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Research Article

Research on the Multiobjective Optimization of Microwave Wireless Power Receiving in an Unmanned Aerial Vehicle Network

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With the wide application of various wireless energy transmission technologies and unmanned aerial vehicle clusters in both production and life, the use of microwave wireless energy transmission to provide a real-time energy supply for an unmanned aerial vehicle network in flight has become an effective way to extend its working time. This paper focuses on the optimization of the energy transmission efficiency and cost in the microwave wireless power receiving process of an unmanned aerial vehicle network. Considering the overall energy transmission efficiency from the power supply terminal to the power receiving network and the cost of the wireless power transmission equipment of the network, we have established a multiobjective wireless power receiving optimization model including a microwave energy emission source and an unmanned aerial vehicle network that receives energy. The model is optimized to select the best wireless power access point and the number of wireless power receiving modules in a network node. In the case study, the optimization model is solved using an evolutionary algorithm, and the solution results verify the effectiveness and correctness of the model.

1. Introduction

To date, near-field wireless power transmission technology, represented by electric field coupling and magnetic field coupling wireless energy transmission technology, has been widely used to conveniently charge consumer electronic products, provide uninterrupted power supplies to sensor networks, and charge electric vehicles [1–5]. In terms of far-field wireless power transmission, the effective wireless power transmission distance currently reaches the kilometer level [6, 7], and wirelessly transmitting power to unmanned aerial vehicles (UAVs) has also been verified in practice [8]. Among the various applications, microwave wireless power transmission, as a far-field wireless energy transmission technology with relatively mature technology and high long-distance transmission efficiency [9, 10], can well meet the needs of providing electrical energy for working UAVs. Therefore, this paper researches the background of microwave wireless power transmission technology.

In the current research on microwave wireless power transmission technology applications, point-to-point energy transmission is often considered [6, 11]. In this context, a higher point-to-point wireless power transmission efficiency is pursued by optimizing the transmission process and improving the efficiency of every energy conversion step [11]. Since UAV clustering research has been widely used, it is necessary to research wireless power transmission efficiency optimization for the power receiving terminals in an actual UAV network.

A microwave beam attenuates exponentially in a uniform atmosphere [12], and, at the same time, geometric attenuation is caused by beam divergence during transmission [13]. Atmospheric attenuation is only related to the transmission distance. Due to the nature of exponential attenuation, the atmospheric attenuation rate is the same when microwaves are transmitted over the same distance in the same medium, regardless of whether they are forwarded through intermediate nodes. Geometric attenuation can be effectively avoided by adding an appropriate number of intermediate nodes during the energy transmission process or increasing the effective area (antenna aperture) of the receiving antenna at the receiving terminal. In the optimization of this paper, this characteristic of microwave wireless power transmission needs to be considered. Figure 1 compares the geometric attenuation of microwave wireless power transmission through the intermediate node and without the intermediate node at the same transmission distance when the antenna aperture of the intermediate node and the power receiving terminal is constant.

In a UAV network, each node is equipped with the same wireless power transmission equipment, and each node can receive and transmit wireless power. When using microwave wireless power transmission technology to power a UAV network, the power supply terminal can only provide point-to-point microwave power transmission. Affected by the size and weight of its equipment, it takes a long time for the power supply terminal to switch the power supply object, retrack, and start wireless power transmission. Therefore, it is necessary to select a node in the network as a wireless power access point (WPAP), which relays microwave power to other network nodes.

The selection of the WPAP needs to consider the power transmission efficiency from the microwave energy source (power supply terminal) to the access point and the transmission efficiency from the access point to the entire UAV network. UAV networks often need to work far away from the energy supply. In this case, if the power transmission efficiency from the power supply terminal to the WPAP is maximized, it is often necessary to select a node at the edge of the UAV network as the WPAP. However, it is known that choosing a point close to the center of the UAV network as the access point can maximize the power transmission efficiency from the WPAP to the entire UAV network. Besides, the choice of the WPAP will affect the performance requirements of the wireless power transmission equipment on the UAV network node and further affect the cost of the wireless power transmission equipment of the entire network. Therefore, optimization needs to be performed to select the best wireless power access point and the number of wireless power receiving modules in a network node considering the relative position of the power supply terminal and the energy receiving UAV network, the environmental conditions in the power transmission process, and the atmospheric attenuation and geometric attenuation during the wireless transmission of microwave energy. In the optimization, the requirement of minimizing the network power transmission equipment cost and the requirement of maximizing the network power receiving efficiency restrict each other, which constitutes a typical multiobjective optimization problem.

