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An advanced fractal optimisation method for network energy and power based on cellular massive MIMO based on photovoltaic technology

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Abstract: User communication needs drive the wide application of cell-free massive MIMO systems. Network energy consumption significantly affects communication quality and efficiency. Photovoltaic systems provide real-time electricity, dynamically adjusting MIMO parameters based on output changes to ensure stable operation. This article aims to enhance user experience and optimise energy distribution in communication systems. It constructs a basic system model, defines network signal power optimisation, applies photovoltaic technology for sustainable energy supply, and solves the optimisation problem using PSO. Simulations compare pre- and post-optimisation effects, revealing a

20.24% energy efficiency improvement in photovoltaic-based communication systems with 100 access points. The proposed method enhances communication efficiency and optimises energy distribution in networks.

Keywords: network signal power optimisation; cell-free massive multiple-input multiple-output; photovoltaic technology; network energy; communication systems.

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1 Introduction

Rapid user growth and the quick development of mobile communication technologies have led to an increasingly severe conflict between the unequal use of resources and energy conversion (Abdulkhaleq et al., 2019). Cell-free (CF) massive MIMO systems’ large data and signal processing capacities have a substantial impact on the system’s computational load as well as its stability (Gao et al., 2019; Jiang et al., 2022). Communication equipment has low energy efficiency in high-speed and high-density data transmission, leading to energy waste and increased operating costs. Various

interferences and attacks in communication networks lead to a decrease in communication connectivity, affecting user experience and the reliability of data transmission. In wireless communication, researching the effective energy and power optimisation of massive MIMO systems is crucial. Photovoltaic power generating systems provide unique benefits in terms of energy consumption and utilisation when compared to traditional energy sources. By using it with MIMO systems, real-time communication system needs may be satisfied while network power and energy are optimised. This is essential for facilitating the health of communication networks and enabling power consumption optimisation. This article aims to explore how to effectively integrate photovoltaic technology into large-scale MIMO networks, optimise energy management and power consumption control strategies, and improve the energy efficiency performance of the network. Driven by photovoltaic technology, the energy consumption of the network can be significantly reduced, the economic benefits of the network can be improved, and the overall energy efficiency performance can be enhanced.

To improve the energy efficiency of communication networks, and enhance the stability and quality of user communication, this article combined photovoltaic technology to study the optimisation method of network signal power for CF massive MIMO. A system simulation test experimental scenario was constructed, and simulation analysis was carried out from three aspects: energy efficiency, signal coverage range, and data transmission rate. In terms of energy efficiency, compared to before optimisation, after system optimisation, the energy efficiency (EE) increased by about 20.24% when the number of APs was 100, and it also showed good energy efficiency under different output powers; at the level of signal coverage, the average coverage range of downlink and uplink signals optimised based on photovoltaic technology in different user density scenarios increased by 6.05% and 2.85%, respectively, compared to the results before optimisation; in terms of data transmission rate, the average data transmission rate of the system optimised based on photovoltaic technology increased by 8.05 megabits per second (Mbps) compared to before optimisation. The innovation of this article lies in applying photovoltaic technology to large-scale MIMO networks, utilising solar energy for energy supply, realising the utilisation of green energy, reducing network energy consumption and environmental impact, ensuring stable communication quality of the network, and avoiding energy waste. In practical applications, photovoltaic technology can effectively optimise the network signal power of CF massive MIMO, improving communication efficiency and quality.

This article optimises traditional communication networks by utilising renewable energy, which not only solves the problem of energy efficiency but also enhances the reliability and user satisfaction of the system, reflecting the concept of green communication and providing a new idea and direction for the future development of wireless communication networks. The research contribution of this article is as follows:

- 1 Integrating renewable energy and advanced communication technology: this article combines photovoltaic technology with MIMO networks, not only utilising solar energy as a clean and renewable energy source but also leveraging the advantages of large-scale MIMO technology in improving spectral efficiency and signal quality.
- 2 Construction of energy power optimisation model: this article constructs an energy power optimisation model that comprehensively considers the characteristics of photovoltaic power generation and network load requirements. By introducing

dynamic power allocation algorithms, the energy utilisation efficiency in large-scale MIMO systems has been optimised.

- 3 Strengthening communication quality and stability: this article further enhances the quality and stability of communication networks through the application of photovoltaic technology and optimisation methods. Effectively ensuring the continuity and reliability of user communication, enabling the network to maintain good performance and service levels.

2 Related works

Matalatala et al. (2019) optimised the location and power level of massive MIMO-long-term evolution (LTE) base stations towards low power consumption (PC), low downlink and uplink electromagnetic exposure, and maximum user coverage. The results indicated that using 3,764 antenna base stations could achieve optimal massive MIMO networks in terms of PC, total dose, and user coverage. To achieve real-time optimisation of network signal power, Chien et al. (2020) developed a deep learning solution that used massive fading information to predict pilot power and data power. The numerical results indicated that in solving the network signal power optimisation problem of a massive MIMO system, PowerNet can generate better spectral efficiency when selecting good data labels for the training phase compared to using an initial point (Van. Khodamoradi et al. (2022) adopted a system-level joint optimisation method and proposed an efficient low-complexity alternative optimisation algorithm to iteratively solve non-convex problems at an acceptable level of computational complexity, optimising the network signal power of massive MIMO. The results showed that when the power transmission capacity of the base station was higher than 3 watts, the proposed low-complexity alternative optimisation algorithm had an energy gain of 15% higher than the equal power allocation scheme and 4% higher than the maximum minimum fairness scheme. Demir and Bjornson (2020) used a realistic nonlinear energy harvesting circuit model with coherent and incoherent transmission strategies to calculate the average gathered energy for wireless uplink information and downlink power transfer in CF massive multi-input multi-output systems. Finally, experiments showed that the proposed method could effectively solve highly coupled non-convex problems, ensuring the convergence and alternating optimisation of network signal power at each step. Pang et al. (2021) investigated the resource optimisation problem of massive (MIMO) systems with mixed energy harvesting to maximise system energy efficiency. He suggested two workable online algorithms – the timing detection system and the Markov chain method – using statistical data. A finite state Markov model is used by the Markov chain approach to forecast expected information, whereas the timing detection strategy just concentrates on resource optimisation inside the present time frame. According to the numerical findings, both online algorithms performed fairly similarly to offline techniques, suggesting that they can strike a solid balance between implementation complexity and performance. For CF massive MIMO systems, Luo et al. (2022) suggested a model-free approach to tackle the downlink maximum and minimum power control issue using feedforward neural networks and a deep deterministic policy gradient algorithm. The findings demonstrated that the suggested deep deterministic policy gradient algorithm method, when compared to conventional convex optimisation

