireless access scheme because of its high transmission power, no electromagnetic interference, security and no need for spectrum authentication [1]. Therefore, VLC becomes a key technology to replace RF [2].

However, visible light cannot be a source of information directly, it is necessary to access the backbone network to avoid being an information isolated island. PLC and Ethernet links can be used as backbone networks. PLC seems a better choice because it can take advantage of the existing
infrastructure of each LED [3]. In addition, the data rate of modern broadband PLC systems is up to hundreds of Mbps or even Gbps, so it is sufficient to support indoor data links [4]. Hybrid PLC and VLC (HPV) channels have been studied in previous work [5-8]. Since multiple LEDs are usually closely located in a room to ensure a uniform lighting level, the resulting overlapping of emissions leads to the interference of VLC signals from adjacent LEDs, which in turn will seriously reduce the performance of the VLC system [5]. In order to utilize overlapping coverage, a system model coordinating different LEDs through a PLC network was proposed in [6]. In [7], M. Kashef et al. proposed that the signal-to-interference-plus-noise-ratio (SINR) could be improved by coordinated VLC systems. Hybrid PLC and VLC channel characteristics for a full link transmission were studied in [8]. However, the above works were discussed in the case of orthogonal multiple access (OMA).

In addition, OMA method can’t make the best use of resources compared to non-orthogonal multiple access (NOMA) [9]. All users can enjoy the entire time and frequency resources using NOMA method, which can improve spectral efficiency [10]. In [11], Ding et al. studied the effect of user pairing on the throughput of NOMA systems with fixed power allocation and cognitive radio heuristics. They found that compared to traditional OMA, NOMA with fixed power allocation tends to select users with unique channel conditions. On the other hand, NOMA, inspired by cognitive radio, tends to pair two users with the optimal channel. In [12], a fair power allocation method was proposed, which show that the capacity of each user in NOMA can always exceed the capacity in OMA. In [13], Oviedo et al. considered a typical NOMA scenario with two users, and optimized the power allocation strategy under the maximum sum rate. Using NOMA technology to improve the throughput in multi-user VLC systems was studied in [14,15]. In [16], Yang et al. studied the maximum throughput of NOMA-VLC systems constrained by user fairness and illumination. It is worth noting that in [11]-[16], the authors focused on applying NOMA to single-channel systems. However, it is disputable to assign all users in one resource block to form a NOMA group as the user with stronger channel response has to demodulate and decode the signals of the users with weaker channel response, which incurs high computational complexity and decoding delay [17]. Therefore, as an effective method to make a compromise between performance and computational complexity in HPV system, we propose a mixed scheme of NOMA and OMA. For example, relatively few users form a NOMA group to use one subcarrier, and different NOMA groups use different subcarriers.

For the subcarrier allocation, an exhaustive search scheme was proposed in [18]. In [19], the authors solved the subcarrier allocation problem by greedy method. However, for a large number of users in NOMA, both of the above methods will cause high computational complexity. In this paper, we propose an improved genetic algorithm based on user pairing to reduce the complexity of subcarrier allocation.

2. HPV system and channel model

![Figure 1. HPV system model.](image-url)
We consider the downlink transmission of an HPV system based on NOMA with 4 LEDs serving \( NU \) users, as shown in Fig. 1. Define \( PP=\{1, 2, \ldots, N_p\} \) and \( UU=\{1, 2, \ldots, N_u\} \) as the index sets of all subcarriers and users, respectively. The power line acts as a backbone network and provides data for the four LEDs. The LEDs operate as a full-duplex relay to process the received PLC signal and forward it to indoor users through VLC. In this paper, the modulation scheme and the carrier spectrum of PLC and VLC are the same. Therefore, there are \( N_p \) PLC subcarriers on the power line, each LED has \( N_p/4 \) VLC subcarriers, 4 LEDs share \( N_p \) VLC subcarriers, and the frequency spectrum of subcarrier \( l \) in PLC and subcarrier \( l \) in VLC are the same. Without loss of generality, we assume that the index number on the first LED is 1, 2, ..., \( N_p/4 \), and so on, the index number on the fourth LED is \( 3N_p/4+1, \ldots, N_p \). Each LED only needs to amplify and forward the received PLC signal to the corresponding VLC subcarrier according to the index number. Fig. 2 shows the block diagram of the HPV system. The data is encoded into the modulator, and then converted into an analog signal through D/A conversion. The signal is sent to the power line through the coupler. When the signal is transmitted in power line channel, it is interfered by power line noise. And then, the signal is transmitted to the LED where an AF relay chip is integrated. In order to drive the LED, a strategy of DC bias must be added in front of it.

