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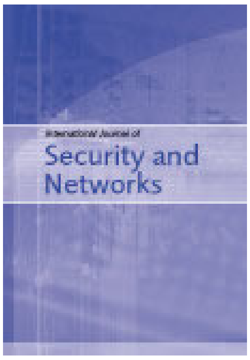

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A semi-grant-free scheme based on electricity information collection networks

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Abstract: In the context of the rapid development of power line communication technology in smart grid and electric energy internet, to cope with the challenge of the growth of user demand, traditional power line communication technology is difficult to meet the modern communication demand due to the limitation of transmission speed and application range. To this end, this paper proposes a semi-grant-free access power line communication system model combined with non-orthogonal multiple access (NOMA) technology, aiming to improve the system's spectral efficiency and the number of user accesses. By introducing the semi-grant-free (SGF) scheme, this paper analyses the application of SGF-NOMA in power line communication, demonstrating its advantages in improving the spectral efficiency and the system rate and guaranteeing the quality of service for users. In addition, this paper considers the impact of imperfect serial interference cancellation receivers on system performance and proposes a power optimisation algorithm to maximise the rate for low-rate users. Simulation results show that the proposed SGF-NOMA scheme can significantly improve the system throughput under different high-rate users' target rate requirements and maintain high spectral efficiency under imperfect serial interference cancellation conditions.

Keywords: power line communication; PLC; non-orthogonal multiple access; NOMA; semi-grant-free; SGF; power optimisation; successive interference cancellation; SIC.

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1 Introduction

Power line communication (PLC) is a communication method based on the existing power line architecture for voice or data signal transmission (Lin et al., 2015). From the point of view of occupied frequency bandwidth, PLC can be divided into narrowband PLC (40–500 kHz) and wideband PLC (10–30 MHz) (Ling, 2001). From the viewpoint of communication rate, it can be divided into low-speed and high-speed PLC. In terms of distribution line voltage level, it can be divided into three types: high-voltage (above 35 kV), medium-voltage (30 kV/10 kV), and low-voltage (below 380V) PLC (Zhang, 2014). PLC networks have the advantages of easy connection, wide coverage, and no need for repeated wiring. With the rapid development of the smart grid and power and energy internet, PLC, as an important field of the internet of things (IoT), has become an attractive communication method for IoT due to its easy

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installation and cost-effective advantages and has been practically applied in many fields.

Under the rapid progress of contemporary communication technology, traditional PLC technology cannot meet the growing user demand due to narrow application areas and limited transmission speed. PLC technology is developing in the direction of high-speed rate, wide connectivity, and high capacity. It is gradually shifting from high-voltage transmission lines to low-voltage distribution networks. Although OFDM technology has been introduced to enhance the system capacity and anti-interference capability of power line carrier communication, the system spectrum utilisation is still low. non-orthogonal multiple access (NOMA) technology has significant value in introducing NOMA technology into PLC systems by allowing multiple users to share the power domain instead of a single user's exclusive use, thus enhancing the system spectrum efficiency and the number of user accesses. In recent years, applying NOMA technology to PLCs to improve system throughput has received much attention. By introducing the power domain at the PLC transmitting side, superposition coding (SC) for multiple users' signals, and using successive interference cancellation (SIC) at the receiving side to eliminate the interference step by step, the PLC users can communicate on the same time and frequency resources. Frequency resources (Dai et al., 2015), thus realising an increase in throughput and transmission rate. Research on reuse techniques in some NOMA systems mainly focuses on deep learning (Jiang, 2022) to achieve higher spectral efficiency.

Semi-grant-free (SGF) schemes have recently received much attention and research in the field of NOMA because they can connect grant-free low-rate users (LUEs) into the channels of grant-based high-rate users (HUEs), which can improve the spectral efficiency more efficiently without interfering with the normal communication of HUEs. It is worth noting that SGF-NOMA also guarantees the QoS of GB users because it only allocates the redundant resources of GB users to GF users. Ding et al. (2019) first proposed the overall framework of the SGF scheme, analysed its interruption probability, and proposed different protocols for this SGF scheme. In the paper (Fayaz et al., 2024), the authors designed power pooling strategies to allocate power pools to GF users and optimised the power pooling dimension. For allocation and optimised the power pooling dimension, Bai and Gu (2023) designed an HSIC receiver scheme for different signal decoding sequences.