algorithms, can successfully achieve a trade-off between performance and complexity, achieving an implementation speed that is 1,000 times faster than the optimal solution produced by conventional numerical convex optimisation solvers and approximately the same achievable user rate. This allows for the effective implementation of power control for large systems. Although existing power optimisation methods have certain regulatory capabilities for the network energy of CF massive MIMO, they lack comprehensive consideration of resource constraints, making it difficult to effectively ensure the sustainability of network signal power optimisation.

Photovoltaic technology is a clean and renewable energy technology that can convert solar energy into electricity (Jaxa-Rozen and Trutnevyte, 2021; Zhang et al., 2021). The mature development of photovoltaic technology provides more possibilities for sustainable optimisation of network signal power. To maximise the continuous optimisation of network energy, Gao et al. (2022) proposed a photovoltaic harvesting collaborative wireless energy communication energy scheduling optimisation problem. This problem jointly optimised the deployment of photovoltaic clusters, energy broadcasting power with time allocation, and data sensing size under the constraint of network energy self-sustaining needs. Given the combination of energy deployment and its strong coupling with energy scheduling, simulation results showed that the proposed photovoltaic harvesting collaborative wireless energy carrying communication energy scheduling optimisation can effectively maximise network energy efficiency and achieve self-sustainability of network energy in remote areas. Tavakkolnia et al. (2021) prepared stable organic photovoltaics by selecting a suitable combination of narrow bandgap donor polymers and non-fullerene acceptors and conducted optical wireless communication experiments in a MIMO setup composed of four laser diodes. The experimental results showed that using organic photovoltaics as data receivers and energy harvesters can enhance wireless data communication performance, optimise network energy power, and extend battery life in mobile devices. Photovoltaic technology can fully consider the resource limitations of network energy and achieve continuous optimisation of network signal power. However, most studies still have certain limitations in terms of communication efficiency.

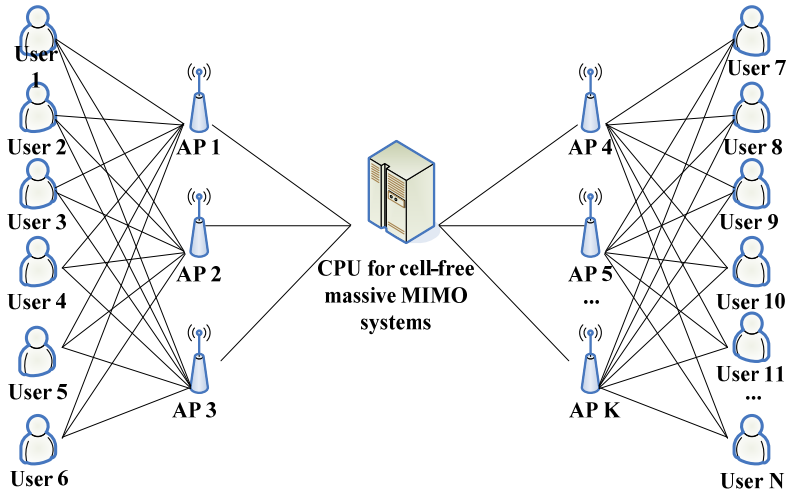
3 Network signal power optimisation for cell-free massive MIMO

3.1 *Description of system modelling and network signal power optimisation problems*

Massive MIMO is a wireless communication technology based on multi-antenna systems (Femenias et al., 2021; Wang et al., 2022a). The CF massive MIMO system is an evolutionary form of massive MIMO technology, which is a new wireless communication system that improves on the traditional base station structure.

CF massive MIMO consists of an AP equipped with multiple antennas and a central processing unit (CPU) (Zhang, 2019), and Figure 1 shows its model. This article defines its network as consisting of N users and K APs, and each AP is equipped with X antennas. In MIMO systems, there are multiple antennas used for transmitting and receiving signals, and user devices communicate with access points through three antennas. The size of the channel matrix is 3×3 .

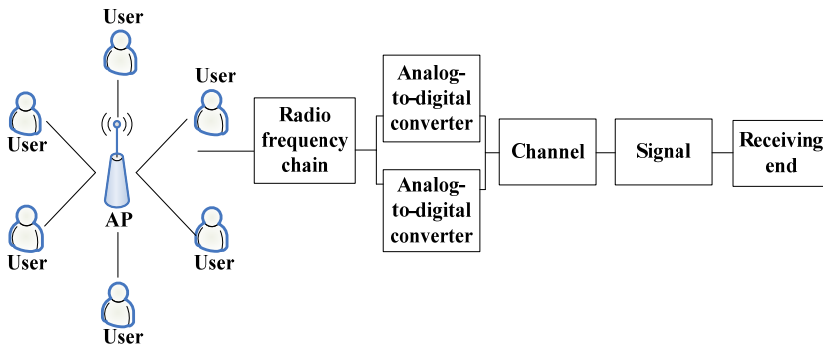
Figure 1 A basic system model of CF massive MIMO (see online version for colours)



From Figure 1, the basic system model of cellular massive MIMO mainly consists of access points (user terminals and base stations) and antenna arrays. User terminals are terminal devices in communication systems; the base station is the core of the entire communication system, responsible for managing and coordinating the communication process; the antenna array is responsible for achieving efficient signal transmission and reception.

It is assumed that the system operates in time division duplexing (TDD) mode, as shown in Figure 2.

