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Microwave Power Transmission Using a Signal-to-Leakage-and-Noise Ratio to Protect Wireless Communication Devices

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Abstract Microwave Power Transmission (MPT) is a promising technology that can be utilized to charge devices wirelessly and remotely. However, most previous studies on MPT focused on improving charging efficiency and have ignored the harmful effects on wireless communication devices that are sensitive to the considerable received signal power caused by the electromagnetic radiation of microwaves. To resolve this problem, this study introduces into MPT the signal-to-leakage-plus-noise ratio (SLNR), used to suppress co-channel interference in multi-user Multiple-Input Multiple-Output (MIMO) downlink communications. We establish a beamforming scheme that maximizes SLNR for MPT. Compared with a beamforming scheme that does not consider leakage power, the proposed method transmits power to intended receivers while suppressing leakage power to protected devices. Based on simulations, our method decreases the leak power to protected devices by over 10 dB while maintaining the received power at the targeted receivers, compared with the conventional method.

Keywords: Microwave power transmission, SLNR for MPT, Beamforming
Classification: Antennas and propagation

1. Introduction

Microwave power transmission (MPT) is currently attracting significant attention as a wireless power transmission method. MPT can deliver power to a receiver at a greater distance than near-field power transmission [1]. However, MPT has some shortcomings, such as lower transmission efficiency compared with near-field power transmission and interference to the wireless communication devices near the MPT transmitter, which may cause malfunctions in the device operation.

Most studies on MPT focused on an improvement in charging efficiency. For example, a method called retro-reflective beamforming, a technique based on the phase conjugation of pilot signals from receivers, was used to achieve high-efficiency MPT [2] [3] [4]. Although these retro-reflective methods are efficient and low-cost for accomplishing accurate beamforming of receivers, they are insufficient in terms of protecting wireless communication devices other than receivers from microwaves compared with near-field power transmission [8].

To overcome the safety challenges caused by electromagnetic radiation (EMR) exposure, other schemes to maximize the received power with EMR value limitations by solving optimization problems for safe charging have been proposed [5] [6] [7]. However, these studies assume a propagation channel model that depends on distance and cannot consider the effects of multipath propagation; hence, they may not be able to properly work in a practical environment.

Given the above background, this study aims to achieve microwave beamforming toward receivers while limiting the leakage power to the protected devices. To realize this, we introduce and extend the signal-to-leakage-plus-noise ratio (SLNR), which is used in multi-user MIMO downlink communications [9] [10] [11]. Normalized beamforming weights are chosen to maximize SLNR for the given locations of the intended receivers and protected devices. Subsequently, final beamforming weights are obtained by multiplying the normalized beamforming weights with an arbitrary constant to adjust the desired received power. According to the simulation results, the proposed beamforming method based on maximizing SLNR for MPT outperforms conventional beamforming methods that do not consider leakage power. Further, our proposed method can be adapted to complex environments once the channels are obtained.

2. Principle

We introduce the SLNR for MPT, which is the ratio of the received power to leak power and the noise power. The concept of SLNR was previously introduced in the multi-user MIMO downlink communication domain [9] [10]; however, we extend the concept to the MPT domain to simultaneously realize highly efficient power transmission and protection.

First, we explain SLNR for multi-user MIMO downlink communications. We consider K users and a base station. The base station comprises N antenna elements and user #k comprises M_k antenna elements. The $N \times 1$ transmitted vector $\mathbf{x}(t)$ at time t is expressed as $\mathbf{x}(t) = \sum_{k=1}^{K} \mathbf{w}_k s_k(t)$, where $s_k(t)$ is the scalar symbol intended for user #k at time t and $\mathbf{w}_k$ is the beamforming weight multiplied by $s_k(t)$. $s_k(t)$ and $\mathbf{w}_k$ are normalized as follows:

$$E[|s_i(t)|^2] = 1, ||\mathbf{w}_k||^2 = 1, \tag{1}$$

for $k = \{1,\cdots,K\}$. The $N \times 1$ transmitted data vector $\mathbf{x}(t)$ is propagated to each receiver through the channels. The $M_i \times 1$ received vector $\mathbf{y}_i(t)$ for user #i is expressed as $\mathbf{y}_i(t) = \mathbf{H}_i\mathbf{x}(t) + \mathbf{v}_i(t)$, where $\mathbf{H}_i$ is $M_i \times N$ channel matrix defined as

