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Asynchronous Focusing Time Reversal Wireless Power Transfer for Multi-Users With Equal Received Power Assignment

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ABSTRACT Time reversal wireless power transfer (TR-WPT) provides an efficient radiated method for wirelessly transferring power to multiple users at a middle distance in complicated multipath environments. However, TR-WPT based on the direct time reversal scheme cannot ensure each user to have the equal received power although the maximum transfer efficiency can be achieved. In order to realize the same received power assignment for each user as well as high transfer efficiency, an asynchronous focusing time reversal (AFTR) scheme is proposed in this paper. Different from the TR-WPT based on the direct time reversal technique, the radiated power does not focus on multi-users at the same time. Instead, the AFTR-WPT system operates in an asynchronous focusing mode. For the continuous-wave wireless power transfer, asynchronous focusing means that the phases of the focused power signals received by multi-users are different. By optimizing the phase of the focused signal received by each user, the AFTR-WPT system can not only transfer the equal power to each user but also achieve the optimal transfer efficiency. To demonstrate the proposed scheme, a porotype of multi-user AFTR-WPT system of 16 transmit antennas and 9 receive antennas is developed with the continuous-wave power transfer in an indoor laboratory environment. Utilizing the proposed asynchronous focusing scheme, we successfully demonstrate the equal power assignment for multiple users and achieve the optimal transfer efficiency, approaching the maximum efficiency of the TR-WPT based on direct time reversal scheme for all studied cases.

INDEX TERMS Wireless power transfer, asynchronous focusing, time reversal, equal power allocation.

I. INTRODUCTION

With the rapid development of internet of things (IoT), sensors are playing a more and more important role in monitoring environmental parameters of smart factories and smart homes. Due to the limited capacity and short service time of the battery, the problem of efficient continuous power supply for the sensors has become a key factor affecting the sustainable work of these sensors. The wired power supply relies on wires, which severely limits the flexibility of power transfer for users. In comparison, wireless power transfer (WPT) provides much more convenience and flexibility in power supply since the cables between power supply and appliances can be completely abandoned. Therefore, WPT gains an increasing attention from applications in smart factories and smart homes in recent years.

At present, inductively coupled power transfer (ICPT), magnetic resonance coupling (MRC) and microwave power transfer (MPT) are widely used in WPT. ICPT uses the near-field magnetic field induction of two aligned low-frequency coils to transmit power [1], [2]. The transfer distance of ICPT is usually in the order of centimeter. MRC uses two coils with the same frequency for resonant coupling power transfer, and the transfer distance can be extended to the order of meters [3]–[6]. However, the power transfer efficiency of MRC dramatically declines as the distance between power

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sources and devices increases up to meters. Theoretically, MPT can transfer the power at a long distance but it requires large aperture transceiver antenna and line of sight (LOS) transfer and may bring potential electromagnetic radiation hazards to human body and organism in the indoor environment due to its directional radiation [7]–[9]. Time reversal wireless power transfer (TR-WPT) is also a radiated wireless power transfer technique, but it differs from MPT. TR-WPT does not transfer power with directional beams. Instead, the power is wirelessly transferred to the devices in the focusing mode. Studies show that TR-WPT is a promising wireless power transfer technique, which has potentials in mid-range WPT applications [10]–[13].

Based on the adaptive spatial-temporal focusing mechanism of time reversal (TR), TR-WPT can focus the radiated electromagnetic power at any position within the region covered by the radiated waves [14], [15]. A method based on the TR invariance property of waves was proposed to adapt the signal-focusing technique for transmit power to sensors and portable or mobile devices [16]. Resorting to the temporal excitation synthesis of a time-reversal mirror (TRM), a method utilizing a number of time reversal (TR) focusing fields to transfer the power to multiple devices with high efficiency was demonstrated [17]. The performance of TR-WPT in comparison to conventional beamforming (BF) based WPT was investigated. The results show that TR achieves higher peak voltages at the receiver compared to BF under the same average transmit power in an indoor multipath environment [18]. In particular, TR can take advantage of rich multipath to deliver more power at the desired locations, especially in complex multipath environments such as factories or indoor rooms [19].

Another advantage of TR-WPT is that multi-users can be wirelessly powered at the same time [20]. The basic idea for multi-user power transfer is to generate a number of time-reversal single-point focusing fields within the power transfer area. Each single-point focusing field corresponds to one user. Based on the direct time reversal scheme, the multi-point focusing TR-WPT system works in the synchronous focusing mode and the power received by users is inversely proportional to their propagation attenuations with respect to the transmitters. For example, if a user is placed closer to the transmitters, it will receive more power. If it is located much farther from the transmitters, its received power will become smaller. Although the power received by remote users can be improved by adding relays [21], it significantly increases the complications and the cost of the system. One method to achieve equal received power for each user is to weight the amplitude of each focusing field and recalculate the time reversal excitation for each transmit antenna. Such method can realize equal received power assignment for each user, but the total transfer efficiency of the system will decrease. The underlying reason is that the direct time reversal-based multi-users TR-WPT focuses the power at all users simultaneously. In such scheme, all focusing fields work in the synchronous focusing mode. Due to the phase difference resulted from different locations, the excitation amplitudes of some transmit antennas become very small, eventually resulting in a decrease of transfer efficiency and a reduction of the total transmit power. Another simultaneous wireless power transfer method is to allocate the power to multiple targets by adjusting the weighted diagonal matrix in accordance with the number of targets, spatial distribution and power intensity at each target [21], [22]. A decrease of the transfer efficiency similar to that in TR-WPT with equal power allocation may occur if the channel losses between the multiusers and the transmitter are greatly different from each other.