Figure 2 TDD mode (see online version for colours)



Channel state information (CSI) is important data and parameters that describe the current situation and characteristics of a communication channel. It provides information about channel quality, transmission characteristics, interference conditions, and other aspects. Assuming that the CSI is unknown and constant during TC coherence, the base station estimates the channel using the pilot information sent by the user. To ensure that no interference factors are distorting the pilot signal during the TC coherence period, it is assumed that the inner product of the waveforms of different pilot signals in the system is

zero during the TC coherence period, and the channel estimation and synchronisation pilot sequence length are $\varsigma \geq N$. It is assumed that p_s is the power occupied by the pilot symbol, and p_t is the transmission power. It is assumed that M is the channel matrix, that is (Wang et al., 2022b; Ding et al., 2023):

$$M = FD^{1/2} \quad (1)$$

In formula (1), F is the matrix of fast fading in the wireless channel from the base station to the user end in the $X \times N$ dimension. It is assumed that the amplitude changes of signals received from different wireless channels are random and independent, that is, $F \sim \sigma\gamma$; D represents an $n \times n$ dimensional diagonal matrix. It is assumed that the diagonal element is b_i ($i = 1, 2, \dots, N$), which represents the signal attenuation of user N during long-distance propagation in wireless channels (Xue et al., 2022). By using the minimum mean square error, the channel is estimated, and the channel estimation matrix $\hat{M}$ is expressed using the formula (Liu et al., 2024):

$$\hat{M} = OW^{1/2} \quad (2)$$

In formula (2), O represents the $X \times N$ dimensional matrix whose elements satisfy Rayleigh decay. If the element of W is the variance of the channel estimation, then for the n^{th} user, the calculation of the channel estimation variance w_n is expressed by the formula:

$$w_n = \frac{\tau p_t b_n^2}{1 + \tau p_t b^2} \quad (3)$$

Among them, τ is the pilot length, b^2 represents the large-scale fading effect on signal transmission, and b_n^2 represents the square of the coefficient of the n th user. Among them, $b^2 = \frac{1}{N} \sum_{n=1}^N b_n^2$. The base station utilises the pilot information in the data communication link transmitted by the network centre to estimate CSI. Assuming that the channel estimation error matrix is represented as $\tilde{M} = \hat{M} - M$, to eliminate mutual interference between received signals, zero forcing reception is performed at the base station end, which utilises phase adjustment and signal overlap to cancel out multiple delayed versions of signals. Assuming the zero forcing reception matrix is set to $Z = Q(Q^H Q)$, the signal received by the base station can be represented as:

$$S = Z^H (\sqrt{p_t} ME + \gamma) = (Q^H Q)^{-1} Q^H (\sqrt{p_t} (\hat{M} - \tilde{M}) E + \gamma) \quad (4)$$

In formula (4), Z^H represents the conjugate transpose of the zero forcing reception matrix. T and E represent the signal vectors received by the base station, Q is the channel transmission matrix of the receiving end, and Q^H is the conjugate transpose of Q . γ represents the background noise during the signal reception process at the receiving end. If T_k and E_k respectively represent the k^{th} element of vectors T and E , then the k^{th} element of the signal vector T is represented as (Di et al., 2021):

$$T_k = \sqrt{p_t} Y_k E_k + \left[(Q^H Q)^{-1} Q^H (\gamma - \sqrt{p_t} \tilde{M} E) \right]_k \quad (5)$$

Among them, Y_k represents the received signal, while E_k represents the channel condition of the signal vector during transmission. $\sqrt{p_t} Y_k E_k$ is the effective signal received by user k , and $[(Q^H Q)^{-1} Q^H (\gamma - \sqrt{p_t} \tilde{M} E)]_k$ is the effective noise of the channel.

The energy efficiency of CF massive MIMO systems is generally expressed as the ratio of total system capacity to total PC. Among them, the power loss of the system includes pilot and transmission power loss, radio frequency (RF) front-end power loss, and static power loss of the transmitter. On this basis, the total PC of the system is expressed by the formula:

$$P(\tau, p_t) = \frac{N}{\phi t_c} (\tau p_s + (t_c - \tau) p_t) + p_{rf} + p_l \quad (6)$$

The definition of a variable in formula (6) is shown in Table 1.

Table 1 Definition of variable in formula (6)

Sequence	Variables	Meaning
1	P	The total PC of the system
2	ϕ	Coefficient of power amplifier
3	p_l	Static PC of the transmitter
4	p_{df}	PC of transmitting antenna RF chain

The energy efficiency of a CF massive MIMO system can be expressed as:

$$\mu(\tau, p_t) = \frac{C(\tau, p_t)}{P(\tau, p_t)} \quad (7)$$

Assuming that the optimisation objective of network signal power is to minimise the total PC of the system, this optimisation objective is expressed by the formula:

$$\min \sum_{n=1}^N \sum_{k=1}^K P(\tau, p_t) \quad (8)$$

Its constraint conditions are:

- 1 The transmission power of each AP cannot exceed its maximum power:

$$0 \leq P(\tau, p_t, X) \leq P_{\max}, \quad \forall n, k \quad (9)$$

- 2 The power of each user's received signal must meet the minimum signal-to-noise ratio requirement:

$$|h_{nk}^H w_{nk}|^2 \geq SINR_n \quad (10)$$

Among them, the definitions of each variable are shown in Table 2.

