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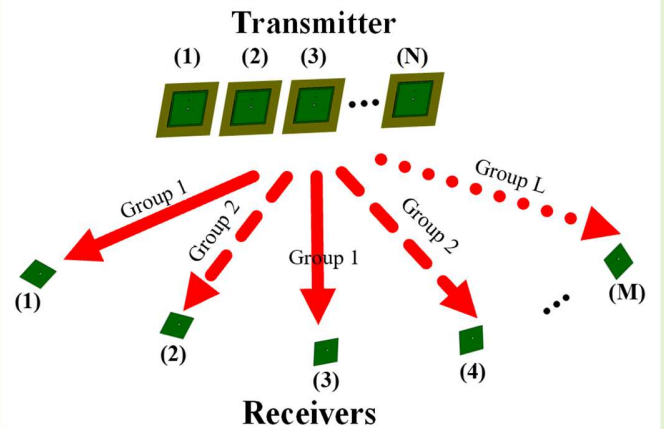
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# High-Efficiency Multi-User Wireless Power Transfer by Sequentially Tracking the Optimal Rectified Power of Multiple Groups with a Power-Limited Transmitter

Lin Hu, Xin Ma, Josep Parron, Pedro de Paco, *Senior Member, IEEE*, Deshuang Zhao, *Member, IEEE*, Bing-Zhong Wang, *Senior Member, IEEE*

**Abstract**—In practical wireless power transfer (WPT) system with multiple nonlinear receivers and a power-limited transmitter, rectification efficiency may be low because the received radio frequency (RF) power of receiver does not match the optimal rectified power. To tackle the challenge that a power-limited transmitter actively transmits RF power to satisfy different power demands with high efficiency and large average output direct current (DC) power, this article proposes a novel high-efficiency multi-user WPT. In this scheme, the transmission signals are optimized based on the receive RF signals with power equal to the optimal rectified power from the selected receivers, so the selected receivers can track the optimal rectified power within a time slot. Then, we formulate a bi-level optimization problem under the constraint of transmit power to group all receivers and optimize the transmission signals of each group. Multiple groups sequentially track the optimal rectified power across multiple time slots with a power-limited transmitter, thereby tackling the challenge. In order to solve the non-convex bi-level optimization problem, a bi-level genetic algorithm is adopted to obtain the optimal solution. Numerical and experimental results show that the RF-RF-DC efficiency and output DC power of the proposed scheme are up to 2.6 and 3.7 times higher than those of the traditional schemes. Additionally, only our scheme meets the different power demands of multiple receivers, ensuring the same survival time. Furthermore, our scheme can also provide guidance for practical WPT system design and has the potential of compatibility with other existing systems.

**Index Terms**—multi-user wireless power transfer, nonlinear, high efficiency, optimal rectified power tracking



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## I. Introduction

WITH the rapid development of the Internet of Things (IoT) era, a large number of sensors, which are located far away from the power transmitter, are embedded in the surrounding environment. However, the power supply for most of these sensors still relies on batteries or cables, thus dimming the bright light of the Internet of Everything (IoE). The microwave power transfer (MPT) technology, which has the advantages of multi-beam [1-5], and long distance [1-2][6], has become a potential solution to make the massive sensors immortal at present [7-9].

Previously, researchers assumed that the efficiency curve of the rectifier circuit follows a linear model (higher power leads

to higher efficiency) [10]. Consequently, time-division or space-division energy beamforming schemes for multi-user MPT, based on the goal of “max-sum”, were proposed. Time-division refers to the allocation of power transmitted by the transmitter to only one receiver in one time slot. Space-division refers to the distribution of RF power transmitted by the transmitter to all receivers at the same time. “Max-sum” refers to the optimization goal of maximizing the sum of output DC power across all receivers.

The optimization trend of “max-sum” is to allocate the RF power to the receivers with high RF-RF efficiency as much as possible. This results in the characteristic of high peak-to-average power ratio in the final output DC power of multiple users. Benefiting from the characteristics of the linear model, the multi-user scheme based on “max-sum” achieves a large sum of output DC power and high rectification efficiency. However, the high peak-to-average power ratio obtained by the “max-sum” may lead to low RF-RF efficiency receivers receiving minimal power, rendering them unable to work (the power blind spot problem) [11].

In order to address the power blind spot problem in low RF-RF efficiency receivers, the goal of “max-min” is proposed. “Max-min” refers to the optimization goal of maximizing the minimal of output DC power of each receiver. The optimization trend of “max-min” is to allocate RF power to low RF-RF efficiency receivers, aiming to make the output DC power from each receiver as consistent as possible. This results in the characteristic of low peak-to-average power ratio in the final output DC power of multiple users.

Both “max-sum” and “max-min” are inspired by the notion that higher power in linear models leads to greater efficiency. However, in practical MPT systems, the relationship between the rectification efficiency and the input RF power of actual rectifier circuits exhibits nonlinear characteristics due to the use of nonlinear components such as diodes [12-13]. This nonlinear characteristic is typically manifested as a single-peak feature in rectification efficiency. This feature causes the results optimized with linear models to deteriorate in actual testing, as the higher power in the real rectifier circuit results in lower efficiency. Therefore, the nonlinear model is introduced to simulate the nonlinear characteristics of rectifier circuits more accurately as shown in Fig.1 [14]. We commonly refer to the input RF power corresponding to the highest rectification efficiency as the optimal rectified power.

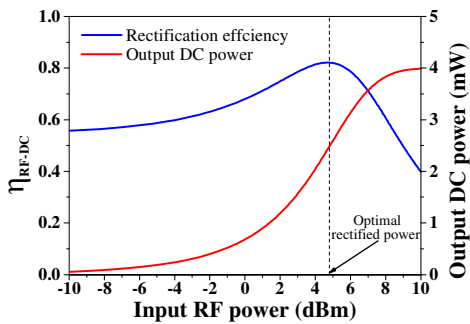


Fig. 1. Nonlinear characteristics of the actual rectifier circuit.

Afterwards, many researchers have investigated multi-user WPT with nonlinear models according to the combination of optimization goals (max-sum and max-min) and diversity techniques (time division and space division) [15-18]. Literature [16-17] achieves a higher total output DC power than the linear model by using a nonlinear model. However, the inherent power blind spot issue of the “max-sum” still persists. Additionally, rectification efficiency is not optimal because the received RF power does not equal the optimal rectified power. Literature [18] adopts a nonlinear model and jointly optimizes the duration of each time slot and the transmission signals, resulting in a higher minimum output DC power. However, the rectification efficiency of the “max-min” is also not optimal because the received RF power does not equal the optimal rectified power.

“max-sum” and “max-min” result in received RF power that does not match the optimal rectified power, leading to low rectification efficiency and low RF-RF-DC efficiency. The low efficiency will lead to poorer system safety, electro-magnetic compatibility, and economy, as the transmitter needs to transmit higher RF power to meet the power demands of receivers. In addition, the power demands of multiple receivers in actual IoT scenarios are different. Nevertheless, both the results with a high peak-to-average ratio obtained by the “max-sum” and the results with a low peak-to-average ratio obtained by the “max-min” fail to meet the diverse power requirements of multiple users in practical scenarios. This thus motivates us to investigate a new high-efficiency multi-user WPT scheme, in order to satisfy different power demands of multiple nonlinear receivers with high efficiency.

Therefore, this article proposes a novel high-efficiency multi-user WPT by sequentially tracking the optimal rectified power of multiple groups. This scheme groups all receivers and optimizes the transmission signals under the limitation of maximum transmitted RF power ( $PT_{max}$ ) to make the receivers in each group to simultaneously track the optimal rectified power within a time slot. As a result, multiple groups perform WPT sequentially, allowing all receivers to track the optimal rectified power across multiple time slots. So, the RF power received at the receiver is converted into DC power with the maximum rectification efficiency to achieve higher efficiency, greater average output DC power that is equal to the multiple of the power demand under the limitation of  $PT_{max}$ .

First, a qualitative description and a simple example of quantitative calculation are used to illustrate the superiority of our optimal rectified power tracking scheme. Then, this scheme formulates the lower-level optimization problem (Follower) to achieve high RF-RF-DC efficiency with the constraint that the received RF power is equal to the optimal rectified power, and formulates the upper-level optimization problem (Leader) to making the power of the transmission signals of each group close to  $PT_{max}$ , so as to achieve the maximum average output DC power under the limitation of  $PT_{max}$ . To solve this non-convex bi-level optimization problem, a solution based on a bi-level genetic algorithm is adopted [19-20].

Numerical simulations and prototype experiments will be carried out to verify that our approach can provide a more

feasible and high-performance solution for achieving immortality of multiple nonlinear users with different power demands in practical indoor scenarios, thereby promoting the application of maintenance-free and immortal wireless sensors in the Internet of Things (IoT).

The remainder of this paper is organized as follows, the related work is introduced in Section II. The system model is described in Section III. The idea and details of our proposed scheme are analyzed in Section IV. The numerical results are presented in Section V. Experiments are carried out in Section VI. Finally, the conclusions are drawn in Section VII.