In order to obtain equal power allocation and high transfer efficiency, in this paper we propose an asynchronous focusing time-reversal wireless power transfer (AFTR-WPT) method for power supply to multi-users. When the devices have enough stored energy, they do not send the request signal and the ARTR-WPT system does not select these devices to transfer the power. If their stored energy has been dissipated under a threshold level, they can send a request signal. In this case, our system transfers the wireless power to these devices. That is to say, only these power-request devices are selected for wireless power transfer. To some extent, the selective wireless power transfer in the AFTR-WPT system differs from the use of scanning beam or multiple beams generated by the traditional phased array to select the devices for power transfer. Also, it should be noticed that, unlike those traditional TR-WPT systems, our method in this study does not transfer power to multi-users at the same focusing instant. Instead, each user receives its focused power at different focusing time. For continuous-wave power transfer, it is equivalent to different phases of the multi-point focusing fields focused at multi-users. By optimizing the phases of these multi-point focusing fields generated by TR, the excitations of the transmit antennas can be optimized to avoid zero-excitation and increase the total radiated power and the transfer efficiency. A protype of multi-user AFTR-WPT system has been developed to demonstrate the proposed method, which obtained satisfactory results for all studied cases.

This paper is organized as follows: Section II introduces the multi-users TR-WPT methods used in this paper. The corresponding experiments and simulations are presented in Section III. Finally, Section IV concludes this paper with a brief summary.

II. MULTI-USERS TR-WPT METHODS

A. TR-WPT BASED ON DIRECT TIME REVERSAL PROCEDURE

Fig. 1 depicts the typical power transfer procedures of multi-users TR-WPT based on direct time reversal technique. First, all users transmit probing signals simultaneously to the transmit antennas. Then, the transmit antennas flip their received signals in the time domain and transmit them back to the users. Based on the space-time focusing mechanism of TR, the transmitted signals will generate multi-point focusing fields and focus the radiated power at these users simultaneously.

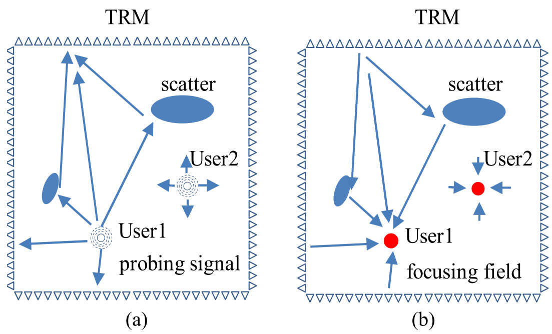

FIGURE 1. (a)Signal probing by users and (b) TR focusing propagation to users.

For the continuous-wave power transfer, the TR processing is equivalent to the phase conjugation. It is assumed that the transmitter is equipped with $N \geq 1$ transmit antennas, and the receiver is equipped with $M \geq 1$ receive antennas respectively. The TR signals radiated by the TRM can be described as follows:

$$\boldsymbol{s} = \boldsymbol{H}^{\mathrm{H}}\boldsymbol{x} \subset C^{N\times 1} \tag{1}$$

where $\boldsymbol{H}^{\mathrm{H}} = [\boldsymbol{h}_1^*, \boldsymbol{h}_2^*, \ldots, \boldsymbol{h}_M^*]^{\mathrm{T}} \subset C^{M\times N}$ is the phase-conjugated channel matrix which is equivalent to time reversal processing. $\boldsymbol{h}_k = [h_{1k}, h_{2k}, \ldots, h_{Mk}]^{\mathrm{T}}$ is the channel transfer vector, h_{jk} is the channel transfer function between the jth user and the kth transmit antenna, $\boldsymbol{x} = [x_1, x_2, \ldots, x_M]^{\mathrm{T}} \subset C^{M\times 1}$ is the weighting coefficient vector (WCV). $[\bullet]^{\mathrm{T}}$, $[\bullet]^*$, and $[\bullet]^{\mathrm{H}}$ represent the transpose, conjugate and conjugate transpose of the vector or matrix respectively. In our study, it is assumed that all the probing signals sent by the multi-users have been normalized with unit power. $\boldsymbol{x}$ is used to weight the excitation amplitudes of the transmit antennas of the TRM for power assignment among M users.

At the receiver, the signals received by M users can be written as

$$\boldsymbol{b} = \boldsymbol{H}\boldsymbol{s} = \boldsymbol{H}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{x} \tag{2}$$

and their total power can be mathematically calculated by

$$P_{\mathrm{rx}} = \boldsymbol{b}^{\mathrm{H}}\boldsymbol{b} = \boldsymbol{x}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}\boldsymbol{H}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{x} \tag{3}$$

The above formula describes the total power received by all users.

