Hindawi
Complexity
Volume 2020, Article ID 8871086, 11 pages
https://doi.org/10.1155/2020/8871086

Research Article

Wireless Energy Transmission Link Optimization considering Microwave Energy Relay

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Received 27 August 2020; Accepted 8 September 2020; Published 16 September 2020

Academic Editor: Shi Cheng

With the widespread application of intelligent unmanned units and the development of wireless energy transmission technology, it has become an urgent requirement in the field of using wireless power transmission to extend the continuous working time of unmanned units. To improve the wireless transmission energy efficiency in practical application as much as possible based on the current development level of wireless transmission technology, this paper first enumerates and analyzes existing wireless energy supply methods and shows that microwave wireless energy transmission technology is most suitable in this study. Then, the necessity of power transmission relay in long-distance microwave wireless power transmission is discussed. Based on the idea of microwave energy relay transmission, the paper constructs a microwave wireless transmission link planning model which considers power relay and uses the evolutionary algorithm to solve the wireless transmission link planning model with two-layer optimization. Finally, the results show that, when the wireless transmission distance exceeds a certain threshold, adding relay nodes to the link can improve the energy transmission efficiency from the power supply node to the power receiving node.

1. Introduction

As a new type of power transmission technology, wireless energy transmission can be used to provide continuous energy supply in the working process of the unmanned units to extend their working time and working range [1, 2]. Roughly speaking, wireless energy transmission technology can be divided into near-field (nonradiation) and far-field (radiation) wireless energy transmission technology [3]. Subdivided from the principle of energy transfer, near-field wireless energy transmission can be divided into electric field coupling (electromagnetic induction) and magnetic field coupling (electromagnetic resonance) wireless energy transmission technologies [3, 4]; far-field wireless energy transmission includes ultrasonic wireless energy transmission, microwave wireless energy transmission, and laser wireless energy transmission [5]. These wireless energy transmission methods are different in energy transmission principle, effective energy transmission distance, transmission efficiency, and maturity. Among them, the more mature wireless energy transmission methods that can be initially put into the practical application are electric field coupling [6, 7], magnetic field coupling [8–10], and microwave wireless energy transmission [11, 12].

Because the unmanned unit tends to move in a larger range when performing tasks, the distance between the control terminal and the unmanned unit is as short as hundreds of meters, as long as several kilometers or even tens of kilometers. In this case, various near-field wireless energy transmission methods [13–15] that generally can only perform wireless energy transmission of the order of 10 m cannot meet the requirements of providing continuous and reliable energy supply for unmanned units at work. Compared with the electric field and magnetic field coupling wireless energy transmission method, microwave wireless energy transmission is also mature and its energy transmission distance can reach several kilometers [11], which can well meet the needs of wireless energy transmission link for unmanned units at work [16, 17].

In a uniform atmosphere, the microwave beam attenuates exponentially [18]. In the processof microwave wireless energy transmission, if only the attenuation caused by the atmosphere, the microwave excitation efficiency, and the efficiency of microwave-electric energy conversion are considered, the microwave wireless energy transmission relay will increase the loss during excitation and reception. In this case, theenergy transmission efficiency of the point-to-point direct microwave energytransmission from the power supply end to the power receiving end must behigher than the efficiency of the power supply end forwarding microwave energy to the power receiving end through the relay end.

However, the loss of the microwave beam in the atmosphere is not only the exponential attenuation through the atmosphere but also the loss caused by the beam spreading in space during long-distance transmission (geometric attenuation) [19]. To minimize the latter loss, microwave wireless energy transmission generally uses a directional beam with a small excitation divergence angle for point-to-point energy transmission and at the same time modulates the beam so that most of its energy is concentrated in the center. Even if the above method is used to reduce the geometric attenuation since the excitation divergence angle cannot be zero, the directional beam cannot be regarded as a section of the cylinder from the microwave excitation node plane to the receiving node plane during long-distance transmission but should be regarded as a cone with the microwave excitation point as the apex and the microwave excitation divergence angle as the apex angle [20, 21]; the receiving node can only receive the energy distributed on the effective area of the receiving node antenna (antenna aperture) in the cross section of the beam cone [18]. Due to the limited receiving area of the receiving node antenna, when the geometric attenuation ratio of the point-to-point direct transmission is much greater than the re-excited relay efficiency after the relay node receives and conversion, it is very necessary to carry out the relay energy transmission in the microwave wireless energy transmission process. Figure 1 is a comparison diagram of geometric attenuation of energy transmission through two relays and without relay when the microwave excitation angle is the same.

Adding relay nodes to the link can reduce the geometric attenuation in microwave wireless energy transmission and improve the efficiency of wireless energy transmission from the power supply node to the power receiving node, but it will inevitably bring additional costs because of the purchase and operation of the relay nodes. Therefore, based on the distance between the power supply node to the power receiving node, the microwave excitation divergence angle of the power supply node, and the receiving antenna aperture of the power receiving node, the number and location of the relay node in the link and the required energy-receiving antenna aperture of relay node are needed to be optimized to achieve higher link wireless energy transmission efficiency with the lowest relay cost. In the decision-making process of link construction, it is necessary to increase the number of relays within a certain range and increase the aperture of the energy-receiving antenna of the relay node to improve the efficiency of link wireless energy transmission; this will lead to an increase in the cost of the link. In the construction, the requirement of minimizing the relay cost and the requirement of maximizing the wireless energy transmission efficiency of the link restricts each other, which constitutes a typical dual-objective optimization problem.