This paper establishes a power receiving optimization model that includes the microwave energy transmission source and an energy receiving UAV network, which is designed to maximize the overall power transmission efficiency and minimize the cost of the wireless power transmission equipment in the network. The model is optimized to select the best WPAP in the UAV network and the number of wireless power receiving modules in a network node. The main contributions of this paper are as follows:

(1) Corresponding unit models have been established for the wireless power supply terminal, UAV network nodes, and wireless power transmission equipment. On this basis, the UAV network power receiving optimization model is further constructed, and the atmospheric attenuation and geometric attenuation of the microwave beam are considered in the model.

(2) According to the nature of the problem and the characteristics of the model constraints, a solution method based on the coevolutionary constrained multiobjective optimization (CCMO) [14] framework is provided.

(3) Through the in-depth analysis of the solution results, the effectiveness and correctness of the viewpoints, the proposed model, and the solution method in this paper are verified.

2. Literature Review

Currently, there have been many studies on optimizing the wireless power receiving efficiency for a power receiving network [15–22]. Literature [15] is based on the near-field broadcast radio frequency signal energy transfer method with the objective of maximizing the amount of transferred energy at all receivers during the charging period and optimizing the energy receiving process of the sensor network. Literature [16] also uses near-field broadcast wireless power transfer technology to optimize the balance of energy collected by the sensor nodes in the network. Literatures [17–19] are based on simultaneous wireless information and power transfer technology, and the objective is to extend the survival time of sensor networks through different optimization methods.

Literature [20] is based on using magnetic field coupling wireless energy transmission technology to power a wireless power transmission network composed of multiple nodes. This kind of wireless power transmission network uses the strong coupling generated between the resonant bodies to form a "high-efficiency power transmission channel." Based on this principle, literature [21] used magnetic field coupling power transmission technology to transmit electrical energy to the receiving end 2 meters away, thus increasing the effective wireless power transmission distance. Literature [22] studies the network survival time optimization problem of this wireless power transmission network under active injection and passive injection. It is verified through experiments that the path optimization of the wireless power transmission network with active injection and passive injection can be effectively solved using the cellular genetic algorithm.

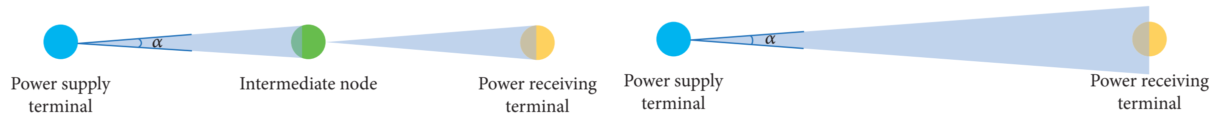

FIGURE 1: Comparison of the geometric attenuation of microwave wireless energy transmission.

In summary, the existing research studies on wireless power supply optimization for the energy receiving network are all based on near-field wireless power transmission technology. In terms of the applied research and related optimal design of far-field wireless power transmission, the receiving terminal is always a single node [6]. Due to the difference in the power transmission principle, far-field wireless energy transmission technology cannot use broadcasting or establish energy transmission channels to supply energy to the power receiving node in the form of a network; therefore, the problem of network wireless power receiving optimization using far-field wireless energy transmission technology urgently needs to be studied.

In this case, using microwave wireless energy transmission technology, this paper constructs a multiobjective optimization model with a UAV network as the energy receiving terminal to fill in the research gap on far-field wireless power supply optimization for the power receiving terminal in the form of a network.

3. Optimization Problem Modeling

3.1. Unit Models. The UAV network power receiving optimization model in this paper involves the wireless power supply terminal, the UAV network node, and the wireless power receiving module that can be mounted on the UAV network node. Since the wireless power transmission performance of the UAV network node is determined by the equipment it carries, the unit model is only constructed for the wireless power supply terminal, the wireless power supply module, and the wireless power receiving module. To simplify the calculation, this paper assumes that the microwave beam used in wireless power transmission is a plane wave, and the energy density on the beam section obeys a uniform distribution [23, 24].