In fact, TR-WPT is capable of selecting any number of users for power supply. By defining a selection matrix $\boldsymbol{E}_{\mathrm{select}}$ with its diagonal element equal to 1 and the other elements equal to 0,

$$e_{ij} = \begin{cases} 1, & i = j, i \in \{m_1, \ldots m_k, \ldots m_K\} \\ 0, & \text{others} \end{cases} \tag{4}$$

and applying the selection matrix to the received signal vector, we get

$$P_{\mathrm{rx}} = \boldsymbol{b}^{\mathrm{H}}\boldsymbol{E}_{\mathrm{select}}\boldsymbol{b} \tag{5}$$

where (4) denotes only K desired users indexed by $\{m_1, \ldots m_k, \ldots m_K\}$ to be selected. Substituting (2) into (5), the total power received by all the selected users can be calculated as

$$P_{\mathrm{rx}} = \boldsymbol{x}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}\boldsymbol{E}_{\mathrm{select}}\boldsymbol{H}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{x} \tag{6}$$

Equation (6) provides a general formula to calculate the total received power for various selection cases. These cases can be realized by setting the diagonal elements of the selection matrix to 1 or 0, where "1" denotes for being selected and "0" for not being selected. For example, if all the diagonal elements of the selection matrix are set to 1, it means that all users will be selected and (6) will have the same values form with (3).

For multi-users TR-WPT based on the direct time reversal technique, the transfer efficiency of the system is

$$\eta_{\mathrm{select}} = \frac{P_{\mathrm{rx}}}{P_{\mathrm{tx}}} = \frac{\boldsymbol{x}^{\mathrm{H}}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{H}\boldsymbol{E}_{\mathrm{select}}\boldsymbol{H}\boldsymbol{H}^{\mathrm{H}}\boldsymbol{x}}{\boldsymbol{s}^{\mathrm{H}}\boldsymbol{s}} = \frac{\boldsymbol{x}^{\mathrm{H}}\boldsymbol{G}^{\mathrm{H}}\boldsymbol{E}_{\mathrm{select}}\boldsymbol{G}\boldsymbol{x}}{\boldsymbol{x}^{\mathrm{H}}\boldsymbol{G}\boldsymbol{x}} \tag{7}$$

where $\boldsymbol{G} = \boldsymbol{H}\boldsymbol{H}^{H}$. Multiplying the two sides of (7) with $\boldsymbol{x}^{\mathrm{H}}\boldsymbol{G}\boldsymbol{x}$ and deleting $\boldsymbol{x}^{\mathrm{H}}$, we can rewrite (7) as

$$\boldsymbol{G}^{\mathrm{H}}\boldsymbol{E}_{\mathrm{select}}\boldsymbol{G}\boldsymbol{x} = \eta_{\mathrm{select}}\boldsymbol{G}^{\mathrm{H}}\boldsymbol{x} \tag{8}$$

Next, deleting $\boldsymbol{G}^{\mathrm{H}}$ from both sides of (8) arrives at

$$\boldsymbol{E}_{\mathrm{select}}\boldsymbol{G}\boldsymbol{x} = \eta_{\mathrm{select}}\boldsymbol{x} \tag{9}$$

By solving the above eigenvalue equation, the maximum transfer efficiency of system can be directly calculated from its maximum eigenvalue $\lambda_{\max}$, i.e.,

$$\max(\eta_{\mathrm{select}}) = \lambda_{\max} \tag{10}$$

Meanwhile, its optimal weighting vector $\boldsymbol{x}$ can be obtained from the eigenvector $\boldsymbol{v}_{\max}$, which is related to the maximum eigenvalue $\lambda_{\max}$, i.e.,

$$\max(\eta_{\mathrm{select}}) = \lambda_{\max} \tag{11}$$

Based on the above solution, the maximum transfer efficiency of the TR-WPT system can be achieved. For single-user power transfer, the problem of equal power allocation does not exist, so this method can achieve the maximum transfer efficiency.

However, if one wants to transfer equal power to users with the direct TR scheme, our studies show that the transfer efficiency decreases. Even if the optimal weighting vector is found for improving the transfer efficiency, the efficiency cannot get a remarkable improvement. By further study, we find that the underlying reason arises from the direct time reversal processing of the TR-WPT. Under the direct time reversal processing, the power simultaneously focuses at multi-users. When a set of weights is applied to the excitations for equal power assignment and keep power synchronously focused at multi-users, some excitations have very small amplitudes and some have high amplitudes. If the weighted excitations feed to the transmit antennas are greatly different in amplitude from each other, the transfer efficiency of the TR-WPT will become quite low.

B. TR-WPT BASED ON ASYNCHRONOUS FOCUSING SCHEME

In order to improve the transfer efficiency and achieve the same power allocation for each user, we propose a TR-WPT based on an asynchronous focusing scheme. It differs from the TR-WPT based on the direct time reversal scheme. In our AFTR-WPT scheme, the focusing signals received by users are allowed to have different focusing time or some different phases for continuous-wave power transfer. That is to say, the power signals received by multi-users are not focused at the same time. By properly designing the focusing time or the phase difference, it is possible to eliminate the abrupt amplitude fluctuations between the excitations of the transmit antennas. Especially, some near-zero excitations can be avoided. As a result, the total transmitted power and the transfer efficiency of the system can be improved.