This paper is based on the microwave wireless energy transmission technology to construct the wireless energy transmission link considering the energy transmission relay. According to the actual situation of the power supply node and the power receiving node, the relay nodes are added to the link to improve the overall link energy transmission efficiency. Based on the multiobjective evolutionary algorithm, the number and location of the relay nodes in the link and the microwave energy-receiving antenna aperture of the relay nodes are optimized. The main contributions of this paper are as follows:

(1) This paper analyzed the principles, advantages, and disadvantages of current wireless energy transmission methods, explained that microwave wireless energy transmission is the most suitable method for continuous energy supply to unmanned units at work, and discussed the necessity of microwave energy transmission relay.
(2) Unit models for the power supply node, energy receiver node and relay node of the energy transmission link are established, and a microwave wireless energy transmission link planning model that considers energy transmission relay based on the unit model is constructed in this study.
(3) The evolutionary algorithm (NSGA-II) is used to solve the planning model of the microwave wireless energy transmission link considering the energy transmission relay based on a two-layer iterative optimization method. The solution result verifies the effectiveness of the microwave energy relay transmission proposed in this paper.

2. Literature Review

The current research on wireless energy transmission links is mostly based on magnetic field coupling wireless energy transmission technology. The team of Professor Sun from Chongqing University proposed the concept of wireless power transmission network based on magnetic field coupling wireless energy transmission technology [22]. In this wireless power transmission network, multiple relay terminals use their resonant coils to form a resonance link and use the strong coupling between the resonators to form a "high-efficiency energy transmission channel." The relay process does not involve the conversion of energy forms. Using this principle, in literature [23], the transmitter transmits power to the receiver 2 meters away through multiple relay nodes, which improves the effective distance

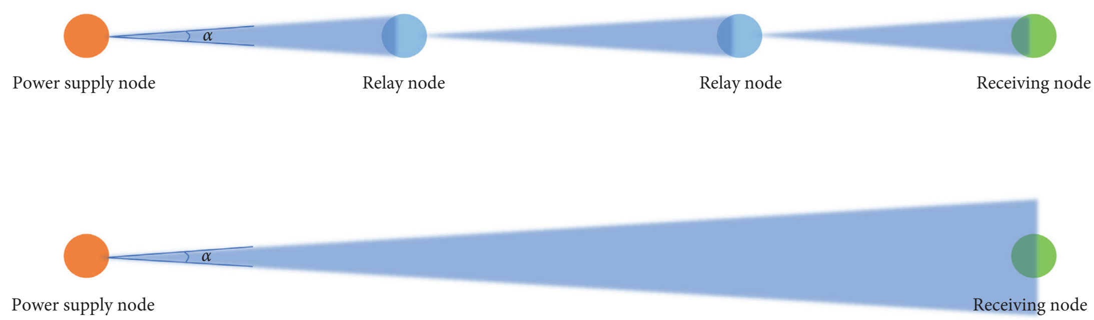

Figure 1: Comparison diagram of geometric attenuation.

of wireless energy transmission. Literature [24] assumes that there are multiple relay nodes randomly distributed in a certain area and uses the ant colony algorithm to realize the optimal selection of relay nodes in the energy transmission link. Under the same assumption, literature [25] uses the cross-entropy algorithm to optimize the energy transmission link, which avoids the problem of ant colony algorithm that is easy to fall into the local optimum in path optimization. Based on whether the wireless power transmission network has a certain transmitting node and whether the transmitting node can provide unlimited power, the wireless power transmission network defined in literature [22] is further divided into active injection wireless power transmission network and passive injection wireless power transmission network in literature [26], and it is proved through experiments that the cellular genetic algorithm can effectively solve the path optimization of wireless power transmission network with active injection and passive injection.

The related research of microwave wireless energy transmission is almost entirely focused on improving the efficiency of DC-microwave conversion, receiving rectification and DC synthesis in the process of direct energy transmission between two points [11, 27]. There is no related research on microwave wireless energy relay transmission. Starting from the microwave wireless energy transmission experiment reported by NASA in 1974, which achieved a DC-to-DC conversion efficiency of 6.7% at a distance of 1.54 km [28], researchers have been committed to improving the overall transmission efficiency of microwave wireless energy transmission. In 2009, the C-band microwave wireless energy transmission system researched by Sichuan University achieved 70% rectification efficiency under the conditions of working frequency 5.8 GHz and transmitting power 600 W; in 2012, a research team from Kyoto University in Japan built an S-band microwave wireless energy transmission system using phased array magnetron; the wireless energy transmission system has a microwave-to-DC conversion efficiency of 54% when the transmission power is 1.9 kW [11]. Literature [27] designed a high-performance microwave source for the power supply node of a microwave wireless power transmission system, using phase-locked loop-based frequency synthesis technology and a monolithically integrated power chip to simplify the circuit system structure.

The idea of relay energy transmission in the wireless power transmission network based on magnetic field coupling wireless energy transmission technology points out a good direction for wireless energy link transmission.

However, limited by the technical principle of magnetic field coupling wireless energy transmission, the wireless power transmission network based on magnetic field coupling wireless energy transmission technology can only provide radio for energy-receiving devices within a range of tens of meters even after multiple relays [23, 26], which is difficult to meet the energy demand of the unmanned unit in this paper. Considering that the microwave wireless energy transmission technology is relatively mature [11], it can carry out the wireless energy transmission of the kilometer level with higher efficiency, and this paper is based on the microwave wireless energy transmission technology to construct the wireless energy transmission link for the working unmanned unit. The position and quantity of the relay node required by the link and the aperture of the energetic antenna at the relay node are optimized to minimize the geometric attenuation of microwave energy in wireless energy transmission and improve the overall efficiency of energy transmission.

What needs to be clear is that, compared with the magnetic field coupling relay energy transmission of Sun Yue's team, the microwave energy relay transmission proposed in this paper uses a similar form of wireless energy link transmission, but whether the energy transmission principle or the meaning of adding relay nodes is completely different from it.