## II. RELATED WORK

In order to immortalize wireless sensors and enter the true wireless era, many researchers have conducted research on multi-user microwave power transfer.

The previous research work on multi-user microwave wireless energy transmission can be roughly summarized as follows: Goal: “max-min” and “max-sum”; Diversity technology: time division and space division.

According to the combination of optimization goals (max-sum and max-min) and diversity techniques (time division and space division), the traditional four schemes can be obtained, which are: Time Division with “max-min” (TD+MAX-SUM or TD-MS), Space Division with “max-min” (SD+MAX-SUM or SD-MS), Time Division with “max-sum” (TD+MAX-MIN or TD-MM), Space Division with “max-sum” (SD+MAX-MIN or SD-MM).

Next, we will give the details of these traditional schemes.

### A. Time Division with “max-sum”

With the goal of maximizing the sum value of the DC output power of all receivers allocated in different time slots by optimizing the time allocation  $[\tau_1, \tau_2, \dots, \tau_M]$  with the basic transmission signal matrix  $\mathbf{X}$

$$\mathbf{P1:} \quad \max_{[\tau_1, \tau_2, \dots, \tau_M]} \sum_{i \in [1, 2, \dots, M]} \tau_i \times P_{DC}(y_i^H y_i) \quad (1)$$

$$\text{s. t.} \quad \sum_{i=1}^M \tau_i = T \quad (2)$$

$$\mathbf{h}_i^* \mathbf{h}_i \leq PT_{max} \quad (3)$$

$$P_{DC}(y_i^H y_i) \leq P_{max}^j \quad (4)$$

where  $P_{max}^j$  represents the maximum output DC power of the  $j$ th rectifier,  $y_i = \mathbf{h}_i^T \mathbf{x}_{SD}$  represents the RF signal received by the  $i$ -th receiver,  $P_{DC}$  represents the output DC power. (3) is the constraint that the transmit power is less than  $PT_{max}$ . (4) is the constraint that the output DC power should be less than  $P_{max}^j$ .

Sequentially feed the column vectors of the basic transmission signal matrix  $\mathbf{X}$  into the transmitter according to the optimized time allocation.

### B. Space Division with “max-sum”

With the goal of maximizing the sum value of the DC output power for all receivers by optimizing the superposition of the basic transmission signals weighted by coefficient  $w_i$  to get the final transmission signal vector  $\mathbf{x}_{SD}$

$$\mathbf{P2:} \quad \max_{[w_1, w_2, \dots, w_M]} \sum_{i \in [1, 2, \dots, M]} P_{DC}(y_i^H y_i) \quad (5)$$

$$\text{s. t.} \quad \mathbf{x}_{SD}^H \mathbf{x}_{SD} \leq PT_{max} \quad (6)$$

$$P_{DC}(y_i^H y_i) \leq P_{max}^j \quad (7)$$

where  $y_i = \mathbf{h}_i^T \mathbf{x}_{SD}$  represents the RF signal received by the  $i$ -th receiver,  $\mathbf{x}_{SD} = \sum_{i=1}^M w_i \mathbf{h}_i^*$  represents the final transmission signal vector obtained by superposition of the weighted basic transmission signal.

Feed the transmission signal vector  $\mathbf{x}_{SD}$  into the transmitter.

### C. Time Division with “max-min”

With the goal of maximizing the minimum value of the DC output power of all receivers allocated in different time slots by optimizing the time allocation  $[\tau_1, \tau_2, \dots, \tau_M]$  with the basic transmission signal matrix  $\mathbf{X}$

$$\mathbf{P3:} \quad \max_{[\tau_1, \tau_2, \dots, \tau_M]} \min_{i \in [1, 2, \dots, M]} \tau_i \times P_{DC}(y_i^H y_i) \quad (8)$$

$$\text{s. t.} \quad \sum_{i=1}^M \tau_i = T \quad (9)$$

$$\mathbf{h}_i^* \mathbf{h}_i \leq PT_{max} \quad (10)$$

$$P_{DC}(y_i^H y_i) \leq P_{max}^j \quad (11)$$

Sequentially feed the column vectors of the basic transmission signal matrix  $\mathbf{X}$  into the transmitter according to the optimized time allocation.

### D. Space Division with “max-min”

Combine the channel and received power information obtained in step 1 and step 2, with the goal of maximizing the minimum value of the DC output power for all receivers by optimizing the superposition of the basic transmission signals weighted by coefficient  $w_i$  to get the final transmission signal vector  $\mathbf{x}_{SD}$

$$\mathbf{P4:} \quad \max_{[w_1, w_2, \dots, w_M]} \min_{i \in [1, 2, \dots, M]} P_{DC}(y_i^H y_i) \quad (12)$$

$$\text{s. t.} \quad \mathbf{x}_{SD}^H \mathbf{x}_{SD} \leq PT_{max} \quad (13)$$

$$P_{DC}(y_i^H y_i) \leq P_{max}^j \quad (14)$$

Feed the transmission signal vector  $\mathbf{x}_{SD}$  into the transmitter.

## III. SYSTEM MODEL

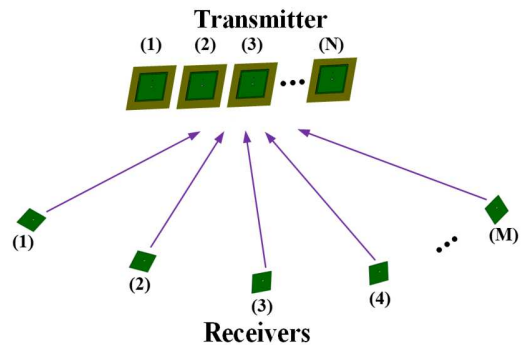


Fig. 2. Illustration of the detection phase of the high-efficiency multi-user WPT.

Fig.2 depicts a multi-user WPT system that includes a transmitter with  $N$  antennas and  $M$  receivers. It is assumed that the channels between the transmitter and the multiple receivers are time-invariant and reciprocal. For all WPT schemes studied

in this article, the suppression of the sidelobe power is performed so that the WPT system can have better security, electromagnetic compatibility, and selectivity.

#### A. Time Reversal method

Time reversal (TR) has the characteristics of adaptive focusing and optimal RF-RF efficiency [4][6]. Therefore, the transmission signal of receiver in all the schemes in this paper is obtained by the TR method. The details of the TR method are as follows:

*Step 1:* Multiple receivers sequentially transmit the pilot signal to the transmitter as shown by the thin purple arrow in Fig.2, and the transmitter extracts the waveform parameters of the pilot signals to obtain the channel information between the transmitting and receiving antennas as follows:

$$\mathbf{H}^{M \times N} = [\mathbf{h}_1, \mathbf{h}_2, \dots, \mathbf{h}_m, \dots, \mathbf{h}_M]^T \quad (15)$$

The  $m$ th row vector  $\mathbf{h}_m^T = [h_{1,m}, h_{2,m}, \dots, h_{N,m}] \in \mathbb{C}^{1 \times N}$  represents the channel information between the  $m$ th receiving antenna and each transmitting antenna.

*Step 2:* The TR operation is performed on the channel information of multiple receivers to obtain the basic transmission signal matrix as follows:

$$\mathbf{X}^{N \times M} = \mathbf{H}^H = [\mathbf{h}_1^*, \mathbf{h}_2^*, \dots, \mathbf{h}_m^*, \dots, \mathbf{h}_M^*] \quad (16)$$

The  $m$ th column vector  $\mathbf{h}_m^*$  represents the transmission signals for generating a focal spot at the  $m$ th receiver. Thus, the received signals for multiple receivers can be expressed in matrix form with  $\mathbf{H}^{M \times N}$  and  $\mathbf{X}^{N \times M}$  as:

$$\mathbf{Y}^{M \times M} = \mathbf{H}\mathbf{X} = \begin{bmatrix} (y_{1,1}) & \dots & (y_{1,m}) & \dots & (y_{1,M}) \\ \vdots & \ddots & \vdots & & \vdots \\ (y_{m,1}) & \dots & (y_{m,m}) & \dots & (y_{m,M}) \\ \vdots & & \vdots & \ddots & \vdots \\ (y_{M,1}) & \dots & (y_{M,m}) & \dots & (y_{M,M}) \end{bmatrix} \quad (17)$$

where the diagonal and off-diagonal elements of the matrix  $\mathbf{Y}$  represent the focused signals harvested by the receivers and the sidelobe signals, respectively.

#### B. Channel model

In order to obtain numerical simulation results that are closer to the actual situation, the widely mentioned Rician fading channel was adopted [18]. In the numerical simulations, the Rician fading channel from the transmitting antenna  $n$  to receiver  $m$  is given by

$$h_{n,m} = \sqrt{\frac{\kappa}{1+\kappa}} h_{n,m}^{LOS} + \sqrt{\frac{1}{1+\kappa}} h_{n,m}^{NLOS} \quad (18)$$

where  $\kappa$  represents the Rician factor with the value of 10 dB,  $h_{n,m}^{LOS}$  is generated by the direct path between the transmitting and receiving antennas calculated by the Green's function combined with the radiation patterns of the transmitting and receiving antennas [6],  $h_{n,m}^{NLOS}$  is generated by multiple scattering paths with the Rayleigh fading channel model.