Table 2 Definition of constraint variables

Sequence	Variables	Meaning
1	$ankh$	Channel gain vector from n^{th} user to k^{th} AP
2	w_{nk}	Signal transmission vector from the n^{th} user to the k^{th} AP
3	$SINR_n$	Minimum signal-to-noise ratio requirement

3.2 Photovoltaic technology

Photovoltaic power generation is a new technology that converts solar energy into electrical energy based on the photoelectric effect (Akhter et al., 2019; Yi et al., 2019). A photovoltaic array is a semiconductor device that converts light energy into electrical energy. Its overall structure is similar to a semiconductor photodiode. Under sunlight irradiation, new hole-electron pairs are formed on its surface, promoting the flow of charges in the array and improving the current efficiency of the array. The mathematical model is represented by a formula (Ghabuzyan et al., 2021):

$$O_I = I_p - I_t \left\{ \exp \left[e_0 (O_V + R_s I) \right] - 1 \right\} - \frac{O_V}{R_D} \quad (11)$$

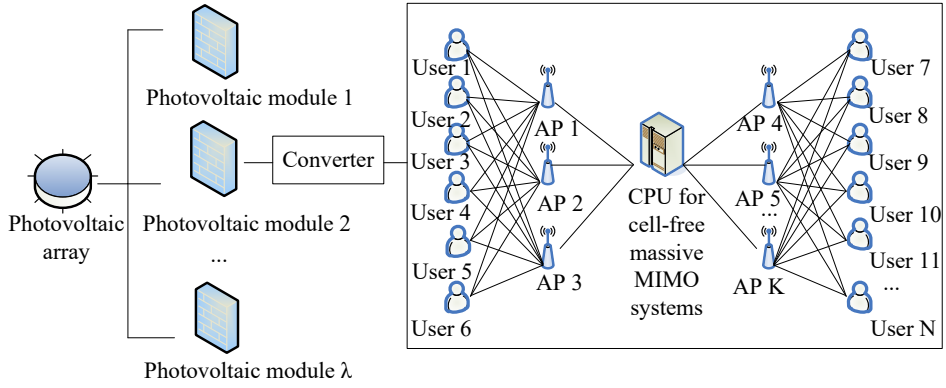
Among them, the definitions of each variable are shown in Table 3.

Table 3 Definition of variable in formula (11)

Sequence	Variables	Meaning
1	O_I	Photovoltaic output current
2	I_p	Photovoltaic effect current in positive-negative junction
3	I_t	Photovoltaic saturation current
4	e_0	Exposure index
5	O_V	Photovoltaic output voltage
6	R_s	Series resistor
7	R_D	Diverter resistor
8	I	Current

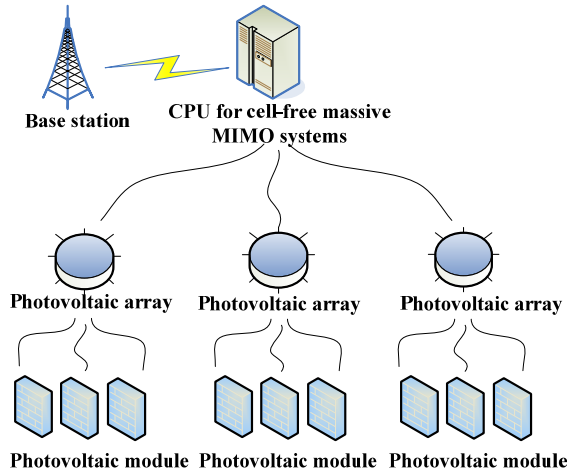
Photovoltaic power generation devices are clean and environmentally friendly and can be modular designed and expanded according to actual usage needs. They can be applied in many scenarios and play an important role in effectively improving energy efficiency. The core of photovoltaic technology is to convert solar energy into electrical energy, which is a renewable energy production method. Compared with traditional fossil fuel power generation, photovoltaic technology does not produce greenhouse gas emissions or other harmful pollutants and has minimal impact on the environment. This not only helps to mitigate global climate change but also helps to protect the natural environment, in line with the goal of sustainable development. In addition, photovoltaic systems can typically be installed on the roofs or other available spaces of buildings, which means energy production can be more decentralised and closer to end-users. This distributed energy supply model reduces the losses caused by long-distance transmission and also lowers the pressure on the power grid. Based on the optimisation objectives and constraints of network signal power, this article deploys it around MIMO systems or in areas with weak signal coverage. Through the deployment of photovoltaic arrays, a more sustainable energy supply can be achieved for CF massive MIMO systems, reducing energy consumption and improving the overall performance of the entire system while ensuring the communication quality of user terminals. The deployment of photovoltaic arrays is shown in Figure 3.

Figure 3 Photovoltaic array deployment (see online version for colours)



In MIMO systems, a distributed topology structure is used to control the layout of photovoltaic arrays. As shown in Figure 4, each photovoltaic string and module in the photovoltaic array can operate independently of each other, thereby improving the spectrum utilisation and signal coverage range of the MIMO system, and improving the distribution of network energy. Because each string under distributed control is independent of each other in the working state of the array, the analysis of photovoltaic strings can also be applied to photovoltaic arrays.

Figure 4 Distributed topology structure (see online version for colours)



In the coverage area of a CF massive MIMO system, it is assumed that a photovoltaic string is composed of λ photovoltaic modules connected in series, and the shielding degree between the modules of the string can be defined as a (in the absence of shielding, $r_o = 1$), where $o = 1, 2, 3, \dots, \lambda$ (Pachauri, 2022; Udell and Toole, 2019). Under the given bus voltage V_B , the modules within the photovoltaic string are automatically adjusted so that the sum of the voltage $V_{B,o}$ output by each module through the inverter is equal to the bus voltage V_B , which is expressed by the formula (Heidari and Hagh, 2019):

$$V_B = \sum_{o=1}^{\lambda} V_{B,o} \quad (12)$$

In the absence of unit-limited voltage, each module in the CF massive MIMO system area can obtain the maximum power value $P_{\max}$, and the output power O_p of the photovoltaic string is equal to the total maximum power value $P_{\max}$ of each module, which is expressed by the formula:

$$O_p = \sum_{o=1}^{\lambda} P_{\max} \quad (13)$$

The output voltage O_V of each photovoltaic module in the string is:

$$O_V = P_{\max} / \left(\frac{O_p}{V_B} \right) \quad (14)$$

If considering the voltage limitation of the unit, if some photovoltaic modules are covered by a larger range within the scope of a CF massive MIMO system, it is easy to cause the output voltage of modules with a smaller coverage range to approach or exceed the limit voltage after passing through the inverter. After the overpressure module adopts pressure limiting measures, other components automatically adjust to achieve maximum power and ensure that the total output voltage is equal to the voltage of the direct-current (DC) bus (Zhang et al., 2023). If another module within the range covered by the system experiences a boost exceeding the limit, the process is repeated continuously. When working independently in a CF massive MIMO system, the photovoltaic array provides power. When the output power exceeds the power demand, the controller stores the excess electrical energy in the device. When the output power is insufficient, the storage device outputs electrical energy to meet the power demand.

