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Multi-Posture Microwave Power Transmission with Dual Alignment of Transmitting and Receiving Beams by Forward and Backward Time Reversal

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Abstract—In actual microwave power transmission (MPT) scenarios such as smart factory, the system efficiency and output dc power will decrease when the receiving antenna array of the multi-posture receiver does not face the transmitting antenna. To address the challenge of efficiently transmitting energy from the transmitter to a multi-posture receiver, a multi-posture MPT scheme based on forward and backward time reversal (TR) is proposed. This letter introduces phase shifters in the multi-posture receiver, enabling the beam of receiver to have steering capabilities. Importantly, inspired by the adaptive beam alignment characteristic of TR, the phase shifters of receiver are configured to align the beam of the offset receiver with the transmitter using the backward TR method, while the phase shifters of transmitter are configured to align the beam of the transmitter with the receiver using the forward TR method. So, dual alignment of the transmitting and receiving beams is achieved. A prototype of the multi-posture MPT system is established. The experiment results show that the output dc power of the multi-posture MPT scheme is 30.6 dB higher than the traditional MPT scheme when the multi-posture receiver changes its orientation, demonstrating the effectiveness of the multi-posture MPT scheme.

Index Terms—multi-posture, microwave power transfer, dual alignment of beams, time reversal.

I. INTRODUCTION

MICROWAVE power transmission (MPT) technology wirelessly delivers power from the transmitter to the target devices through antennas, enabling target devices to operate indefinitely without the need for power cables or battery replacement [1-5]. Recently, MPT technology has attracted growing attention in various scenarios like the Internet of Things, unmanned factories, and smart warehousing [6-8].

Among the existing MPT researches, both TR method [9-13]

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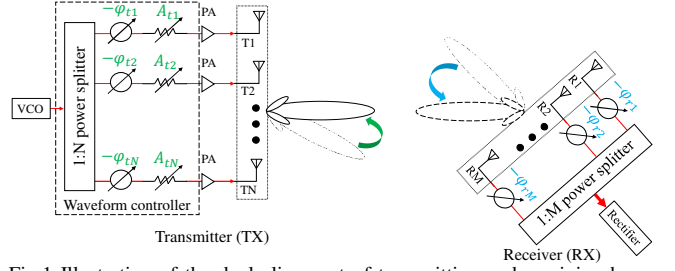


Fig.1 Illustration of the dual alignment of transmitting and receiving beams characteristic of the forward and backward TR method

and retro-directive (RD) method [14-20] are favored by many researchers, thanks to their ability to enable the power beam of transmitter to adaptively align with the receiver. In these MPT systems investigated with the TR or RD method in quasi-free-space scenarios, directional antennas (such as microstrip antennas) are commonly used for the receiver to efficiently capture the microwave energy transmitted from the transmitter [11][15-18]. Furthermore, researchers have explored the use of multiple receiving antennas arranged in an array to enhance the gain of receiver, enabling higher efficiency and larger output dc power [14][19]. But it is worth noting that all these studies on TR or RD method have configured the receiving antenna to always face the transmitting antenna. The rationale behind this configuration lies in the limitation of the TR or RD method, which can only adaptively align the beam of transmitter with the receiver but lacks the capability to adaptively align the beam of receiver with the transmitter.

However, in actual MPT application scenarios, the receiving antenna of receiver is integrated with the multi-posture target devices such as wearable devices or mobile devices. This means that the receiving antenna of a multi-posture receiver will not facing the transmitting antenna after changing the orientation of receiver, resulting in a degradation in the system efficiency and the output dc power. The degradation in system performance is caused by the beam of receiving antenna no longer aligning with the transmitting antenna after changing the orientation of receiver.