In the experiment, the channel information between the transmitter and receiver is obtained through step 1 of the TR method described above.

#### C. Rectifier model

In order to evaluate the RF-RF-DC efficiency, a nonlinear rectifier circuit model is adopted [14], where the output DC

power  $P_{DC}$  and the input RF power  $P_{in}$  shows a nonlinear relationship. The rectification efficiency  $\eta_{RF-DC}$  of the rectifier circuit increases first and then decreases with the input RF power  $P_{in}$ .

$$\eta_{RF-DC}(P_{in}) = \frac{P_{max}/(1 + e^{-a(P_{in}-b)}) - P_{max}/(1 + e^{ab})}{e^{ab}P_{in}/(1 + e^{ab})} \quad (19)$$

$$P_{DC}(P_{in}) = P_{in} \times \eta_{RF-DC}(P_{in}) \quad (20)$$

where  $P_{max}$  represents the maximum DC output power of the rectifier circuit,  $a$  and  $b$  are two constants to describe the nonlinearity of the specific rectifier circuit, respectively.

A detailed list of symbols, terms or concepts and their description is provided in Table I.

TABLE I  
DESCRIPTION OF THE SYMBOLS TERMS, AND CONCEPTS USED IN THIS PAPER

| Symbol                    | Description                                                                            |
|---------------------------|----------------------------------------------------------------------------------------|
| Bold letters              | Denote matrices or vectors                                                             |
| $\text{diag}()$           | Operator for converting a vector to a diagonal matrix                                  |
| $()^*$                    | Conjugate operation                                                                    |
| $()^T$                    | Transpose operation                                                                    |
| $()^H$                    | Conjugate transpose operation                                                          |
| $\mathbb{R}$              | Space of real number                                                                   |
| $\mathbb{C}$              | Space of complex numbers                                                               |
| $\tau_i$                  | Time allocation                                                                        |
| $T$                       | Period                                                                                 |
| $P_{DC}$                  | Output DC power                                                                        |
| $N$                       | Number of transmitting antenna                                                         |
| $M$                       | Number of receiver                                                                     |
| $P_{Tmax}$                | Maximum transmitted RF power                                                           |
| $\mathbf{h}_m$            | Channel information between the $m$ th receiving antenna and each transmitting antenna |
| $y_i$                     | RF signal received by the $i$ -th receiver                                             |
| $P_{in}$                  | Input power of rectifier                                                               |
| $P_{max}$                 | Maximum output DC power of rectifier                                                   |
| $\mathbf{X}$              | Basic transmission signal matrix obtained from TR                                      |
| $\mathbf{x}_{SD}$         | Transmission signal matrix of space diversion                                          |
| $\mathbf{X}_{ORPT}$       | Transmission signal matrix of our scheme                                               |
| $w_i$                     | Weighted coefficient to get $\mathbf{x}_{SD}$                                          |
| $\kappa$                  | Rician factor                                                                          |
| $\eta_{RF-DC}$            | Efficiency of RF-DC                                                                    |
| $\eta_{RF-RF-DC}$         | Efficiency of RF-RF-DC                                                                 |
| $a, b$                    | Two constants to describe the nonlinearity of the specific rectifier circuit           |
| $pr_m$                    | Optimal rectified power of the $m$ th receiver                                         |
| $Pd_m$                    | Dissipated power of the $m$ th receiver                                                |
| $\eta_m^{max}$            | Maximum rectification efficiency of the $m$ th receiver                                |
| $\mathbf{D}^{L \times M}$ | Grouping matrix                                                                        |
| $L$                       | Number of group                                                                        |
| $y_{lm}$                  | Signal received by the $m$ th receiver within the $l$ th time slot                     |
| $\varphi_m$               | Phase of $y_{lm}$                                                                      |
| $\theta_m$                | Angle of the $m$ th receiver                                                           |
| $Power_t$                 | Transmission power corresponding to each scheme                                        |

## IV. HIGH EFFICIENCY MULTI-USER WPT SCHEME

### A. Idea of Optimal Rectified Power Tracking Scheme

Distinct from the “max-sum” and “max-min”, inspired by higher power in linear models leads to greater efficiency, we conceived a new approach based on the single-peak feature in

rectification efficiency of the actual rectifier circuit. The idea is that if we can make the received RF power at the receiver equal to the optimal rectified power, so we can achieve the highest rectification efficiency. And if we can obtain the transmission signal with the minimum power while keeping the received RF power fixed, then we achieve optimal RF-RF efficiency [21], thereby realizing higher system efficiency. We refer to this idea as Optimal Rectified Power Tracking (ORPT).

The minimum power transmission signals are optimized from the receive signals with power equal to the optimal rectified power, which we call the high efficiency optimization problem without transmit power constraints (elaborated later in the optimization problem **P6**).

Additionally, in order to meet different power demands, the optimal rectified power of the receiver in this article is designed according to its dissipated power as

$$pr_m = \frac{M \times Pd_m}{\eta_m^{max}} \quad (21)$$

where  $pr_m$  represents the optimal rectified power of the  $m$ th receiver,  $Pd_m$  represents the dissipated power of the  $m$ th receiver,  $\eta_m^{max}$  represents the maximum rectification efficiency of the  $m$ th receiver. This design can ensure that all receivers can survive for the same duration after tracking the optimal rectified power in a time block, which helps the realization of immortal receivers in practical scenarios [22].

### B. Idea of Sequentially Tracking the Optimal Rectified Power of Multiple Groups with a Power-Limited Transmitter

However, it should be noted that the above implementation can realize the optimal rectified power tracking but does not consider the constraint of the maximum transmitted RF power available. In fact, any WPT system is limited by its maximum transmitted RF power  $PT_{max}$ . On the one hand, simultaneously tracking the optimal rectified power of all receivers (SD-ORPT) results in a transmit power much greater than  $PT_{max}$ . So, the received RF power less than the optimal rectified power with a power limited transmitter, resulting in low efficiency. On the other hand, tracking the optimal rectified power of each receiver sequentially (TD-ORPT) results in a transmit power much less than  $PT_{max}$ . As a result, the average output DC power is small throughout the entire time block, although the optimal rectified power tracking is achieved.

In summary, SD-ORPT cannot be achieved because the required transmission power in this case far exceeds  $PT_{max}$ . On the other hand, TD-ORPT can be realized, but the reason for the lower average output power is that the transmission power is much less than  $PT_{max}$ . This inspires the idea that if we increase the number of receivers in a time slot, allowing the power levels of the transmission signals corresponding to these receivers to be closest to  $PT_{max}$ , then we can achieve both optimal efficiency and maximum output DC power under the constraint of  $PT_{max}$ .

Therefore, this article proposes the sequentially tracking the optimal rectified power of multiple groups scheme to achieve optimal rectified power tracing and large average output DC power under the limitation of  $PT_{max}$  (elaborated later in the bi-level optimization problem). This scheme jointly optimizes

grouping matrix **D** (**Leader** of the bi-level optimization problem) and the transmission signal matrix **X** (**Follower** of the bi-level optimization problem) to ensure that the power of the transmission signals  $\mathbf{x}_l$  in each group is close to  $PT_{max}$ , and that the transmission signals  $\mathbf{x}_l$  with minimum power in each group can simultaneously track the optimal rectified power of the receivers selected by each group. Finally, multiple groups perform WPT sequentially, allowing all receivers to track the optimal rectified power across multiple time slots.

### C. Superiority of Sequentially Tracking the Optimal Rectified Power of Multiple Groups with a Power-Limited Transmitter

Firstly, we qualitatively demonstrate the superiority of the proposed scheme through the specific implementation process.

Step1: Obtaining parameters such as the number of transmitting antennas, the number of receivers, the transmission distance, and the dissipated power of the receivers based on the specific requirements of practical application scenarios such as sensors in smart agriculture, home automation, and environmental monitoring and so on.

Step2: Obtaining the optimal rectified power value corresponding to the receiver through equation (13) and dissipation power information, and designing a rectification circuit based on the specified indicators.

Step3:  $PT_{max}$  is set as a variable, and the optimal grouping matrix and transmission signal matrix are obtained for different  $PT_{max}$  scenarios through the bi-level optimization problem. An appropriate  $PT_{max}$  is selected to guide the design of the transmitter that can meet the actual power requirements.

Therefore, we present universally applicable results obtained in step3 to qualitatively describe the superiority of our proposed solution. Let the optimal grouping matrix be denoted as  $\mathbf{D}^{L \times M} = [\mathbf{d}_1, \mathbf{d}_2, \dots, \mathbf{d}_L]^T$ , and the optimal transmission signal matrix as  $\mathbf{X}_{ORPT} = [\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_L]^T$ .