This paper focuses on only the use of continuous radio-frequency waves to transfer the power. Continuous-wave based wireless power transfer can ensure consistent power supply. Meanwhile, the focusing time of the signals received by users can be controlled by their phases. For the convenience of controlling the phases of the signals received by the users, excitations of the transmit antennas of the TRM for each user need to be worked out. These excitations can be solved with the following equation

$$\boldsymbol{s} = (\boldsymbol{H}\boldsymbol{H}^H)^{-1}\boldsymbol{H}^H\boldsymbol{b} \tag{12}$$

by utilizing

$$\boldsymbol{b} = [0, \ldots, b_i e^{j\varphi_{b_i}}, \ldots, 0]^T \tag{13}$$

In the above equations, $\boldsymbol{s} \in C^{N\times 1}$ is the excitation vector, $\boldsymbol{b} \in C^{M\times 1}$ is the receive signal vector. b_i and φ_i denotes the amplitude and phase of the signal received by the ith user respectively.

Let

$$\boldsymbol{A} = (\boldsymbol{H}\boldsymbol{H}^H)^{-1}\boldsymbol{H}^H \tag{14}$$

and repress $\boldsymbol{A}$ with its column vectors as

$$\boldsymbol{A} = [\boldsymbol{a}_1, \boldsymbol{a}_2, \ldots, \boldsymbol{a}_M] \tag{15}$$

the excitation signals of the transmit antennas to focus the power at the ith user can be simplified as

$$\boldsymbol{s}_i = \boldsymbol{a}_i b_i e^{j\varphi_{b_i}} \tag{16}$$

In this way, excitations for each user are obtained. Notice that all these excitations are designed for focusing the power at a single user and no power is transmitted to any other user.

For powering multi-users, we can express their received signals as

$$\boldsymbol{b} = \sum_{i=1}^{M} \boldsymbol{b}_i \tag{17}$$

Applying (16), the total excitations for multi-user AFTR-WPT can be calculated by

$$\boldsymbol{s} = \boldsymbol{A}(\sum_{i=1}^{M} \boldsymbol{b}_i) = \sum_{i=1}^{M} \boldsymbol{s}_i = \sum_{i=1}^{M} \boldsymbol{a}_i b_i e^{j\varphi_{b_i}} \tag{18}$$

and the transfer efficiency can be computed as

$$\eta = \frac{P_{\text{rx}}}{P_{\text{tx}}} = \frac{\boldsymbol{b}^H \boldsymbol{E}_{\text{select}} \boldsymbol{b}}{\boldsymbol{s}^H \boldsymbol{s}} \tag{19}$$

where $\boldsymbol{E}_{\text{select}}$ is the selection matrix of its elements defined in (4).

If one wants to assign equal received power to the desired users and achieve the maximum transfer efficiency, only the phases of the focusing signals received by the selected users need to be optimized with the following equations.

$$\begin{aligned} \max_{\varphi_{b_i}} \quad & \eta = \frac{\boldsymbol{b}^H \boldsymbol{E}_{\text{select}} \boldsymbol{b}}{\boldsymbol{s}^H \boldsymbol{s}} \\ \text{subjectto} \quad & \boldsymbol{s} = \sum_{i=1}^{M} \boldsymbol{s}_i, \boldsymbol{s}_i = \boldsymbol{a}_i b_i e^{j\varphi_{b_i}} \\ & \boldsymbol{A} = (\boldsymbol{H}\boldsymbol{H}^H)^{-1}\boldsymbol{H}^H = [\boldsymbol{a}_1, \boldsymbol{a}_2, \ldots, \boldsymbol{a}_M] \\ & \boldsymbol{b} = [b_1 e^{j\varphi_1}, \ldots, b_M e^{j\varphi_M}] \end{aligned} \tag{20}$$

For equal received power allocation, only phases φ_i ($i = 1, 2, \ldots, M$) are the optimal variables and the amplitudes of selected users are set to 1, while others are set to 0. This means that the optimal transfer efficiency can not be achieved if only the amplitude is processed.

III. EXPERIMENTS AND DISCUSSION

A. AFTR-WPT EXPERIMENT SETUP

To verify the feasibility of the proposed method, a protype of AFTR-WPT system is developed in the indoor laboratory environment. The schematic diagram, the geometrical structure model and the photo of the AFTR-WPT system are displayed in Figs. 2(a), (b) and (c), respectively.

The system consists of 16 transmit antennas and 9 receive users. The transmit antennas of the TRM are fixed on 4 plastic plates. The power transfer region enclosed by the plastics is 90 cm × 90 cm × 40 cm. In this system, we employ 9 LEDs to imitate multi-users. Each LED is connected to a rectifier circuit and a receive antenna. They are arranged in a 3*3 array and placed at the center of the power transfer region. A 1*16-way feed network with a capability of phase and amplitude adjustment is designed to perform the phase-conjugated operation and phase/amplitude adjustment so that the optimal excitations can be generated for 16 transmit antennas. The radio frequency signal generator is used to generate the continuous-wave signals and the power amplifier (PA) is used to amplify the continuous-wave for increasing the transmit power.

Fig. 3 depicts the photo of the transmit antenna used in the TRM. The size of the transmit antenna is 340 mm × 76 mm, which is made of 1*4 microstrip antennas. The transmit antenna works at 2.40 GHz with the measured bandwidth of 50 MHz and the maximum gain of 11.7 dB. The radiation efficiency is 70.2% and the half power beam width of the radiation pattern in the E-plane is 19°.