In order to efficiently transmitting energy from the transmitter to a multi-posture receiver after changing the orientation of receiver, this letter proposes a multi-posture MPT scheme based on the forward and backward TR method. This letter introduces phase shifters in the multi-posture receiver, enabling the beam of receiver to have steering capabilities. Importantly, drawing inspiration from the adaptive beam alignment characteristic of TR [11], the phase shifters of

receiver are configured to align the beam of the offset receiver with the transmitter using the backward TR method (elaborated later in Section III. A), while the phase shifters of transmitter are configured to align the beam of the transmitter with the receiver using the forward TR method (i.e. the traditional TR method). So, dual alignment of the transmitting and receiving beams is achieved. A prototype of the multi-posture MPT is established to verify the effectiveness of the new scheme.

II. PERFORMANCE ANALYSIS OF MULTI-POSTURE MPT

A. Theoretical derivation of the focused field at the receiver

The system model is shown in Fig.1, where the number of transmitting antennas at one transmitter is set to N , and the number of receiving antennas at one receiver is set to M . The acquisition of the TR focused field for a single receiving antenna has been studied [11]. Additionally, the field of an array composed of multiple antennas can be obtained by linearly superposing the field of each individual antenna. Hence, this letter begins by analyzing the TR focused field for each individual receiving antenna, and then by superposing these fields to obtain the TR focused field of an array composed of multiple receiving antennas.

In [13], we derive the characteristics of MIMO systems. Therefore, the received signal matrix is directly written as follows:

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

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

$$y_{m,1} = h_{1,m}h_{1,1}^* + \cdots + h_{n,m}h_{n,1}^* + \cdots + h_{N,m}h_{N,1}^* \quad (2)$$

$$y_{m,m} = h_{1,m}h_{1,m}^* + \cdots + h_{n,m}h_{n,m}^* + \cdots + h_{N,m}h_{N,m}^* \quad (3)$$

$$y_{m,M} = h_{1,m}h_{1,M}^* + \cdots + h_{n,m}h_{n,M}^* + \cdots + h_{N,m}h_{N,M}^* \quad (4)$$

Where $h_{n,m}$ represents the channel information between the n th transmitting antenna and the m th receiving antenna, $(\cdot)^*$ indicates conjugate operation, $y_{m,M}$ indicates the sidelobe signal at the m th receiving antenna when the focus spot is generated at the M th receiving antenna.

According to the principle of linear superposition, the actual received signal of each receiving antenna in the array is a superposition of its own focused signal and the sidelobe signals from other receiving antennas. Thus, the field at the m -th receiving antenna is

$$b_m = y_{m,1} + \cdots + y_{m,m} + \cdots + y_{m,M} \quad (5)$$

Actually, b_m is the sum of one row of the $\mathbf{Y}^{M \times M}$ matrix.

B. Why does the system performance deteriorate after changing the orientation of receiver?

For a receiver with M antennas facing the transmitter as shown in Fig. 2, because the distance between the transmitter and receiver is much greater than the aperture size of the receiving antennas, the path lengths from one transmitting antenna to each receiving antenna are approximately equal. Therefore, in an MPT system operating in quasi-free-space conditions, it can be derived that

$$h_{n,1} \approx h_{n,m} \approx h_{n,M} \quad (6)$$

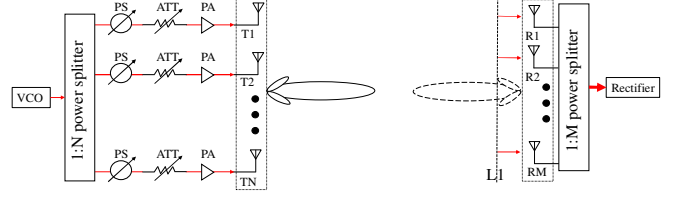


Fig.2 A MPT system in which the receiver facing the transmitter

Thus, it can be derived, by combining (2), (3), (4) and (6), that

$$y_{m,1} \approx \cdots \approx y_{m,m} \approx \cdots \approx y_{m,M} \quad (7)$$

So, the field at the m -th receiving antenna facing the transmitter can be approximated as:

$$b_m = y_{m,1} + \cdots + y_{m,m} + \cdots + y_{m,M} \approx M y_{m,m} \quad (8)$$

Because the phase of $h_{n,m}$ cancels the phase of $h_{n,m}^*$ and all receiving antennas transmit the pilot signal in phase, so the phase of each term to the right of the equal sign in (3) is the same. Thus, the phase of the diagonal elements $y_{1,1}$ to $y_{M,M}$ is the same. Additionally, b_1 , b_m and b_M are coherent according to (8). Furthermore, we represent the equiphasic surface arriving at the receiving antennas with dashed line $L1$, which is parallel to the receiving antenna array, in Fig. 2.

