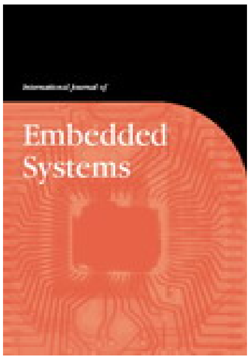

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Abstract: A novel minimum optimisation scheme for IRS-assisted NOMA (MOS-IRS) is proposed to minimise the power of the power station. Firstly, optimisation problem of minimising power is constructed with the users' throughput requirements as constraints, and the optimisation variables are time allocation and IRS phase shift. Secondly, we simplify the optimisation problem and separate the phase shift optimisation problem for the wireless energy transfer (WET) and wireless information transfer (WIT) process. Then, the multi-variables optimisation problem is transformed into that with a single-variable, and the alternating optimisation method is used to solve the phase shift for the WET and WIT process. Finally, the optimal time allocation is obtained by using the functional extremum method with given IRS phase shift. Simulation results show that the required power of the proposed scheme is lower than that of the existing schemes for the same scenario when the other parameters are the same.

Keywords: non-orthogonal multiple access; NOMA; intelligent reflecting surface; resource allocation; time; phase shift.

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1 Introduction

Intelligent reflecting surface (IRS) is a uniform planar array composed of many passive reflecting elements, each of which can adjust the amplitude and phase of the incident signals (Patil and More, 2023; Kang et al., 2022; Sun and Jing, 2022). Thus, the equivalent channel of the signals can be adjusted according to the wireless environment (Chen et al., 2023; Liu et al., 2022; Xie et al., 2023). It has been shown that IRS can not only suppress inter-user interference (Li et al., 2023; Ajam et al., 2022; Kumar et al., 2024; Liu et al., 2020), but also provide additional diversity gain and passive array gain, thus improving channel gain and quality of user service (Mu et al., 2021; Li et al., 2022a; Singh et al., 2024; Yang et al., 2023; Lin et al., 2023). Therefore, IRS is one of the research hotspots in recent years.

Wireless power transfer (WPT) technology is beneficial to prolong the life cycle of energy-constrained networks (Chowdhury, 2022). Based on the WPT wireless network framework, some scholars have proposed wireless powered communication networks (WPCN) (Kumar et al., 2024; Hua and Wu, 2022). WPCN provides power to wireless devices remotely through wireless power technology, freeing them from the need to replace batteries. Previous studies have shown that WPCN can reduce energy consumption and improve energy efficiency, and the introduction of IRS in WPCN can enhance the effect of energy harvesting. Therefore, IRS-assisted WPCN system has attracted the attention of academia and industry.

Non-orthogonal multiple access (NOMA) is one of the key technologies for future wireless communication (Wang et al., 2023b; Arfaoui et al., 2022; Zhuang et al., 2022). NOMA is divided into power domain NOMA and code domain NOMA. The basic idea of NOMA in power domain is to linearly superimpose the signals of multiple users on the same time-frequency resource at the transmitter, and adopt successive interference cancellation technology at the receiver to reduce the interference between users and detect the expected received signals (Lima and Ghrayeb, 2022; Wang et al., 2022; Yue and Liu, 2022). Compared with the traditional orthogonal multiple access, NOMA can access more users and has higher spectral efficiency (Zhang et al., 2024; Li et al., 2024; Wang et al., 2023). In addition, NOMA can be combined with IRS to further improve system performance. The outage probability and capacity of IRS-assisted NOMA system are derived in Hua et al. (2020). The simulation results show that the performance of this system is better than that of NOMA system and IRS-assisted orthogonal multiple access system.

Since IRS, WPCN, and NOMA are key technologies for the future wireless communications, combining these three technologies will not only increase the power harvested by wireless devices through WPCN, but also allow more users to access them at the same time (Lyu et al., 2022; Zhang et al., 2021; Liu et al., 2023; Wu et al., 2022). Therefore, a lot of researches have been done on IRS-assisted NOMA WPCN. The communication process of IRS-assisted NOMA WPCN is divided into two sub-processes, namely, downlink wireless energy transfer (WET) and uplink wireless information transfer (WIT). In the WET process, the power station sends energy to the user and the IRS, the IRS reflects the received energy to the user, and the user harvests the energy from the power station and the IRS. In the WIT process, the user sends signals to the access point (AP) and the IRS, which reflects the signals received by the user to the AP. At present, scholars have proposed a variety of methods for maximising sum rate for IRS-assisted NOMA WPCN systems. The WPCN studied in Wu et al. (2021) and Yeong et al. (2021) consists of a hybrid AP, an IRS, and multiple users, in which AP transmits energy during the downlink WET process and receives signals during the uplink WIT process. Both schemes in Wu et al. (2021) and Yeong et al. (2021) use iterative methods to obtain IRS phase shift and time allocation to maximise system throughput. Yeong et al. (2021) maximise the throughput of NOMA WPCN by jointly optimising transmission time, power and IRS phase shift. The power station and AP in Li et al. (2022b) are two different devices. The authors construct a joint optimisation problem of time allocation and IRS phase shift in IRS-assisted NOMA WPCN with the goal of maximising throughput. In order to solve the optimisation problem, the function extremum method is used to obtain the time allocation of maximising the system throughput under the given IRS phase shift, then, the IRS phase shift in WET and WIT processes is optimised alternately by iterative method with known time allocation. However, there is no work to investigate the method of minimising the power of the power station when the users harvest energy linearly. Therefore, the methods of minimising power for IRS-assisted NOMA WPCN need to be studied.

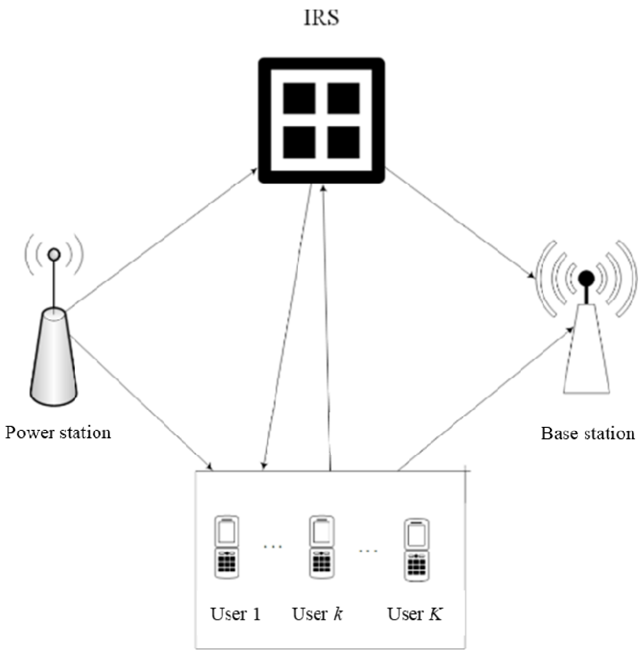
To sum up, a novel minimum optimisation scheme for IRS-assisted NOMA (MOS-IRS) is proposed when the users harvest energy linearly. Firstly, the optimisation problem of minimising power is established. The optimal variables include time allocation and IRS phase shift, and one of the constraints is the users' minimum throughput requirement. Then, the optimisation problem is simplified according to the relationship between the power required by a single user and the channel, IRS phase shift, time allocation, and the minimum throughput required by the user per unit time. Next, the IRS phase shift optimisation problem is constructed, and the multi-variables optimisation problem is transformed into a single-variable optimisation problem. Finally, with given phase shift of IRS, the function extremum method is used to get the optimal time allocation. The simulation results show that the proposed scheme requires less power than the existing schemes for the same scenario when other parameters are the same.

2 System model

Consider IRS-assisted NOMA WPCN depicted in Figure 1, comprising a power station, K users, an IRS, and an AP. Notably, all nodes in the system are equipped with a single antenna with the exception of the IRS. The IRS is deployed within the coverage area of both the power station and the AP. The IRS consists of a total of N reflecting elements, each of which can change the phase shift of the incident signals, without changing the amplitude of the incident signals.

The communication process of IRS-assisted NOMA WPCN is divided into two sub-processes, WET and WIT. In the WET process, the power station sends energy to user k, $k = 1, 2, \cdots, K$, and the IRS reflects the energy received from the power station to user k. In WIT, user k sends signals to the AP, and the IRS reflects the signals received from user k to the AP. The duration of the downlink WIT process is denoted as τ_0 where $\tau_0 \in (0, 1)$. The duration of the uplink WIT process is represented as τ_1, where $\tau_0 \in (0, 1)$, which satisfies $\tau_0 + \tau_1 = 1$.

Figure 1 IRS-assisted NOMA WPCN system



The IRS phase shift matrices during the downlink WET and uplink WIT are ϕ_0 and ϕ_1 respectively, $\phi_t = diag(e^{j\theta_{t,1}}, e^{j\theta_{t,2}}, \cdots, e^{j\theta_{t,N}})$, $t = 0, 1$, where $\theta_{t,n}$ is the phase shift of the n-th reflecting element of IRS, $\theta_{t,n} \in \Delta$, $n = 1, 2, \cdots, N$, and $\Delta = \{0, 2\pi / 2^{\zeta}, \cdots, 2\pi(2^{\zeta} - 1) / 2^{\zeta}\}, \varsigma$ is the number of bits required to represent the IRS phase shift in binary, $j = \sqrt{-1}$.