3. Model Construction

3.1. Unit Model. In this paper, the microwave wireless energy transmission link that considers energy relay transmission consists of a fixed energy supply platform (power supply node) as a wireless power transmission source, a relay platform (relay node) that functions as an energy relay in the link, and an unmanned unit (power receiving node) that receives energy. To simplify the calculation, this paper assumes that the microwave beam used in wireless energy transmission is a plane wave and the energy density on the beam section obeys a uniform distribution [20, 21]; the maximum microwave transmission power of the power supply node and the maximum receiving and forwarding power of microwave energy at the relay node is determined according to the power requirements and the microwave energy-receiving capability of the receiving node; this study does not involve the optimization of the transmitting and receiving power of each node in the link.

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

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

where $P_{\mathrm{wes}}^{\mathrm{ps}}$ is the actual microwave transmit power at the power supply node; γ is the atmospheric attenuation coefficient, which is related to the atmospheric conditions on 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 Power Receiving Node. The unmanned unit as the power receiving node receives the microwave energy directly transmitted by the power supply node or forwarded by the relay node during the process of completing the predetermined work.

The parameters of power receiving node include the receiving antenna aperture $S_{\mathrm{wer}}^{\mathrm{pr}}$, the efficiency ($\eta_{\mathrm{wer}}^{\mathrm{pr}}$) of converting the microwave energy distributed on the effective area of the receiving antenna into electrical energy, and the three-dimensional coordinates of the equivalent center point of the receiving antenna (using this as the power receiving node coordinate $\mathrm{POS}_{\mathrm{pr}}$). When the distance between the power receiving node and the microwave emitting source is L_{wet}, the electric power $P_{\mathrm{wer}}^{\mathrm{pr}}$ converted by microwave energy is calculated by the following formula:

$$P_{\mathrm{wer}}^{\mathrm{pr}} = \eta_{\mathrm{wer}}^{\mathrm{pr}} \cdot \min\left(\frac{S_{\mathrm{wer}}^{\mathrm{pr}}}{S_{\mathrm{wav}}\left(\alpha_{\mathrm{wav}}, L_{\mathrm{wet}}\right)}, 1\right) \cdot P_{\mathrm{mwsec}}\left(L_{\mathrm{wet}}\right). \tag{2}$$

Under the plane wave assumption, the beam cross-sectional area $S_{\mathrm{wav}}(\alpha_{\mathrm{wav}}, L_{\mathrm{wet}})$ in the formula is related to the beam cone angle α_{wav} and the transmission distance L_{wet}:

$$S_{\mathrm{wav}}\left(\alpha_{\mathrm{wav}}, L_{\mathrm{wet}}\right) = \pi\left(\tan\left(\frac{\alpha_{\mathrm{wav}}}{2}\right) \cdot L_{\mathrm{wet}}\right)^{2}, \quad \alpha_{\mathrm{wav}} \in (0, \pi). \tag{3}$$

3.1.3. Model of the Relay Node. The relay node plays the role of energy relay and forwarding in the link. Its main parameters include the aperture of the receiving antenna $S_{\mathrm{wer}}^{\mathrm{re}}$, the efficiency ($\eta_{\mathrm{wer}}^{\mathrm{re}}$) of converting the microwave energy distributed on the receiving antenna into electric energy, the excitation angle $\alpha_{\mathrm{wav}}^{\mathrm{re}}$ of the microwave beam, the conversion efficiency ($\eta_{\mathrm{wes}}^{\mathrm{re}}$) of converting electric energy into microwave energy, and the three-dimensional coordinates $\mathrm{POS}_{\mathrm{re}}$ of the relay node.

When the distance between the relay node and the microwave emission source is L_{wet}, the electric power $P_{\mathrm{wer}}^{\mathrm{re}}$ converted by microwave energy is calculated by the following formula:

$$P_{\mathrm{wer}}^{\mathrm{re}} = \eta_{\mathrm{wer}}^{\mathrm{re}} \cdot \min\left(\frac{S_{\mathrm{wer}}^{\mathrm{re}}}{S_{\mathrm{wav}}\left(\alpha_{\mathrm{wav}}, L_{\mathrm{wet}}\right)}, 1\right) \cdot P_{\mathrm{mwsec}}\left(L_{\mathrm{wet}}\right). \tag{4}$$

While receiving energy, the relay node begins to forward microwave energy to the power receiving node or another relay node, and the loss of the transformer and stabilizing circuit in the process is merged into the conversion efficiency ($\eta_{\mathrm{wes}}^{\mathrm{re}}$) of the electric energy to microwave energy. When the relay node emits microwaves, the energy distributed on the beam section at a distance of L_{wet} from it can be calculated by the following formula:

$$P_{\mathrm{mwsec}}\left(L_{\mathrm{wet}}\right) = \eta_{\mathrm{wes}}^{\mathrm{re}} \cdot \kappa \cdot e^{-\gamma \cdot L_{\mathrm{wet}}} \cdot P_{\mathrm{wer}}^{\mathrm{re}}. \tag{5}$$

3.2. Modeling of Microwave Wireless Energy Transmission Link. The relay node in the wireless energy transmission link can have various forms according to actual needs, such as a power relay drone, a relay powered vehicle, or a fixed relay platform. Figure 2 is a schematic diagram of a microwave wireless energy transmission link with power relay drones as relay nodes; the use of power relay drones in the wireless energy transmission link can avoid the interference from ground obstacles. In this paper, the planning model chooses power relay drones as relay nodes to avoid interference from ground obstacles.