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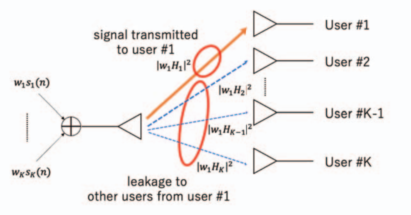

Fig. 1 Leakage power to other users from the signal transmitted to user #1 in MIMO downlink communication

$$\mathbf{H}_i = \begin{bmatrix} h_i^{(1,1)} & \cdots & h_i^{(1,N)} \\ \vdots & \ddots & \vdots \\ h_i^{(M_i,1)} & \cdots & h_i^{(M_i,N)} \end{bmatrix}. \tag{2}$$

$h_i^{(k,l)}$ represents the channel coefficient from the l-th antenna at the base station to the receiver #k antenna at user #i. The additive noise vector $\mathbf{v}_i(t)$ is assumed to have independent complex Gaussian elements with variance σ_i^2 and is spatially white, described as $E\left[\mathbf{v}_i(t)\mathbf{v}_j(t)^*\right] = \sigma_i^2 \mathbf{I}_{M_i}\delta_{ij}$, where I_{M_i} is the $M_i \times M_i$ identity matrix. δ_{ij} is 1 if $i = j$, otherwise 0.

Under these conditions, the average power of the transmitted signal for user #i is described as $||\mathbf{H}_i\mathbf{w}_i||^2$ and the power of the interference caused by the signal transmitted to user #i on the signal received by another user #k is expressed as $||\mathbf{H}_k\mathbf{w}_i||^2$. Thus, the total leakage power from the signal transmitted to user #i is expressed as $\sum_{k=1,k\neq i}^{K} ||\mathbf{H}_k\mathbf{w}_i||^2$. A conceptual diagram of the leak power from the signal transmitted to user #1 is shown in Fig.1. Based on these assumptions, the SLNR for user #i, denoted as $SLNR_i$, is defined as follows:

$$\begin{aligned} SLNR_i &= \frac{||\mathbf{H}_i\mathbf{w}_i||^2}{M_i\sigma_i^2 + \sum_{k=1,k\neq i}^{K} ||\mathbf{H}_k\mathbf{w}_i||^2} \\ &= \frac{||\mathbf{H}_i\mathbf{w}_i||^2}{M_i\sigma_i^2 + ||\tilde{\mathbf{H}}_i\mathbf{w}_i||^2}. \end{aligned} \tag{3}$$

$\tilde{\mathbf{H}}_i$ is the matrix in which all channels except for $\mathbf{H}_i$ are concatenated and defined as

$$\tilde{\mathbf{H}}_i = [\mathbf{H}_1^T \cdots \mathbf{H}_{i-1}^T \mathbf{H}_{i+1}^T \cdots \mathbf{H}_K^T]^T. \tag{4}$$

Beamforming weights $\mathbf{w}_i^o$ are obtained by maximizing (3) subject to (1) and are expressed as follows:

$$\mathbf{w}_i^o = \underset{\mathbf{w}_i \in C^{N\times 1}}{\text{argmax}} \ \frac{\mathbf{w}_i^*\mathbf{H}_i^*\mathbf{H}_i\mathbf{w}_i}{\mathbf{w}_i^*(M_i\sigma_i^2\mathbf{I}_{M_i} + \tilde{\mathbf{H}}_i^*\tilde{\mathbf{H}}_i)\mathbf{w}_i}. \tag{5}$$