Because of the high path loss, the signals that are reflected twice or more by IRS are ignored. Thus, the signal received by user k during the downlink WET process can be expressed as

$$y_k = \left(p_{d,k} + \boldsymbol{p}_{r,k}{}^T \phi_0 \boldsymbol{a}_0\right) \sqrt{P_0} x_0 + n_k \tag{1}$$

where $k = 1,2,\ldots,K$, $p_{d,k}$ is the channel from the power station to user k, $\boldsymbol{p}_{r,k}$ and $\boldsymbol{a}_0$ represent the channel from IRS to user k, from power station to IRS, respectively, with the dimension of $N\times1$, $(\cdot)^T$ denotes the transpose, x_0 and P_0 are the energy signal and the power, respectively, n_k represents the complex Gaussian white noise received by user k, with a mean value of 0.

User k linearly harvests energy within τ_0 time, then the harvested energy can be expressed as

$$E_k = \eta\tau_0 P_0 \left|p_{d,k} + \boldsymbol{p}_{r,k}{}^T \phi_0 \boldsymbol{a}_0\right|^2 = \eta\tau_0 P_0 \left|p_{d,k} + \boldsymbol{a}_0{}^T \phi_0 \boldsymbol{p}_{r,k}\right|^2 \tag{2}$$

where $k = 1,2,\ldots,K$, η is the energy receiving conversion efficiency, $|\cdot|$ represents the absolute operation. Because the energy consumed in τ_1 cannot be greater than the energy received in τ_0, the transmit power P_k of user k in τ_1 satisfies $P_k \le \frac{E_k}{1-\tau_0}, k = 1, 2, \cdots, K.$ In order to maximise throughput, it is assumed that user k consumes all the harvested energy in signal transmission. Therefore, P_k can be expressed as $P_k = \frac{E_k}{1-\tau_0}, k = 1, 2, \cdots, K.$

During the uplink WIT process, the received signal at AP can be expressed as

$$y_0 = \sum_{k=1}^{K} \left(g_k + \mathbf{h}_{BS}^T \phi_1 \mathbf{h}_k\right) \sqrt{P_k} s_k + n_0 \tag{3}$$

where g_k is the channel from user k to AP, $\mathbf{h}_k$ and $\mathbf{h}_{BS}$ are the channels from user k to IRS, from IRS to AP, with the dimension of $N\times1$. s_k and P_k are the normalised transmission signal and the power of user k, and n_0 is complex Gaussian white noise with a mean value of 0.

3 Resource allocation scheme

In this section, firstly, the optimisation problem of minimising power is established. Secondly, the optimisation problem is simplified based on the throughput requirement of the user. Next, the phase shift optimisation problem is separated and the optimisation problem is simplified, during which the multi-variables phase-shift optimisation problem is transformed into a single-variable phase-shift optimisation problem. In what follows, an algorithm is presented to solve the IRS phase-shift in WET (WIT) process when the IRS phase shift in WIT (WET) is known. Based on this algorithm, the IRS phase shift for WET process and the IRS phase shift for WIT process are alternately optimised. Finally, with given IRS phase shift, the function extremum method is used to find the optimal time allocation for minimising power.

3.1 Establishment of optimisation problem

Without loss of generality, it is assumed that

$$P_1\left|g_1+\mathbf{h}_{BS}^T\phi_1\mathbf{h}_1\right|^2 \geq P_2\left|g_2+\mathbf{h}_{BS}^T\phi_1\mathbf{h}_2\right|^2 \geq \cdots \geq P_K\left|g_K+\mathbf{h}_{BS}^T\phi_1\mathbf{h}_K\right|^2.$$

According to the working principle of NOMA, when AP detects s_k, the signal to interference and noise ratio (SINR) is

$$SINR_k=\frac{\eta\tau_0 P_0 z_k}{\eta\tau_0 P_0\sum_{i=k+1}^{K} z_i+\tau_1\sigma^2} \tag{4}$$

where

$$z_k=\left|g_k+\mathbf{h}_{BS}^T\phi_1\mathbf{h}_k\right|^2\left|p_{d,k}+\boldsymbol{a}_0{}^T\phi_0\boldsymbol{p}_{r,k}\right|^2,$$

$$k=1,2,\cdots,K,$$

$$\sum\nolimits_{i=k+1}^{K} z_i=0$$

for $k = K$. The throughput of user k per unit time is

$$R_k=\tau_1\log_2\left(1+SINR_k\right) \tag{5}$$

The goal of the proposed scheme is to minimise the power of the power station by jointly designing time allocation and IRS phase shift under the condition of satisfying users' throughput. The goal is expressed in a formula as

$$\begin{aligned}&\min_{\tau_0,\tau_1,\phi_0,\phi_1} P_0\\ &s.t.\quad \tau_0\in(0,1),\tau_0+\tau_1=1\\ &\qquad R_k\geq e_k, k=1,2,\cdots,K\\ &\qquad \theta_{t,n}\in\Delta, t=0,1, n=1,2,\cdots,N\end{aligned} \tag{6}$$

where e_k is the minimum throughput required by user k in unit time. It can be known from $R_k \geq e_k$ that $SINR_k \geq r_k$, $r_k=2^{e_k/\tau_1}-1$, $k = 1,2,\ldots,K$, where r_k is the SINR corresponding to the minimum throughput required by user k in unit time.

3.2 Simplification of the optimisation problem

Next, the relationship between the power required by a single user and the channel, IRS phase shift, time allocation, and the minimum throughput required by the user per unit time is derived.

Let $M_k=\left|g_k+\mathbf{h}_{BS}^T\phi_1\mathbf{h}_k\right|^2$, $k=1,2,\cdots,K$. When $k = K$, it can be obtained from $SINR_K \geq r_K$ that

$$P_K\geq\frac{\sigma^2 r_K}{M_K} \tag{7}$$

When $k = K-1$, it can be deduced from $SINR_{K-1} \geq r_{K-1}$ that

$$P_{K-1}\geq\frac{r_{K-1}\left(r_K+1\right)}{M_{K-1}}\sigma^2 \tag{8}$$

Using the same method, we can obtain

$$P_{K-2}\geq\frac{r_{K-2}\left(r_{K-1}+1\right)\left(r_K+1\right)}{M_{K-2}}\sigma^2 \tag{9}$$

$$P_{K-3}\geq\frac{r_{K-3}\left(r_{K-2}+1\right)\left(r_{K-1}+1\right)\left(r_K+1\right)}{M_{K-3}}\sigma^2 \tag{10}$$

Using the method of induction, we can get

$$P_k\geq\frac{r_k\prod_{m=k+1}^{K}\left(r_m+1\right)}{M_k}\sigma^2 \tag{11}$$

where $k = 1,2,\ldots,K$, $\prod_{m=k+1}^{K}\left(r_m+1\right)=1$ for $k = K$. It can be obtained from $P_k=\dfrac{E_k}{1-\tau_0}$ and (2) and (11) that

$$P_k=\frac{\eta\tau_0 P_0\left|p_{d,k}+\boldsymbol{a}_0{}^T\phi_0\boldsymbol{p}_{r,k}\right|^2}{1-\tau_0}\geq\frac{r_k\prod_{m=k+1}^{K}\left(r_m+1\right)}{M_k}\sigma^2 \tag{12}$$

Then, we have

$$P_0\geq\frac{\left(1-\tau_0\right)r_k\prod_{m=k+1}^{K}\left(r_m+1\right)}{\eta\tau_0 M_k\left|p_{d,k}+\boldsymbol{a}_0{}^T\phi_0\boldsymbol{p}_{r,k}\right|^2}\sigma^2, k=1,2,\ldots,K \tag{13}$$

Let

$$b_k=r_k\prod_{m=k+1}^{K}\left(r_m+1\right).$$

Combined with (13), the optimisation problem in (6) can be equivalently written as

$$\begin{aligned}&\min_{\tau_0,\tau_1,\phi_0,\phi_1}\max\left\{\begin{array}{l}\dfrac{\left(1-\tau_0\right)b_k\sigma^2}{\eta\tau_0\left|g_k+\mathbf{h}_{BS}^T\phi_1\mathbf{h}_k\right|^2\left|p_{d,k}+\boldsymbol{a}_0^T\phi_0\boldsymbol{p}_{r,k}\right|},\\ k=1,2,\cdots,K\end{array}\right\}\\ &s.t.\quad \tau_0\in(0,1),\tau_0+\tau_1=1\\ &\qquad \theta_{t,n}\in\Delta, t=0,1, n=1,2,\cdots,N\end{aligned} \tag{14}$$

3.3 Construction and simplification of the phase shift optimisation problem

The optimisation variables of the optimisation problem in (14) are time and IRS phase shift, which is not easy to solve. When the other parameters are the same, the larger $|g_k + \mathbf{h}_{BS}^T \phi_1 \mathbf{h}_k|^2 |p_{d,k} + \boldsymbol{a}_0{}^T \phi_0 \boldsymbol{p}_{r,k}|^2$, the lower the power required by the system, so that IRS phase shift can be first solved by maximising $|g_k + \mathbf{h}_{BS}^T \phi_1 \mathbf{h}_k|^2 |p_{d,k} + \boldsymbol{a}_0{}^T \phi_0 \boldsymbol{p}_{r,k}|^2$, and then τ_0 and τ_1 can be obtained with fixed IRS phase shift.