3.1.1. Model of the Microwave Wireless Power Supply Terminal. The main parameters of the power supply terminal (fixed microwave energy-emitting source) include the microwave beam excitation angle ($\alpha_{\text{wav}}^{\text{ps}}$), the conversion efficiency ($\eta_{\text{wes}}^{\text{ps}}$) of converting electrical energy into microwave energy, and the three-dimensional coordinates (POS_{ps}) of the microwave source. When the microwave emitter at the power supply node emits microwaves in a certain direction in space, the energy distributed on the beam cross section ($P_{\text{mwsec}}(L_{\text{wet}})$) with a distance of L_{wet} from the power supply node can be calculated by the following formula:

$$P_{\text{mwsec}}(L_{\text{wet}}) = \eta_{\text{wes}}^{\text{ps}} \cdot \kappa \cdot e^{-\gamma \cdot L_{\text{wet}}} \cdot P_{\text{wes}}^{\text{ps}}, \tag{1}$$

where $P_{\text{wes}}^{\text{ps}}$ is the actual power of the microwave emitter at the power supply terminal; γ is the atmospheric attenuation coefficient, which is related to the atmospheric conditions along the beam transmission path; and κ is the tracking loss coefficient. The values of γ and κ are determined based on actual weather conditions and equipment conditions during transmission.

3.1.2. Model of the Microwave Wireless Power Supply Module. The microwave wireless power supply module is a modularized microwave energy emission source, and its main parameter types include the microwave beam excitation angle ($\alpha_{\text{wav}}^{\text{smod}}$), the conversion efficiency ($\eta_{\text{wes}}^{\text{smod}}$), and the module weight (m_{smod}). When the wireless power supply module emits microwaves in a certain direction in space, the energy distributed on the beam cross section ($P_{\text{mwsec}}(L_{\text{wet}})$) with a distance of L_{wet} from the wireless power supply module can be calculated by the following formula:

$$P_{\text{mwsec}}(L_{\text{wet}}) = \eta_{\text{wes}}^{\text{smod}} \cdot \kappa \cdot e^{-\gamma \cdot L_{\text{wet}}} \cdot P_{\text{wes}}^{\text{smod}}, \tag{2}$$

where $P_{\text{wes}}^{\text{smod}}$ is the actual working power of the wireless power supply module.

3.1.3. Model of the Microwave Wireless Power Receiving Module. The main parameters of the microwave wireless power receiving module are the receiving antenna aperture ($S_{\text{wer}}^{\text{rmod}}$), the efficiency ($\eta_{\text{wer}}^{\text{rmod}}$) of converting the microwave energy distributed on the effective area of the antenna into electric energy, and the module weight (m_{rmod}). When the distance between the receiving antenna and the microwave emitting source is L_{wet}, the beam excitation angle of the emitting source is α_{wav}, and the electric power P_{wer} converted from microwave energy by the receiving module is calculated by the following formula:

$$P_{\text{wer}} = \eta_{\text{wer}}^{\text{rmod}} \cdot \min\left(\frac{S_{\text{wer}}^{\text{rmod}}}{S_{\text{wav}}(\alpha_{\text{wav}}, L_{\text{wet}})}, 1\right) \cdot P_{\text{mwsec}}(L_{\text{wet}}). \tag{3}$$

Under the plane wave assumption, for the beam cross-sectional area in the equation, $S_{\text{wav}}(\alpha_{\text{wav}}, L_{\text{wet}})$, there is

$$S_{\text{wav}}(\alpha_{\text{wav}}, L_{\text{wet}}) = \pi\left(\tan\left(\frac{\alpha_{\text{wav}}}{2}\right) \cdot L_{\text{wet}}\right)^2, \quad \alpha_{\text{wav}} \in (0, \pi). \tag{4}$$

3.2. Microwave Wireless Power Receiving Model of the UAV Network. The UAV network microwave wireless power receiving model is mainly composed of a wireless power supply terminal and UAV network nodes equipped with wireless power transmission modules. The power receiving process of the UAV network is as follows:

(a) Electric energy is first converted into microwave form at the wireless power supply terminal and transmitted to a WPAP node in the network in a point-to-point manner.

(b) When the WPAP receives microwave energy, it reserves the power needed to maintain its normal operation and transmits the remaining power to the node in the network with the least remaining power at that time via wireless power transmission. When the node that is receiving energy is no longer the node with the least remaining power in the network, the WPAP will switch the power transfer object to the node with the least remaining power in the network.