Link transmission efficiency is the most important attribute of a wireless energy transmission link. The goal of relaying energy transmission is to reduce the geometric attenuation of microwave energy during transmission. For any two nodes (i, j) in the link, the energy transfer efficiency from node i to node j is calculated by the following formula:

$$\eta_{i-j} = \kappa_{i-j} \cdot \gamma^{L_{i-j}} \cdot \eta_{\mathrm{wes}}^{i} \cdot \eta_{\mathrm{wer}}^{j} \cdot \min\left(\frac{S_{\mathrm{wer}}^{j}}{S_{\mathrm{wav}}^{i}}, 1\right). \tag{6}$$

The cross-sectional area S_{wav}^{i} of the microwave beam emitted by node i at node j is calculated by the following formula:

$$S_{\mathrm{wav}}^{i}\left(\alpha_{\mathrm{wav}}^{i}, L_{i-j}\right) = \pi \cdot \left(\tan\left(\frac{\alpha_{\mathrm{wav}}^{i}}{2}\right) \cdot L_{i-j}\right)^{2}, \tag{7}$$

where L_{i-j} is the straight-line distance from node i to node j.

3.3. Optimization Objectives. The primary goal of wireless energy transmission link construction is to maximize the

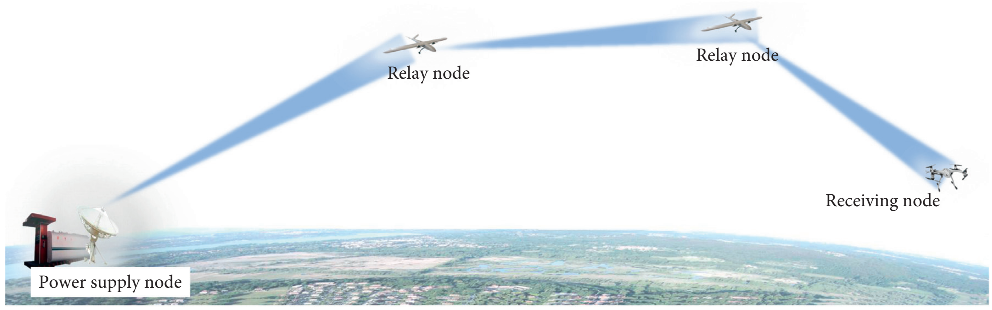

FIGURE 2: Schematic diagram of microwave wireless energy transmission link with multiple relays.

energy transmission efficiency during the energy transmission process from the power supply node to the power receiving node, and the additional cost of adding a relay node must also be considered. Therefore, maximizing link energy transfer efficiency and minimizing relay cost of the link are the optimization objectives for constructing wireless energy transmission links.

3.3.1. Energy Transfer Efficiency of the Link. The energy relay transmission in the microwave wireless energy transmission link is to reduce geometric attenuation and improve the energy transmission efficiency of the link from the power supply node to the power receiving node.

When there are n relay nodes in the link, the link transmission efficiency at a certain moment is calculated as follows:

$$\eta_{\text{link}} = \eta_{\text{ps-re}}\left(L_{\text{ps-re}}\right) \cdot \prod_{i=1}^{n-1} \eta_{\text{re-re}}^{i}\left(L_{\text{re-re}}^{i}\right) \cdot \eta_{\text{re-pr}}\left(L_{\text{re-pr}}\right), \tag{8}$$

where $\eta_{\text{ps-re}}(L_{\text{ps-re}})$, $\eta_{\text{re-re}}^{i}(L_{\text{re-re}}^{i})$, and $\eta_{\text{re-pr}}(L_{\text{re-pr}})$ are the transmission efficiency functions from the power supply node to the nearest relay node, the i^{th} relay node to the next relay node, and the last relay node to the power receiving node.

The specific calculation method of the transmission efficiency at energy time refers to formulae (7) and (8); A, B, and C are, respectively, the power supply node to the nearest relay node, the i^{th} relay node to the next relay node, and the microwave energy transmission distance from the last relay node to the power receiving node. The specific calculation method of the transmission efficiency when energy is directly transmitted between two points refers to equations (7) and (8). $L_{\text{ps-re}}$, $L_{\text{re-re}}^{i}$, and $L_{\text{re-pr}}$ are the microwave transmission distance from power supply node to the nearest relay node, the i^{th} relay node to the next relay node, and the last relay node to the power receiving node, respectively.

3.3.2. Relay Cost of the Link. In energy-related network planning, the cost of a network unit generally includes three parts: acquisition cost, maintenance cost, and operating cost [29]. Since the planning model in this paper is aimed at verifying the effectiveness of relay energy transmission in the link, only the purchase cost of the relay nodes is considered in the optimization. When there are n relay nodes in the link, for the relay cost C_{link}, there is

$$C_{\text{link}} = \sum_{i=1}^{n}\left(C_{\text{fmre}}^{i} + C_{\text{wer}}^{i}\left(S_{\text{wer}}^{i}\right)\right), \tag{9}$$

where C_{fmre}^{i} is the purchase cost of the microwave energy-receiving equipment at the relay node and $C_{\text{wer}}^{i}(S_{\text{wer}}^{i})$ is the purchase cost of the microwave energy-receiving equipment related to the energized antenna aperture S_{wer}^{i} of the i^{th} relay node.

4. Model Solving

In the microwave wireless energy transmission link planning, it is necessary to consider the two mutually restrictive objectives of maximizing the energy transmission efficiency of the link and minimizing the link relay cost, which is a typical dual-objective optimization problem. Among the various existing multiobjective evolutionary algorithms [30, 31], the fast nondominated sorting genetic algorithm with elite strategy (NSGA-II) [32], as an excellent algorithm, has been widely used in many disciplines [33, 34]; its characteristics also fit for the experiments in this study. Therefore, this paper uses NSGA-II to solve the wireless energy transmission link planning model considering energy relay transmission.

To achieve the continuous energy supply of the unmanned unit at work with the relay energy transmission link based on microwave wireless energy transmission technology, while maximizing the transmission efficiency, the number and location of the relay nodes in the link and the aperture of the relay node antenna need to be optimized based on the coordinates and the performance (beam excitation angle, energy-receiving antenna aperture, etc.) of the power supply node and the power receiving node.