In time slot 1 as shown in Fig. 3(a), the transmission signals  $\mathbf{x}_1$  fed into the transmitter, the transmitter forms focal spots with the optimal rectified power only at the receivers selected in the group of  $\mathbf{d}_1$ . The RF power received by the receivers selected in the group of  $\mathbf{d}_1$  is converted into DC power with the highest efficiency by virtue of the received RF power at each receiver equal to the optimal rectified power. Furthermore, since  $\mathbf{x}_1$  exhibits optimal RF-RF efficiency characteristics, our scheme achieves optimal RF-RF-DC efficiency, as RF-RF-DC efficiency is the product of RF-RF efficiency and RF-DC efficiency. Moreover, due to the power level of  $\mathbf{x}_1$  being closest to  $PT_{max}$  and the system having optimal RF-RF-DC efficiency, our scheme attains the maximum output DC power as the output DC power is the product of the power of transmission signal  $\mathbf{x}_1$  and RF-RF-DC efficiency.

In time slot 2 as shown in Fig. 3(b) and in time slot L as shown in Fig. 3(c), our scheme exhibits the same characteristics as time slot 1, including optimal RF-DC efficiency, optimal RF-RF-DC efficiency, and maximum output DC power.

Finally, all receivers achieve optimal rectified power tracking through sequentially feeding the row vectors of the optimal transmission signals matrix  $\mathbf{X}_{ORPT} = [\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_L]^T$  into the transmitter across multiple time slots with a power-

limited transmitter.

Therefore, our scheme can tackle the challenge that a power-limited transmitter actively transmits RF power to satisfy different power demands with high efficiency and large average output direct current (DC) power.

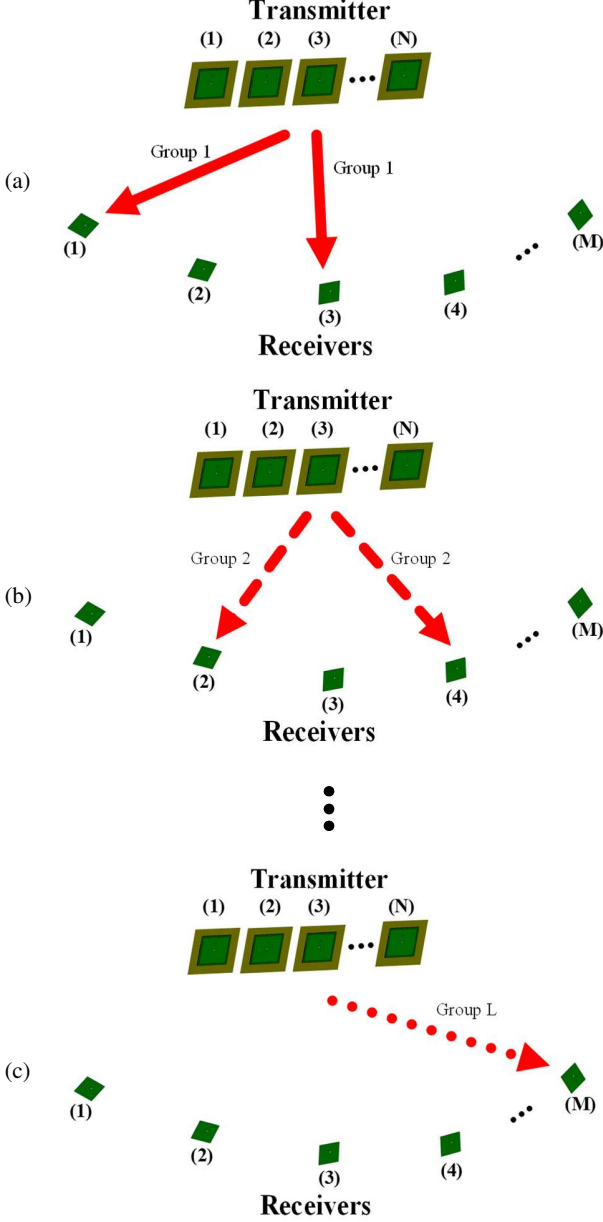


Fig. 3. Illustration of the power transfer phase of the high-efficiency multi-user WPT: (a) time slot 1, (b) time slot 2 and (c) time slot L

Secondly, a simple numerical example of quantitative calculation is used to further illustrate the superiority of our scheme.

#### Example 1:

Considering that the WPT system has 8 transmitting antennas and 4 receivers. For the sake of simplicity in calculations and a better understanding of the underlying mechanisms of each scheme, the channels between receivers have been configured to be orthogonal. So this paper assume that the channels of the

four receivers are  $\mathbf{h}_1^T = [0.01, 0.01, 0, 0, 0, 0, 0, 0]$ ,  $\mathbf{h}_2^T = [0, 0, 0.01, 0.01, 0, 0, 0, 0]$ ,  $\mathbf{h}_3^T = [0, 0, 0, 0, 0.01, 0.01, 0, 0]$ ,  $\mathbf{h}_4^T = [0, 0, 0, 0, 0, 0, 0.01, 0.01]$ .

The setting for  $PT_{max}$  is the transmission power corresponding to the scenario where two receivers simultaneously receive the optimal rectification power. So, this configuration can show the shortcomings of low rectification efficiency of time diversion schemes with excessive received RF power and space diversion schemes with insufficient received RF power. Therefore, this paper set  $PT_{max} = 29.5$  W, and the nonlinear model of each receiver is set as  $P_{max} = 4$  mW,  $a = 0.77$ ,  $b = 2$  to obtain a rectifier circuit with optimal rectified power of 2.95 mW and optimal rectification efficiency of 82% [9] as shown in Fig.1. The time block  $T$  is set as 1. Based on this setup, the results for the five principles are as follows.

TD-MS:  $T$  is divided into 4 time slots, and the output DC power of R1 is  $5.9\text{mW} \times 0.63 = 3.717\text{mW}$ , the output DC power of R2, R3 and R4 is 0 mW. The average power of each receiver is 3.717mW, 0 mW, 0 mW, 0 mW.

SD-MS:  $T$  is not divided, the output DC power of R1 and R2 is  $2.95\text{mW} \times 0.82 = 2.419$  mW, and the output DC power of R3 and R4 is 0 mW. The average power of each receiver is 2.419 mW, 2.419 mW, 0 mW, 0 mW.

The quantitative calculation results from TD-MS and SD-MS clearly indicate the existence of a power blind spot problem in "max-sum".

TD-MM:  $T$  is divided into 4 time slots with a duration of 0.25, and the output DC power of each receiver at each time slot is  $5.9\text{mW} \times 0.63 = 3.717\text{mW}$ . The average power of each receiver is  $3.717\text{mW} \div 4 = 0.93\text{mW}$ .

SD-MM:  $T$  is not divided, the output DC power of R1, R2, R3, and R4 is  $1.475\text{mW} \times 0.73 = 1.077\text{mW}$ . The average power of each receiver is 1.077mW.

This work:  $T$  is divided into two time slots with a duration of 0.5, and the output DC power of receiver R1 and R2 are both  $2.95\text{mW} \times 0.82 = 2.419\text{mW}$  at time slot 1, the output DC power of R3 and R4 at time slot 2 are both  $2.95\text{mW} \times 0.82 = 2.419\text{mW}$ . The average power of each receiver is  $2.419\text{mW} \div 2 = 1.21\text{mW}$ .

Sequentially tracking the optimal rectified power of multiple groups (This work) proposed by us achieved better system performance, and we will elaborate on it in detail below.

#### D. Formulation of the Bi-Level Optimization Problem

The grouping matrix  $\mathbf{D}^{L \times M} = [\mathbf{d}_1, \mathbf{d}_2, \dots, \mathbf{d}_L]^T$  of all receivers is optimized to making the power of the transmission signals of each group close to  $PT_{max}$  in optimization problem **P5**. In each group, the transmission signals with minimum power are optimized from the receive signals with power equal to the optimal rectified power in optimization problem **P6**. The parameter (the power of the transmission signal) used to optimize the grouping matrix in optimization problem **P5** are constrained by a high-efficiency optimization problem **P6**, and the two optimization problems interact with each other. Therefore, in order to obtain the optimal grouping matrix  $\mathbf{D}^{L \times M} = [\mathbf{d}_1, \mathbf{d}_2, \dots, \mathbf{d}_L]^T$  and the optimal transmission signals matrix  $\mathbf{X}_{ORPT} = [\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_L]^T$ , the non-convex bi-level optimization problem is formulated as

**Leader:** obtain the optimal grouping matrix to making the power of the transmission signals of each group close to  $PT_{max}$

$$\mathbf{P5} \quad \min_{\mathbf{D}} \sum_{i=1}^L \tau_i \Delta P t_i \quad (22)$$

$$\text{s. t.} \quad \Delta P t_l = PT_{max} - \mathbf{x}_l^H \mathbf{x}_l, \Delta P t_l \geq 0 \quad (23)$$

$$\mathbf{D} = [\mathbf{d}_1, \mathbf{d}_2, \dots, \mathbf{d}_L]^T \in \mathbf{R}^{L \times M},$$

$$\sum_{i=1}^L \mathbf{d}_i^T = [1, 1, 1, \dots, 1]^{1 \times M} \quad (24)$$

where  $\mathbf{D}$  is the grouping matrix with a total of  $L$  rows; and  $L$  is the number of time slots,  $M \geq L \geq 1$ ; the duration of time slot  $\tau_l$  is set as  $T/L$ , and the row vector  $\mathbf{d}_l^T$  represents the grouping vector of the  $l$ th time slot. (15) is the constraint that the transmit power is less than  $PT_{max}$ . (16) is the constraint that the receivers are not grouped repeatedly.