Fig. 4(a) shows the receive module which consists of a monopole receiving antenna, a rectifier circuit and an LED.

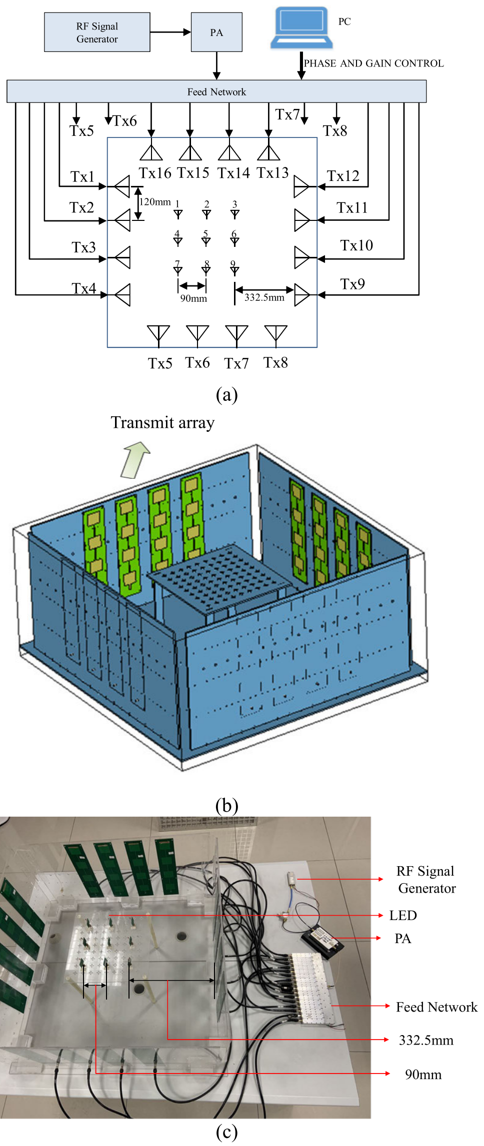

FIGURE 2. (a) Schematic diagram of AFTR-WPT, (b) the geometric structure of AFTR-WPT experiment setup, and (c) the photo of AFTR-WPT experiment setup.

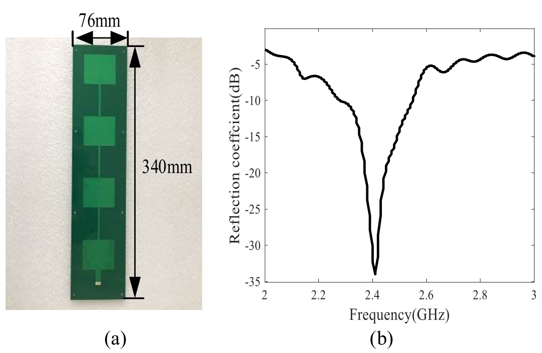

FIGURE 3. (a) The photo of the transmit antenna and (b) the measured S11 of transmit antenna.

The receiving antenna is used to receive the electromagnetic wave radiated by the transmit antennas. The rectifier circuit converts the high-frequency power into DC power and drives

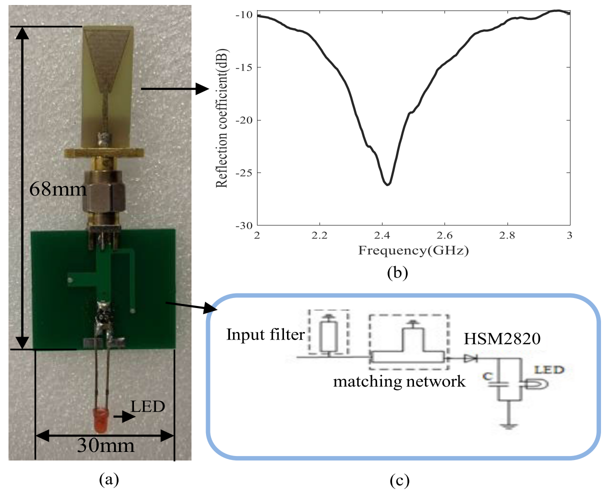

FIGURE 4. (a) Photo of the receive module, (b) the measured S11 of the receive monopole antenna, and (c) the schematic diagram of the rectifier circuit.

the LED. The rectifier circuit is fabricated on the FR4 substrate of a thickness of 1.6 mm and the relative permittivity of 4.6. Fig. 4(b) illustrates the schematic diagram of the rectifier circuit and Fig. 4(c) displays the measured S11 of the received monopole antenna.

B. ANALYSES FOR MULTI-USER TR-WPT BASED ON THE DIRECT TIME REVERSAL SCHEME AND THE ASYNCHRONOUS FOCUSING SCHEME

After obtaining the channel matrix between 16 transmit antennas and 9 receive antennas via Vector Network Analyzer (Agilent E5071C), one can start the experiments on the wireless power transfer with the WPT system. First, we studied the performance of the multi-users TR-WPT based on the direct time reversal scheme, which focused the power at users simultaneously without any phase differences.