With IRS phase shift as variables, the optimisation problem to maximise

$$\sum_{k=1}^{N} \left| g_k + \mathbf{h}_{BS}^T \phi_1 \mathbf{h}_k \right|^2 \left| p_{d,k} + \boldsymbol{a}_0{}^T \phi_0 \boldsymbol{p}_{r,k} \right|^2$$

can be expressed as

$$\begin{aligned} &\max_{\phi_0,\phi_1} \sum_{k=1}^{N} \left| g_k + \mathbf{h}_{BS}^T \phi_1 \mathbf{h}_k \right|^2 \left| p_{d,k} + \boldsymbol{a}_0{}^T \phi_0 \boldsymbol{p}_{r,k} \right|^2 \\ &s.t. \quad \theta_{t,n} \in \Delta, n = 1,2,\cdots,N, t = 0,1 \end{aligned} \tag{15}$$

The variables in (15) are ϕ_1 and ϕ_0. Alternating optimisation can be employed to solve this problem, the idea of which is as follows: first assign initial value to ϕ_0, solve ϕ_1 with fixed ϕ_0, then solve ϕ_0 with fixed ϕ_1, next, repeat this process until ϕ_0 and ϕ_1 converge.

With fixed ϕ_0, the optimisation problem in (15) can be transformed into

$$\begin{aligned} &\max_{\phi_1} \sum_{k=1}^{N} V_k \left| g_k + \mathbf{h}_{BS}^T \phi_1 \mathbf{h}_k \right|^2 \\ &s.t. \quad \theta_{1,n} \in \Delta, n = 1,2,\cdots,N \end{aligned} \tag{16}$$

where $V_k = \left| p_{d,k} + \boldsymbol{a}_0{}^T \phi_0 \boldsymbol{p}_{r,k} \right|^2$ is a constant, $k = 1,2,\cdots,K$. With fixed ϕ_1, the optimisation problem in (15) can be transformed into

$$\begin{aligned} &\max_{\phi_0} \sum_{k=1}^{N} M_k \left| p_{d,k} + \boldsymbol{a}_0{}^T \phi_0 \boldsymbol{p}_{r,k} \right|^2 \\ &s.t. \quad \theta_{0,n} \in \Delta, n = 1,2,\cdots,N \end{aligned} \tag{17}$$

where $M_k = \left| g_k + \mathbf{h}_{BS}^T \phi_1 \mathbf{h}_k \right|^2$ is a constant, $k = 1,2,\cdots,K$. Next, the solution of the optimisation problem in (16) is given.

The optimisation objective function in (16) can be equivalently expressed as

$$\begin{aligned} \sum_{k=1}^{K} V_k \left| g_k + \mathbf{h}_{BS}^T \phi_1 \mathbf{h}_k \right|^2 &= \sum_{k=1}^{K} V_k \left| g_k + \theta_1 \mathrm{d}_k \right|^2 \\ &= \theta_1 \Phi \theta_1^H + 2\,\mathrm{Re}(\theta_1 \alpha) + \sum_{k=1}^{K} V_k g_k g_k^* \end{aligned} \tag{18}$$

where

$$\boldsymbol{\theta}_1 = \left[e^{j\theta_{1,1}}, e^{j\theta_{1,2}}, \cdots, e^{j\theta_{1,N}} \right], \boldsymbol{\Phi} = \sum_{k=1}^{K} V_k \mathbf{d}_k \mathbf{d}_k{}^H,$$

$$\boldsymbol{\alpha} = \sum_{k=1}^{K} V_k g_k{}^* \mathbf{d}_k, \mathbf{d}_k = diag\left(\mathbf{h}_{BS}\right) \mathbf{h}_k,$$

$\mathrm{Re}(\cdot)$ denotes real part, $(\cdot)^*$ and $(\cdot)^H$ represent the complex conjugate and conjugate transpose, respectively.

We use d_{ki} to represent the i^{th} element of the vector $\mathbf{d}_k$, then $\boldsymbol{\Phi}$ can be written as

$$\begin{aligned} \boldsymbol{\Phi} &= \sum_{k=1}^{K} V_k \mathbf{d}_k \mathbf{d}_k{}^H \\ &= \sum_{k=1}^{K} V_k \begin{bmatrix} d_{k1} d_{k1}^* & d_{k1} d_{k2}^* & \cdots & d_{k1} d_{kN}^* \\ d_{k2} d_{k1}^* & d_{k2} d_{k2}^* & \cdots & d_{k2} d_{kN}^* \\ \vdots & \vdots & \ddots & \vdots \\ d_{kN} d_{k1}^* & d_{kN} d_{k2}^* & \cdots & d_{kN} d_{kN}^* \end{bmatrix} \end{aligned} \tag{19}$$

Let ψ_{ui} denote the u^{th} row and i^{th} column of $\boldsymbol{\Phi}$, $u = 1,2,\cdots,N, i = 1,2,\cdots,N$, then we have $\psi_{ui} = \psi_{iu}{}^*$. Substituting $\boldsymbol{\theta}_1 = \left[e^{j\theta_{1,1}}, e^{j\theta_{1,2}}, \cdots, e^{j\theta_{1,N}} \right]$ into $\boldsymbol{\theta}_1 \boldsymbol{\Phi} \boldsymbol{\theta}_1{}^H$, we have

$$\boldsymbol{\theta}_1 \boldsymbol{\Phi} \boldsymbol{\theta}_1{}^H = \sum_{i=1}^{N} \psi_{ii} + 2\,\mathrm{Re}\left(\sum_{i=1}^{N-1} \sum_{l=i+1}^{N} \psi_{il} e^{j(\theta_{1,i} - \theta_{1,l})} \right) \tag{20}$$

The i^{th} element of $\boldsymbol{\alpha}$ is represented by α_i, $i = 1,2,\ldots,N$, then $\sum_{k=1}^{K} V_k \left| g_k + \mathbf{h}_{BS}^T \phi_1 \mathbf{h}_k \right|^2$ can be expressed as

$$\begin{aligned} \sum_{k=1}^{K} V_k \left| g_k + \mathbf{h}_{BS}^T \phi_1 \mathbf{h}_k \right|^2 &= \sum_{i=1}^{N} \psi_{ii} \\ &+ 2\,\mathrm{Re}\left[\sum_{i=1}^{N-1} \sum_{l=i+1}^{N} \psi_{il} e^{j(\theta_{1,i} - \theta_{1,l})} \right] \\ &+ 2\,\mathrm{Re}\left[\sum_{i=1}^{N} \alpha_i e^{j\theta_{1,i}} \right] + \sum_{k=1}^{K} V_k g_k g_k^* \end{aligned} \tag{21}$$

The second and third terms on the right side of (21) relate to ϕ_1, and the first and fourth terms have nothing to do with ϕ_1. Therefore, the optimisation problem in (16) can be transformed into

$$\begin{aligned} &\max_{\phi_1} 2\,\mathrm{Re}\left[\sum_{i=1}^{N-1} \sum_{l=i+1}^{N} \psi_{il} e^{j(\theta_{1,i} - \theta_{1,l})} \right] + 2\,\mathrm{Re}\left[\sum_{i=1}^{N} \alpha_i e^{j\theta_{1,i}} \right] \\ &s.t. \quad \theta_{1,n} \in \Delta, n = 1,2,\cdots,N \end{aligned} \tag{22}$$

The optimisation objective function in (22) consists of two items, namely

$$2\,\mathrm{Re}\left[\sum_{i=1}^{N-1} \sum_{l=i+1}^{N} \psi_{il} e^{j(\theta_{1,i} - \theta_{1,l})} \right]$$

and

$$2\,\mathrm{Re}\left[\sum_{i=1}^{N}\alpha_i e^{j\theta_{1,i}}\right].$$

When $\theta_{1,l}-\theta_{1,i}=\angle\psi_{il}$, that is

$$\theta_{1,l}=\theta_{1,1}+\angle\psi_{1l},\ 2\,\mathrm{Re}\left[\sum_{i=1}^{N-1}\sum_{l=i+1}^{N}\psi_{il}e^{j(\theta_{1,i}-\theta_{1,l})}\right]$$

reaches its maximum, where $\angle\psi_{il}$ is phase angle of ψ_{il} for $l=2,3,\cdots,N$. Then, the optimisation problem in (22) can be transformed into

$$\max_{\theta_{1,1}} 2\,\mathrm{Re}\left[\alpha_1 e^{j\theta_{1,1}}+\sum_{i=2}^{N}\alpha_i e^{j(\theta_{1,1}+\angle\psi_{1i})}\right] \quad (23)$$
$$s.t.\quad \theta_{1,1}\in\Delta$$

The optimisation problem in (23) contains only one variable, thus the multi-variables optimisation problem is transformed into that with single-variable.