**Follower:** obtain the optimal transmission signals with minimum power from the receive signals with power equal to the optimal rectified power

$$\mathbf{P6} \quad \min_{[\varphi_1, \varphi_2, \dots, \varphi_M]} \mathbf{x}_l^H \mathbf{x}_l \quad (25)$$

$$\text{s. t.} \quad \mathbf{x}_l = \sum_{i=1}^M \mathbf{a}_i y_{li} \quad (26)$$

$$\mathbf{A} = (\mathbf{H}\mathbf{H}^H)^{-1} \mathbf{H}^H = [\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_M] \quad (27)$$

$$\mathbf{y}_l = [1e^{j\varphi_1}, 1e^{j\varphi_2}, \dots, 1e^{j\varphi_M}] \times \text{diag}(\mathbf{d}_l^T)$$

$$\times \text{diag}(\sqrt{\mathbf{pr}})$$

$$= [y_{l1}, y_{l2}, \dots, y_{lM}] \quad (28)$$

Where  $y_{lm}$  represents the signal received by the  $m$ th receiver within the  $l$ th time slot,  $\varphi_m$  represents the phase of  $y_{lm}$ ,  $\mathbf{pr} = [pr_1, pr_2, \dots, pr_M]$  represents the optimal rectified power matrix of all receivers. (18) and (19) are the constraint that how the transmission signal is calculated from the receive signals. (20) is the constraint that the power of the receive signal is equal to the corresponding optimal rectified power.

### E. Solving of the Bi-Level Optimization Problem

Genetic Algorithm (GA) uses randomness evolution to parallel search for optimal region, showing potential for robustly solving non-convex problem [16]. Therefore, the asynchronous evolutionary bi-level genetic algorithm is adopted to solve this non-convex bi-level optimization problem [17].

The essence is that in each iteration, **Follower** independently optimizes each individual in the current population that evolves in **Leader**, until the optimal value of **Follower** with each individual from **Leader** is obtained and fed back to **Leader**. Then **Leader** evaluates, selects, and evolves based on the feedback of the optimal values. The optimality of this bi-level optimization problem is obtained by using optimal value of **Follower** in **Leader** and by iteratively solving the resulting **Leader** optimization problem [17]. The details of the algorithm are shown in Algorithm 1.

The double solid line loop (repeat to until) and the tilde loop (repeat to until) search for the optimal solution of the **Follower**

with the latest grouping matrix population given by **Leader**.

#### Algorithm 1: Optimal Rectified Power Tracking Scheme

- 1: **Initialization**: Randomly generate the initial grouping matrix population  $\mathbf{D}_1^{q-1}, \mathbf{D}_2^{q-1}, \dots, \mathbf{D}_A^{q-1}$ ; set the index  $l=1, a=1, q=1$ , and  $p=1$
- 2: **repeat**
- 3: Copy the latest grouping matrix population  $\mathbf{D}_1^{q-1}, \mathbf{D}_2^{q-1}, \dots, \mathbf{D}_A^{q-1}$  to the **Follower** optimization problem
- 4: **repeat**
- 5: Assign the  $l$ -th row vector of  $\mathbf{D}_a^{q-1}$  to  $\mathbf{d}_l^T$ , and randomly generate the initial phase population  $\varphi_1^{p-1}, \varphi_2^{p-1}, \dots, \varphi_B^{p-1}$
- 6: **repeat**
- 7: Evaluate the **Follower** optimization problem with a given  $\mathbf{d}_l^T$  and the latest phase population
- 8: Select elite individual  $\varphi$ ,  $p = p + 1$ , and evolve a new phase population  $\varphi_1^{p-1}, \varphi_2^{p-1}, \dots, \varphi_B^{p-1}$
- 9: **until** get the transmission signal  $\mathbf{x}_l^a$  with minimum power, record  $\mathbf{x}_l^a$
- 10:  $l = l + 1$ , if  $l > L$  of  $\mathbf{D}_a^{q-1}$ ,  $l = 1$  and  $a = a + 1$
- 11: **until**  $a > A$ ,  $a = 1$ , get the optimal transmission signal matrix  $\mathbf{X}^1, \mathbf{X}^2, \dots, \mathbf{X}^A$  corresponding to the grouping matrix population, and feed it back to the **Leader** optimization problem
- 12: Evaluate the **Leader** optimization problem with the optimal transmission signal matrix  $\mathbf{X}^1, \mathbf{X}^2, \dots, \mathbf{X}^A$  which fed back by **Follower** optimization problem
- 13: Select the elite individual  $\mathbf{D}$ ,  $q = q + 1$ , and evolve a new grouping matrix population  $\mathbf{D}_1^{q-1}, \mathbf{D}_2^{q-1}, \dots, \mathbf{D}_A^{q-1}$
- 14: **until** get the smallest  $\sum_{i=1}^L \tau_i \Delta P t_i$ , output the optimal  $\mathbf{D}$  and the corresponding transmission signal matrix  $\mathbf{X}_{ORPT}$

The single solid line loop (repeat to until) searches for the optimal solution of **Leader** with the optimal solution fed back by **Follower**. The optimality of this bi-level optimization problem is obtained by using optimal value of **Follower** in **Leader** and by iteratively solving the resulting **Leader** optimization problem.

### V. NUMERICAL RESULTS

This section provides numerical results to validate the performance of our proposed scheme compared to the four traditional schemes mentioned in Section II.

In the numerical simulations, the Rician fading channel from the transmitting antenna  $n$  to receiver  $m$  is adapted. The gains of transmitting and receiving antennas are set to 6 dBi and 7 dBi, respectively. The number of transmitting antennas ( $N$ ) and receivers ( $M$ ) are both set to 9. The distance between the receivers and the transmitter is 3.5 m. The time block  $T$  is set as 1 hour. The transmitting antenna elements are arranged at half wavelength interval. The angle of the  $m$ th receiver is set to  $\theta_m = -\pi/3 + \pi(m-1)/12$ .

The dissipated power of the 9 receivers is set to [0.27, 0.27, 0.27, 0.48, 0.48, 0.48, 0.27, 0.27, 0.27] mW. According to (21)

and the dissipated power of the 9 receivers, the optimal rectified power matrix  $\mathbf{pr}$  for 9 receivers is set to be: [2.95, 2.95, 2.95, 5.25, 5.25, 5.25, 2.95, 2.95, 2.95] mW. Therefore, as for the nonlinear rectifier circuit model, we set  $P_{max} = 4$  mW,  $a = 0.77$ ,  $b = 2$  to obtain a rectifier circuit with optimal rectified power of 2.95 mW and optimal rectification efficiency of 82%, and set  $P_{max} = 7$  mW,  $a = 0.44$ ,  $b = 3.5$  to obtain a rectifier circuit with optimal rectified power of 5.25 mW and optimal rectification efficiency of 82% [14].

Table II shows the grouping matrix with different  $PT_{max}$ . It is observed that our scheme will search for the optimal grouping matrix according to different  $PT_{max}$ , laying the foundation for sequentially tracking the optimal rectified power of multiple groups.