![Figure 2. Block diagram of the HPV system](image-url)

**2.1 PLC Channels**

M. Gotz proposed a power line channel model [20], and the channel gain \( H_p(f) \) can be expressed as:

\[
H_p(f) = \sum_{i=1}^{N} a_i g_i e^{i(\phi_i + \phi_{0})} e^{-j2\pi f \tau_i};
\]

The model represents the superposition of signals from \( N \) different paths, where \( a_i \) and \( g_i \) are constants, \( g_i \) represents the reflection and transmission factor on path \( i, -1 \leq g_i \leq 1 \). The delay \( \tau_i \) on path \( i \) can be expressed as \( \tau_i = \frac{l_i}{v_p} \), where \( l_i \) and \( v_p \) are the length of path \( i \) and phase speed, respectively. \( X_p(l) \) represents the frequency domain transmission signal on subcarrier \( l \) in PLC. At the \( k \)-th LED, the received frequency-domain signal \( Y_k^{l,u}(l) \) at user \( u \) on subcarrier \( l \) can be expressed as:

\[
Y_k^{l,u}(l) = H_k^{l,u}(l)X_p(l) + N_k^{l,u}(l)
\]

where \( H_k^{l,u}(l) \) and \( N_k^{l,u}(l) \) are the PLC frequency-domain channel gain and received noise of user \( u \) on subcarrier \( l \) at the \( k \)-th LED, respectively. Besides, \( N_k^{l,u}(l) \) denotes the additive Gaussian noise with zero mean and variance \( s_{n,u}^2(l) \), where \( s_{n,u}^2(l) = \text{E}[N_k^{l,u}(l)^2] \).
2.2 VLC Channels

The frequency-domain channel gain $H_v(f)$ between the user and the LED can be expressed as:

$$H_v(f) = \frac{(m+1)A_{\text{req}}}{2\rho D_j^2} \cos^2(f) T_c(j) g(j) \cos(j)$$

where $m=\ln 2 / \ln (\cos F_{1/2})$ denotes the order of Lambertian emission, $F_{1/2}$ denotes LED’s transmitter semi-angle at half-power, $A_{\text{req}}$ denotes the area of photo detector, $D_j$ denotes the distance between the receiver and the LED, $T_c(j)$ denotes the gain of optical filter, $j$ denotes incidence angle of the PD, $g(j) = n^2 / \sin^2 j$ denotes the gain of optical lens, $j$ denotes field-of-view (FOV) of the PD and $n$ denotes the refractive index.

$X_v^k(l)$ indicates the frequency-domain transmitted signal on subcarrier $l$ at the $k$-th LED, $Y_v^k,u(l)$ indicates the received frequency-domain signal on subcarrier $n$ at user $u$.

$$Y_v^k,u(l) = H_v^k,u(l)X_v^k(l) + N_v^k,u(l)$$

where $H_v^k,u(l)$ and $N_v^k,u(l)$ are the VLC channel gain and noise for subcarrier $n$ between the $k$-th LED and user $u$, respectively. Besides, $N_v^k,u(l)$ denotes the additive Gaussian noise with zero mean and variance $s_{\text{un}}^2(n)$, where $s_{\text{un}}^2(n)=E[N_v^k,u(l)^2]$. In equation (4), $X_v^k(l)=bY_v^k,u(l)$, where $\beta$ is amplification factor. $Y_v^k,u(l)$ can be transformed into the following forms:

$$Y_v^k,u(l) = bH_v^k,u(l)H_v^k,u(l)X_v^k(l) + bH_v^k,u(l)N_v^k,u(l) + N_v^k,l$$

Therefore, in the HPV system, the overall HPV channel gain on subcarrier $l$ is $H_{\text{hp,v}}^k(l)=bH_v^k,u(l)H_v^k,u(l)$, and the total noise is $N_{\text{hp,v}}^k(l)$, which denotes the additive Gaussian noise with zero mean and variance $s_{\text{hp,v}}^2(n)$.