However, due to the multiplexing of multiple signals in the same power domain, serious interference between different signals is bound to occur, and reasonable power allocation techniques are needed to control the interference generated by multiplexing effectively. Many scholars in the wireless field have studied the power allocation scheme in downlink NOMA systems and achieved important results. Zhu et al. (2017) summarise the power allocation scheme's objectives as maximising the sum rate, energy efficiency, and user fairness. It investigates the power allocation that maximises the above objectives in downlink NOMA systems. Tian et al. (2020) investigate a power allocation scheme for a NOMA system containing two users, where the objective is to maximise the fairness among users and calculate the total throughput of the users using an iterative algorithm; Benjebbour et al. (2014) propose a full search power allocation (FSPA) algorithm, where an exhaustive method is used to calculate the sum rate of various power allocations so that the sum rate is maximised. Rate to maximise the sum rate, but its calculation is relatively complex.

NOMA performance depends critically on the SIC process, especially when considering uplink transmission. Therefore, it is necessary to consider the impact of SIC imperfections on our proposed SGF-NOMA scheme. When multiple signals arrive at the receiver simultaneously, the receiver employs a SIC receiver to sort and decode the user's power individually and then delete them. Still, when the number of signals is too large, the SIC receiver will have incomplete interference deletion, i.e., an imperfect SIC receiver (Zeng et al., 2020). This paper also considers the impact of imperfect SIC receivers on the system performance.

There is currently limited research on resource allocation in power line carrier communication. Relevant studies mainly focus on wireless communication, and the algorithms used have shortcomings, such as high complexity and low resource allocation rates. At the same time, resource allocation in power line carrier communication mainly focuses on allocating resources such as bits, power, and subcarriers in the physical layer, with little consideration given to issues such as fairness, user service quality, and priority among different users. In addition, security is also an issue and challenge that distribution equipment and similar IoT devices in current power line systems need to consider (Sumit et al., 2024).

At present, the application of NOMA technology in power line systems is particularly limited, and the spectrum efficiency of existing technologies is relatively low. Therefore, to improve spectrum efficiency and user speed, it is necessary to introduce SGF models for the power line system.

The specific contributions of this article are as follows:

- A combined power line system model, power line noise model, and SGF scheme in NOMA technology were proposed, which can effectively improve the spectral efficiency of the system and the total rate of users and ensure the service quality of different users.
- A power optimisation method was proposed for the proposed SGF power line scheme system model, and simulation verification showed that the proposed power optimisation method can effectively improve user speed.
- Analysed the impact of imperfect SIC receivers on SGF access schemes for power lines and compared the system performance under different SIC receiver parameters through simulation.

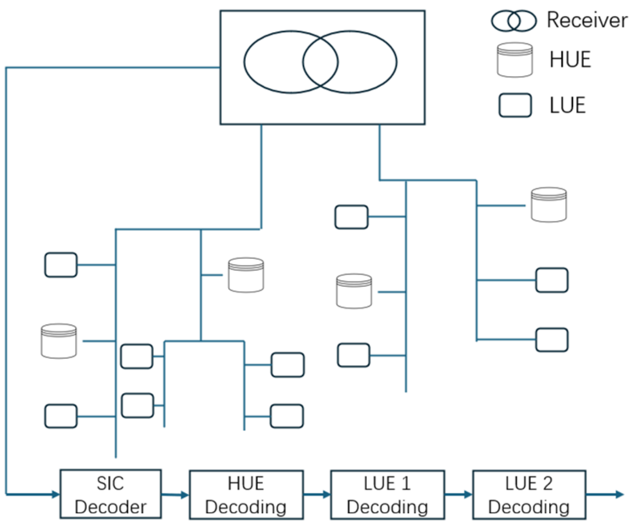
The rest of this article is structured as follows. Section 2 introduces the SGF-NOMA scheme in the PLC system and optimisation algorithm. In Section 3, we compared the performance of our proposed SGF-NOMA scheme with the comparison scheme through simulation. We analysed that our proposed power optimisation scheme can improve the system's throughput. Section 4 concludes the article.