Since the number of relay nodes in the decision variable determines the number of coordinates of the relay nodes, encoding the number and the coordinates of relay nodes in the same individual will cause the chromosome length of each individual to be different. In evolutionary calculations, chromosomes of different lengths cannot be crossed. Therefore, the inner layer optimization of the positions of the relay nodes is performed separately, and the optimization of the number and the antenna aperture of relay nodes are completed based on the returned optimization results and other relevant parameters.

Figure 3 shows the solution process of the wireless energy transmission link planning model considering energy relay transmission: the solution adopts the double-layer optimization method. The decision variables of the outer layer optimization are the number and the aperture of the energy-receiving antenna of relay nodes. The optimization objectives are to maximize the link energy transmission efficiency and minimize the link relay cost; the decision variable of the inner optimization is the relay node coordinates, and the optimization objective is to maximize the link energy transmission efficiency. In solution, first, enter the number of population individuals and the number of optimization goals, set the value range of the decision variables, generate the outer optimized initial population, and set the maximum evolutionary generation. Before calculating the objective function value, based on the number and the antenna aperture of relays in the individual, the inner layer optimization calculation is performed on the position of each relay in the link with the objective of maximizing the energy transmission efficiency of the link. Then, save the coordinates of each relay node in the obtained optimization results and use the link energy transfer efficiency of the inner optimization result as one of the objective values of the current individual of the outer layer optimization; the other objective value of the outer layer optimization (relay cost of the link) is calculated based on the input parameters and related formulas. After fast nondominant sorting, crowding calculation, selection, crossover, mutation, and other operations on the initial population, a new generation of population is obtained and double-layer loop iterations are continuously performed before reaching the maximum number of evolutionary iteration. When reaching the maximum number of evolutionary iteration, terminate the loop and output the solution result.

Based on the optimization objectives, decision variables and constraints that have been determined previously, the dual-objective planning problem of wireless energy transmission links considering energy relay transmission can be described as follows:

(a) Outer layer optimization

Objective function:

$$\min F_{\mathrm{obj}} = \left(1 - \eta_{\mathrm{link}}, C_{\mathrm{link}}\right). \tag{10}$$

Restrictions:

$$N_{\mathrm{re}} \geq 0. \tag{11}$$

$$S^{\mathrm{re}}_{\mathrm{wermin}} \leq S^{\mathrm{re}}_{\mathrm{wer}} \leq S^{\mathrm{re}}_{\mathrm{wermax}}. \tag{12}$$

(b) Inner layer optimization

Objective function:

$$\min\left(1 - \eta_{\mathrm{link}}\right). \tag{13}$$

Restrictions:

$$X_{\mathrm{ps}} \leq X_{\mathrm{re}} \leq X_{\mathrm{pr}}. \tag{14}$$

$$Y_{\mathrm{ps}} \leq Y_{\mathrm{re}} \leq Y_{\mathrm{pr}}. \tag{15}$$

$$Z_{\mathrm{ps}} \leq Z_{\mathrm{re}} \leq Z_{\mathrm{pr}}. \tag{16}$$

In the previous formula, F_{obj} represents the objective function including two objectives. The decision variables N_{re} and $S^{\mathrm{re}}_{\mathrm{wer}}$ are the number of relay nodes in the link and the aperture of the energy-receiving antenna at the relay nodes. $S^{\mathrm{re}}_{\mathrm{wermax}}$ and $S^{\mathrm{re}}_{\mathrm{wermin}}$ are the upper and lower limits of the aperture of the energy-receiving antenna at the relay nodes; $(X_{\mathrm{ps}}, Y_{\mathrm{ps}}, Z_{\mathrm{ps}})$ and $(X_{\mathrm{pr}}, Y_{\mathrm{pr}}, Z_{\mathrm{pr}})$ are the coordinates of the power supply node and the energy-receiving node, respectively. The coordinate $(X_{\mathrm{re}}, Y_{\mathrm{re}}, Z_{\mathrm{re}})$ of the relay node is the decision variable for inner optimization, and its value range must meet formulae (13)–(15).

When using NSGA-II to solve the dual-objective planning problem of wireless energy transmission link by two-layer iteration, set the number of individuals in the outer optimization population to 50 and the maximum number of iterations to 100; set the number of individuals in the inner optimization population to 25, the maximum number of iterations is floating according to the actual number of decision-making variables in the inner optimization; the genetic operators all use simulated binary crossover (SBX) and polynomial mutation (PM); for specific parameters, refer to related discussions in [32, 35, 36] and the actual situation in algorithm debugging. The coding of the chromosome in the solution adopts real number coding. In the outer layer optimization, each chromosome is composed of 2 genes (decision variables): $[N_{\mathrm{re}} \mid S^{\mathrm{re}}_{\mathrm{wer}}]$, and in the inner optimization, each chromosome is composed of n genes $(n = 3 \times N_{\mathrm{re}})$: $[X^1_{\mathrm{re}} \mid Y^1_{\mathrm{re}} \mid Z^1_{\mathrm{re}} \mid X^2_{\mathrm{re}} \mid Y^2_{\mathrm{re}} \mid Z^2_{\mathrm{re}} \mid \ldots \mid X^n_{\mathrm{re}} \mid Y^n_{\mathrm{re}} \mid Z^n_{\mathrm{re}}]$.

5. Case Study

5.1. Experimental Data. To verify the effectiveness of energy relay transmission in microwave wireless energy transmission, wireless energy transmission link optimization is performed based on the equipment technical parameters and cost data sorted out from related literature [11, 12, 18, 21]. The actual form of the relay node is an unmanned aerial vehicle carrying energy relay transmission equipment. 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.