3.4 Solving the phase shift optimisation problem

In this sub-section, the procedure of solving the phase shift optimisation problem is given. We use $W(\theta_{1,1})$ to denote the objective function in (23), then $W(\theta_{1,1})$ can be expressed as

$$W(\theta_{1,1})=2\,\mathrm{Re}\left[\alpha_1 e^{j\theta_{1,1}}+\sum_{i=2}^{N}\alpha_i e^{j(\theta_{1,1}+\angle\psi_{1i})}\right] \quad (24)$$

When $\theta_{1,1}\in[0,2\pi]$, $W(\theta_{1,1})$ is a continuous function of $\theta_{1,1}$. Extreme values occur at boundary points (that is $\theta_{1,1}=0$) or points where the derivative is zero. Let the first derivative of $W(\theta_{1,1})$ with respect to $\theta_{1,1}$ be equal to zero, that is

$$\frac{d\left(W(\theta_{1,1})\right)}{d\theta_{1,1}}=\frac{d\left(2\,\mathrm{Re}\left[\alpha_1 e^{j\theta_{1,1}}+\sum_{i=2}^{N}\alpha_i e^{j(\theta_{1,1}+\angle\psi_{1i})}\right]\right)}{d\theta_{1,1}}=0 \quad (25)$$

where $\frac{d\left(W(\theta_{1,1})\right)}{d\theta_{1,1}}$ is the first derivative of $W(\theta_{1,1})$ with respect to $\theta_{1,1}$.

Let Ω_1 be an empty set and solve the equation as presented in (25). If there are solutions to (25), we put the solutions within the range of 0 to 2π into the set Ω_1. We denote the cardinality of the set Ω_1 as $|\Omega_1|$. We use $\bar{\theta}_{1,1}$ to denote the element of $\{\Omega_1, 0\}$ corresponding to

$$\max\left\{W(f_1),W(f_2),\cdots,W\left(f_{|\Omega_1|+1}\right)\right\},$$

where $f_1, f_2,\ldots, f_{|\Omega_1|+1}$ represent the elements of the set $\{\Omega_1, 0\}$ in turn, then the element closest to $\bar{\theta}_{1,1}$ in Δ is the optimal solution to the optimisation problem in (23) and the solution to the optimisation problem in (16) can be further obtained.

To sum up, with given $\boldsymbol{\phi}_0$, the method of solving IRS phase shift matrix $\boldsymbol{\phi}_1$ consists of the following six steps, denoted as Algorithm 1.

Algorithm 1 Algorithm for solving IRS phase shift matrix $\boldsymbol{\phi}_1$

1 Initial $\boldsymbol{\phi}_1$
2 Let Ω_1 be an empty set.
3 Let the first derivative of $W(\theta_{1,1})$ with respect to $\theta_{1,1}$ equal to zero to obtain (25);
4 Solve the equation in (25) and put the solutions within the range of 0 to 2π into the set Ω_1.
5 use $\bar{\theta}_{1,1}$ to denote the element of $\{\Omega_1, 0\}$ corresponding to $\max\left\{W(f_1),W(f_2),\cdots,W\left(f_{|\Omega_1|+1}\right)\right\}$, then the element closest to $\bar{\theta}_{1,1}$ in Δ is the optimal solution to the optimisation problem in (23), denoted as $\tilde{\theta}_{1,1}$.
6 Let $\tilde{\theta}_{1,l}=\tilde{\theta}_{1,1}+\angle\psi_{1l}$, $l=2,3,\ldots,N$, $\tilde{\theta}_{1,1}$ in step 5 and $\tilde{\theta}_{1,l}$ in this step are the solution to the optimisation problem in (16).

The solution of $\boldsymbol{\phi}_1$ is given when $\boldsymbol{\phi}_0$ is known. Similarly, in the case of known $\boldsymbol{\phi}_1$, the method of solving the optimisation problem in (17) is as follows, denoted as Algorithm 2.

Algorithm 2 Algorithm for solving IRS phase shift matrix $\boldsymbol{\phi}_0$

1 Initial $\boldsymbol{\phi}_1$.
2 Let Ω_2 be an empty set.
3 Let the function
$$Z(\theta_{0,1})=2\,\mathrm{Re}\left[\beta_1 e^{j\theta_{0,1}}+\sum_{i=2}^{N}\beta_i e^{j(\theta_{0,1}+\angle\chi_{1i})}\right]$$
where β_i represents the i^{th} element of $\boldsymbol{\beta}$, $i=1,2,\ldots,N$, $\boldsymbol{\beta}=\sum_{k=1}^{K}M_k p_{d,k}{}^{*}\mathbf{u}_k$, $\mathbf{u}_k=diag(\boldsymbol{a}_0)\boldsymbol{p}_{r,k}$, $\angle\chi_{1i}$ represents the phase angle of χ_{1i}, χ_{1i} is the element of row 1 and column i of $\sum_{k=1}^{K}M_k\mathbf{u}_k\mathbf{u}_k{}^{H}$, let the first derivative of $Z(\theta_{0,1})$ with respect to $\theta_{0,1}$ be equal to zero to obtain $\frac{d\left(Z(\theta_{0,1})\right)}{d\theta_{0,1}}=0.$
4 Solve the equation $\frac{d\left(Z(\theta_{0,1})\right)}{d\theta_{0,1}}=0$ and put the solutions within the range of 0 to 2π into the set Ω_2.
5 use $z_1, z_2,\ldots, z_{|\Omega_2|+1}$ to represent the elements of the set $\{\Omega_2, 0\}$, and find the elements of the set $\{\Omega_2, 0\}$ corresponding to $\max\left\{Z(z_1),Z(z_2),\cdots,Z\left(z_{|\Omega_2|+1}\right)\right\}$, represented by $\bar{\theta}_{0,1}$. Let $\tilde{\theta}_{0,1}$ denote the element closest to $\tilde{\theta}_{0,1}$ in Δ.
6 Let $\tilde{\theta}_{0,l}=\tilde{\theta}_{0,1}+\angle\chi_{1l}$, $l=2,3,\ldots,N$, $\tilde{\theta}_{0,1}$ in step 5 and $\tilde{\theta}_{0,l}$ in this step are the solution to the optimisation problem in (17).

The solution to the optimisation problems in (16) and (17) is given above. As mentioned above, the solution of the optimisation problem in (15) is as follows: first assign initial value to $\boldsymbol{\phi}_0$, then solve $\boldsymbol{\phi}_1$ when $\boldsymbol{\phi}_0$ is known, then solve $\boldsymbol{\phi}_0$ when $\boldsymbol{\phi}_1$ is known, and repeat the process, until $\boldsymbol{\phi}_0$ and $\boldsymbol{\phi}_1$ converge. Therefore, the alternate optimisation algorithm for solving the optimisation problem in (15) consists of the following four steps.

Algorithm 3 Alternating optimisation algorithm for problem in (15)

1. Set initial value for IRS phase shift during WET to zero, let $q = 0$ and $\theta_{0,i}^{q} = 0$ for $i = 1,2,\ldots,N$;
2. If $q = 0$, let the value of $\boldsymbol{\phi}_0$ in (16) be the initial value, otherwise, let the value of $\boldsymbol{\phi}_0$ in (16) be the latest optimal solution. Employ Algorithm 1 to solve the optimisation in (16) to get the optimal solution, and assign the optimal solution to $\theta_{1,i}^{q}$, $i = 1,2,\ldots,N$.
3. Let $q = q + 1$, and let the value of $\boldsymbol{\phi}_1$ in (17) be the latest optimal solution. Employ Algorithm 2 to solve the optimisation problem in (17) to obtain the optimal solution, and assign the optimal solution to $\theta_{0,i}^{q}$, $i = 1,2,\ldots,N$.
4. Repeat steps 2 to 3 until $\left|\theta_{0,i}^{q} - \theta_{0,i}^{q-1}\right| < \varepsilon$ and $\left|\theta_{1,i}^{q} - \theta_{1,i}^{q-1}\right| < \varepsilon$, $i = 1,2,\ldots,N$, the preset threshold ε is a positive number.

In this alternating optimisation algorithm, q represents the number of iterations. In step 1, $q = 0$ means that the iteration has not started yet. In steps 2 to 4, assign the phase shift calculated in the q^{th} iteration to $\theta_{0,i}^{q}$ and $\theta_{1,i}^{q}$, $i = 1,2,\ldots,N$. $\theta_{0,i}^{q}$ and $\theta_{1,i}^{q}$ for $i = 1,2,\ldots,N$ at the end of step 4 are the solutions to the optimisation problem in (15).

Although the existing schemes for this scenario also alternately optimise the IRS phase shift in WET process and the IRS phase shift in WIT process, the proposed scheme is different from the existing schemes. The reason is that, the proposed scheme solves single-variable optimisation problem in the process of alternating optimisation, while the existing schemes solve multi-variables optimisation problem in this process.