Based on the aforementioned energy receiving process, the UAV network can extend its working time as much as possible through the WPAP. The power transmission efficiency η_{PS-AP} from the power supply terminal to the WPAP is calculated by the following formula:

$$\eta_{PS-AP} = \kappa \cdot \gamma^{L_{PS-AP}} \cdot \eta_{wes}^{PS} \cdot \eta_{wer}^{rmod} \cdot \min\left(\frac{S_{wer}^{N}}{S_{wav}\left(\alpha_{wav}^{ps}, L_{PS-AP}\right)}, 1\right), \tag{5}$$

where L_{PS-AP} is the distance from the power supply terminal to the WPAP and S_{wer}^{N} is the energy receiving antenna aperture of a single UAV network node. Its calculation method is

$$S_{wer}^{N} = N_{rmod} \cdot S_{wer}^{rmod}, \tag{6}$$

where N_{rmod} is the number of wireless power receiving modules carried by a single UAV network node. The energy transfer efficiency η_{AP-N}^{i} from the WPAP to the ith node in the network except the WPAP is calculated by the following formula:

$$\eta_{AP-N}^{i} = \kappa \cdot \gamma^{L_{AP-N}^{i}} \cdot \eta_{wes}^{PS} \cdot \eta_{wer}^{rmod} \cdot \min\left(\frac{S_{wer}^{N}}{S_{wav}\left(\alpha_{wav}^{smod}, L_{AP-N}^{i}\right)}, 1\right), \quad i \in \{1, 2, \ldots, N_{node} - 1\}, \tag{7}$$

where L_{AP-N}^{i} is the distance from the WPAP to the ith node in the network except the WPAP and N_{node} is the total number of nodes in the UAV network.

3.3. Optimization Objectives. The primary goal of UAV network power receiving optimization is to maximize the overall power transmission efficiency from the power supply terminal to the power receiving network. In addition, the cost of the wireless power transmission equipment of the network needs to be considered. Therefore, the optimization objectives are to maximize the overall power transmission efficiency and minimize the cost of the wireless power transmission equipment of the network.

(a) *Overall Power Transmission Efficiency*. The overall power transfer efficiency (η_{PS-UN}) from the power supply terminal to the power receiving UAV network is calculated by the following formula:

$$\eta_{PS-UN} = \eta_{PS-AP} \cdot \frac{1 + \sum_{i=1}^{N_{node}-1} \eta_{AP-N}^{i}}{N_{node}}. \tag{8}$$

(b) *Cost of the Network Wireless Power Transmission Equipment*. The cost of the network wireless power transmission equipment (C_{mod}) is calculated by the following formula:

$$C_{mod} = N_{node} \cdot N_{rmod} \cdot C_{rmod}, \tag{9}$$

where C_{rmod} is the price of a single microwave wireless power receiving module. Since the number of microwave power supply modules is not involved in the optimization of this paper, their related costs are not reflected in C_{mod}.

4. Solving the Model

In the power receiving optimization of the UAV network in this paper, two mutually restrictive goals, maximizing the overall energy transmission efficiency (η_{PS-UN}) and minimizing the cost of the wireless power transmission equipment of the network (C_{mod}), need to be considered, which forms a typical multiobjective optimization problem. To solve this problem, it is necessary to optimize the overall energy transmission efficiency from the power supply terminal to the power receiving network and the cost of the wireless power transmission equipment of the network considering the atmospheric attenuation and geometric attenuation during the wireless transmission of microwave energy based on the relative position of the power supply terminal, the energy receiving UAV network, and the environmental conditions in the energy transmission process. In recent years, many new evolutionary algorithms with excellent performance have been continuously proposed [25, 26], and various coevolutionary algorithms have been applied to solve optimization problems in many fields [27, 28]. CCMO, as a newly proposed framework of multiobjective coevolutionary algorithms, has shown excellent performance on multiple benchmark problems [14], and its characteristics are also suitable for the experiments in this paper. Therefore, the optimization model in this paper is solved via CCMO.

In the solution, the decision variables are the serial number (SN_{WPAP}) of the UAV network node selected as the

WPAP and the number of wireless power receiving modules (N_{rmod}) in the UAV network node. Since the number of power supply modules carried by the UAV network node does not affect the efficiency of network power receiving, the number of power supply modules is not involved in the optimization. By default, all nodes of the UAV network are equipped with a set of wireless power supply modules. Besides, because the objective function in the optimization needs to be in a minimized form, the aforementioned optimization objective is converted to minimize the overall power loss rate ($1 - \eta_{\text{PS-UN}}$) and the wireless power transmission (WPT) equipment cost of the UAV network (C_{mod}) when solving the model.