Ten times of link planning was carried out in the experiment, and the relative distance between the power supply node and the power receiving node increased linearly in each time. The coordinate system is established with the

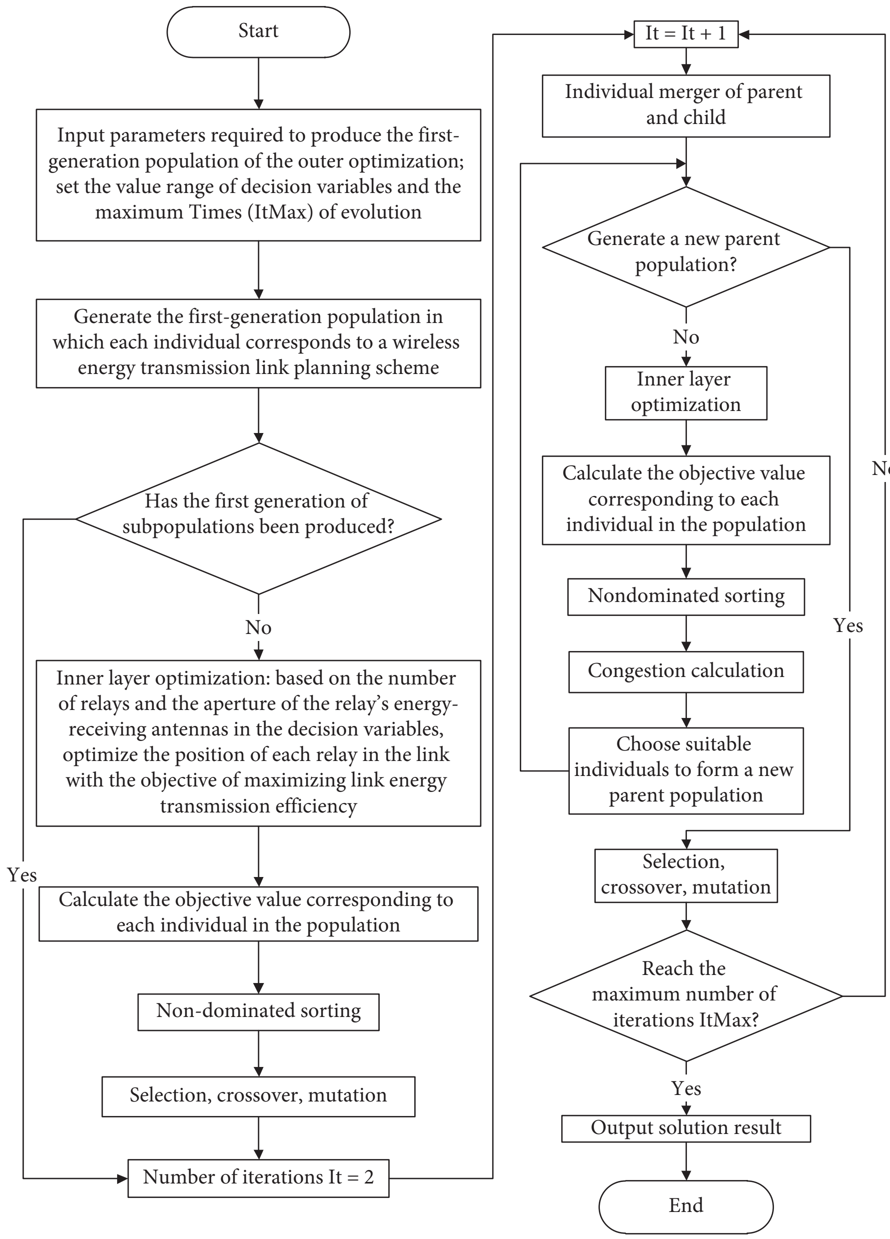

Figure 3: The solution process of the wireless energy transmission link planning model considering energy relay transmission.

power supply node as the origin. The *X-Y* plane position of the power receiving node in the 10 times of planning is shown in Figure 4. The related parameter settings required in the planning are shown in Tables 1 and 2.

5.2. Experimental Results. When using the CCMO and NSGA-II algorithms to solve the problem of wireless energy transmission link planning by a two-layer iterative method, firstly generate an initial population containing 50 individuals of outer optimization and then perform 100 times of two-layer iterative evolution. During iteration, each individual in each generation of the outer layer optimization must complete an inner layer optimization to calculate the value of objectives. The optimal Pareto fronts obtained by solving 10 times in the experiment are displayed in colors on the same graph, as shown in Figure 5. In the figure, the ordinate "Objective 1" is $1 - \eta_{\text{link}}$, and the abscissa "target value 2" is C_{link}.

It can be seen from Figure 5 that there is an obvious negative correlation between the relay cost (C_{link}) and energy transmission loss rate ($1 - \eta_{\text{link}}$) of the link in the solution results of the 10 times planning. To reduce the energy transmission loss rate (that is, to improve the energy transmission efficiency η_{link}) of the link will increase the link relay cost. In other words, a wireless energy transmission link with higher energy transmission efficiency requires a higher link relay cost; the optimal link planning scheme will be obtained by weighing these two optimization objectives. No planning scheme can minimize the relay cost and the energy loss rate of the link at the same time.

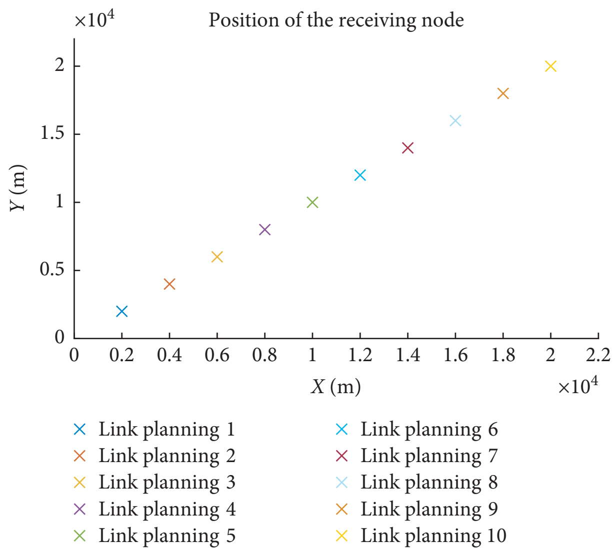

Figure 4: The position of the receiving node in the 10 times of optimization.