3.5 Construction and solution of time optimisation problem

When IRS phase shift is known, the optimisation problem in (14) can be equivalently expressed as

$$\min_{\tau_0} \max \left\{ \frac{\left(1-\tau_0\right)\left(2^{e_k/(1-\tau_0)}-1\right) \prod_{m=k+1}^{K}\left(\left(2^{e_k/(1-\tau_0)}-1\right)+1\right)\sigma^2}{\eta\tau_0 c_k}, \; k = 1,2,\cdots,K \right\} \tag{26}$$

$$s.t \quad \tau_0 \in (0,1)$$

where

$$c_k = \left|g_k + \mathbf{h}_{BS}^{T}\boldsymbol{\phi}_1\mathbf{h}_k\right|^2 \left|p_{d,k} + \boldsymbol{a}_0^{T}\boldsymbol{\phi}_0\boldsymbol{p}_{r,k}\right|^2, \; k = 1,2,\ldots,K.$$

c_k is a constant when IRS phase shift is known. Next, the method to solve the optimisation problem in (26) is given. Let

$$\Gamma_k\left(\tau_0\right) = \frac{\left(1-\tau_0\right)\left(2^{e_k/(1-\tau_0)}-1\right)\prod_{m=k+1}^{K}\left(\left(2^{e_m/(1-\tau_0)}-1\right)+1\right)\sigma^2}{\eta\tau_0 c_k},$$

$$k = 1,2,\cdots,K.$$

When $\tau_0 \in (0,1)$, $\Gamma_k(\tau_0)$ is a continuous function of τ_0. The extreme values occur at the points where the derivative is zero.

In summary, when IRS phase shift is known, the step of solving τ_0 is as follows.

Algorithm 4 Algorithm to solve τ_0

1. Initial $\boldsymbol{\phi}_0$ and $\boldsymbol{\phi}_1$.
2. Let Λ_k be an empty set for $k = 1,2,\ldots,K$.
3. Let the first derivative of $\Gamma_k(\tau_0)$ with respect to τ_0 be equal to zero, and put the solution to $\frac{d\Gamma_k\left(\tau_0\right)}{d\tau_0} = 0$ within the range of 0 and 1 into the set Λ_k, $k = 1,2,\ldots,K$.
4. Use $|\Lambda_k|$ to represent the cardinality of the set Λ_k, and use $\lambda_{k1}, \lambda_{k2}, \cdots\cdots, \lambda_{k|\Lambda_k|}$ to represent the elements of the set Λ_k in turn for $k = 1,2,\ldots,K$.
5. Find the element of $\left\{\Lambda_k, k = 1,2,\cdots,K\right\}$ corresponding to $\min\max\left\{\Gamma_k\left(\lambda_{k1}\right), \Gamma_k\left(\lambda_{k2}\right), \cdots, \Gamma_k\left(\lambda_{k|\Lambda|}\right), k = 1,2,\cdots,K\right\}$, which is the optimal solution to the optimisation problem in (26).

4 Analysis of simulation results

This section simulates the minimum power required to meet the rate requirements by the proposed scheme, the schemes in Yeong et al. (2021) and Li et al. (2022b), powered IRS-assisted NOMA scheme with random phase shift and powered IRS-assisted NOMA scheme with average time (these two schemes are called random phase shift scheme and average time scheme respectively in this sub-section). The IRS phase shift in the random phase shift scheme is generated randomly, and the time allocation is optimised by the proposed scheme. The average time scheme has the same WET time and WIT time, and the IRS phase shift is optimised using the proposed scheme. For these simulations, parameters are set as follows: energy receiving conversion efficiency is 0.8, the noise power density at the power station is –80 dBm, and the noise power density at the users is –120 dBm. The channels from the power station to IRS, the channel from IRS to user k, the channel from user k to IRS and the channel from IRS to AP are respectively defined as

$$\boldsymbol{a}_0 = \sqrt{\frac{\tilde{K}}{\tilde{K}+1}}\boldsymbol{a}_0{}^{LoS} + \sqrt{\frac{1}{\tilde{K}+1}}\boldsymbol{a}_0{}^{NLoS},$$

$$\boldsymbol{p}_{r,k} = \sqrt{\frac{\tilde{K}}{\tilde{K}+1}}\boldsymbol{p}_{r,k}{}^{LoS} + \sqrt{\frac{1}{\tilde{K}+1}}\boldsymbol{p}_{r,k}{}^{NLoS},$$

$$\mathbf{h}_k = \boldsymbol{p}_{r,k}^T,$$

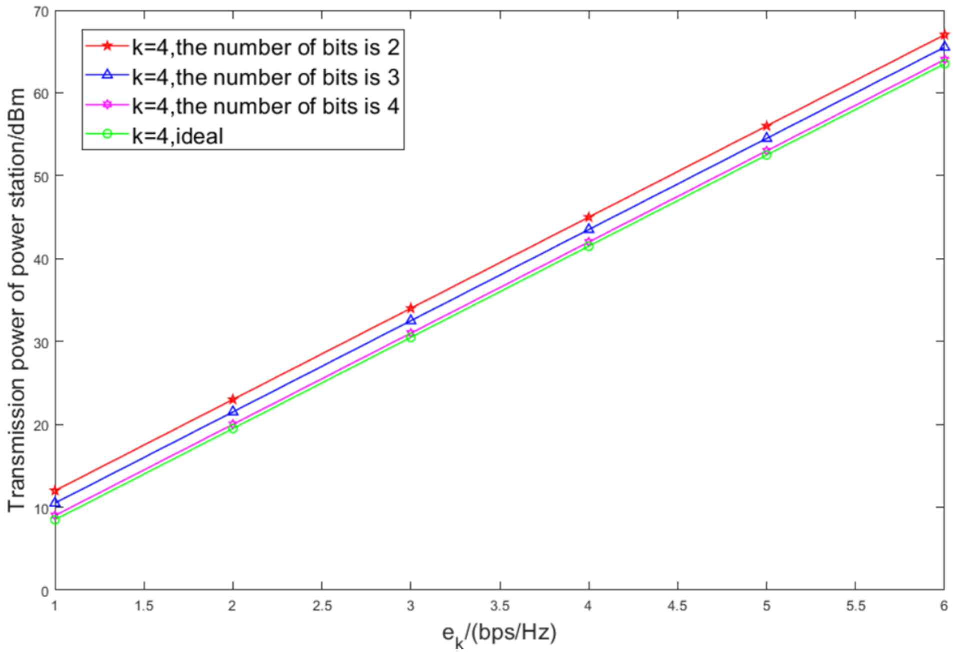
$$\mathbf{h}_{BS} = \sqrt{\frac{\tilde{K}}{\tilde{K}+1}}\mathbf{h}_{BS}^{LoS} + \sqrt{\frac{1}{\tilde{K}+1}}\mathbf{h}_{BS}^{NLoS},$$

where $\boldsymbol{a}_0{}^{LoS}$, $\boldsymbol{p}_{r,k}{}^{LoS}$ and $\mathbf{h}_{BS}^{LoS}$ are the line of sight deterministic component corresponding to the channel coefficient, $\boldsymbol{a}_0{}^{NLoS}$, $\boldsymbol{p}_{r,k}{}^{NLoS}$ and $\mathbf{h}_{BS}^{NLoS}$ are non-line of sight components of Rayleigh fading, $\tilde{K}$ is Rice coefficient, $\tilde{K} = 5$ dB. The path loss parameters between the power station and IRS, IRS and AP, power station and user k, user k and AP, IRS and user k are 2.2, 2.2, 3.6, 3.6 and 2.6 respectively.

Figure 2 plots the minimum power required by the proposed scheme with changing ζ, where ζ is the number of bits required by the IRS phase shift in binary, $N = 32$. The horizontal coordinate in Figure 2 represents the minimum throughput required by the user per unit time, and 'ideal' represents the ideal situation where IRS phase shifts are not quantified. As can be seen from Figure 2, when the other parameters are the same, the higher the minimum throughput required by the users per unit time, the higher the minimum power required by the system, and the minimum power required decreases with the increase of ζ. The minimum power required at $\zeta = 4$ is almost the same as ideal and slightly lower than at $\zeta = 2$. It also can be seen that the power in Figure 2(b) is higher than that in Figure 2(a). The reason is that while other conditions remain unchanged, the more users, the higher the required power.