$$s_{\text{hp,v}}^2(n) = b[H_v^k,u(l)]^2 s_{\text{un}}^2(n) + s_{\text{un}}^2(l)$$

3. Problem Formulation and Solving

In order to strike a balance between system performance and computational complexity, a mixed scheme of NOMA and OMA, e.g., a relatively small number of users form a NOMA group to use one subchannel and different NOMA groups use different subchannels, was proposed as an effective approach. In each subcarrier, we consider two users paired as a NOMA group and different NOMA groups use different subcarriers. Considering that different users have different channel conditions in the indoor environment, in order to ensure the rate of each user and improve the fairness among users, we propose a joint user pairing and subcarrier allocation based on fairness (Joint User Pairing and Subcarrier Allocation, JUPSA) scheme. Firstly, all users in the room are paired with the goal of maximizing the system rate. And then, all the paired NOMA groups are assigned subcarriers while considering the system throughput and the fairness.

3.1 User pairing scheme

We assume that the number of users $U$ is an even number. If $U$ is an odd number, there must be a user not paired, then this user occupies a subcarrier alone. For the system of $N_p$ subcarriers and $U$ users in this paper, there will be $N_p \times U$ channel gains, for example, user $1$ will have a channel gain in each subcarrier, namely $[h_{1,1}, h_{1,2}, \ldots, h_{1,N_p}]$. We define the average channel gain of user $u$ as $[h_u]$. 

In [19], the author pointed out that when studying the user pairing scheme, for $U$ users in the system, without loss of generality, it is assumed that the user’s channel gain satisfies $|h_1| < |h_2| < \cdots < |h_U|$, when user $m$ and user $U-m+1$ are paired, for example, user 1 User $U$ pairing, user 2 and user $U-1$ pairing, etc., the throughput of the system is the largest. However, in the above pairing rule, two adjacent users will pair together, that is, user $U-1$ and user $U$ pair together. To solve this problem, we propose to divide the users sorted in ascending order of average channel gain into four groups, and the users in the first group are paired with the users in the third group, the users in the second group are paired with the users in the fourth group. The pairing scheme of the two groups is the same as the pairing scheme in [21], so as to avoid pairing of adjacent users, and can maximize the throughput of the system.

3.2. Subcarrier Allocation Scheme
There are many possible schemes for paired users to be allocated to different subcarriers, but the system performance is different in all schemes. In order to find the best subcarrier allocation scheme, we use an intelligent optimization algorithm, namely genetic algorithm. However, it is easy to fall into local optimal, we need to set a large number of iterations. In order to improve the convergence performance and speed of the algorithm, we propose an improved genetic algorithm for subcarrier allocation.

3.2.1. Fitness function based on fairness
The fitness function is the basis for the genetic algorithm to select chromosomes, and its design is crucial. We design individual fitness function $f(c)$ as:

$$f(c) = \sum_{i=1}^{U} \log(R_i)$$

In equation (8), $R_i$ is the rate of user $i$. Maximizing the logarithm of the system throughput could improve the system throughput while achieving rate balance among users [22].

3.2.2. Construct chromosome
Each gene position in the chromosome characterizes the subcarrier number, the value $(i,j), (i,j) \in U, n \in N_p$ of the gene position $n$ represents the user pair served by the subcarrier $n$, and a group of subcarrier allocation results constitute a chromosome $c = \left[ (1, 3U/4), (2, 3U/4), (3, 1/4), \ldots, (U, 3U/4), U+1, N_p \right]$ together. For example, chromosome $c_1 = \left[ (1,6), (2,5), (3,8), (4,7), (1,6) \right]$ means: There are 5 subcarriers and 8 users in the HPV system, and 8 users are paired into 4 user pairs; the set of subcarriers serving the paired users (1,6) is \{1,5\}, the set of subcarriers serving the paired users (2,5) is \{2\}, the set of subcarriers serving the paired users (3,8) is \{3\}, and the set of subcarriers serving the paired users (4,7) is \{4\}.