Table 1: Experimental equipment parameters.

$\eta_{\text{wes}}^{\text{ps}}$	0.80
$\eta_{\text{wes}}^{\text{re}}$	0.90
$\eta_{\text{wer}}^{\text{pr}}$	0.95
$\eta_{\text{wer}}^{\text{re}}$	0.95
$\alpha_{\text{wav}}^{\text{ps}}$ (rad)	9.81×10^{-4}
$\alpha_{\text{wav}}^{\text{re}}$ (rad)	9.81×10^{-4}
γ	1.01×10^{-3}
κ	0.95
$S_{\text{wer}}^{\text{pr}}$ (m^2)	1
Z_{ps} (m)	0
Z_{pr} (m)	500
$S_{\text{wermax}}^{\text{re}}$ (m^2)	30
$S_{\text{wermin}}^{\text{re}}$ (m^2)	0

In the optimal Pareto set obtained after 100 iterations, the number of nondominated candidate solutions is 50, that is, 50 nondominated dynamic wireless energy transmission link planning schemes are finally obtained (the same in Link Planning 1, 50 schemes have been obtained, but many schemes have similar target values and are not easy to distinguish on the graph). These schemes are all theoretically optimal schemes, and decision-makers can choose the most suitable planning scheme according to their preferences. In terms of scheme selection, many methods can be used to assist decision-makers in making decisions [37–39]. For example, when a decision-maker uses the expectation level method [40] to choose a solution, he can specify that a certain expectation value needs to be achieved on a certain objective and then choose the solution that can achieve this expectation value while performing the best on another objective.

Besides, Figure 5 shows that, when the distance between the power supply node and the power receiving node increases linearly, the maximum energy transmission efficiency that the link can achieve decreases exponentially. This is because the relay node added to the link can only reduce the geometric attenuation in the microwave wireless energy transmission but cannot reduce the atmospheric attenuation in the energy transmission process, so the highest energy transmission efficiency that the link can achieve is mainly affected by the transmission process. The influence of atmospheric attenuation is reflected in the linear increase of the energy transmission distance, and the maximum energy transmission efficiency decays exponentially.

Another feature presented in Figure 5 is that the Pareto front obtained by the solution shows a linear negative correlation when the link relay cost is small and shows a nonlinear negative correlation when the link relay cost is high.

The Pareto front obtained from the sixth solution is selected to further analyze this feature. The Pareto front obtained by the sixth solution is shown in Figure 6; the 10 schemes uniformly drawn from the Pareto front obtained by the sixth solution are shown in Table 3. The target value in the table has converted the energy transmission loss rate $(1 - \eta_{\text{link}})$ into the average link energy transmission efficiency η_{link} of the link, and the schemes in the table are arranged in ascending order according to the value of η_{link}.

It can be seen from Figure 6 that the objective values show a linear negative correlation in the x-axis coordinates (0, 290,000) and (420,000, 550,000). This is because the schemes add the same number of relays in the link (Table 3, schemes 2–4, 5, and 6), and the geometric attenuation during energy transmission decreases linearly with the increase of the antenna aperture mounted on the relay node.

The Pareto front has a gap between the intervals (0, 290,000) and (420,000, 550,000). This is because the scheme in the (420,000, 550,000) interval adds 1 relay node compared with the scheme in the (0, 290,000) interval, and the high single unit cost (29999 CNY) of the relay node causes this gap on the front. When the front edge is in (550,000, 830,000), the two objective values show a distinct nonlinear negative correlation. This is because there are many relay nodes in the link on this part of the front, and the geometric attenuation in the wireless energy transmission process is already very small; further increasing the aperture of the energy-receiving antenna of the relay node has a reduced effect on reducing geometric attenuation. The sudden change of the slope in the middle of this part of the front is because the number of relay nodes on both sides of the slope sudden change point has changed. In general, the shape of the Pareto front obtained by the solution is in line with theoretical expectations and the two-layer iterative solution has found the optimal Pareto front.

In Table 3, the energy transmission efficiency of the link is generally low due to the long distance between the power supply node and the power receiving node (12 kilometers). Scheme 1 does not add a relay node to the link. At this time, although the link relay cost is 0, the energy transmission efficiency of the link is only 0.057%. Wireless energy transmission with such a low energy transmission efficiency will result in huge energy waste, and this scheme is not feasible in practical applications. In contrast, scheme 4 only adds a repeater to the link (the energy-receiving antenna aperture is 19 m^2), which makes the energy transfer efficiency increasing

Table 2: Equipment cost parameters.

Relay node purchase cost (CNY)	29999
Cost of the energy-receiving antenna and related rectifier equipment (CNY/m^2)	10400