This optimization problem is known as the Rayleigh quotient [9] and the optimal beamforming weights are obtained by solving the eigenvalue problem (6):

$$\mathbf{w}_i^o \propto \max\ \text{eigenvector}((M_i\sigma_i^2\mathbf{I}_{M_i} + \tilde{\mathbf{H}}_i^*\tilde{\mathbf{H}}_i)^{-1}\mathbf{H}_i^*\mathbf{H}_i). \tag{6}$$

Second, we describe SLNR of MPT. In the case of K receivers and L protected devices, the transmitter, receiver #k, and protected device l comprise N, $M_{\text{rx},k}$, and $M_{\text{dev},l}$ antenna elements, respectively. In this study, we define the criterion $SLNR_{\text{MPT}}$ as the SLNR for MPT. In the case of MPT, signal communications were not conducted, and it is natural to treat the aforementioned scalar symbol $s_k(t)$ as one. This assumption satisfies (1). Thus, $SLNR_{\text{MPT},k}$, which is the SLNR for MPT at receiver #k, can be written as follows:

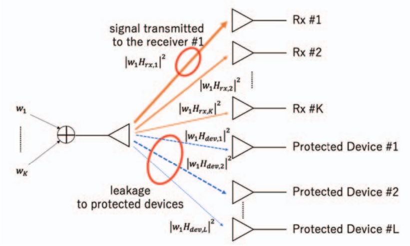

Fig. 2 Leakage power to the protected devices from the signal transmitted to receiver #1 in MPT

$$\begin{aligned} SLNR_{\text{MPT},k} &= \frac{||\mathbf{H}_{\text{rx},k}\mathbf{w}_k||^2}{M_{\text{rx},k}\sigma_k^2 + \sum_{l=1}^{L} ||\mathbf{H}_{\text{dev},l}\mathbf{w}_k||^2} \\ &= \frac{||\mathbf{H}_{\text{rx},k}\mathbf{w}_k||^2}{M_{\text{rx},k}\sigma_k^2 + ||\tilde{\mathbf{H}}_{\text{dev}}\mathbf{w}_k||^2}, \end{aligned} \tag{7}$$

where $\mathbf{H}_{\text{rx},k}$ is the channel matrix between the transmitter and receiver #k, and $\mathbf{H}_{\text{dev},l}$ is the channel between the transmitter and protected device, #l. The channel coefficients are expressed as follows:

$$\mathbf{H}_{\text{rx},k} = \begin{bmatrix} h_{\text{rx},k}^{(1,1)} & \cdots & h_{\text{rx},k}^{(1,N)} \\ \vdots & \ddots & \vdots \\ h_{\text{rx},k}^{(M_{\text{rx},k},1)} & \cdots & h_{\text{rx},k}^{(M_{\text{rx},k},N)} \end{bmatrix}, \tag{8}$$

$$\mathbf{H}_{\text{dev},l} = \begin{bmatrix} h_{\text{dev},l}^{(1,1)} & \cdots & h_{\text{dev},l}^{(1,N)} \\ \vdots & \ddots & \vdots \\ h_{\text{dev},l}^{(M_{\text{dev},l},1)} & \cdots & h_{\text{dev},l}^{(M_{\text{dev},l},N)} \end{bmatrix}. \tag{9}$$

where $h_{\text{rx},k}^{(i,j)}$ is the channel coefficient from the j-th antenna element in the transmitter to the i-th antenna element in the receiver #k, and $h_{\text{dev},l}^{(i,j)}$ is the channel coefficient from the j-th antenna element in the transmitter to the i-th antenna element in the protected device #l. $\tilde{\mathbf{H}}_{\text{dev}}$ is a matrix in which all channels between the transmitter and protected devices are concatenated and defined as follows:

$$\tilde{\mathbf{H}}_{\text{dev}} = [\mathbf{H}_{\text{dev},1}^T \cdots \mathbf{H}_{\text{dev},L}^T]^T. \tag{10}$$

In the case of SLNR for MPT, calculating $SLNR_{\text{MPT},k}$ does not require consideration of the leak power to receivers other than receiver #k, as shown in Fig.2. Non-targeted receivers do not experience any malfunctioning regardless of whether the leakage power to the receivers is considerably large.