Assuming that the power generation of the photovoltaic array is P , an energy supply model for the photovoltaic array is established considering the light intensity and the conversion efficiency of the photovoltaic panel:

$$P_{pv} = \eta \times \zeta \quad (15)$$

η is the conversion efficiency, and ζ is the light intensity. Based on energy supply and system power consumption models, establish an objective function for energy power optimisation:

$$\min \sum_{n=1}^N \sum_{k=1}^K P_{pv} - P(\tau, p_t, X) \quad (16)$$

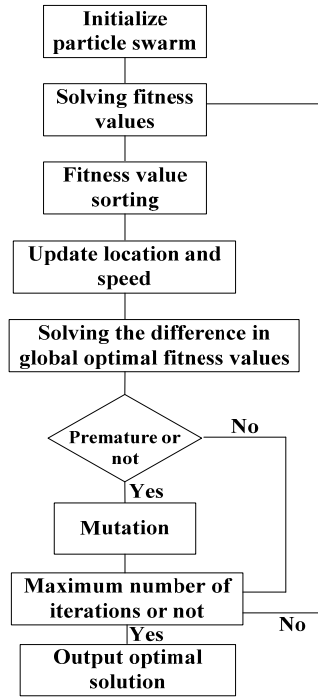
Its constraint conditions are:

- 1 the energy provided by the photovoltaic array should meet the energy requirements of the communication system, that is $P_{pv} > P(\tau, p_t, X)$
- 2 capacity constraint of the photovoltaic array: the output power of the photovoltaic array should not exceed its rated power, that is $P_{pv} \leq P_{pv_{\max}}$.

Based on controlling the layout of the photovoltaic array, the MIMO system is optimised and managed for network signal power. The implementation of the PSO algorithm is relatively simple and has global search capability (Gad, 2022). The PSO algorithm can achieve global search by simulating the information sharing and cooperative behaviour

among individuals in a bird flock. It has good convergence speed and adaptability, and in large-scale communication network optimisation problems, the PSO algorithm can help search for a wider solution space and find better solutions. Through the PSO algorithm, the network optimal energy and power optimisation results for a CF massive MIMO system are obtained, as shown in Figure 5.

Figure 5 Network signal power optimisation management



In Figure 5, firstly, the particle swarm representing the network signal power optimisation results of the CF massive MIMO system is initialised and combined with the output power, load power, and the main parameters of the particle swarm. The maximum number of iterations is set, and the upper and lower limits of position and speed are defined. The number of iterations is set to 0 and initialised according to the principle of chaos to determine the fitness value. The forward and backward substitution method is used to solve the PC of the system. Based on this, individual extremum points are updated and the global optimum is updated. By ranking the optimal matching degree of the energy power of the system in the number of groups, half of the optimal position and fastest speed in the number of groups are adopted to replace the half with poor position and speed, and their position and speed are updated. On this basis, the optimisation result is judged to be premature by calculating the difference between the global optimal adaptability values. If premature exists, mutation operation is performed. If not, the number of iterations is determined to be maximised. If the number of iterations reaches its maximum value, terminate the step and output the optimal solution for optimising network signal power. If the number of iterations does not reach its maximum value, return to the step of solving the fitness value to continue execution. Its pseudocode is:

Function initialise_particle_swarm():

For each particle i:

Randomly initialise position position[i] within position limits

Randomly initialise velocity velocity[i] within velocity limits

Calculate fitness value fitness[i] = calculate_fitness(position[i])

If fitness[i] is better than personal best fitness personal_best_fitness[i], update personal_best_fitness[i] and personal_best_position[i]

Find global best position global_best_position and fitness global_best_fitness

Function update_particle_swarm():

For each particle i:

Update velocity and position:

Update velocity: velocity[i] = calculate_new_velocity(velocity[i+1]
= w * velocity[i] + c1 * r1 * (personal_best_position[i]-position[i])
+ c2 * r2 * (global_best_position[i]-position[i]))

Update position: position[i+1] = position[i] + velocity[i+1]

Calculate fitness value fitness[i] = calculate_fitness(position[i])

If fitness[i] is better than personal best fitness personal_best_fitness[i], update personal_best_fitness[i] and personal_best_position[i]

Find global best position global_best_position and fitness global_best_fitness

Main program:

initialise_particle_swarm()

While iteration count < maximum iteration count:

update_particle_swarm()

Check for premature optimisation:

If premature:

For each particle in the population:

if random() < mutation_probability:

for each dimension in particle:

particle.position[dimension] += mutation_range * (random() - 0.5)

If the iteration count reaches the maximum:

Terminate

Output the optimised solution for network energy power

In algorithm implementation, it is considered to minimise the total PC of the system in the basic system model of CF massive MIMO, while considering the limitations of the output power and load power of the photovoltaic array. Assuming the maximum number of iterations of the algorithm is 100 and the number of particle swarms is 50, by continuously updating the position and velocity of particles, utilising swarm intelligence for global search, the optimal power allocation scheme is calculated:

The output power of the photovoltaic array is P_{pv} , the load power is P_{load} ,

$$P_{pv} = P_{load} + \sum_{k=1}^n P_{tx_k}, \text{ and the channel matrix is } M = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}.$$

Calculate the received power for each user based on the given parameters:

$$P_{rx} = \left| \sqrt{p_t} \times M \times P_{tx} \right|^2 \quad (17)$$

Among them, P is the transmission power vector, $P_{tx} = [P_{tx,1}, P_{tx,2}, \dots, P_{tx,N}]$.