TABLE II

| GROUPING MATRIX WITH DIFFERENT $PT_{max}$ |                             |                                                                                                                                       |                     |
|-------------------------------------------|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------|---------------------|
| $PT_{max}$                                | Time division               | This work                                                                                                                             | Space division      |
| 37                                        | $diag([1,1,1,1,1,1,1,1,1])$ | $diag([1,1,1,1,1,1,1,1,1])$                                                                                                           | [1,1,1,1,1,1,1,1,1] |
| 39.2                                      | $diag([1,1,1,1,1,1,1,1,1])$ | $\begin{Bmatrix} 1,1,0,0,0,0,0,0,0 \\ 0,0,1,0,1,0,0,0,0 \\ 0,0,0,1,0,0,1,0,0 \\ 0,0,0,0,0,1,0,0,0 \\ 0,0,0,0,0,0,0,1,1 \end{Bmatrix}$ | [1,1,1,1,1,1,1,1,1] |
| 41.1                                      | $diag([1,1,1,1,1,1,1,1,1])$ | $\begin{Bmatrix} 1,1,0,1,0,0,0,0,0 \\ 0,0,1,0,1,0,1,0,0 \\ 0,0,0,0,0,1,0,1,1 \end{Bmatrix}$                                           | [1,1,1,1,1,1,1,1,1] |
| 43                                        | $diag([1,1,1,1,1,1,1,1,1])$ | $\begin{Bmatrix} 1,1,0,1,0,1,0,0,0 \\ 0,0,1,0,1,0,1,1,1 \end{Bmatrix}$                                                                | [1,1,1,1,1,1,1,1,1] |
| 45                                        | $diag([1,1,1,1,1,1,1,1,1])$ | [1,1,1,1,1,1,1,1,1]                                                                                                                   | [1,1,1,1,1,1,1,1,1] |

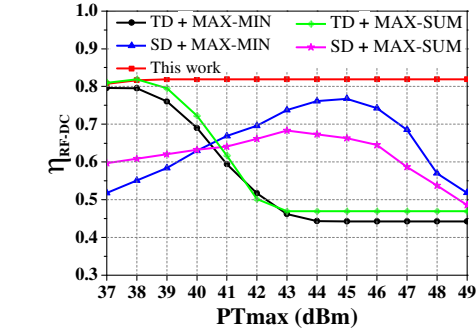
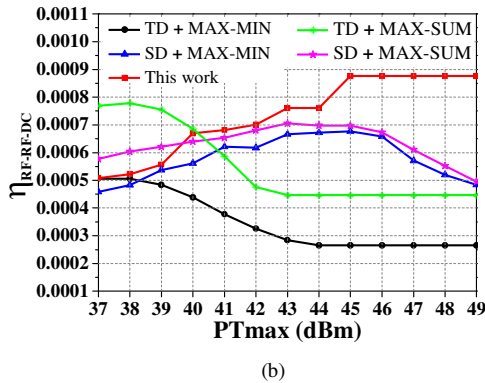


Fig. 4. Simulation results of (a) the rectification efficiency  $\eta_{RF-DC}$ , (b) the efficiency of RF-RF-DC  $\eta_{RF-RF-DC}$ .

When  $PT_{max} = 41.1$  dBm, we can get  $L = 3$ ,  $\mathbf{d}_1^T =$

$[1,1,0,1,0,0,0,0,0]$ ,  $\mathbf{d}_2^T = [0,0,1,0,1,0,1,0,0]$ ,  $\mathbf{d}_3^T = [0,0,0,0,0,1,0,1,1]$ , which means that the selected receivers of the first group are R1, R2, R4; the selected receivers of the second group are R3, R5, R7; the selected receivers of the third group are R6, R8, R9. The sequentially tracking the optimal rectified power of multiple groups method is running in the hardware environments of a 2.8-GHz Inter core i7 processor CPU and 16-GB memory. The program's runtime is 47.88 seconds, which is averaged by the results of ten runs.

Fig. 4 (a) shows the rectification efficiency verse  $PT_{max}$ . The rectification efficiency obtained by our scheme is the optimal with different  $PT_{max}$ , which proves that the sequentially tracking the optimal rectified power of multiple groups scheme is effective.

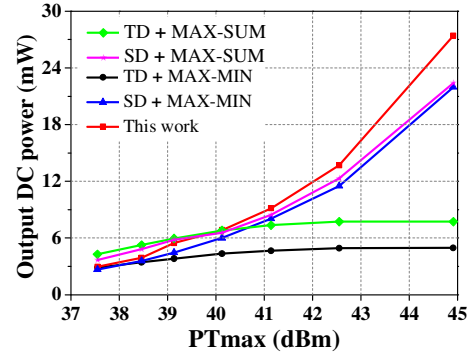
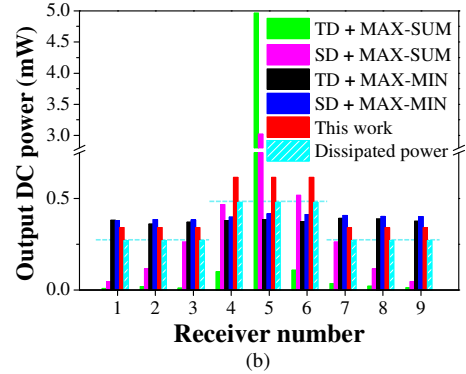
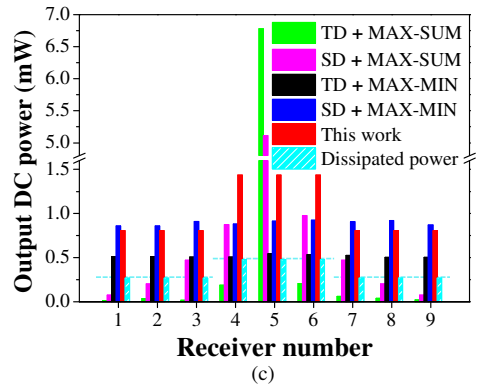


Fig. 5. Simulation results of (a) the average output DC power of all receivers, (b) the average output DC power of each receiver when  $PT_{max} = 38.46$  dBm and (c) the average output DC power of each receiver when  $PT_{max} = 41.1$  dBm

Fig. 4 (b) shows the efficiency of RF-RF-DC verse  $PT_{max}$ . It is observed that the RF-RF-DC efficiency of our scheme is almost the highest by virtue of the optimal rectification

efficiency, but lower than the “max-sum” when  $PT_{max}$  lower than 40 dBm. The reason for the high RF-RF-DC efficiency of ‘max-sum’ when  $PT_{max}$  is lower than 40 dBm is that “max-sum” allocates RF power as much as possible to receivers with high RF-RF efficiency, thereby giving the max-sum a higher RF-RF efficiency.

Fig.5 (a) shows the average output DC power of all receivers when the average transmitted RF power of our scheme is consistent with the SD scheme. It is observed that the output DC power of our scheme is almost the highest thanks to the high RF-RF-DC efficiency, but lower than the “max-sum” when  $PT_{max}$  lower than 40 dBm. However, it is worth noting that the high efficiency and large overall output DC power of ‘max-sum’ are achieved at the expense of sacrificing the receivers with low RF-RF efficiency.

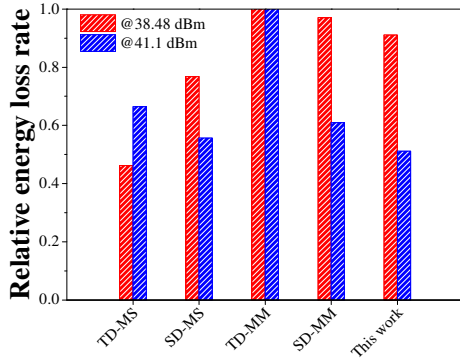


Fig. 6. Simulation results of relative energy loss rate

TABLE III  
SURVIVAL TIME OF EACH RECEIVER AFTER PERFORMING WPT FOR ONE TIME  
BLOCK WHEN  $PT_{max}=41.1$  dBm

| R. | This work<br>/h | TD-MS<br>/h | SD-MS<br>/h | TD-MM<br>/h | SD-MM<br>/h |
|----|-----------------|-------------|-------------|-------------|-------------|
| 1  | 2               | NOT         | NOT         | 0.90        | 2.19        |
| 2  | 2               | NOT         | NOT         | 0.90        | 2.19        |
| 3  | 2               | NOT         | 0.76        | 0.88        | 2.39        |
| 4  | 2               | NOT         | 0.83        | 0.06        | 0.84        |
| 5  | 2               | 13.17       | 9.69        | 0.13        | 0.91        |
| 6  | 2               | NOT         | 1.04        | 0.11        | 0.92        |
| 7  | 2               | NOT         | 0.76        | 0.95        | 2.37        |
| 8  | 2               | NOT         | NOT         | 0.87        | 2.43        |
| 9  | 2               | NOT         | NOT         | 0.88        | 2.24        |

NOT: The output DC power is less than the dissipation power, rendering the sensor cannot work.

Fig.5 (b) illustrates the average DC output power of each receiver when  $PT_{max}=38.46$  dBm. It can be observed that receivers 4, 5 and 6 cannot survive due to their received power is less than the dissipated power for both TD-MM and SD-MM schemes, and receivers 1, 2, 3, 4, 7, 8 and 9 cannot survive due to their received power is less than the dissipated power for both TD-MS and SD-MS schemes.

Fig.5 (c) illustrates the average DC output power of each receiver when  $PT_{max}=41.1$  dBm. As  $PT_{max}$  increases to 41.1 dBm, on the one hand, the output DC power of receivers 1, 2, 8 and 9 is still less than the dissipated power for both TD-MS and SD-MS schemes. On the other hand, TD-MM and SD-MM

schemes achieve received power greater than dissipated power for all receivers, but the survival time of each receiver after stopping WPT is different as the output DC power to dissipated power ratio is different for each receiver. In contrast, our scheme can ensure that all receivers can survive for the same duration after sequentially tracking the optimal rectified power of multiple groups in a time block as shown in table III. This is due to the fact that the output DC power for each receiver in our scheme is a multiple of the dissipated power.