Without loss of generality, 4 LEDs (No.3, 4, 7, 9) were selected from 9 LEDs to demonstrate the performance of TR-WPT based on the direct time reversal scheme. Fig. 5 shows the power distribution (a.u.) received by 9 LEDs when the system achieves the maximum transfer efficiency. It can be seen from Fig. 5 that under the maximum efficiency of TR-WPT, the power received by four LEDs (No. 3, 4, 7, 9) are not equal. Among the four LEDs, the power received by No.7 is the highest and that received by No.4 is the lowest. The maximum power is about four times of the minimum. In addition, the non-selected LEDs (No. 1, 6) also receive some power because the sidelobes of the focusing fields appear at the positions of these non-selected users. Similar results are observed in different numbers of selected users. Due to the page limit, we do not present them in this paper. From these experiments, it can be concluded that if one wants to achieve the maximum transfer efficiency for the TR-WPT system based on the direct time reversal scheme, equal power assignment cannot be ensured for each user.

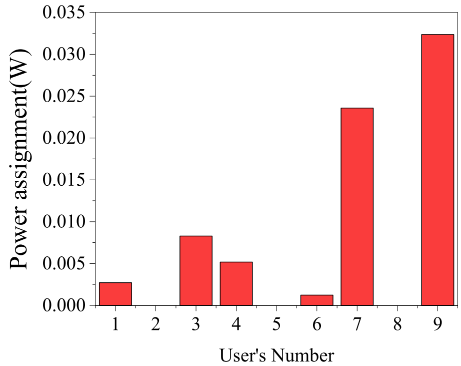

FIGURE 5. **The receive power assignment between the selected users (No.3,4,7,9) by the TR-WPT based on the direct time reversal scheme with the total transmitted power of 1W.**

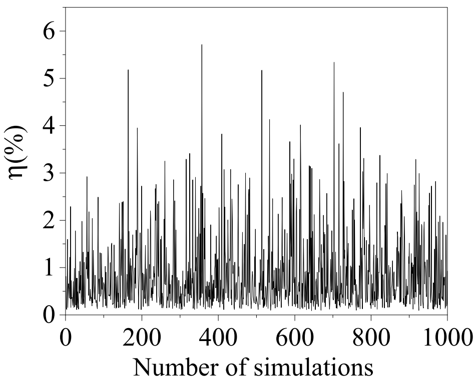

FIGURE 6. **The calculated transfer efficiencies of the AFTR-WPT under the cases of random phase differences among the focusing signals received by multi-users.**

Some experiments on the AFTR-WPT were then conducted. In these experiments, we did not require power to focus simultaneously at the selected multi-users. Some phase difference among the focusing signals received by the multi-users is allowed but all the selected users should have the same received power in all experiments. With the same 4 LEDs selected, a total of 1000 sets of experiments with the asynchronous focusing scheme were carried out. The phase difference among the signals focused at the users were randomly selected within the range from $-\pi$ to π. Fig. 6 presents the calculated power transfer efficiency of the AFTR-WPT. The fluctuation of the power transfer efficiency varies from 0.09% to 5.71%. Fig. 7 gives the statistical data for different transfer efficiencies. These data show that the transfer efficiency changes with the phase difference distribution and in most cases the transfer efficiency is very low. The probability of the transfer efficiency being less than 1% is higher than 70%. However, if the phase differences among the focusing signals are properly designed, the transfer efficiency of the system can be higher than 5.7%. From these results, we infer that, by optimizing the phase differences among the focusing signals received by multi-users, it is possible for AFTR-WPT to achieve a satisfactory transfer efficiency for the users allocated with equal receive power assignment.

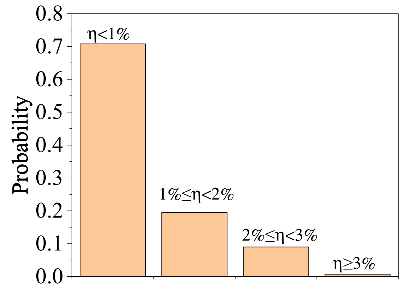

FIGURE 7. **Probability property of the transfer efficiency of AFTR-WPT under the cases of random phase differences among the focusing signals received by multi-users.**

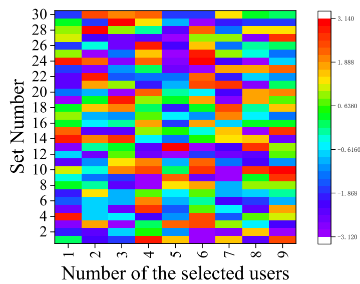

FIGURE 8. **A total of 30 sets of random phase differences among the focusing signals received by multi-users.**

C. ANALYSES FOR MULTI-USERS AFTR-WPT WITH EQUAL RECEIVED POWER ASSIGNMENT

In order to further study the effects of the phase difference among the focusing signals on the transfer efficiency of the AFTR-WPT with equal power assignment for multi-users, we studied the cases from 2 to 9 LEDs that are selected for wireless power supply. Their transfer efficiencies are compared with 30 sets of the same random phase differences valued in $[-\pi, \pi]$, as shown in Fig. 8.

Fig. 9 shows the calculated transfer efficiency of the AFTR-WPT with the same receive power for different selected users by utilizing the same random phase difference among the focusing signals. It can be seen from Fig. 9 that by using different phase differences, the transfer efficiencies are different. In some cases, the AFTR-WPT achieves relatively high transfer efficiency. However, in most cases, the transfer efficiency is rather low. Therefore, phase optimization is needed to achieve the highest transfer efficiency.