2 System model

2.1 SGF-NOMA scheme in PLC system

We consider an uplink multiuser network in a PLC line, where the users are categorised into HUEs and LUEs, as shown in Figure 1.

Figure 1 SGF-NOMA in PLC lines (see online version for colours)



The receiver can provide N user accesses, including two kinds of users, assuming that M HUEs have information transmission requirements. LUE user accesses can also be accommodated to share the channel, and we define the set of high-speed rate users with the requirement of sending data as

$$\mathcal{P} = P_1, P_2, ..., P_M \tag{1}$$

We define P_m, where $m \in [1, M]$, as the m HUE with transmission information requirement, and the same, the set of LUEs with transmission information requirement can be denoted as

$$\mathcal{S} = \{S_1, S_2, ..., S_{N-M}\} \tag{2}$$

Define S_m, where $m \in [1, M]$, is the m LUE with transmission information requirement. The HUE and LUE have the minimum rate requirement for QoS, and the rate requirement of the HUE is greater than the rate requirement of the LUE. The receiver divides the channel into sub-channels and assigns one HUE and two SUEs to each sub-channel.

In the SGF model, the receiver first establishes a connection with the HUE users on the subchannel, and the receiver broadcasts a synchronisation beacon to notify all devices of its presence. The beacon contains information about the identifier and the guide frequency symbols for channel estimation. Upon reception of the beacon, both the HUE and the LUE perform channel estimation. The HUE then sends an access request signal and their target rate requirements. Based on the access request signal, the receiver obtains knowledge about the number of HUEs, their target rate requirements, and their respective channel state information (CSI). During the GB access phase of the HUEs, using the information about the number of HUEs, their DR requirements, and their respective CSIs, the receiver generates several RRBs equal to the number of HUEs (i.e., M). It assigns a single HUE to each RRB in a manner that maximises the target rate and is greater than the desired target rate. Thereafter, the receiver sends the access permission signal and the HUE-RRB allocation information to the HUEs. In addition, the receiving end broadcasts the available RRBs and the maximum interference that can be introduced to each RRB without violating the desired target rate of the corresponding HUE. During the LUE GF access phase, the LUEs receive information about the available RRBs. They broadcast their CSI information, target rate requirements, and transmission probabilities through an auxiliary cognitive radio network between the LUEs. Thus, all LUEs know the CSI, the target rate requirement, the transmission probability of the remaining LUEs, and the level of interference that each RRB can tolerate. The following figure represents the difference between our proposed SGF scheme and conventional OMA transmission in power systems:

Figure 2 Difference between the SGF scheme and OMA transmission (see online version for colours)

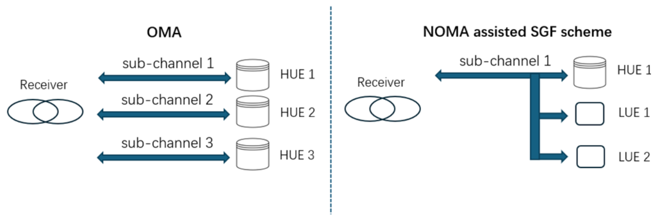
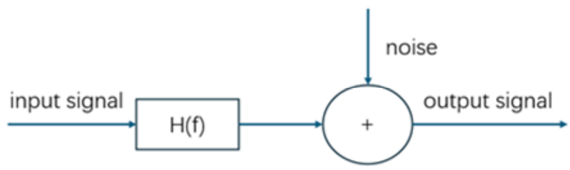


Figure 3 PLC channel model (see online version for colours)



The latest research content models the multiplicative fading coefficients of the power line channel as log-normally distributed (log normal, Log-N) random variables (Dubey et al., 2014), and comparing the statistical properties of the measured data finds that they match (Stefano, 2011), which is suitable for theoretical analysis and algorithmic research of PLC in application scenarios of low-voltage distribution networks with dynamic topology.