Therefore, the signal received at the receiver facing the transmitter is the result of the coherent superposing of signals received by M receiving antennas through phase-coherent combiners in each path, and it is given by:

$$b = b_1 + \cdots + b_m + \cdots + b_M = M|y_{1,1}|\cos\theta + \cdots + M|y_{m,m}|\cos\theta + \cdots + M|y_{M,M}|\cos\theta \quad (9)$$

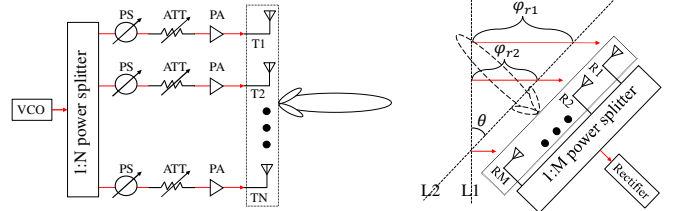


Fig.3 A MPT system in which the receiver not facing the transmitter

In practice, however, the receiver may not face the transmitter as shown in Fig. 3. Because the orientation of the receiving antenna array changes from being parallel to dashed line $L1$ to being parallel to dashed line $L2$, causing the phase of the signal received by each receiving antenna to change from being in phase to being out of phase.

Therefore, the superposed result of phase-varying signals received by M receiving antennas through the phase-coherent combiner in each path is

$$b = b_1 + \cdots + b_m + \cdots + b_M = M|y_{1,1}|\cos\varphi_{r1} + \cdots + M|y_{m,m}|\cos\varphi_{rm} + \cdots + M|y_{M,M}|\cos\varphi_{rM} \quad (10)$$

(Example1: Taking the example of four receiving antennas spaced 0.6 wavelengths apart, with a distance of 2m between the transmitter and the receiver, operating at a frequency of 2.435 GHz. If the offset angle θ for the receiving antennas in Fig.3 are set to 45° , then the phase variations $(\varphi_{r1}, \varphi_{r2}, \varphi_{r3}, \varphi_{r4})$ of the signals received by the four receiving antennas are $(0^\circ, 153^\circ, 305^\circ, 98^\circ)$. The power of the superposed signals with these phase differences in (10) is 13.6 dB lower compared to their coherent superposition in (9).)

From the perspective of beam direction, the receiving antenna array cannot effectively capture the energy of the power

beam of transmitter because the high-gain direction of the beam of receiver is offset from the transmitter, resulting in the degradation of system performance.

III. MULTI-POSTURE MPT SCHEME BY FORWARD AND BACKWARD TR METHOD

A. Idea of forward and backward TR method

On the one hand, if the phases of the received signals with different phases at the input ports of the combiner (i.e. the 1:M power splitter) could be changed to ensure coherent superposition, the offset receiver would efficiently receive the power signal, as depicted in (11).

$$b = b_1 e^{-j\varphi_{r1}} + \dots + b_m e^{-j\varphi_{rm}} + \dots + b_M e^{-j\varphi_{rM}} = M|y_{1,1}|\cos(\varphi_{r1} - \varphi_{r1}) + \dots + M|y_{m,m}|\cos(\varphi_{rm} - \varphi_{rm}) + \dots + M|y_{M,M}|\cos(\varphi_{rM} - \varphi_{rM}) \quad (11)$$

In other words, if it were possible to realign the beam of the offset receiver with the transmitter, the offset receiver could still efficiently capture the power signal. Therefore, this letter introduces phase shifters between the receiving antennas and the input ports of the combiner at the receiver. Thus, by controlling these phase shifters, the beam of the offset receiver can be realigned with the transmitter.