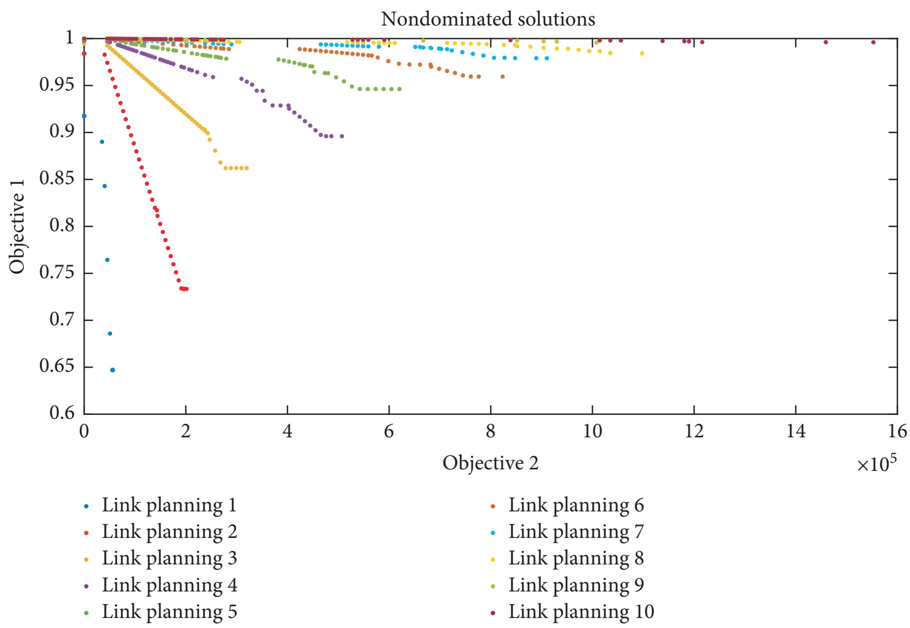

Figure 5: The optimal Pareto front obtained by solving 10 times.

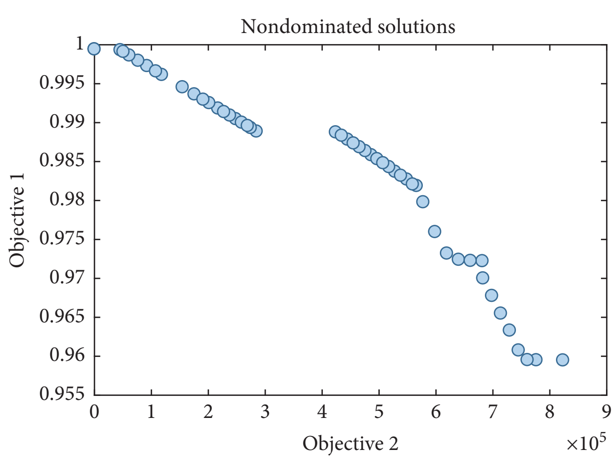

Figure 6: The Pareto front obtained by link planning 6.

Table 3: The Pareto solution of link planning 6.

Serial number	Decision variable		Objective value	
	N_{re}	S_{wer}^{re} (m^2)	η_{link} (%)	C_{link} (CNY)
1	0	0	0.057547	0
2	1	4.5	0.204328	76799
3	1	12	0.544805	154799
4	1	19	0.862794	227599
5	2	17.5	1.123708	423998
6	2	21.5	1.519537	507198
7	5	8	1.811696	565995
8	4	13.5	2.777558	681596
9	3	23.5	4.051886	823197

by about 15 times compared with scheme 1 (to 0.86%). Of course, the energy transfer efficiency of 0.86% also has lower practical feasibility, but the huge improvement of scheme 4 compared with scheme 1 fully shows that adding a suitable number of relay nodes to the link can effectively improve the average energy transmission efficiency of the link.

After the previous in-depth analysis of the optimal Pareto frontier obtained by the solution, the optimal Pareto solution is generally in line with the expected solution result based on the input data information and model constraints. The solution scheme shows a good optimization effect, and the effectiveness of the wireless energy transmission link multiobjective planning model in this paper has been verified; energy relay transmission in the microwave wireless energy transmission link in this paper can effectively improve the energy transmission efficiency of the link. Decision-makers can weigh the energy transfer efficiency requirements and economic cost budgets to choose a suitable scheme on the optimal Pareto frontier.

6. Conclusion

Aiming at the problem of realizing wireless power supply for unmanned units at work based on the current wireless energy transmission technology level and improving the energy transmission efficiency as much as possible, this paper proposes an energy supply method based on microwave wireless energy transmission technology, which transmits microwave energy from the power supply node to the power receiving node through a certain number of relay nodes.

First, the paper analyzes the characteristics of several types of currently more mature wireless energy transmission technologies and concludes that microwave wireless energy transmission is the most suitable way in the current application context. Then, under the condition that the receiving antenna aperture of the receiving node is fixed, the feasibility of effectively reducing the geometric attenuation in long-distance microwave wireless energy transmission by relaying microwave energy is discussed; the planning model of microwave wireless energy transmission link considering energy relay transmission is established and solved. Finally, an experiment was designed to verify the important role of microwave energy relay transmission in reducing the geometric attenuation in the process of microwave wireless energy transmission.

The geometric attenuation of microwave wireless energy transmission increases sharply with the increase of the energy transmission distance. When the divergence angle of the microwave excitation at the power supply node is constant and the antenna aperture of the power receiving node is limited, adding an appropriate number of relay nodes between the power supply node and the power receiving node of long-distance microwave wireless energy transmission can effectively reduce the geometric attenuation during transmission. When the number and the receiving antenna aperture of relay nodes are optimal, the effect of nearly completely avoiding geometric attenuation during transmission can be achieved at a lower additional cost, and the transmission efficiency from the power supply node to the receiving node can be maximized.

Besides, because the relay nodes can be deployed flexibly, the power supply node can also use microwave energy relay transmission to transmit energy to the power receiving node which is blocked by obstacles during point-to-point linear transmission. These characteristics reflect the feasibility of providing continuous energy supply to unmanned units in operation based on the current microwave wireless energy transmission technology, and the value of microwave energy relays transmission in practical applications.

The follow-up research will further enrich the planning model of microwave wireless energy transmission links based on the existing microwave wireless energy transmission technology and the idea of relay energy transmission. The research results of this paper can provide theoretical support for the subsequent theoretical research and engineering design of medium/long-distance wireless energy transmission links and wireless energy transmission networks.

Data Availability

The data used to support the study are presented within the article. Other data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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