A PLC channel model is shown in Figure 2, which characterises the low-pass and transmission delay of signal propagation over a low-voltage power line channel. A frequency response linear filter can characterise all losses except noise. Noise on the power line channel can be viewed as additive random interference, which is modelled here using the Mid-A model, and the power line channel is modelled using the same modelling approach as the power line module in the literature (Chen et al., 2017). The transmitter sends a signal with power P over the power line channel to the receiver, then the received signal on a certain sub-channel at the same moment can be expressed as

$$\begin{aligned} y = & P_B H(f)_B X_B + \theta_{s1} P_{S_1} H(f)_{s1} X_{s1} \\ & + \theta_{s2} P_{S_2} H(f)_{s2} X_{s2} + Z_0 \end{aligned} \tag{3}$$

where $\theta_i = \begin{cases} 1, S_i \text{ transmits} \\ 0, \text{ otherwise} \end{cases}$, representing whether or not this user transmits, $H(f) = h(f) / (d_D)^\beta$, and $h(f)$ is the power line fading coefficient satisfies the lognormal distribution with $h(f) \sim \log N(\mu_D, \sigma_D^2)$, then it can be expressed as

$$\begin{aligned} f_{H(f)}\left(H(f), \mu_D, \sigma_D\right) = & \frac{1}{H(f)\sigma_D\sqrt{2\pi}} \\ & \times \exp\left(-\frac{\left(\ln H(f) - \mu_D\right)^2}{2}\right) \end{aligned} \tag{4}$$

where μ_D and σ_D are the mean and mean square deviation of $\ln H(f)$, respectively. Let $E(H(f)^2) = \exp(2\mu_D + 2\sigma_D^2) = 1$, then $\mu_D = -\sigma_D^2$, where the channel fading envelope energy is normalised to ensure that the average power value of the signal is not affected by channel fading.

The Z_0 in equation (3) is the impulse noise in the low-voltage power line channel. The Middleton Class A impulse noise model is used in this section to simulate the noise in the PLC line. As a mathematical model that can independently describe the Gaussian noise and impulse noise components in the PLC channel, the Middleton Class A noise model can more accurately simulate the PLC channel noise environment. The model's probability density function models the channel's noise environment. The noise model consists of impulse noise Z_I and Gaussian background noise Z_G, and the probability density function of the impulse noise amplitude Z is

$$P_M(Z) = \sum_{k=0}^{\infty} \frac{A^k \exp(-A)}{k!} * \frac{1}{\sqrt{2\pi Z_k}} * \exp\left(-\frac{Z^2}{Z_k}\right) \tag{5}$$

where k is the number of pulse superpositions, obeying the Poisson distribution with mean value A, which is $P(X = k) = \frac{e^{-A} A^k}{k!}$, Z_k is the instantaneous noise power of k pulse; Z is the parameter. In the PLC system, the reasonable value range of A is distributed between 0.0001 and 0.35, and the larger the value of A is, the closer the model is to the Gaussian white noise model, and the smaller the value of A is, the more the model exhibits the characteristics of pulse noise. The smaller the value, the more the model exhibits pulsed noise characteristics.

$Z_0 = Z_G + Z_I$ represents the average total noise power, then the instantaneous total noise power of the power line can be expressed as $Z_0 = Z_D(k / A + T) / (1 + T)$, where T is the ratio of the background noise power to the impulse noise power.