On the other hand, how can the phase values be obtained to realign the beam of the offset receiver with the transmitter? Taking inspiration from TR-MPT systems that enable the beam to self-align to the receiving antenna, this letter proposes a method where one transmitting antenna transmits the pilot signal, enabling M receiving antennas to capture the pilot signals for channel information. Subsequently, by setting the phase shifters of receiver based on the conjugate values of the channel information, the beam of receiver can be aligned with the transmitter. We refer to this method as the backward TR method.

Upon realigning the beam of the offset receiver with the transmitter using the backward TR method, employing the forward TR method (the traditional TR method) enables the beam of transmitter to align with the receiver. This ultimately achieves dual alignment of the transmitting and receiving beams by forward and backward TR method.

B. Details of the multi-posture MPT scheme

Summing up, this paper proposes a multi-posture MPT scheme by introducing phase shifters at the receiver. By double leveraging the adaptive beam alignment characteristic of TR, it achieves dual alignment of the transmitting and receiving beams, thereby enabling multi-posture MPT. The specific details of the scheme are outlined as follows:

Step1(The detection mode of the backward TR): one transmitting antenna transmits the pilot signal S_1 , enabling M receiving antennas to capture the pilot signal S_1 for getting channel information $\mathbf{H}_1 = [A_{r1}e^{j\varphi_{r1}}, A_{r2}e^{j\varphi_{r2}}, A_{r3}e^{j\varphi_{r3}}, A_{r4}e^{j\varphi_{r4}}]$ as shown in Fig.4.

Step2(The detection mode of the forward TR): setting the phase shifters at the offset receiver as $[-\varphi_{r1}, -\varphi_{r2}, -\varphi_{r3}, -\varphi_{r4}]$, and the offset receiver, whose beam realign to the transmitter, transmits a pilot signal S_2 . This enables N transmitting antennas to capture the pilot signal S_2 for getting channel information $\mathbf{H}_2 = [A_{t1}e^{j\varphi_{t1}}, A_{t2}e^{j\varphi_{t2}}, A_{t3}e^{j\varphi_{t3}},$

$A_{t4}e^{j\varphi_{t4}}]$ as shown in Fig.5.

Step3(The power transfer mode of the forward TR): setting the phase shifters at the transmitter as $[-\varphi_{t1}, -\varphi_{t2}, -\varphi_{t3}, -\varphi_{t4}]$, and the transmitter transmits the power signal to achieve multi-posture MPT with dual alignment of transmitting and receiving beams as shown in Fig.6.