Here, 4 LEDs (No.3, 4, 7, 9) are still chosen to illustrate the power assignment for multi-users by phase optimization of the focusing signals. Fig. 10 shows the power assignment for the selected LEDs after phase optimization. It can be seen that the four selected LEDs are allocated with almost the same power. At the same time, the non-selected LEDs receive almost no power.

Then phase optimization was carried out for different number of selected LEDs from 2 to 9 for further demonstration of the performance of the AFTR-WPT system. Table 1 compares the maximum efficiencies obtained by the phase optimization for all studied cases. Fig. 11 compares the maximum efficiencies of AFTR-WPT with the maximum

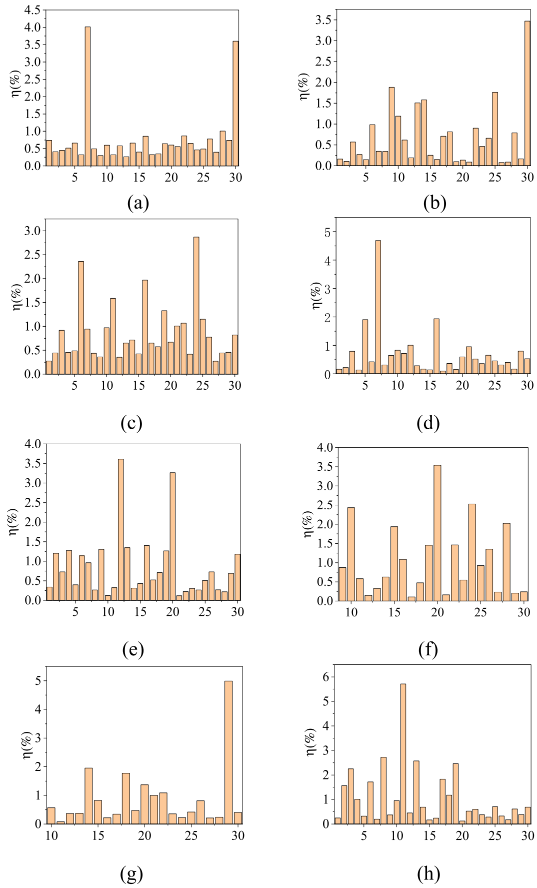

FIGURE 9. The calculated transfer efficiency of AFTR-WPT with the same receive power for (a) 2 users, (b) 3 users, (c) 4 users, (d) 5 users, (e) 6 users, (f) 7 users, (g) 8 users and (h) 9 users.

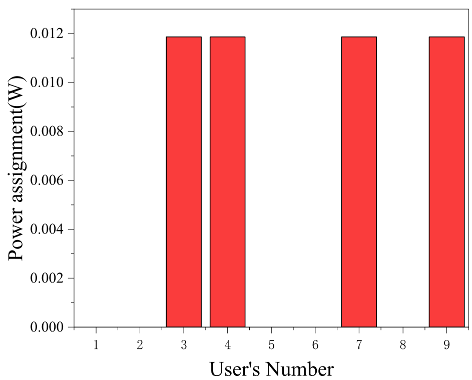

FIGURE 10. The receive power assignment among the selected LEDs (No.3, 4, 7, 9) achieved by the AFTR-WPT after phase optimization with the total transmit power of 1W.

one of TR-WPTF based on the direct time reversal scheme. It can be seen from these data that in all cases the optimal transfer efficiencies of the AFTR-WPT are higher than 6%. What's more, most of them approach the maximum transfer efficiency of the TR-WPT based on the direct time reversal scheme with non-equal receive power allocation. These data give a confirming verification that AFTR-WPT is a good approach to achieve the equal received power assignment for multi-users and high transfer efficiencies.

TABLE 1. Efficiency comparison of AFTR-WPT after phase optimization for different cases.

Number of powered users	The selected users to be powered	the optimal transfer efficiency
2	1, 7	7.82%
	3, 9	6.85%
	4, 6	6.38%
	7, 9	6.76%
3	1, 2, 7	8.58%
	1, 3, 7	7.95%
	1, 3, 9	7.05%
	1, 7, 9	8.01%
4	1, 2, 7, 8	9.61%
	1, 3, 7, 9	8.37%
	2, 3, 8, 9	8.89%
	4, 6, 7, 9	7.93%
5	1, 2, 3, 7, 8	9.68%
	1, 2, 3, 8, 9	9.10%
	1, 3, 4, 6, 7	8.07%
	3, 4, 6, 7, 9	7.99%
6	1, 2, 4, 6, 8, 9	8.87%
	1, 3, 4, 6, 7, 9	8.55%
	2, 3, 4, 6, 7, 8	8.78%
	2, 4, 6, 7, 8, 9	8.59%
7	1, 2, 3, 4, 6, 7, 8	9.77%
	1, 2, 3, 5, 7, 8, 9	9.91%
	1, 2, 4, 6, 7, 8, 9	9.78%
	2, 3, 4, 6, 7, 8, 9	9.09%
8	1, 2, 3, 4, 5, 6, 7, 9	8.89%
	1, 2, 3, 4, 5, 6, 8, 9	9.24%
	1, 2, 4, 5, 6, 7, 8, 9	9.88%
	1, 3, 4, 5, 6, 7, 8, 9	8.77%
9	1, 2, 3, 4, 5, 6, 7, 8, 9	9.98%

TABLE 2. Comparison of simulation and measured efficiency.