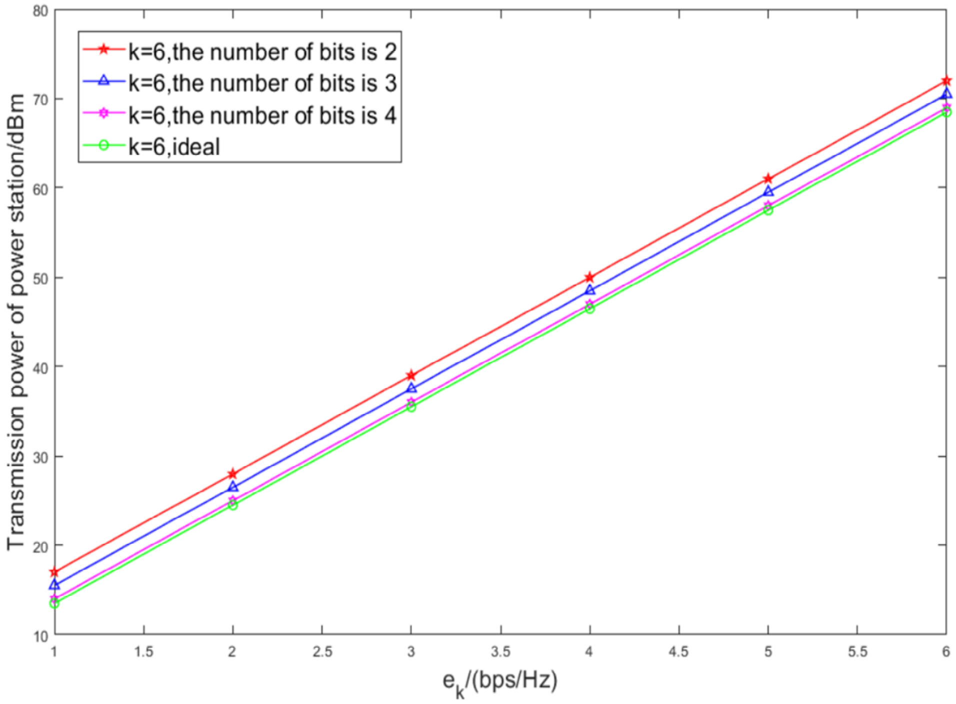
Figure 3 depicts the power required by these five schemes for $N = 32$, where $K = 4$ in Figure 3(a) and $K = 6$ in Figure 3(b). The horizontal coordinate in Figure 3 represents the minimum throughput required by the users per unit time. As can be seen from Figure 3, the power required by each scheme increases with the increase of e_k, and the power required by the proposed scheme is significantly lower than that of the other four schemes. The goal of Yeong et al. (2021) and Li et al. (2022b) is to maximise the system sum rate, and the goal of the proposed scheme is to minimise power, so the power required by the proposed scheme is lower than that required by Yeong et al. (2021) and Li et al. (2022b). The random phase shift scheme only optimises the time, and the average time scheme only optimises the IRS phase shift, so the power required by these two schemes is higher than that of the first three schemes. It can also be seen from Figure 3 that the power required by average time scheme is much lower than that required by random phase shift scheme. This is because, under other conditions, the most important factor affecting the system performance is the channel. The average time scheme optimises the phase shift, which means that the IRS phase shift can change the equivalent channel, leading to enhanced channel gain. A comparison of Figure 3(a) and Figure 3(b) shows that the power required by all five schemes at $K = 6$ is higher than that at $K = 4$. This is because the more users there are, the higher the power required to provide the rate requirements for the users.

Figure 2 The total power required by the system with changing ζ, (a) the total power with changing ζ and $k = 4$ (b) the total power with changing ζ and $k = 6$ (see online version for colours)



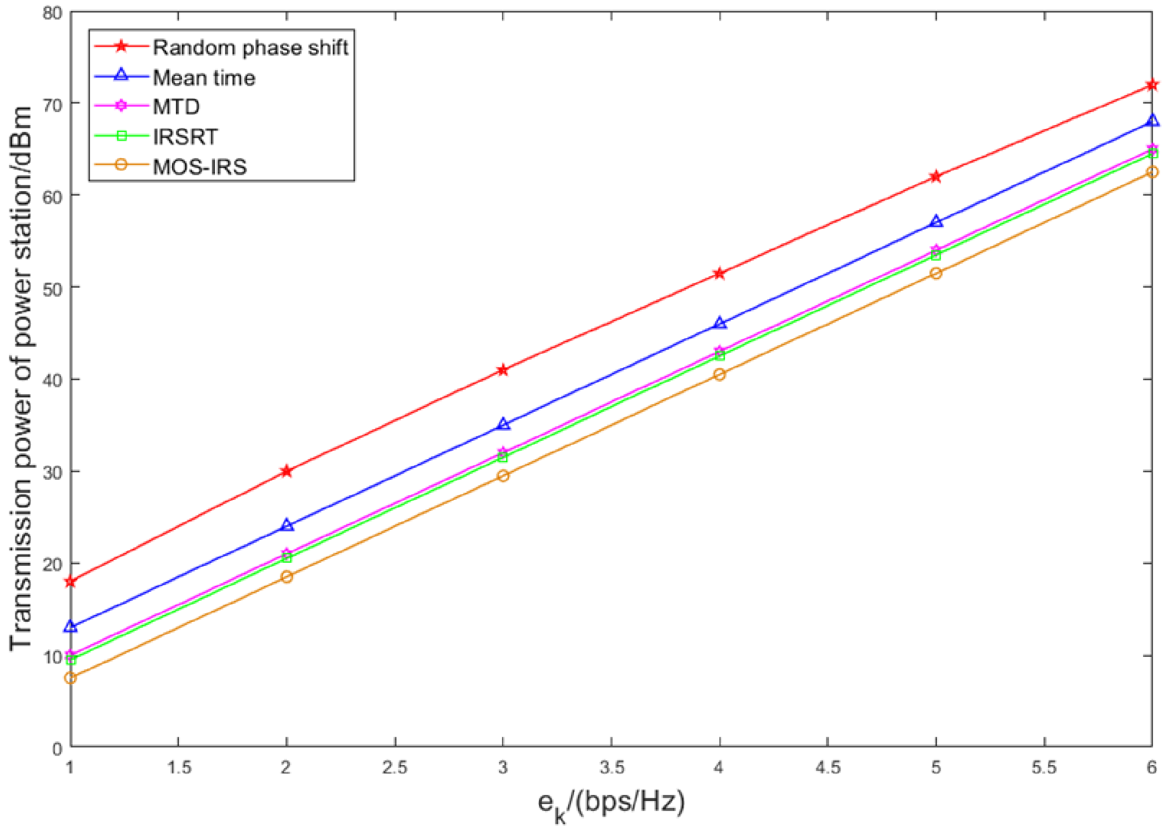
(a)

Figure 2 The total power required by the system with changing ζ, (a) the total power with changing ζ and $k = 4$ (b) the total power with changing ζ and $k = 6$ (continued) (see online version for colours)



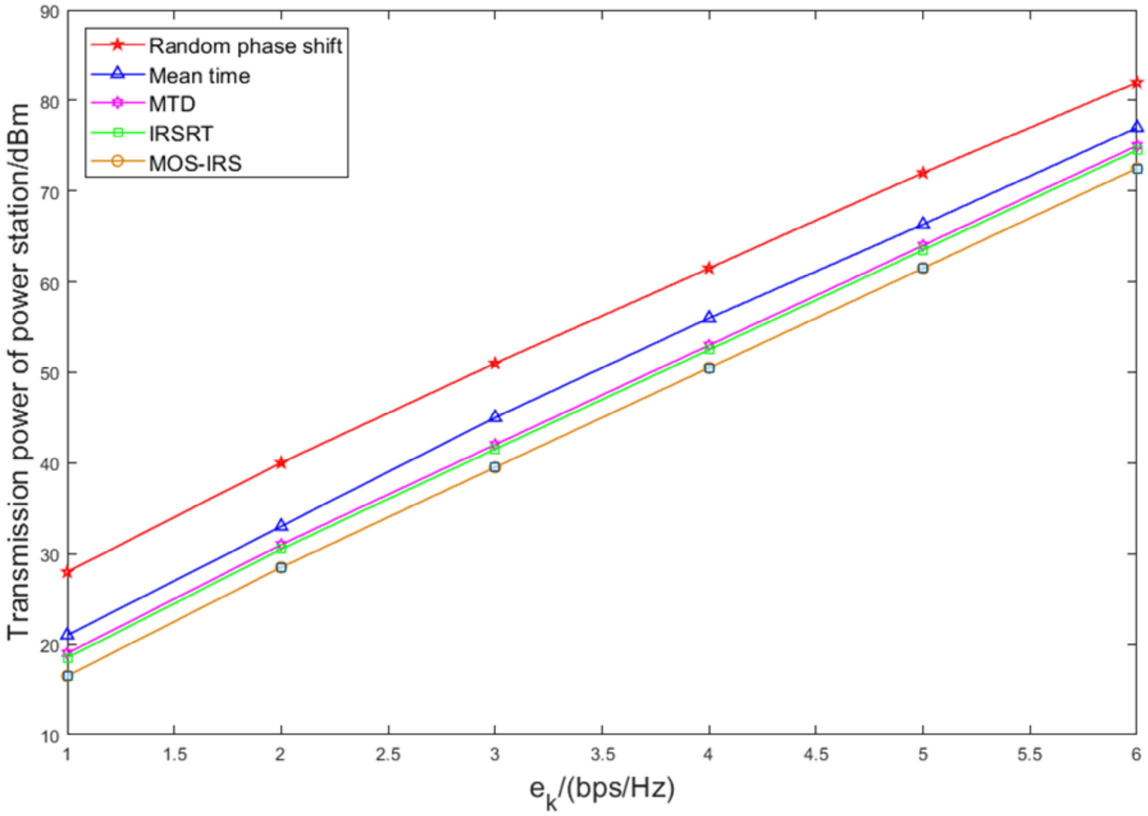
(b)

Figure 3 The total power of the five schemes for $N = 32$, (a) the five schemes power for $K = 4$ and $N = 32$ (b) the five schemes power for $K = 6$ and $N = 32$ (c) the five schemes power for $K = 8$ and $N = 32$ (see online version for colours)