Figure 2 shows the solution process of the UAV network power receiving optimization model based on CCMO. First, enter the parameters required for optimization: the model constraints, the range of decision variables, the number of population individuals, and the maximum number of iterations. Next, produce the initial main population and initial archive population and calculate the fitness of the individuals in the two populations. Then, enter the main loop of the algorithm through the coevolution of the archive population that only calculates the fitness of the individual and the main population that calculates the fitness of the individual and the degree of constraint violation simultaneously to quickly and effectively solve the constraint optimization problem in this paper. Finally, after reaching the maximum number of iterations, the resulting solution is output.

Based on the optimization objectives, decision variables, and constraints that have been determined above, the power receiving optimization problem of the UAV network can be described as follows:

Objective function:

$$\min F_{\text{obj}} = \left(1 - \eta_{\text{PS-UN}}, C_{\text{mod}}\right). \tag{10}$$

Restrictions:

$$\begin{aligned} \text{SN}_{\text{WPAP}} &\in \{1, 2, \ldots, N_{\text{node}}\}; \\ N_{\text{rmod}} &\geq 0,\ N_{\text{rmod}} \in Z; \\ N_{\text{rmod}} \cdot m_{\text{rmod}} + N_{\text{smod}} \cdot m_{\text{smod}} &\leq \text{ML}_{\text{node}}. \end{aligned} \tag{11}$$

In the previous formula, F_{obj} represents the objective function including two objectives; Z is the integer set; N_{smod} represents the number of wireless power supply modules carried by the UAV network node, which takes the value 1 in the solution of this paper; and ML_{node} represents the maximum load capacity of the UAV network node.

5. Case Study

5.1. Data Preparation. To verify the effectiveness of the optimization model, this paper conducts UAV network microwave wireless power receiving optimization based on the equipment technical parameters and cost data required for optimization, which are compiled from related literature and public data on commercial UAV platforms [6, 7, 12, 13]. The optimization process does not consider the occlusion caused by terrain changes or other reasons and assumes that the atmospheric environment in the experiment remains uniform and undisturbed.

The X-Y plane coordinates of the power supply terminal and the energy receiving UAV network node in the experiment are shown in Figure 3. The Z-axis coordinate of the power supply terminal is 0, and the Z-axis coordinates of the UAV network nodes are all 500. In the experiment, the UAV network nodes are numbered in the order from left to right and bottom to top (on the X-Y plane); the node number in the lower-left corner of the network in the figure is 1, and the node number in the upper right corner is 16. The experimental parameter settings in the solution are shown in Table 1.

5.2. Results and Analysis. When using CCMO to solve the UAV network power receiving optimization problem, the initial main population and the initial archive population containing 25 individuals are first generated, and then 100 evolutions are performed. The result of the last generation of the solution, the optimal Pareto frontier, is shown in Figure 4.

From the trend of the Pareto frontier in Figure 4, it can be seen that the overall power loss rate ($1 - \eta_{\text{PS-UN}}$) and the cost (C_{mod}) of network wireless power transmission equipment have an obvious negative correlation. An energy receiving UAV network with a low overall power loss rate needs to be at the expense of high network wireless power transmission equipment costs. Several sudden changes occurred on the slope of the Pareto frontier in Figure 4. This is because the schemes on the left and right of the slope change the point by selecting different nodes as the WPAP.

After 100 iterations, 25 nondominated UAV network microwave wireless power receiving schemes are finally obtained. These schemes are all theoretically optimal schemes, and decision makers can choose the most suitable planning scheme according to their preferences. For example, decision makers can prioritize the efficiency index of the UAV network power receiving, that is, they can select the optimal solution according to the value of $\eta_{\text{PS-UN}}$. In the Pareto frontier shown in Figure 4, eight representative solutions are selected for further analysis. The selected solutions are shown in Table 2.