According to formula (19), calculate the received power for each user and minimise the objective function:

$$P_{rx,n} = \left| \sqrt{p_t} \times \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \times P_{tx} \right|^2 \quad (18)$$

According to the calculation results, $P_{rx,n}$ represents the received power under the optimal power allocation scheme optimised by the PSO algorithm given the output power and load power limitations of the photovoltaic array. By allocating power reasonably and reducing unnecessary power waste, the energy consumption of the system can be effectively reduced. Maximising the data transmission throughput of the system without increasing the total power of the system, improving the communication efficiency and data transmission rate of the system.

Optimisation using the PSO algorithm minimises the PC of the whole system while increasing the signal power received by each user, subject to certain energy constraints. This means that when transmitting data, the system can utilise the energy more efficiently, and therefore the energy savings are improved. Minimising energy wastage and improving the efficiency of energy use while maintaining communication requirements. By appropriately allocating the transmitting power, the system can be made to have a larger coverage area and a larger user space. Under the condition of limited spectrum resources, the data transmission rate of the system can be improved by using the optimal scheme derived from this method.

4 Network signal power optimisation simulation experiment

To verify the effectiveness of the network signal power optimisation method based on photovoltaic technology for CF massive MIMO, this paper uses MATLAB R2023a simulation software to build a system simulation test experimental scene and conducts experimental analysis from three aspects: energy efficiency, signal coverage range, and data transmission rate. This software is known for its powerful numerical computing capabilities and rich toolbox, suitable for communication system simulation. To ensure the reliability and effectiveness of the experimental results, simulate a densely deployed cellular network environment. By running simulation programs, simulate the performance of CF massive MIMO systems in different testing scenarios, and compare the system performance between unoptimised and photovoltaic-based optimised systems.

4.1 *Experimental setup*

4.1.1 *Layout of photovoltaic power generation system*

In the experimental scenario, the photovoltaic array was placed within the coverage range of a CF massive MIMO system base station to fully utilise photovoltaic technology. The inclination angle of the photovoltaic string was set to 35 degrees, covering an area of approximately 1 square kilometre.

4.1.2 *Communication system parameter settings*

Sixty-four antenna arrays were set up in the system to provide sufficient spatial freedom for multi-user communication and beamforming. The power of each antenna was dynamically adjusted based on the user's geographical location and communication requirements. Beamforming technology was adopted to achieve signal coverage. By adjusting the beam angle of the antenna array, the energy of the signal can be better distributed at the location of the user's equipment. The specific parameter settings are shown in Table 4.

Table 4 Simulation parameter settings

<i>Sequence</i>	<i>Parameter</i>	<i>Specifications</i>
1	Number of AP	100
2	Number of users	500
3	Large-scale fading effect parameters	0.1
4	Load power	30 W
5	Output power	50 W
6	signal bandwidth	20 MHz
7	Number of particle swarm	50
8	Maximum number of iterations	100

4.1.3 *Experimental scenario description*

A large number of terminals were placed around the base station, forming full coverage of the entire experimental scene. To ensure the continuity of electricity, the photovoltaic power generation system is always in operation. Massive MIMO systems continuously operate, monitoring the location and communication needs of user devices in real-time, and adjusting antenna power and beam direction based on dynamic power allocation strategies and beamforming techniques.

4.2 *Experimental results*

4.2.1 *Energy efficiency*

EE is an important indicator for measuring the optimisation of network signal power, defined as the energy consumed per unit of transmitted data. It is the ratio of transmission rate per unit spectrum resource to total PC. Its calculation is shown in the formula:

$$\mu(\tau, p_t) = \frac{C(\tau, p_t)}{P(\tau, p_t)} \quad (19)$$

In the formula, $C(\tau, p_t, X)$ represents the effective amount of data transmitted. $P(\tau, p_t, X) = p_t \times T$, T is the transmission time.

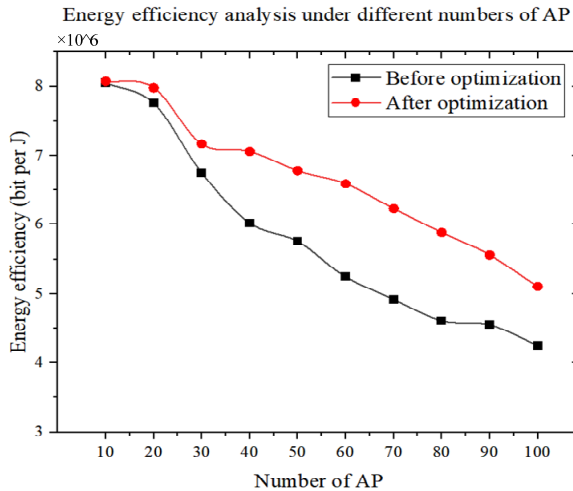
$$C(\tau, p_t, X) = B \log_2(1 + SINR_n) \times T \quad (20)$$

$$\mu(\tau, p_t) = \frac{B \log_2(1 + SINR_n) \times T}{p_t \times T} \quad (21)$$

$$\mu(\tau, p_t) = \frac{B \log_2(1 + SINR_n)}{p_t} \quad (22)$$

In the actual operation of the system, each access point requires some energy for data transmission and signal processing. This article first compared the EE results before and after system optimisation by setting different numbers of access points. The specific comparison results are shown in Figure 6.