The following equation can give the target rate requirement for HUE and LUE during SGF transmission:

$$R_{HUE} = B \log_2\left(1 + \gamma_B\right) \geq R_T \tag{6}$$

The target rate of the LUE is limited by the signal strength that can be accommodated by the HUE access, as specified in the following equation:

$$\tau\left(|H(f)|^2\right) = \max\left\{0, \frac{P_B |H(f)_B|^2}{2^{R_T} - 1} - 1\right\} \tag{7}$$

For the receiver side using a SIC receiver to demodulate the signal for the same subchannel, it is possible to demodulate the signals of at most three users, and the signal power magnitude of the three users is different, which is a great challenge for the SIC receiver, and perfect SIC demodulation is impossible to realise in reality, so we consider imperfect SIC demodulators, and we define $I_{sic} = \in^2 \sum_{i=k}^{N} P_i \left|H(f)_i\right|^2$ (Chen et al., 2017) to represent the interference of the previously demodulated of the user to the current demodulated user, and $\in^2$ is the imperfect SIC interference coefficient, the size of which depends on the hardware factors and the environmental effects, and we will analyse the effects of different parameter sizes on the system performance in following section. Firstly, demodulate the signal of HUE, and then the signal-to-noise ratio of HUE can be expressed as

$$\gamma_B = \frac{P_B |H(f)_B|^2}{P_{S_1}\left|H(f)_{S_1}\right|^2 + P_{S_2}\left|H(f)_{S_2}\right|^2 + Z_0} \tag{8}$$

Secondly, demodulate the more powerful one of the LUEs, i.e., the user. For the user, the signal-to-noise ratio at the receiver can be expressed as

$$\gamma_{S_1} = \frac{P_{S_1}\left|H(f)_{S_1}\right|^2}{P_{S_2}\left|H(f)_{S_2}\right|^2 + I_{sic} + Z_0} \tag{9}$$

Finally, the demodulation of S_2 users with low power in the LUEs is the same as S_1 users, and the signal-to-noise ratio at the receiver can be expressed as

$$\gamma_{S_2} = \frac{P_{S_2}\left|H(f)_{S_2}\right|^2}{I_{sic} + Z_0} \tag{10}$$

2.2 Power optimisation algorithm

For LUEs on the same sub-channel, they all know the tolerance threshold on that subchannel, so we propose a globally optimal power allocation algorithm based on the rate maximisation problem for LUE users and finally use the forced-zero water injection algorithm to solve the globally optimal solution of the problem described in equation (11).

$$\begin{aligned}&\max_{p}\sum_{k=1}^{K} log_2\left(1+\frac{p_k}{Z_0}\left|H(f)_k\right|^2\right)\\ &s.t\sum_{k=1}^{K} p_k = \tau\left(\left|H(f)\right|^2\right) = P_{max}\\ &\qquad p_k \geq 0, \forall k \in \mathcal{S}\end{aligned} \tag{11}$$

where p_k denotes the power assigned to the k LUE user $H(f)_k$ denotes the channel gain of the k user. The power sum of all users cannot exceed the total power limit $P_{\max}$, i.e., the tolerance threshold of HUE users on that channel $\tau(|h(f)|^2)$. This optimisation problem can be solved optimally by the Lagrange multiplier method. The original problem can be transformed into

$$\begin{aligned}L(\mathbf{p}, \lambda) = &\sum_{k=1}^{K} log_2\left(1+\frac{p_k}{Z_0}\left|H(f)_k\right|^2\right)\\ &+\lambda\left(P_{max}-\sum_{k=1}^{K} p_k\right)\end{aligned} \tag{12}$$

where $\lambda \in R$ is the Lagrange multiplier. Then the derivative function of $L(\mathbf{p}, \lambda)$ with respect to p_k is

$$\frac{\partial L(\mathbf{p}, \lambda)}{\partial p_k} = \frac{1}{ln2}\cdot\frac{\left|H(f)_k\right|^2 / Z_0}{1+p_k\left|H(f)_k\right|^2 / Z_0} - \lambda = 0 \tag{13}$$

$$p_k = \frac{1}{\lambda \cdot ln2} - \frac{Z_0}{\left|H(f)_k\right|^2} \tag{14}$$