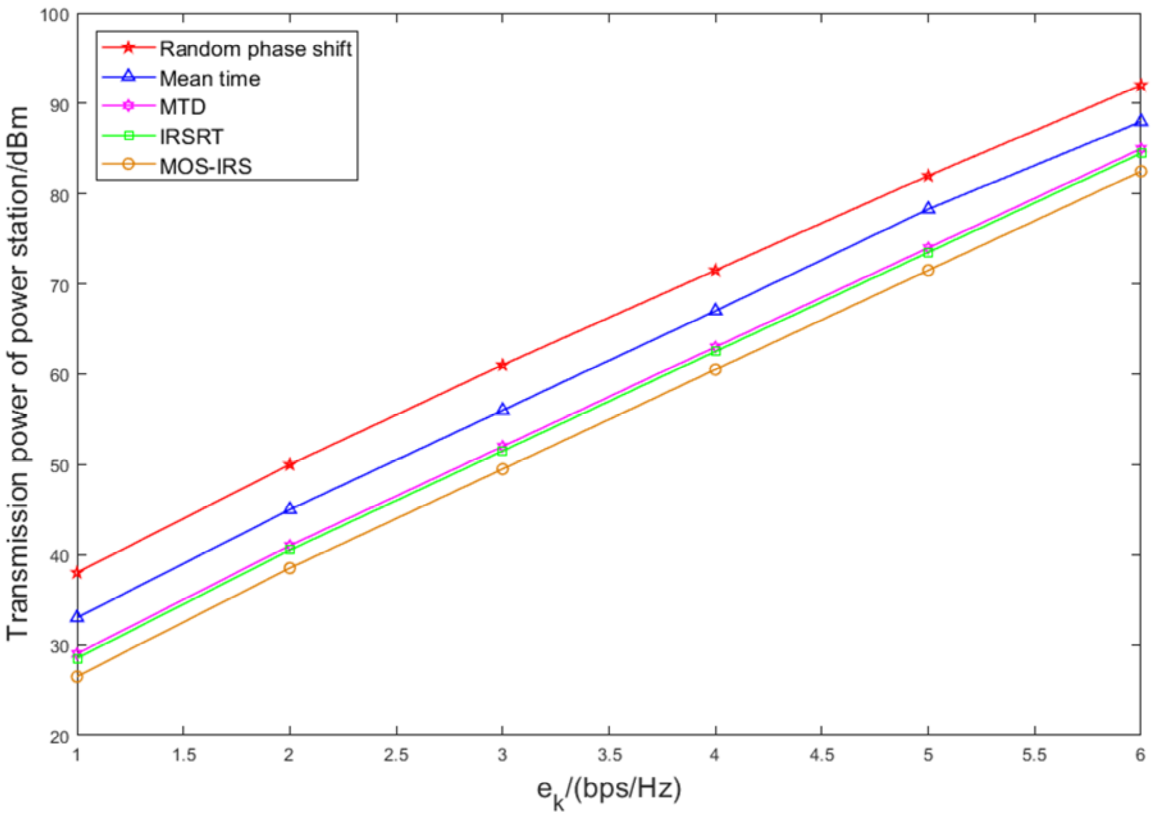


(a)

Figure 3 The total power of the five schemes for $N = 32$, (a) the five schemes power for $K = 4$ and $N = 32$ (b) the five schemes power for $K = 6$ and $N = 32$ (c) the five schemes power for $K = 8$ and $N = 32$ (continued) (see online version for colours)

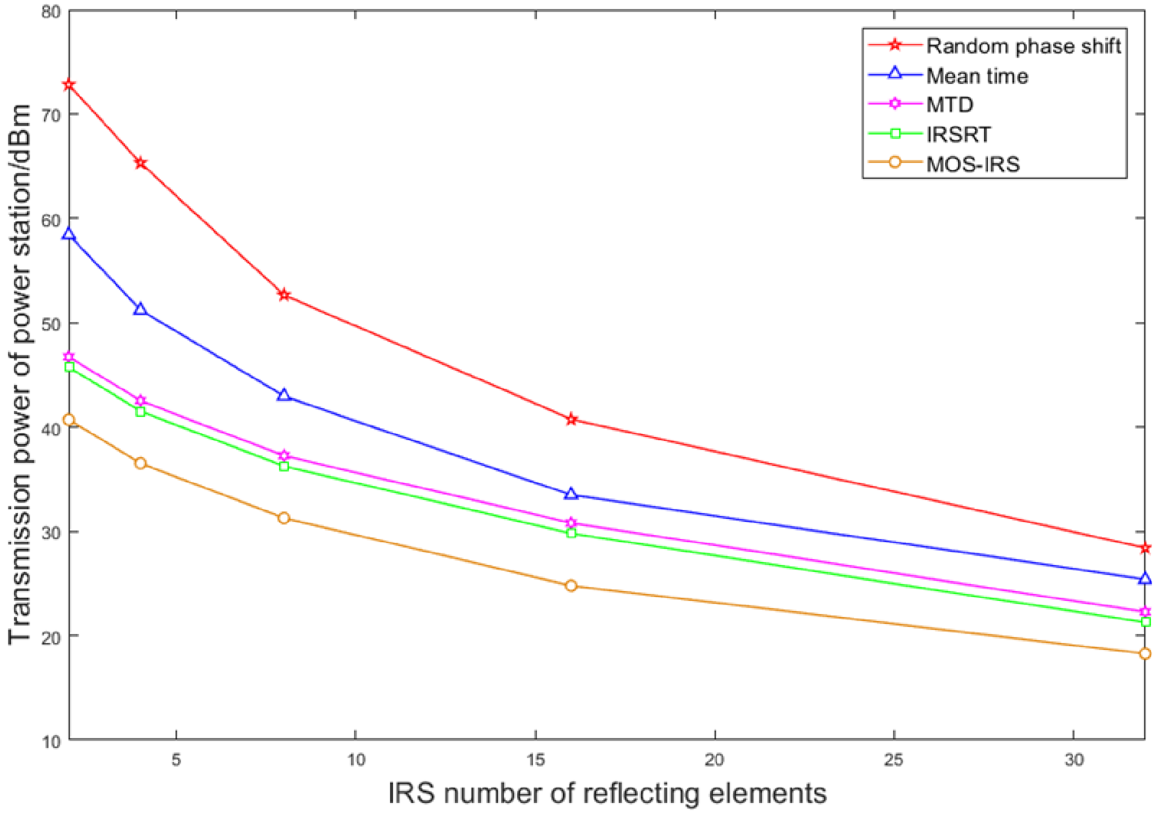


(b)

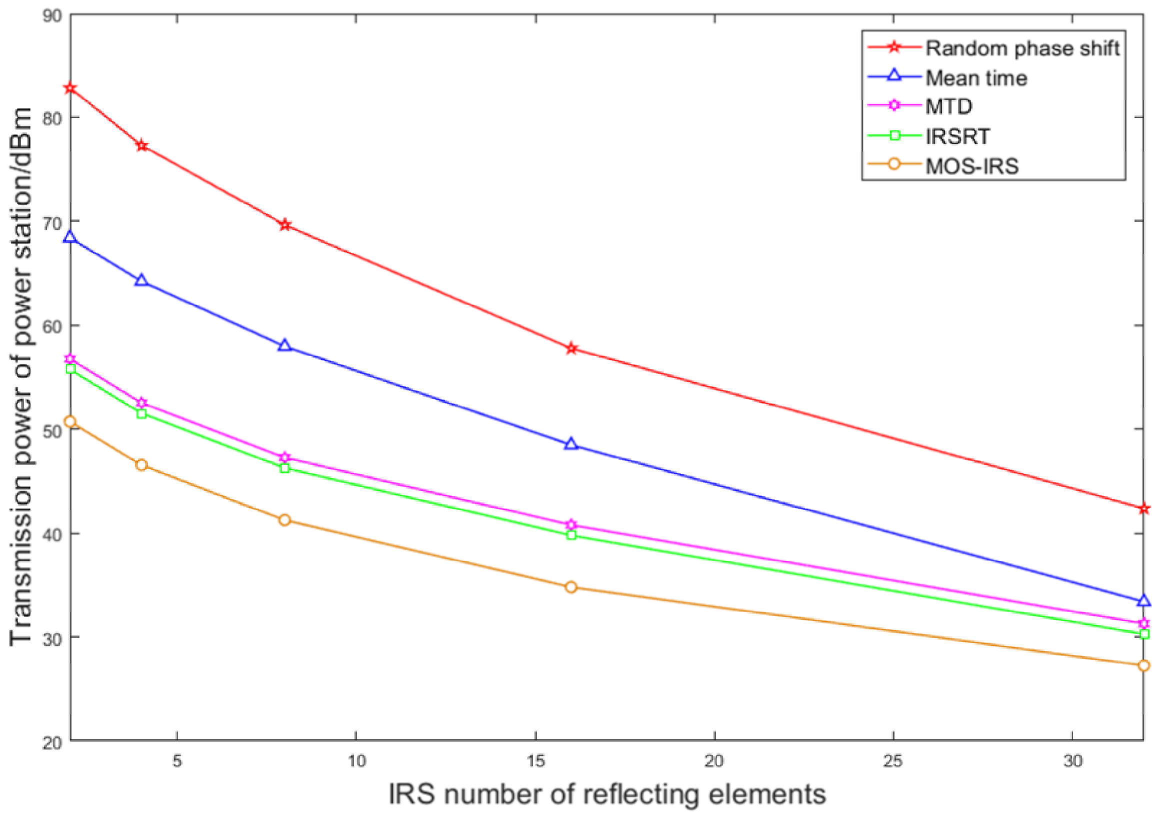


(c)