Fig.6 illustrates the simulation results of relative energy loss rate. The formula for calculating the energy loss rate over a period  $T$  is as follows:

$$\text{Energy loss rate} = (Power_t * (1 - \eta_{RF-RF-DC}) * T) / T \quad (29)$$

where  $Power_t$  represents the transmission power corresponding to each scheme. From (29), it can be seen that for the same transmission power, the energy loss rate is inversely proportional to the RF-RF-DC efficiency. This indicates that the higher the RF-RF-DC efficiency, the smaller the energy loss rate, and consequently, the smaller the relative energy loss rate. when  $PT_{max}=38.46$  dBm, it can be observed that, TD-MS has the lowest relative energy loss rate. This is because TD-MS sacrifices the receivers with low RF-RF efficiency to achieve a higher RF-RF-DC efficiency. When  $PT_{max}=41.1$  dBm the relative energy loss rate of “this work” is the lowest by virtue of that our scheme has the highest RF-RF-DC efficiency.

Specifically, when  $PT_{max}=41.1$  dBm, our scheme achieved higher RF-RF-DC efficiency and output DC power, which is 1.24 times higher than that of the TD-MS scheme, 1.08 times higher than that of the SD-MS scheme, 1.94 times higher than that of the TD-MM scheme and 1.13 times higher than that of the SD-MM scheme. Additionally, the DC power harvested by each receiver is 3 times the dissipated power when performing WPT. Therefore, the immortality of all receivers can be realized by conducting WPT for 8 hours per day.

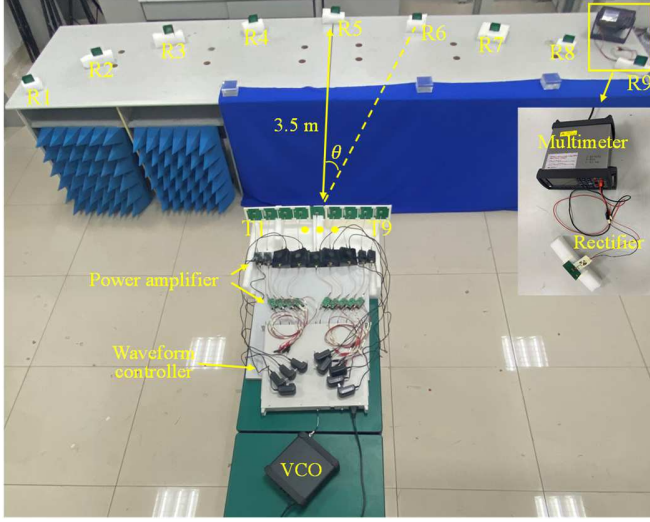
Numerical results show that our approach can provide a more feasible and high-performance solution for achieving immortality of multiple nonlinear sensors with different power demands under the limitation of  $PT_{max}$ . Moreover, by considering numerical results and practical scenario requirements, we can select an appropriate  $PT_{max}$  to design a transmitter that meets the different power demands of the immortal wireless sensors in specific scenario.

## VI. EXPERIMENTAL RESULTS

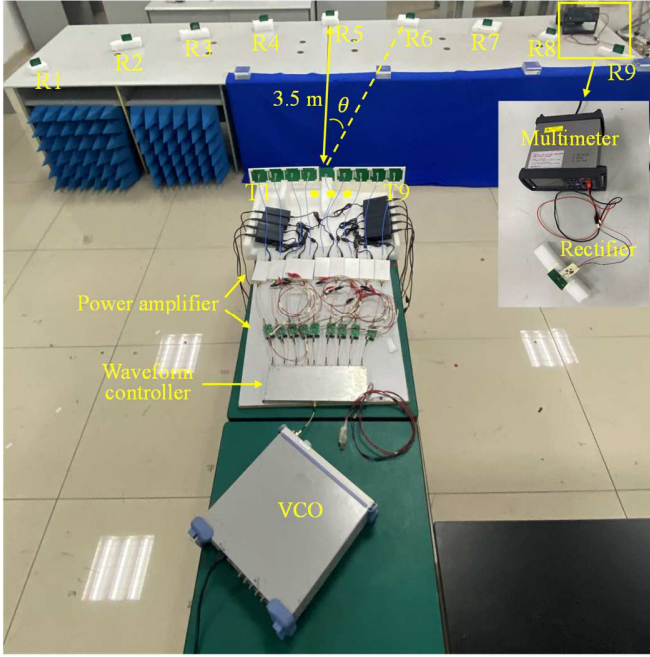
In order to further validate the feasibility and superiority of the sequentially tracking the optimal rectified power of multiple groups scheme under the limitation of  $PT_{max}$  proposed in this paper, two prototype systems with different  $PT_{max}$  were set up to conduct experiments based on the existing microwave components in the laboratory.

Fig.7 illustrates the experimental setup of the multi-user MPT system. The number and arrangement of transmitting antennas, the number and angles of receiving antennas, and the distance between transmitter and receivers in the two prototype multi-user WPT systems are consistent with the numerical simulation settings. The S11 measurement results for the transmitting antenna unit or the receiving antenna unit at 2.435

GHz are below -10 dB.



(a) S1



(b) S2

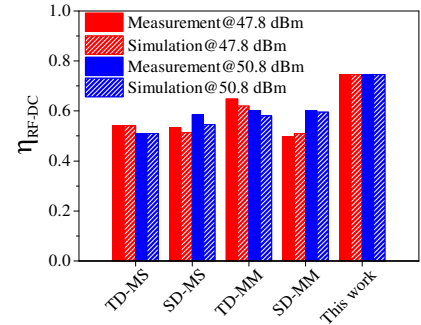
Fig. 7. Experimental setup for the multi-user MPT system: (a)  $PT_{max} = 47.8$  dBm, (b)  $PT_{max} = 50.8$  dBm

Therefore, we chose 2.435 GHz as the system operating frequency. The gain of both the transmitting and receiving antennas at the operating frequency is 6.4 dBi. The dissipated power of the 9 receivers is set to [0.83, 0.83, 0.83, 1.65, 1.65, 1.65, 0.83, 0.83, 0.83] mW. According to (21) and the dissipated power of the 9 receivers, the optimal rectified power matrix  $\mathbf{pr}$  for 9 receivers is set to be: [10, 10, 10, 20, 20, 20, 10, 10, 10] mW. Corresponding rectifier 1 and rectifier 2 have been designed based on this guiding information. The measured maximum conversion efficiency of the rectifier 1 is 74.6%, which achieves at an input RF power of 10 dBm with a load of 5100  $\Omega$ . The measured maximum conversion efficiency of the rectifier 2 is 74.2%, which achieves at an input RF power of 13

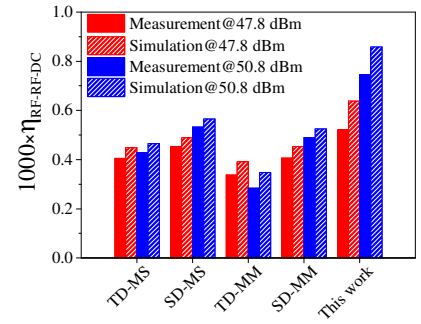
dBm with a load of 4700  $\Omega$ .

Fig. 7 (a) shows the experimental setup for the multi-user MPT system with a transmitter of  $PT_{max} = 47.8$  dBm. The phase control accuracy and amplitude control accuracy of the waveform controller are set to  $1^\circ$  and 0.1dB, respectively. The gain of the two-stage power amplifier in series is 54 dB. The maximum transmit RF power of each port of the transmitting antenna is 38.3 dBm. Fig. 7 (b) shows the experimental setup for the multi-user MPT system with a transmitter of  $PT_{max} = 50.8$  dBm. The phase control accuracy and amplitude control accuracy of the waveform controller are set to  $1^\circ$  and 0.1dB, respectively. The gain of the two-stage power amplifier in series is 49 dB. The maximum transmit RF power of each port of the transmitting antenna is 41.3 dBm.

| $PT_{max}$ | Time division                      | This work                                                                                   | Space division      |
|------------|------------------------------------|---------------------------------------------------------------------------------------------|---------------------|
| 47.8       | $\text{diag}([1,1,1,1,1,1,1,1,1])$ | $\begin{Bmatrix} 1,1,1,0,0,0,0,0,0 \\ 0,0,0,1,1,0,1,0,0 \\ 0,0,0,0,0,1,0,1,1 \end{Bmatrix}$ | [1,1,1,1,1,1,1,1,1] |
| 50.8       | $\text{diag}([1,1,1,1,1,1,1,1,1])$ | [1,1,1,1,1,1,1,1,1]                                                                         | [1,1,1,1,1,1,1,1,1] |



(a)



(b)

Fig. 8. Simulation and experimental results of (a) the rectification efficiency  $\eta_{RF-DC}$ , (b) the efficiency of RF-RF-DC  $\eta_{RF-RF-DC}$ .

As described in the Section III, the channel information between the transmitting antenna and receiving antenna in the experiment was obtained using the TR method with the help of a vector network analyzer (VNA) with the model number E5026A.

Table IV shows the grouping matrix for two different transmitters. It is observed that our scheme will search for the optimal grouping matrix according to different  $PT_{max}$ .