Let $\mu = \frac{1}{\lambda . \ln 2}$:

$$p_k = \mu - \frac{Z_0}{\left|H(f)_k\right|^2} \tag{15}$$

Due to the presence of the $p_k \geq 0$ constraint, there is then

$$p_k = \max\left(\mu - \frac{Z_0}{\left|H(f)_k\right|^2}, 0\right) \tag{16}$$

Due to $\sum_{k=1}^{K} p_k = P_{\max}$, the final injection surface can be obtained as

$$\mu = \frac{P_{\max} + \sum_{k=1}^{K} Z_0 / \left|H(f)_k\right|^2}{K} \tag{17}$$

Using the above forced-zero water injection algorithm may produce problems that the allocated power is greater than the constrained power $P_{\max}$, so it is necessary to sort $\frac{Z_0}{|H(f)_k|^2}$ in the algorithm after the reverse order of water injection, which can be expressed as the water will be injected into the highest step flush with the highest step if there is remaining water then $\mu - \frac{Z_0}{|H(f)_k|^2} > 0$, using the water injection algorithm for the solution if there is no remaining water, it means that the highest step, then the highest step cannot be injected, and then to determine the status of the water level, whether it is between the second high and the first high if in then it means that the highest water level does not allocate water. Then, the other steps are injected with water.

3 Simulation results

We validate our proposed SGF scheme in the power line system by Monte Carlo simulation and analyse the throughput enhancement by the water injection power optimisation algorithm with the simulation parameters designed as follows:

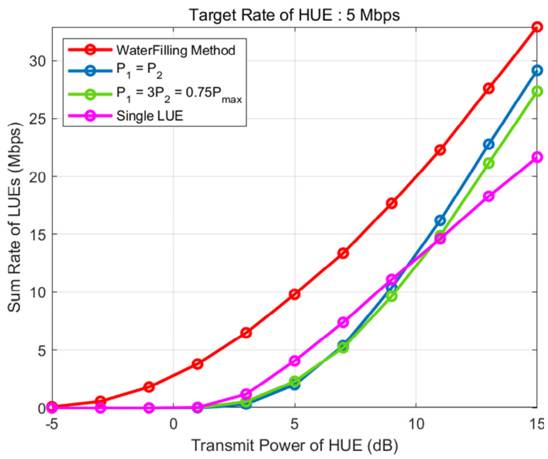
Table 1 Simulation parameters

Parameters	*Values*
System bandwidth B	5 MHz
average value A	0.2
Power line attenuation factor β	1.5
The ratio of background noise power to impulse noise power T	0.01
communication distance	100~500 m
Minimum transmission rate for HUE users	{5, 10, 15} Mbps
System decay coefficient variance σ_D	2 dB
Noise model $\in^2$	Middleton class A 0.1, 0.01, 0.001

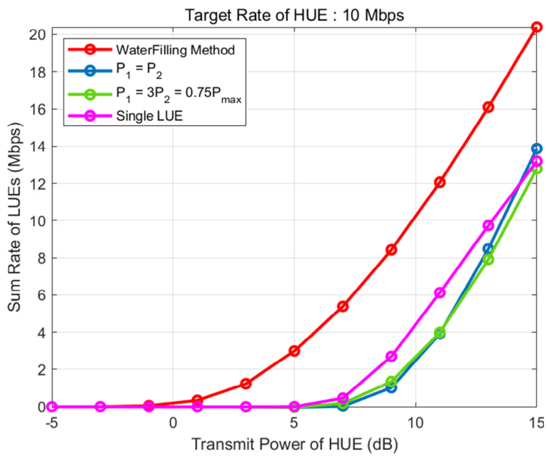
In this paper, we analyse the comparison of the LUEs and rates of the system for our proposed power-optimised SGF scheme with power averaging and $P_{S_1} = 3P_{S_2} = 0.75P_{\max}$ power allocation scheme, as well as the SGF scheme with a single LUE for the three HUEs with the minimum transmission rate requirements of 5 Mbps, 10 Mbps, and 15 Mbps, and the simulation results are as follows.