Figure 4 The total power of the five schemes for $K = 6$, (a) the five schemes power for $K = 6$ and $e_k = 1$ bps/Hz (b) the five schemes power for $K = 6$ and $e_k = 6$ bps/Hz (see online version for colours)

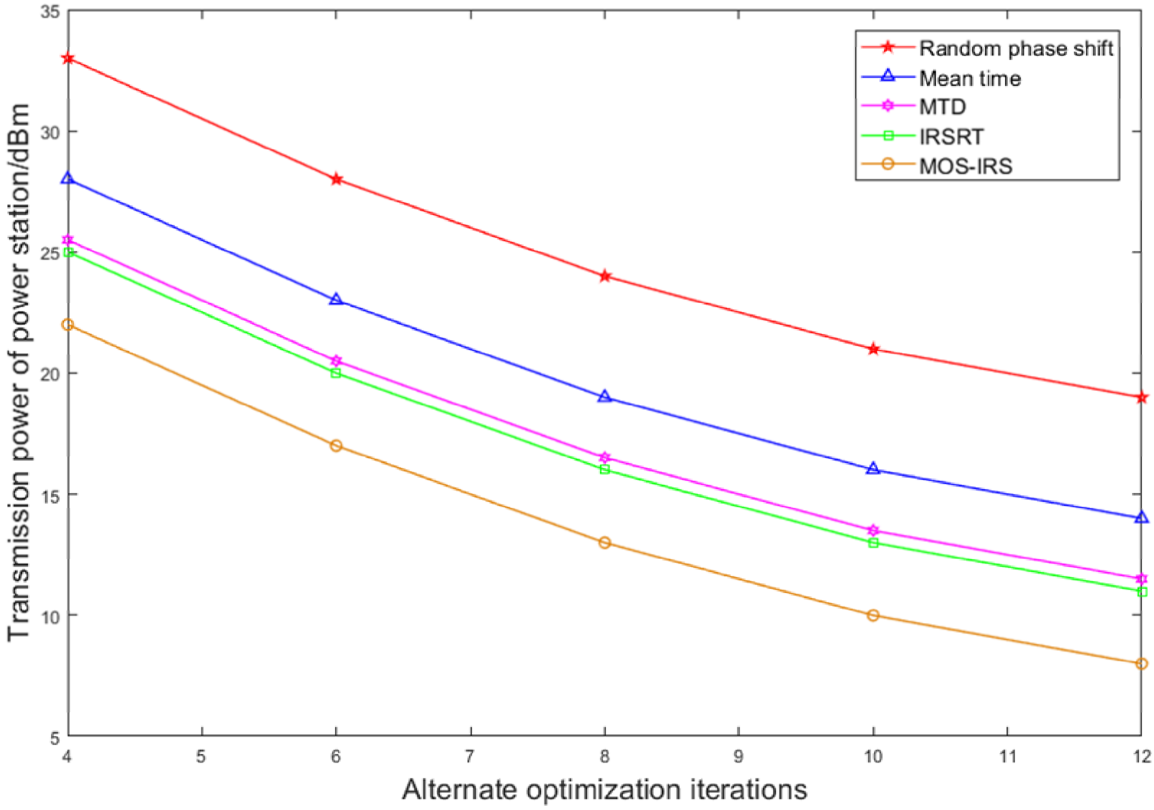


(a)

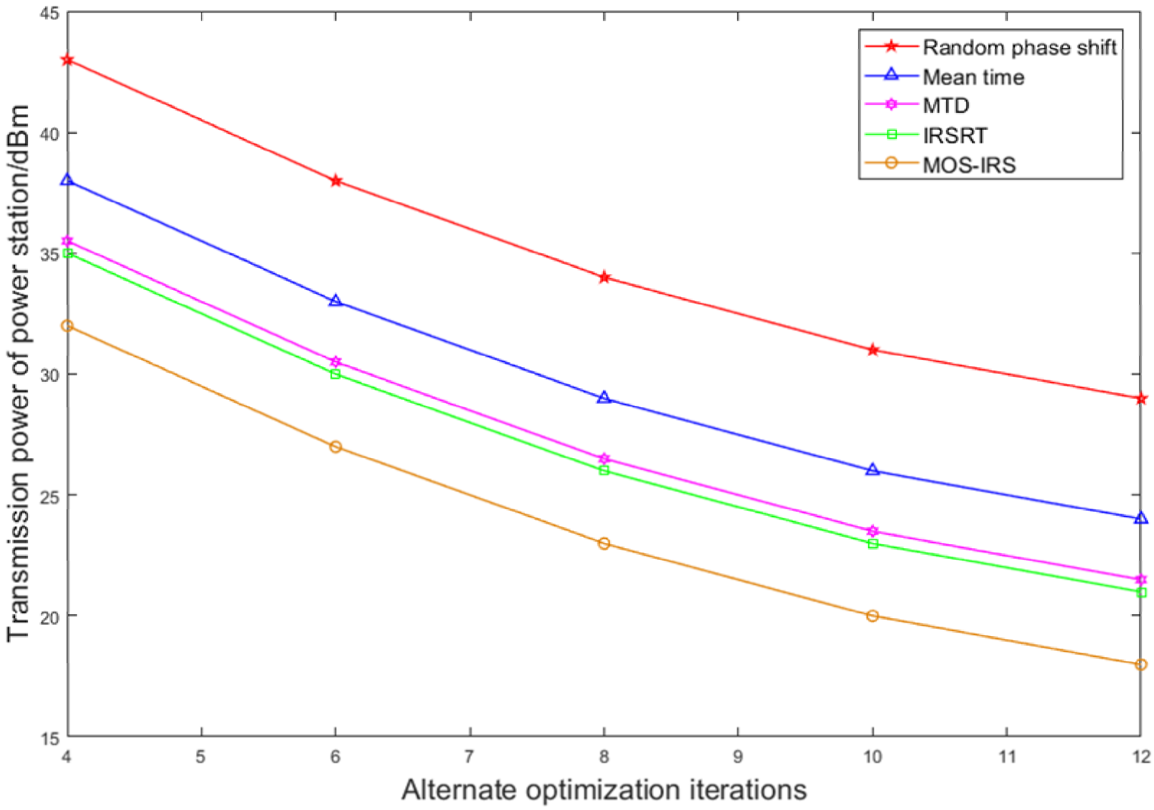


(b)

Figure 5 The effect of alternating optimisation iterations on the required power for $e_k = 1$ bps/Hz, (a) Alternating optimisation iterations for $K = 4$ and $e_k = 1$ bps/Hz (b) alternating optimisation iterations for $K = 6$ and $e_k = 1$ bps/Hz (see online version for colours)



(a)



(b)

Figure 4(a) simulates the power required by these five schemes, where $K = 6$ and $e_k = 1$ bps/Hz in Figure 4(a), and $K = 6$ and $e_k = 6$ bps/Hz in Figure 4(b). The horizontal coordinate in Figure 4 is the number of IRS reflection elements. As can be seen from Figure 4, the power required by the proposed scheme is significantly lower than that of the other four schemes, and the power required by each scheme decreases as the number of IRS reflection elements increases. This is because the more reflection elements the IRS has, the more parameters it has to adjust the equivalent channel of the signal, thus increasing the equivalent channel gain and thus reducing the power required. It also can be seen from Figure 4 that the power requirement of the average time scheme is much lower than that of the random phase shift scheme. This shows that the influence of phase shift on system performance is higher than that of time allocation. A comparison of Figure 4(a) and Figure 4(b), the power required by each of the five schemes for $e_k = 6$ bps/Hz is higher than that for $e_k = 1$ bps/Hz. This is because the higher the users' rate requirements, the higher the power required.

Figure 5 simulates the effect of alternating optimisation iterations on the required power of the system, where e_k=1 bps/Hz and $N = 32$, $K = 4$ in Figure 5(a), and $K = 6$ in Figure 5(b). The horizontal coordinate is the number of iterations for alternating optimisation. From Fig. 5, it can be seen that as the number of iterations increases, the power required by the system first decreases rapidly, and then the speed of reduction slows down. This is because as the number of iterations increases, the alternating optimisation tends to converge, so the speed of required power reduction slows down.

5 Conclusions

In this paper, the method of MOS-IRS-assisted NOMA is proposed, and the optimisation problem of minimising power is constructed. Different from the existing optimisation methods for the same scenario, the proposed scheme transforms the multi-variables phase-shift optimisation problem into that with single-variable. Then, we present an algorithm for solving phase shift in WIT (WET) with given phase shift in WET (WIT), based on which, the IRS phase shift in WET process and the IRS phase shift in WIT process are alternately optimised. Furthermore, the optimal time allocation is obtained by using the function extremum method. Simulation results demonstrate that the power required by the proposed scheme is lower than that required by the other schemes within the same scenario. However, it's important to note that the proposed resource allocation scheme assumes the absence of channel estimation errors and hardware impairments. In practical systems, these factors are inevitable. Therefore, future research will explore the impact of channel estimation errors and hardware impairments on the performance of the IRS auxiliary power supply NOMA system.

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