Users	1, 4, 7	1, 6, 9	1, 5, 7, 9	1, 3, 5, 7, 9
Simulated efficiency	3.58%	3.28%	3.98%	5.61%
Measured efficiency	2.29%	2.18%	3.08%	3.71%
Error	1.29%	1.10%	0.90%	1.90%

Before experiments, a simulation model shown in Fig. 2(b) was established by the commercial software CST Studio Suite. We select some LEDS (NO.1, 6, 9) and (NO.1, 4, 7) for power transfer, and the simulation result is shown in Fig. 12.

Four cases are selected to compare the measured power transfer efficiency with the simulated power transfer efficiency, as shown in Table 2. It can be seen from Table 2 that

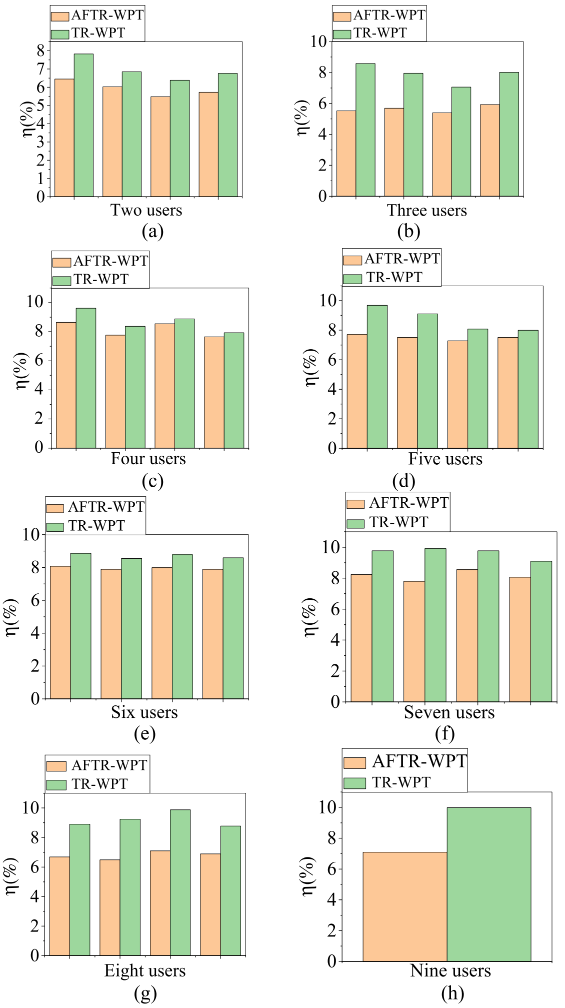

FIGURE 11. **Comparison between the optimal transfer efficiencies of the AFTR-WPT and the maximum transfer efficiencies of the TR-WPT based on the direct time reversal procedure for (a) 2 users, (b) 3 users, (c) 4 users, (d) 5 users, (e) 6 users, (f) 7 users, (g) 8 users and (h) 9 users.**

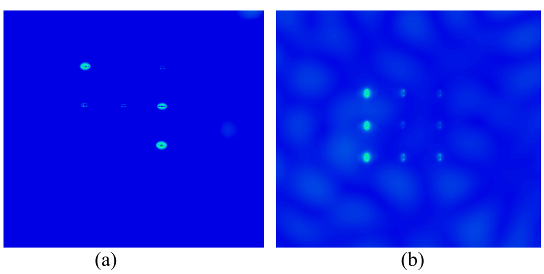

FIGURE 12. **The simulated results of AFTR-WPT (a) (NO.1, 6, 9) and (b) (NO.1, 4, 7).**

all the measured power transfer efficiencies agree well the simulated ones with small errors lower than 2%.

IV. CONCLUSION

In this paper, an AFTR-WPT scheme for multi-users power supply with equal received power assignment is proposed and investigated by experiments and simulations. The basic idea of AFTR-WPT is that the power focuses at the selected multi-users at different time. The transfer efficiencies of the AFTR-WPT system is compared with those of the TR-WPT based on direct time reversal procedure. In our study, we investigate the systems by utilizing only the continuous RF waves for wireless power transfer. Thus, the focusing time can be simply controlled by optimizing the phase differences among the focusing signals received by multi-users. By optimizing these phases, the transfer efficiency performance of the multi-users AFTR-WPT with equal received power allocation is studied for powering different number of users based on the experimental data. Results show that after the phase optimization, the AFTR-WPT can not only allocate equal power to multi-users but also achieve the optimal transfer efficiency. Both simulations and experiments are carried out for validations. In all cases studied, the optimal transfer efficiencies are close to the maximum value obtained by the TR-WPT based on the direct time reversal scheme. The proposed AFTR-WPT system indicates important potentials of applications in complicated multipath indoor scenarios such as smart homes and smart factories. In follow-up study, the system will be improved in such a way that some users are chosen to carry out the power transfer, and at the same time, some others to carry out information transfer, so as to establish an AFTR simultaneous wireless information and power transfer (AFTR-SWIPT).

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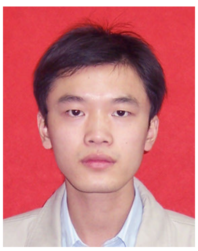

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