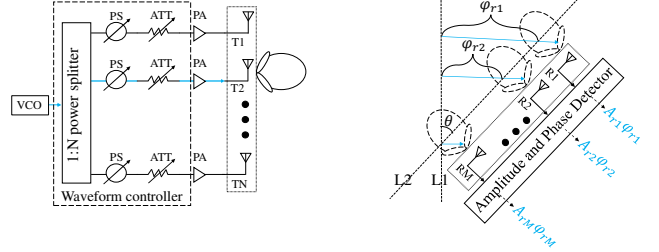


Fig.4 Block diagram of the detection mode of the backward TR method

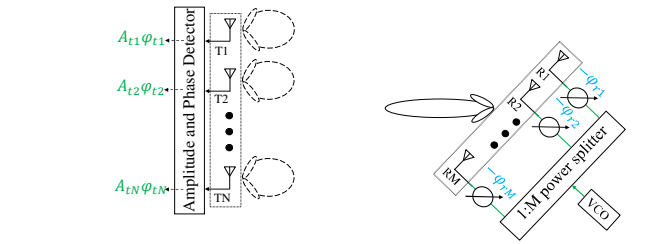


Fig.5 Block diagram of the detection mode of the forward TR method

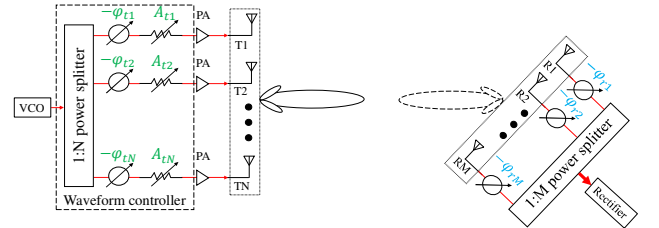


Fig.6 Block diagram of the power transfer mode of the forward TR method

IV. EXPERIMENTAL RESULTS

A. Performance of the multi-posture MPT scheme

To evaluate the performance of the multi-posture MPT scheme proposed in this letter, an experimental system was constructed. The number of transmitting antennas (N) and receiving antennas (M) are both set to 4. The distance between the receivers and the transmitter is 2 m. The S11 measurement results for the transmitting antenna unit or the receiving antenna unit at 2.435 GHz are below -10 dB. Therefore, we chose 2.435 GHz as the system operating frequency.

Fig.7 illustrates the experimental setup of the multi-posture MPT system. The channel information in Fig. 7(a) and Fig. 7(b) was obtained through a vector network analyzer (Agilent E5026A). The phase control accuracy and amplitude control accuracy of the waveform controller are set to 1° and 0.1dB, respectively. The gain of the two-stage power amplifier in series is 54 dB. The maximum RF power of each port of the transmitting antenna is 34.5 dBm. The gains of the transmitting and receiving antennas at the operating frequency both are 6.4 dBi. The phase control accuracy of the phase shifter in receiver is set to 1°. A rectifier with a class-F⁻¹ topology is designed, utilizing the Schottky diode HSMS2822. The maximum conversion efficiency of the rectifier is 71.9%, which achieves at an input RF power of 20 dBm with a load of 5200 Ω.

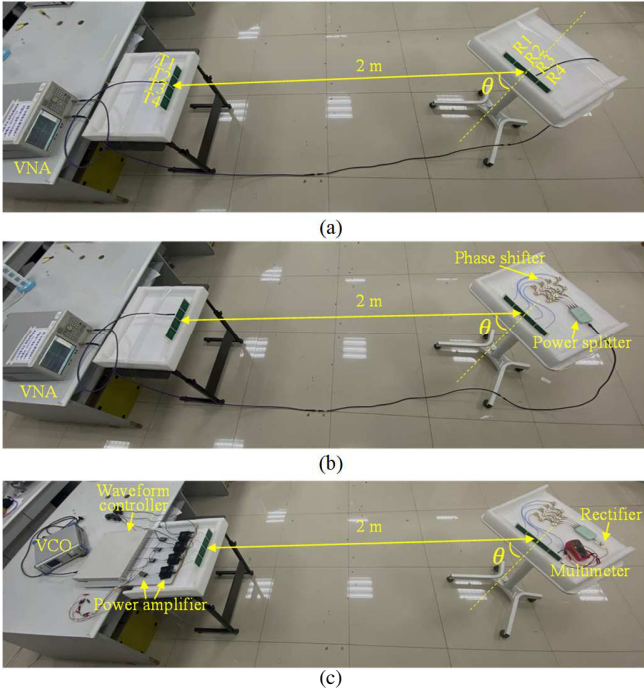


Fig.7 Experimental setup for the multi-posture MPT system: (a) *Step1*, (b) *Step2* and (c) *Step3*

TABLE I
COMPARISON OF THE CHANNEL GAINS OF DIFFERENT SCHEMES

	Traditional TR	Multi-posture MPT
A_{t1}	-46.8 dB	-34.6 dB
A_{t2}	-46.6 dB	-34.5 dB
A_{t3}	-49.3 dB	-35.1 dB
A_{t4}	-52.3 dB	-37 dB

Table 1 presents the channel gains, obtained from Fig.7(b), between a single transmitting antenna and the receiving array for both the multi-posture MPT scheme and traditional TR scheme when $\theta = +45^\circ$. From Table 1, it can be observed that the channel gain of the multi-posture MPT scheme is approximately 13 dB higher compared to the traditional TR scheme when $\theta = +45^\circ$. This indicates that the backward TR method can realign the beam of the offset receiver with the transmitter by adjusting the phase shifters of receiver.