Fig. 8 (a) shows the simulation and experimental rectification efficiency for different schemes. The rectification efficiency

obtained by our scheme is the highest in both two prototype multi-user MPT systems, which proves that the optimal rectified power tracking scheme is effective. Fig.8 (b) shows the simulation and experimental efficiency of RF-RF-DC for different schemes. It is observed that the RF-RF-DC efficiency of our scheme is also the highest in both two prototype multi-user MPT systems by virtue of the optimal rectification efficiency.

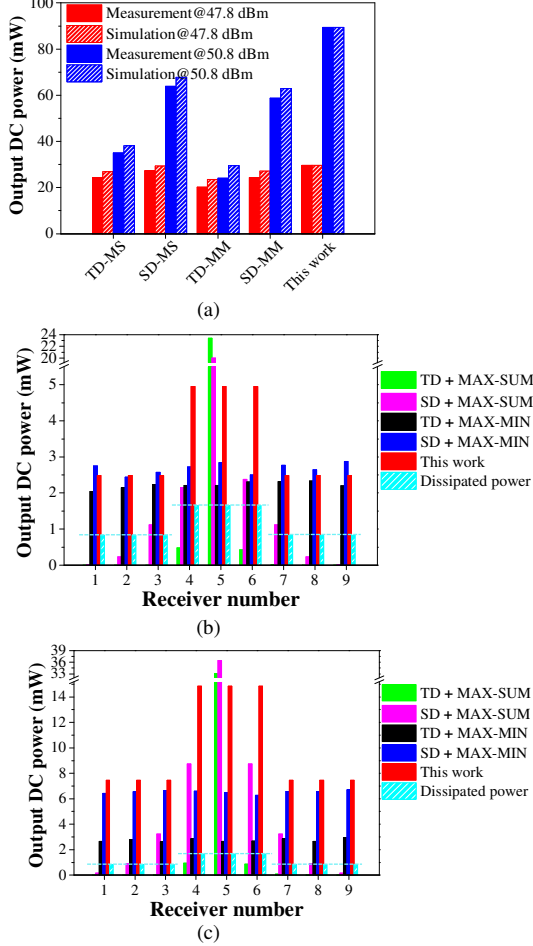


Fig. 9. Simulation and experimental results of (a) the average output DC power of all receivers, (b) the average output DC power of each receiver when  $PT_{max} = 47.8$  dBm and (c) the average output DC power of each receiver when  $PT_{max} = 50.8$  dBm

Fig.9 (a) shows the simulation and experimental output DC power of all receivers. It is observed that the output DC power of our scheme is the highest thanks to the high RF-RF-DC efficiency. Fig.9 (b) and (c) illustrates the simulation and experimental output DC power of each receiver when  $PT_{max} = 47.8$  dBm and  $PT_{max} = 50.8$  dBm. It can be observed that both the TD-MS and SD-MS schemes cannot ensure that the output DC power of all receivers is greater than their corresponding dissipated power in both two prototype multi-user MPT systems. And both TD-MM and SD-MM schemes cannot ensure that all receivers survive for the same duration in both two prototype multi-user MPT systems, as shown in Table V. In contrast, our scheme can ensure that all receivers can survive for the same duration as shown in table V in both two prototype

multi-user MPT systems. When  $PT_{max} = 50.8$  dBm, the measured RF-RF-DC efficiency of our scheme is 1.74 times higher than that of the TD-MS scheme, 1.4 times higher than that of the SD-MS scheme, 2.6 times higher than that of the TD-MM scheme and 1.5 times higher than that of the SD-MM scheme. And the measured output DC power of our scheme is 2.56 times higher than that of the TD-MS scheme, 1.4 times higher than that of the SD-MS scheme, 3.7 times higher than that of the TD-MM scheme and 1.5 times higher than that of the SD-MM scheme.

Fig.10 shows the simulation and experimental results of relative energy loss rate. Regardless of whether  $PT_{max} = 47.8$  dBm or  $PT_{max} = 50.8$  dBm, the relative energy loss rate of this work is the lowest due to its highest RF-RF-DC efficiency.

It can be found that the simulation and measurement results coincide well, which further proves the effectiveness of the sequentially tracking the optimal rectified power of multiple groups mechanism in addressing the challenge that a power-limited transmitter actively transmits RF power to satisfy different power demands with high efficiency and large average output DC power. It is worth noting that experimental results obtained from two transmitters built with existing microwave components indicate that our scheme has the potential to integrate with the existing transmitter with different  $PT_{max}$  of communication system or positioning system. This lays the foundation for the practical application of immortal wireless sensor networks without the need for additional WPT transmitters.

TABLE V

SURVIVAL TIME OF EACH RECEIVER AFTER PERFORMING WPT FOR ONE TIME BLOCK

| R. | This work |    | TD-MS |       | SD-MS |       | TD-MM |      | SD-MM |      |
|----|-----------|----|-------|-------|-------|-------|-------|------|-------|------|
|    | S1        | S2 | S1    | S2    | S1    | S2    | S1    | S2   | S1    | S2   |
| 1  | 2         | 8  | NOT   | NOT   | NOT   | NOT   | 1.46  | 2.18 | 2.31  | 6.74 |
| 2  | 2         | 8  | NOT   | NOT   | NOT   | 0.07  | 1.58  | 2.33 | 1.94  | 6.90 |
| 3  | 2         | 8  | NOT   | NOT   | 0.35  | 2.90  | 1.70  | 2.16 | 2.10  | 6.99 |
| 4  | 2         | 8  | NOT   | NOT   | 0.30  | 4.30  | 0.34  | 0.73 | 0.65  | 3.00 |
| 5  | 2         | 8  | 13.18 | 19.04 | 11.11 | 21.11 | 0.34  | 0.60 | 0.72  | 2.92 |
| 6  | 2         | 8  | NOT   | NOT   | 0.44  | 4.30  | 0.40  | 0.62 | 0.52  | 2.81 |
| 7  | 2         | 8  | NOT   | NOT   | 0.35  | 2.90  | 1.78  | 2.44 | 2.33  | 6.91 |
| 8  | 2         | 8  | NOT   | NOT   | NOT   | 0.07  | 1.81  | 2.19 | 2.19  | 6.92 |
| 9  | 2         | 8  | NOT   | NOT   | NOT   | NOT   | 1.65  | 2.55 | 2.46  | 7.08 |

NOT: The output DC power is less than the dissipation power, rendering the sensor cannot work; S1: the system with  $PT_{max} = 47.8$  dBm; S2: the system with  $PT_{max} = 50.8$  dBm; And the unit of the data in the table V is hours.

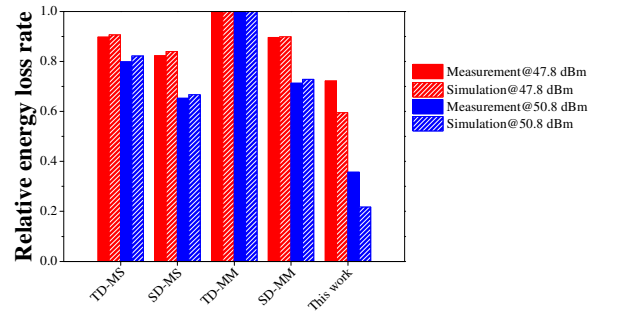


Fig. 10. Simulation and experimental results of relative energy loss rate

## VII. CONCLUSION

In this article, a novel high-efficiency multi-user wireless power transfer with a power-limited transmitter is studied by virtue of sequentially tracking the optimal rectified power of multiple groups. Formulating a bi-level optimization problem and solving it using an asynchronous evolutionary bi-level genetic algorithm to obtain the optimal grouping matrix and the optimal transmission signals matrix. As a result, multiple groups perform WPT sequentially, allowing all receivers to track the optimal rectified power across multiple time slots. So, the RF power received at the receiver is converted into DC power with the maximum rectification efficiency to achieve higher efficiency, greater average output DC power that is equal to the multiple of the power demand under the limitation of  $PT_{max}$ .

The simulation and measurement results coincide well, which further proves the effectiveness of the sequentially tracking the optimal rectified power of multiple groups mechanism in addressing the challenge that a power-limited transmitter actively transmits RF power to satisfy different power demands with high efficiency and large average output DC power. Especially when  $PT_{max} = 50.8$  dBm, the measured RF-RF-DC efficiency and output DC power of the proposed scheme are up to 2.6 and 3.7 times higher than those of the traditional schemes. Furthermore, only our scheme meets the different power demands of multiple receivers, ensuring the same survival time. This reveals the potential to immortalize wireless sensor networks.

In addition, by considering numerical results and practical scenario requirements, we can select an appropriate  $PT_{max}$  to design a transmitter that meets the different power demands of the immortal wireless sensors in specific scenario. Moreover, experimental results obtained from two transmitters built with existing microwave components indicate that our scheme has the potential to integrate with the existing transmitter with different  $PT_{max}$  of communication system or positioning system. This lays the foundation for the practical application of immortal wireless sensor networks without the need for additional WPT transmitters.

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