By naturally extending SLNR for MIMO downlink communication, beamforming weights obtained by maximizing SLNR for MPT are expressed as follows:

$$\mathbf{w}_i^o = \underset{\mathbf{w}_i \in C^{N\times 1}}{\text{argmax}} \ \frac{\mathbf{w}_i^*\mathbf{H}_{\text{rx},i}^*\mathbf{H}_{\text{rx},i}\mathbf{w}_i}{\mathbf{w}_i^*(M_{\text{rx},i}\sigma_i^2\mathbf{I}_{M_{\text{rx},i}} + \tilde{\mathbf{H}}_{\text{dev}}^*\tilde{\mathbf{H}}_{\text{dev}})\mathbf{w}_i}, \tag{11}$$

and solved as

$$\mathbf{w}_i^o \propto \max\ \text{eigenvector}((M_{\text{rx},i}\sigma_i^2\mathbf{I}_{M_{\text{rx},i}} + \tilde{\mathbf{H}}_{\text{dev}}^*\tilde{\mathbf{H}}_{\text{dev}})^{-1}\mathbf{H}_{\text{rx},i}^*\mathbf{H}_{\text{rx},i}). \tag{12}$$

In addition, unlike wireless communications, uniform power transmission to every receiver is important for MPT.

Table I General conditions of simulation settings

Radiation pattern of antenna elements	Omnidirectional
Antenna deployment	Rectangular
Transmitter direction	y-axis positive
Receiver direction	y-axis negative
Number of antenna elements	64 (8×8)
Interval of antenna elements	half wavelength
Frequency	2.4 GHz
Reference received power	30 dBm
Noise power σ_i^2	10^{-6} W

Thus, we adjusted beamforming weights by multiplying them by a constant. In particular, the beamforming weight for user #i $\mathbf{w}_i$ is obtained by multiplying the normalized beamforming weights for users #i and $\alpha_i = \sqrt{\frac{c}{||\mathbf{H}_{\mathrm{rx},i}\mathbf{w}_i||^2}}$, where c denotes an arbitrary constant called the reference received power and is used to calculate a scaling factor, α_i. α_i represents a coefficient of the beamforming weight, which is used to adjust the received power. This means that the received power is equal to the reference received power only if one receiver exists. However, when there are multiple receivers, the received power is not perfectly equal to the reference received power and can vary slightly from the reference received power since interference occurs due to a summation of the beamforming weights for transferring power to multiple receivers. Using the scaling factors, the final beamforming weight $\mathbf{w}$ is calculated as $\mathbf{w} = \sum_{i=1}^{K} \alpha_i \mathbf{w}_i$, and the total transmitting power P_t is expressed as $P_t = ||\sum_{i=1}^{K} \alpha_i \mathbf{w}_i||^2$ for each case. Moreover, the received power at the i-th receiver $P_{\mathrm{rx},i}$ is calculated by $P_{\mathrm{rx},i} = ||\mathbf{H}_{\mathrm{rx},i}\mathbf{w}||^2 + M_{\mathrm{rx},i}\sigma_i^2$, and the received power at the j-th protected device $P_{\mathrm{dev},j}$ is calculated by $P_{\mathrm{dev},j} = ||\mathbf{H}_{\mathrm{dev},j}\mathbf{w}||^2 + M_{\mathrm{dev},j}\sigma_j^2$.