3.2.3. Genetic manipulation
The improved genetic algorithm operations proposed in this paper include selection operations, crossover operations, and mutation operations. The selection operation adopts roulette selection. The roulette selection selects the individual according to the individual’s fitness function value. The individual with the higher fitness function value is selected and the probability of survival is greater. The probability of the individual being selected in the selection operation is
In equation (9), $U$ is the number of individuals in a population, and $\sum_{n=1}^{U} f(m)$ is the sum of fitness function values of all individuals in the population.

Traditional genetic algorithms mostly use a two-point crossover method, that is, randomly generate two Crosspoint sites, and exchange genes between the two Crosspoint sites. However, with the ongoing evolution of the population, the differences among the individuals in the population will gradually decrease, so the similarity among the individuals will gradually increase. Crossover operations on two parents with high similarity will destroy the excellent gene pattern and lead to more iterations. Therefore, we propose a crossover method based on crossover threshold. The equation for the crossover threshold value is:

$$r = \frac{1 + \sqrt{\frac{g}{G}}}{3}$$

In equation (10), $r$ represents the crossover threshold value, $g$ represents the evolutionary generation of the population, and $G$ represents the total evolutionary generation. It can be seen from the equation (10) that $r$ is a number between $\left(\frac{1}{3}, 1\right]$, and it keeps increase with the growth of the current evolutionary generation. The similarity of two individuals is defined as:

$$s = \frac{c}{n}$$

In equation (11), $s$ represents the similarity of two individuals, $c$ represents the length of the longest common substring of the two individuals, and $n$ represents the length of the individual chromosome code in the population. If the similarity $s$ of the two parent individuals that need to be crossed is less than the current crossover threshold value $r$, the two parent individuals are allowed to perform the cross operation. Otherwise, the two parent individuals are not allowed to perform the cross operation to avoid destroying their excellent genetic patterns.

In this paper, the adaptive mutation operation is used to adaptively adjust the mutation probability according to the maximum fitness value and the average fitness value of the chromosomes in the population. The adaptive mutation probability equation is:

$$P_m = \begin{cases} \arcsin\left(\frac{f}{f_{\text{avg}}}\right), & f \geq f_{\text{avg}} \\ \arcsin\left(\frac{f_{\text{max}}}{f}\right), & f < f_{\text{avg}} \end{cases}$$

In equation (12), $P_{m_{\text{max}}}$ is the preset maximum mutation probability, $f_{\text{avg}}$ is the average fitness value of the chromosomes in the population, $f_{\text{max}}$ is the maximum fitness value of the chromosomes in the population, and $f$ is the fitness value of the chromosome to be mutated.

The following tables summarize the JUPSA scheme based on improved genetic algorithm.

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**Algorithm 1. JUPSA Scheme based on Improved Genetic Algorithm**

**Input:** $N_P$, $U$

if: the number of users $U$ is divisible by 4
    Sorted by channel gain, and divided into 4 groups for pairing;
else:
    Sorted by channel gain, and paired the first user with the last user. The remaining $U$-2 users are divided into four groups for pairing.

Initialization: Improved genetic algorithm evolution generation $a=0$;
Calculate the fitness value of individuals in a population;
while $a$ is greater than the set maximum generation or 15 consecutive generations of optimal individual fitness value unchanged do
    Perform roulette selection operation;
    Perform crossover operation in an improved crossover mode;
    Perform mutation operation according to mutation probability;
    Generate new population;
    $a=a+1$;
end while
Output: Subcarrier allocation scheme for all user pairs

4. Analysis of Algorithm Simulation Results
In this section, we evaluate the performance of the HPV system. We consider a $5m \times 5m \times 3m$ room with 4 LEDs, the positions of the four LEDs are $(1.25m, 1.25m, 3m)$; $(1.25m, -1.25m, 3m)$; $(-1.25m, -1.25m, 3m)$; $(-1.25m, 1.25m, 3m)$. The noise power spectral density is $10^{-24} W/Hz$. $l_i$ denotes the length of the power line connecting the PLC modem and the $i$-th LED, $l_1=7m$, $l_2=8m$, $l_3=9m$, $l_4=10m$. The main simulation parameters in the HPV system are given in Table 1.