We set the transmission power of HUEs in the range of –5 dB to 15 dB and plot the variation of the sum rate of LUEs users under different HUE target rate scenarios as the transmission power of HUE users increases. It can be seen that under the three HUE target rates of 5 Mbps, 10 Mbps, and 15 Mbps, our proposed power-optimised SGF scheme can effectively increase the rate of the HUE users, and the power available for allocation to the LUEs is greatly reduced under the high-speed requirement of the HUE target rate of 15 Mbps, and under this demanding condition, our proposed power-optimised SGF scheme under these demanding conditions, our proposed power-optimised SGF scheme can increase the system rate by 100% compared to a single LUE user and by 140% compared to the average power allocation, and $P_{S_1} = 3P_{S_2} = 0.75P_{\max}$ power allocation method. Even at 5 Mbps and 10 Mbps, the power-optimised SGF scheme achieves 30% to 50% system rate improvement over the other three schemes.

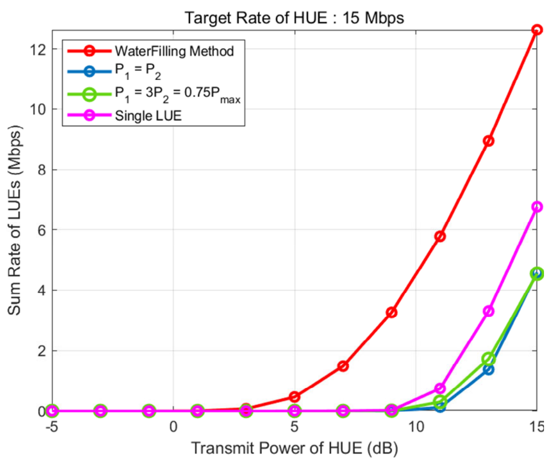
Figure 4 Sum rate of LUEs (see online version for colours)



(a)



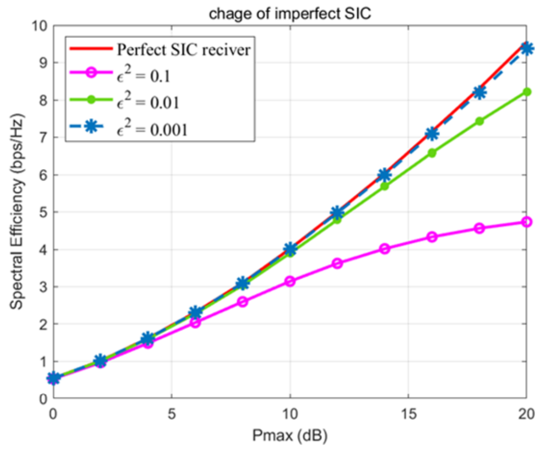
(b)



(c)

The following figure shows the effect of our imperfect SIC receiver on the system's spectral efficiency. We simulated the system spectral efficiency change with different SIC receiver performance differences as the power allocated to the available LUEs varies. We set the size of the imperfect receiver parameter $\in^2$ to 0.1, 0.01, and 0.001 for three cases (Zeng et al., 2020; Wang et al., 2021).

Figure 5 Spectral efficiency of Various power (see online version for colours)



The scenario that we analyse is the SGF power optimisation scenario. We can see that when $\in^2 = 0.001$, the interference of the previous layer on the current layer is still very small, and the system performance is basically the same as that of the perfect SIC receiver, and the system performance slightly decreases by about 5% when $\in^2 = 0.01$. The residual impact of the power of the previous demodulation layer already greatly impacts the current layer when $\in^2 = 0.1$. The interference term of the final demodulated LUE in this scenario will be very large, which seriously affects the reachable rate. It can be seen that the spectral efficiency of the system drops by about 50%.

4 Conclusions

This paper proposes a novel communication scheme combining the SGF technology of NOMA and designing a power optimisation algorithm to address the traditional techniques and existing challenges in PLC systems. Through theoretical analysis and simulation experiments, the effectiveness of the proposed scheme in improving system user rate and guaranteeing QoS is verified. In particular, under imperfect SIC conditions, the proposed power optimisation algorithm can effectively improve the system's spectral efficiency, showing the advantages of the SGF scheme in practical PLC applications. Future work will focus on further optimising the algorithm to adapt to more complex communication environments.

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