Figure 6 EE analysis results under different numbers of APs (see online version for colours)

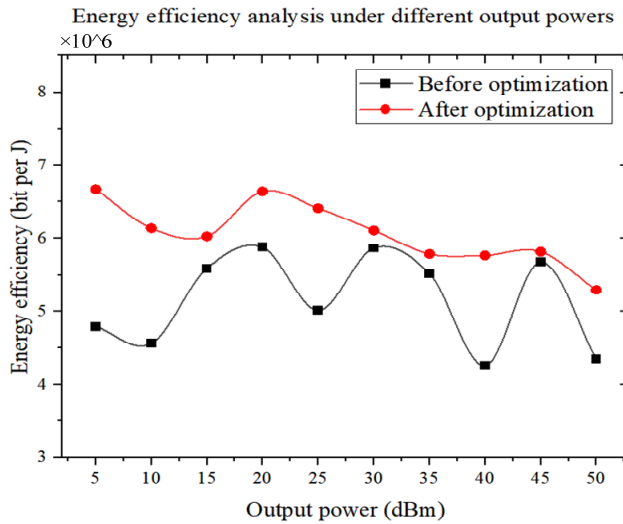


From Figure 6, it can be seen that as the number of APs increased, the EE of the system decreased to a certain extent. This is mainly because in the process of network signal power allocation, some APs only provide a small amount of services to local users, and there is little improvement in the communication services of the entire user. Moreover, this part of APs still needs to consume a certain amount of network energy to maintain operation. Even though this portion of the AP can contribute a small amount of power allocation to all users, it is still included in the energy consumption of the entire system. When the number of APs was 10, the system EE before and after optimisation was 8.05×10^6 bit per Joule (bit per J) and 8.07×10^6 bit per J, respectively, and the difference in system energy efficiency in the initial stage was relatively small; when the number of

APs was 100, the system EE before and after optimisation was 4.25×10^6 bit per J and 5.11×10^6 bit per J. From the specific comparison of system energy efficiency before and after optimisation, it can be seen that the EE of the CF massive MIMO system optimised based on photovoltaic technology has significantly improved. Compared to before optimisation, after system optimisation, the EE increased by approximately 20.24% when the number of APs was 100. The variation of EE under different output powers is relatively stable, and when the output power reaches 50 dBm, the EE value significantly improves compared to before optimisation, indicating that the optimised system can produce higher energy efficiency when using the same output power.

To compare the EE changes of the system before and after optimisation more comprehensively, based on the results in Figure 6, this article fixed the number of system APs to 100 and compared the EE of the system before and after optimisation at different output powers. The final result is shown in Figure 7:

Figure 7 EE analysis results under different output powers (see online version for colours)



From Figure 7, it can be seen that there were significant differences in EE before and after system optimisation under different output powers. Before system optimisation, the trend of EE variation was strong under different output powers. Within a certain range, increasing the output power can improve the coverage range of the signal. When the output power increases to a certain extent, signal interference may occur, leading to unstable changes in system EE. When the output power reached 50 Decibel-milliwatt (dBm), its EE was 4.35×10^6 bit per J; after system optimisation, the EE changes were relatively stable under different output powers. When the output power reached 50 dBm, the EE was 5.29×10^6 bit per J. From the comparison results, it can be seen that the optimised system has higher EE under different output powers.

4.2.2 Signal coverage range

The signal coverage range refers to the proportion of areas covered by effective downlink signals and uplink signals in the system network. The expansion of signal coverage

means a wider range of services and a better user experience. Calculate the strength of the signal at the receiving point based on the transmission power and propagation loss of the signal source. Use a path loss model to estimate. As shown in the formula:

$$PL = 20 \log_{10}(d) + 20 \log_{10}(f) + 20 \log_{10}(4\pi/c) \quad (23)$$

PL represents path loss, d is the transmission distance, f is the signal frequency, and c is the speed of light. Subtract the path loss from the transmission power of the signal source to obtain the predicted signal strength at that location. Then, compare the predicted signal strength with the receiving sensitivity of the receiver to determine the signal coverage range. In the experimental scenario, the receiving sensitivity of the receiving end is set to -110 dBm. The signal coverage calculation for the uplink is based on the signal coverage calculation for the uplink, while the transmission power of the base station and path loss between the user equipment are considered for the downlink.

Describe the signal attenuation through a path loss model, where the received power is equal to the transmitted power minus the path loss:

$$P_{rx} = P_{tx} - PL \quad (24)$$

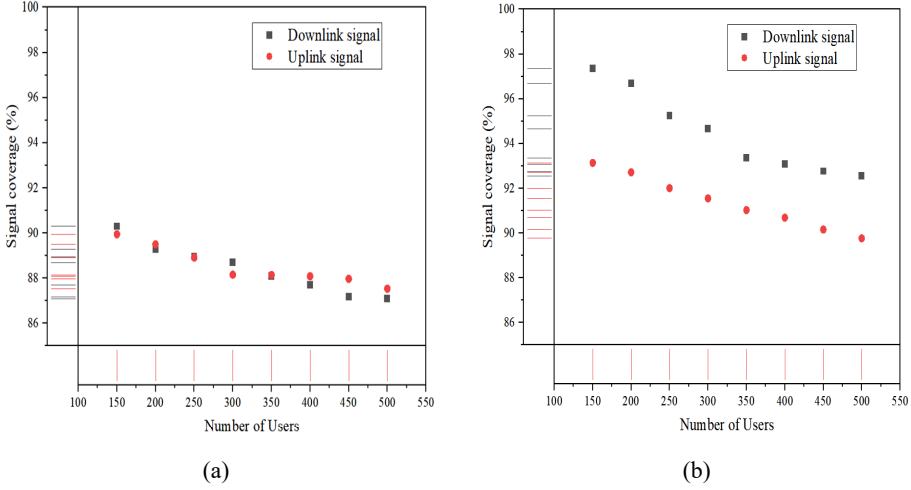
Due to the fixed sensitivity S_{rx} of the receiving end, the maximum transmission distance $d_{\max}$ is represented as:

$$d_{\max} = \frac{P_{tx} - S_{rx}}{20 \log_{10}(d) + 20 \log_{10}(f) + 20 \log_{10}(4\pi/c)} \quad (25)$$

Consider the maximum transmission distance as the coverage range. By optimising the network signal power configuration, the coverage range can be improved.

This article tested and analysed the signal coverage range before and after system optimisation by setting different numbers of users and simulating scenarios with different user densities. The results are shown in Figure 8.