Fig.8 shows the measured and simulated RF power and dc power received by the receiver at different orientation. When the receiver is facing the transmitter ($\theta = 0^\circ$), the power levels of the multi-posture MPT scheme and the traditional TR scheme are approximately equal. This indicates that the multi-posture MPT scheme can also align the transmitting beam towards the receiver, benefiting from the forward TR method. In a scenario where the receiver is not directly facing the transmitter, such as $\theta = 45^\circ$, it can be observed that the received dc power of the multi-posture MPT scheme (6.5 dBm) is 30.6 dB higher than that of the traditional TR scheme (-24.1 dBm). The reason is that the multi-posture MPT achieves dual alignment of the offset receiving beam and the transmitting beam through backward TR method and forward TR method, resulting in a higher received RF power (10.7 dBm) compared to the traditional TR scheme (-1.8 dBm) that only aligns the transmitting beam towards the offset receiver. This validates the

effectiveness of our proposed multi-posture MPT with dual alignment of transmitting and receiving beams. Furthermore, the combination of forward and backward TR method with two-dimensional antenna arrays can also precisely align the beams from the offset receiver and transmitter at different heights.

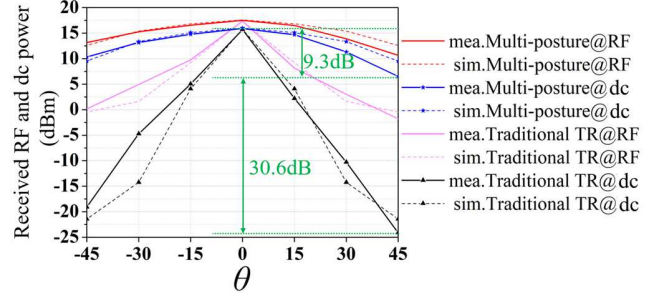


Fig.8 The measured and simulated RF power and dc power received by the receiver at different orientation.

We also find that the difference in the received dc power is greater than difference in the received RF power when $\theta = +45^\circ$ in Fig. 8. This is because the rectification efficiency of rectifier decreases as the RF power decreases when the RF power is lower than its optimal input RF power. (20dBm@71.9%; 11dBm@40.1%; -1dBm@0.6%)

B. Comparison with other MPT Systems

TABLE II COMPARISON OF THE RELATED MPT SYSTEMS					
Ref.	Power drop of the offset receiver	Receiver's offset angle /°	Method of beam alignment	Number of receiving antenna	multi-posture MPT
[6][11]	N/A	0	TX → RX	1	NO
[15-18]	N/A	0	TX → RX	2	NO
[14]	N/A	0	TX → RX	6	NO
This work	9.3 dB	±45	TX ↔ RX	4	YES

N/A: not available

*: Graphically estimated

Table II compares the critical specifications of the proposed approach with the related works. Compared with the systems in [6][11][14-18], the proposed approach achieves maximum offset angle of the receiver and multi-posture MPT with dual alignment of transmitting and receiving beams, which paves a critical step for the practical MPT applications with multi-posture devices.

IV. CONCLUSION

In this letter, we present a multi-posture MPT scheme based on forward and backward time reversal. The phase shifters of receiver are configured to align the beam of the offset receiver with the transmitter using the backward TR method, while the phase shifters of transmitter are configured to align the beam of the transmitter with the receiver using the forward TR method. The measured received dc power of the multi-posture MPT scheme is 30.6 dB higher than that of the traditional TR scheme, which demonstrate that the proposed approach can achieving multi-posture MPT with dual alignment of transmitting and receiving beams. The experimental results show the potential for wirelessly powering multi-posture devices such as randomly oriented wearable devices or mobile devices.

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