It can be seen that in the optimal scheme, when the UAV network node closest to the power supply terminal is selected as the WPAP, the network node carrying fewer power receiving modules can optimize the power receiving efficiency of the network. When choosing the node closer to the center of the network as a WPAP, the network nodes need to carry more power receiving modules to achieve the optimal energy receiving efficiency of the network. Only by choosing a node closer to the center of the network as a WPAP can higher network power receiving efficiency be achieved. At

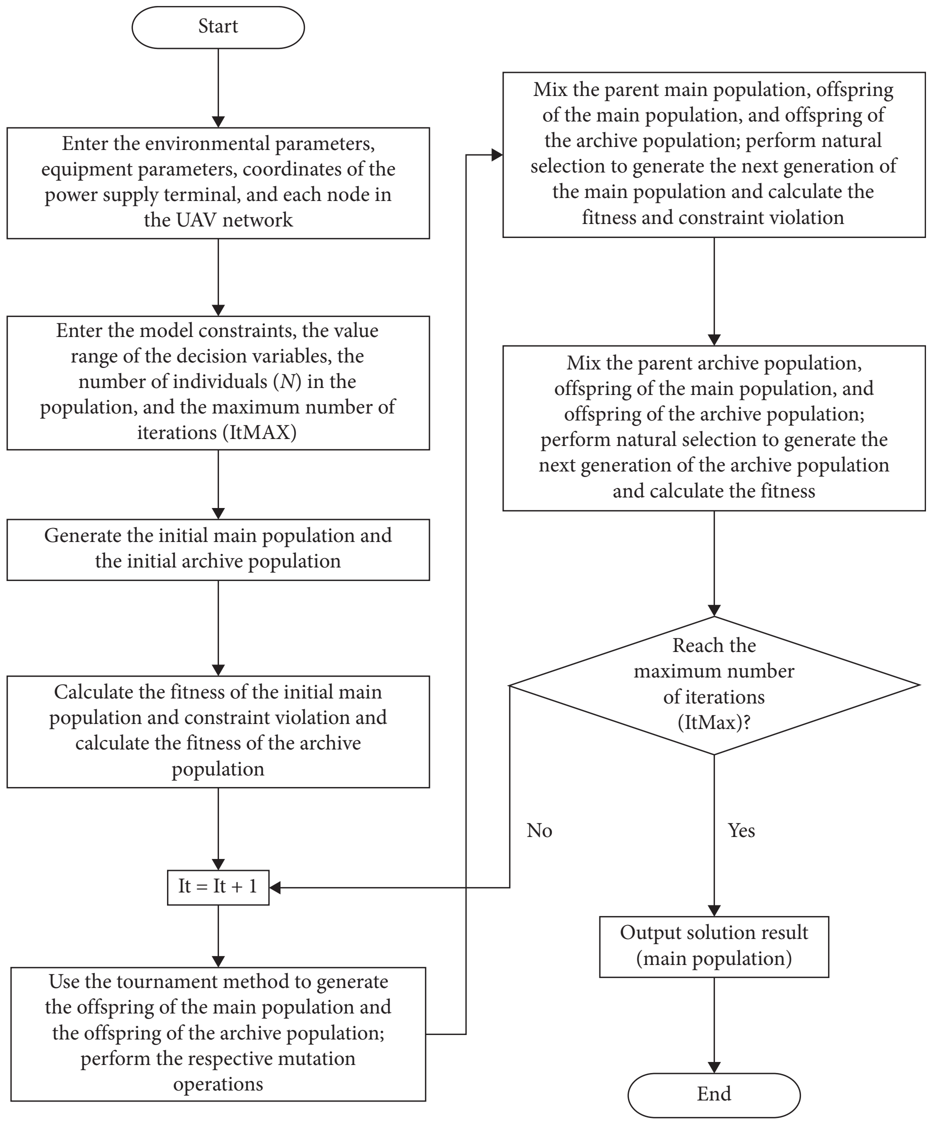

FIGURE 2: Flowchart of the solution based on CCMO.

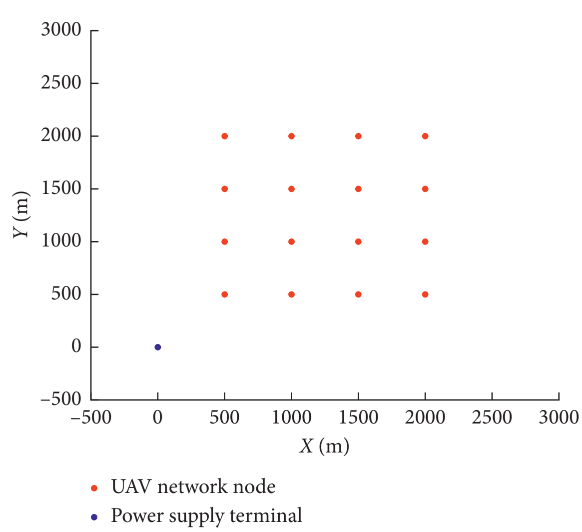

FIGURE 3: X-Y plane coordinates of UAV network nodes and the power supply terminal.