| Parameter                      | Value |
|--------------------------------|-------|
| Half-intensity radiation angle, $F_{1/2}$ | $70^\circ$ |
| Amplification factor, $\beta$ | 1     |
| LED power                      | 3W    |
| Signal bandwidth               | 30MHz |
| Subcarrier number, $N_p$       | 128   |
| Receiver FOV, $j_c$            | $90^\circ$ |
| Genetic algorithm population size, $N_{popu}$ | 50     |
| Gain of optical filter, $T_j(\lambda)$ | 1.0 |
| Refractive index, $n$          | 1.0   |
| PD area, $A_{pd}$              | $1.0cm^2$ |

In Table 2, we can find that when the user pairing method is determined, the improved genetic algorithm can improve the convergence speed of subcarrier allocation by comparing the IGA-JUPSA scheme and the GA-JUPSA scheme, the IGA-RUPSA scheme and the GA-RUPSA scheme. The number of generations at convergence of IGA is only one third of GA, because the improved genetic algorithm uses a crossover method based on crossover threshold and adaptive mutation operation. Therefore, the improved genetic algorithm proposed in this paper can improve the convergence speed of the algorithm. By analyzing the average user rate of the HPV system, we find that the IGA-JUPSA scheme is 20.00% higher than the IGA-RUPSA scheme, and the GA-JUPSA scheme is 21.28% higher than the GA-RUPSA scheme. It can be concluded that when the same subcarrier allocation algorithm is used, the optimal user pairing scheme can increase the average user rate of the HPV system. Therefore, the IGA-JUPSA scheme proposed in this paper can improve the convergence speed of the algorithm while ensuring the HPV system throughput.

| Scheme       | Number of generations at convergence | Average user rate (Mbps) |
|--------------|--------------------------------------|--------------------------|
| IGA-JUPSA    | 52                                   | 60                       |
| GA-JUPSA     | 163                                  | 61.25                    |
| IGA-RUPSA    | 55                                   | 50                       |
| GA-RUPSA     | 168                                  | 50.5                     |
Figure 3 shows the system fairness versus different number of users in the HPV system. Figure 4 shows the system throughput versus different number of users in the HPV system. In figure 3, it can be concluded that the improved genetic algorithm can improve the fairness of the HPV system by comparing the convergence of the IGA-JUPSA scheme and the GA-JUPSA scheme, because the improved genetic algorithm takes fairness into account when designing individual fitness functions. In figure 4, it can be seen that the system throughput of the IGA-JUPSA scheme and the GA-JUPSA scheme are basically equal. However, the system throughput of the IGA-JUPSA scheme is significantly better than the IGA-RUPSA scheme, the system throughput of the IGA-JUPSA scheme is 21% higher than the IGA-RUPSA scheme, because the pairing scheme adopted in this article can improve the system throughput. The comprehensive analysis of the above two figures can be concluded that the IGA-JUPSA scheme proposed in this paper can ensure the system throughput while improving the fairness of the system.
three schemes. Because the JUPSA scheme can increase the throughput of the HPV system, and the IGA algorithm can improve the fairness of the HPV system. Therefore, the IGA-JUPSA scheme can increase the proportion of satisfied users and enable more users to obtain a better user experience.

Figure 5. Proportion of satisfied users versus different number of users.

5. Conclusion
In this paper, we introduce NOMA technology in HPV system to improve spectrum utilization, which causes high computational complexity and decoding delay. Therefore, we propose an IGA-JUPSA scheme to achieve a compromise between system performance and computational complexity. In the user pairing phase, the IGA-JUPSA scheme can maximize the throughput of the HPV system, and avoid pairing of adjacent users, which is convenient for decoding. In the subcarrier allocation phase, the improved genetic algorithm in the IGA-JUPSA scheme can find the optimal subcarrier allocation scheme with less convergence generations. The simulation results show that the proposed IGA-JUPSA scheme can reduce the computational complexity while ensuring the performance of the HPV system, and can also take into account the fairness and user satisfaction.

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