Network signal power optimisation should be able to achieve effective coverage of downlink and uplink signals, that is, in dense user situations, the network can maintain good downlink and uplink communication quality. It can be found from the signal coverage analysis results in Figure 8 that there were significant differences in the downlink and uplink signal coverage of the system before and after optimisation. From Figure 8(a), it can be seen that before optimisation, the average coverage range of downlink and uplink signals in different user density scenarios was about 88.41% and 88.53%, respectively. From Figure 8(b), it can be seen that after optimisation, the average coverage range of the system's downlink and uplink signals in different user density scenarios reached approximately 94.46% and 91.38%, respectively. From the specific comparison results, based on photovoltaic technology optimisation, the average coverage range of the system's downlink and uplink signals in different user density scenarios increased by 6.05% and 2.85%, respectively. Photovoltaic technology can be combined with antenna design to increase antenna gain and reduce the impact of signal attenuation in the signal transmission path, such as reducing multipath effects and fading, improving signal transmission quality and stability, and thereby expanding signal coverage.

Figure 8 Analysis results of signal coverage range, (a) signal coverage range before optimisation (b) signal coverage range after optimisation (see online version for colours)

4.2.3 Data transmission rate

The goal of the data transmission rate generally depends on user needs. Generally speaking, in high-density urban areas or high-demand application scenarios, CF massive MIMO systems need to ensure good and stable data transmission rates to meet the needs of users. The calculation of the data transmission rate R_i is shown in the formula:

$$R_i = B \log_2 (1 + SINR_n) \quad (26)$$

Among them, B is the channel bandwidth, and $SINR_n$ is the signal-to-noise ratio.

$$SINR_n = \frac{P_{rx}}{\gamma} \quad (27)$$

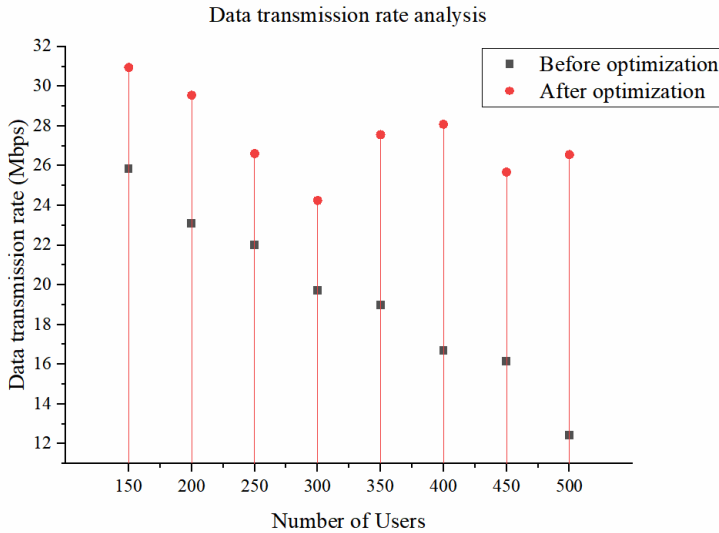
γ represents the background noise during the signal reception process at the receiving end. From the formula, optimising energy power can also improve the data transmission rate.

This article also tested and analysed the data transmission rate before and after system optimisation by setting different numbers of users and simulating scenarios with different user densities. Figure 9 shows the results.

From Figure 9, it can be observed that the data transmission rate of the system before optimisation was more affected by the number of users, and its data transmission rate showed a significant decrease as the number of users increased. When the number of users was 150, the data transmission rates of the system before and after optimisation were 25.83 Mbps and 30.95 Mbps, respectively; when the number of users was 500, the data transmission rates before and after system optimisation were 12.43 Mbps and 26.56 Mbps, respectively. In different user density scenarios, the average data transmission rate of a CF massive MIMO system before optimisation was about 19.36 Mbps. With the support of photovoltaic technology, the average data transmission rate after system optimisation reached about 27.41 Mbps. Compared to the average data

transmission rate, the optimised system improved by 8.05 Mbps. This result indicates that the CF massive MIMO system based on photovoltaic technology has more ideal performance in communication data transmission.

Figure 9 Analysis results of data transmission rate (see online version for colours)



5 Discussion

In the simulation experiment analysis, this article validated the network signal power optimisation effect of the CF massive MIMO system based on photovoltaic technology from three aspects: energy efficiency, signal coverage range, and data transmission rate. In EE analysis, the optimised system showed more ideal EE results under different scenarios with different numbers of APs and output power settings. The pre-optimised system often consumes a considerable amount of electricity to maintain the operation of the base station and equipment, resulting in low EE and weak stability. Photovoltaic technology utilises natural light energy to provide some or even all of its electricity, reducing system energy consumption and improving energy efficiency. In signal coverage analysis, the average coverage range of the optimised downlink and uplink signals has been improved in different user-density scenarios. With photovoltaic technology, the system capacity and anti-interference ability have been enhanced, enabling effective signal coverage even in dense user scenarios. In data transmission rate analysis, CF massive MIMO systems based on photovoltaic technology have higher data transmission rates. Photovoltaic technology, as an effective way of energy utilisation, can support more antennas and larger MIMO systems, effectively improving the efficiency of communication data transmission.

6 Conclusions

With the expansion of the communication infrastructure construction scale, the allocation of energy power and energy consumption in communication networks have become increasingly important obstacles to the sustainable development of communication. To improve communication efficiency, energy consumption, and energy power allocation in communication networks, this article combined photovoltaic technology to conduct in-depth research on the optimisation of network energy power for CF massive MIMO. This has not only effectively improved energy efficiency but also expanded the effective coverage range of communication network downlink and uplink signals to a certain extent, and improved communication data transmission rate. This article was based on photovoltaic technology to optimise the network signal power of CF massive MIMO. Although it has a guiding role in promoting sustainable development of communication, there are still limitations in this article. Photovoltaic cells have certain requirements for environmental conditions and light intensity, which increases the difficulty of energy storage and management and requires optimised layout and network design. This article did not deeply consider the deployment cost and complexity of the system. In future research, we will consider conducting in-depth studies from the perspective of balancing network capacity and coverage, and comprehensively consider the impact of environmental factors to improve the optimisation effect of system network signal power. Develop more efficient algorithms to further improve the energy efficiency and data transmission rate of the system, explore how to achieve more refined power control and resource allocation on the existing basis, and promote the high-quality development of future communication.

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