Table 1: Experimental parameters.

Symbol	Value
$\eta_{\text{wes}}^{\text{ps}}$	0.85
$\eta_{\text{wes}}^{\text{smod}}$	0.90
$\eta_{\text{wer}}^{\text{rmod}}$	0.70
γ	1.01×10^{-3}
κ	0.95
N_{node}	16
$\alpha_{\text{wav}}^{\text{ps}}$ (rad)	9.81×10^{-4}
$\alpha_{\text{wav}}^{\text{smod}}$ (rad)	9.81×10^{-4}
m_{smod} (kg)	0.55
m_{rmod} (kg)	0.30
ML_{node} (kg)	6
$S_{\text{wer}}^{\text{rmod}}$ (m^2)	0.1
C_{rmod} (CNY)	1040

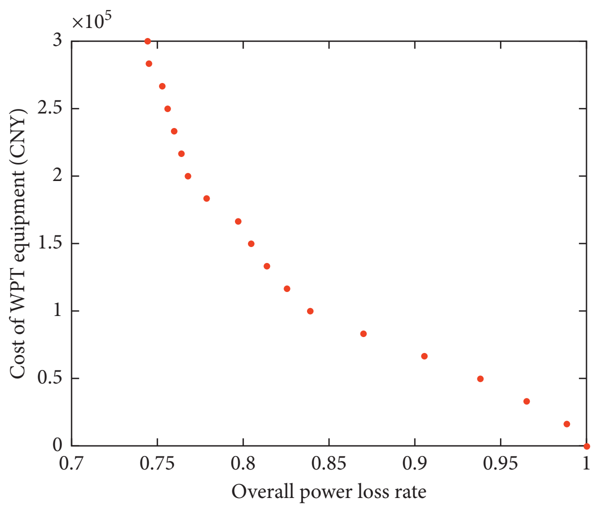

Figure 4: Last generation of the solution.

Table 2: The selected solutions.

Scheme number	Decision variable		Objective	
	SN_{WPAP}	N_{rmod}	$\eta_{\text{PS-UN}}$ (%)	C_{mod} (CNY)
1	1	3	6.20	49920
2	1	6	16.10	99840
3	5	11	22.11	183040
4	2	12	23.22	199680
5	2	14	24.00	232960
6	5	15	24.39	249600
7	6	17	25.48	282880
8	6	18	25.53	299520

this time, the cost of network power receiving equipment is also higher.

In summary, the optimal Pareto front can be obtained by solving the model. The frontier shape conforms to theoretical expectations, and the correctness and effectiveness of the model have been verified. From the solution results, the closer the WPAP is to the energy supply end, the lower the cost of the network power receiving equipment required to achieve the optimal network power receiving efficiency. However, to achieve high network power receiving efficiency, it is necessary to select a node closer to the center of the UAV network as the WPAP, and this will result in higher network power receiving equipment costs.

6. Conclusions

To address the optimization problem of applying microwave wireless power transmission to supply electricity to the UAV network, this paper establishes a corresponding optimization model and performs optimization focused on the selection of the wireless power receiving point and the capacity of the wireless power receiving equipment on the UAV network node. In the practical application of various wireless power transmission technologies, the power transmission efficiency is always one of the key indicators. Besides, the impact of cost must be considered in practice. Therefore, the overall power transmission efficiency and the cost of network wireless power transmission equipment are adopted as objectives in the optimization. Considering that there is a strong coupling between the selection of the WPAP and the capacity optimization of the network power transmission equipment, the sequence number of the WPAP and the number of power receiving modules are coded on an individual in the model solving process based on CCMO. The solution results verify the effectiveness and correctness of the model and solution method in this paper. To achieve higher network power receiving efficiency, it is necessary to select a WPAP closer to the center of the UAV network, but this will cause higher network wireless power receiving equipment costs.

The follow-up research will modify and improve the model and solution method in this paper according to actual needs. The research results of this paper can provide theoretical support for the follow-up research on the construction and optimization of microwave wireless power supply networks composed of multiple links.

Data Availability

Almost all the data are presented in the tables of this paper. If there is a need for any other information, the corresponding author may be contacted by email.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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