3. Simulations

In this section, the beamforming scheme based on SLNR for MPT is preliminarily evaluated through MATLAB simulations. Simulations were performed in an environment free of reflections or scattering and the channel matrices were obtained using the MATLAB phased array system toolbox. As listed in Table I, the noise power at each element of receiver #i σ_i^2 or protected device #j σ_j^2 is 10^{-6} for $i = \{1,\cdots,K\}$ and $j = \{1,\cdots,L\}$ and is added to the channels after estimation. We conducted simulations for two cases, particularly at several positions of the transmitter, receiver, and protection devices, to obtain the directivity pattern, power at the receiving antenna and protection device, and beamforming weight calculation time for each case. The simulation results based on SLNR for MPT were compared with those of the conventional beamforming method, which maximized the gain toward a receiver without considering the leakage. The general conditions of the simulation settings are listed in Table I. In this case, the reference received power was set to 30 dBm to clarify our contribution to the suppression of leakage, as mentioned in Section 2.

Table II Conditions of simulation setting #1 (unit: meters)

Position of transmitter	$(x, y, z) = (0.0, 0.0, 1.0)$
Position of receiver	$(x, y, z) = (3.0, 3.0, 1.0)$
Position of protected device	$(x, y, z) = (-3.0, 3.0, 1.0)$

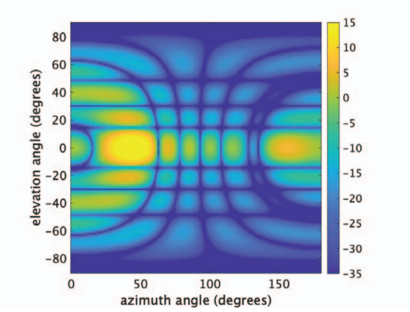

Fig. 3 Two-dimensional directivity based on the SLNR for MPT for simulation setting #1. (azimuth,elevation)=(45°,0°) is for the receiver and (azimuth,elevation)=(135°,0°) is for the protected device.

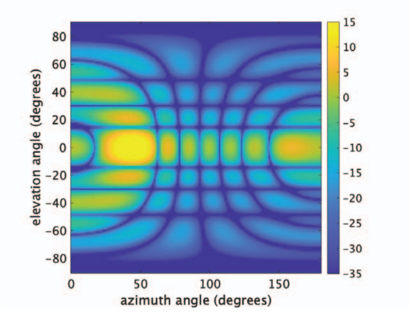

Fig. 4 Two-dimensional directivity based on the conventional method for simulation setting #1. (azimuth,elevation)=(45°,0°) is for the receiver and (azimuth,elevation)=(135°,0°) is for the protected device.

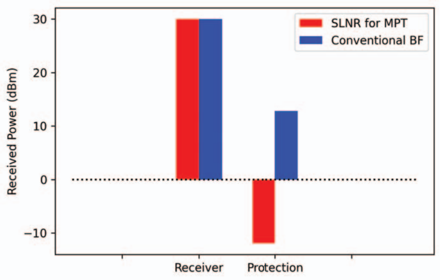

Fig. 5 Power comparison for simulation setting #1. The total transmitting power is 46.6 dBm using SLNR for MPT and 46.5 dBm using conventional beamforming.

The position parameters are presented in Table II. One transmitter, receiver, and protected device were defined in the simulations. The 2D directivity based on SLNR for MPT and the conventional method are shown in Fig.3 and Fig.4, respectively. This shows that the directivity toward the protected device weakens. A comparison of the received power at the receiver and the protected device is shown in Fig.5. From the figure, our method based on SLNR for MPT maintained the received power at the receiver and significantly decreased the leakage power on the protected device.

Next, we set the parameters for the positions listed in Table III. Beamforming weights of the three receivers were summed. The 2D directivities based on our proposed method and the conventional method are shown in Fig.6 and Fig.7, respectively. A comparison of the received power at

Table III Conditions of simulation setting #2 (unit: meters)

Position of the transmitter	$(x, y, z) = (0.0, 0.0, 1.0)$
Positions of receivers	$(x, y, z) = (3.0, 3.0, 1.0)$, $(2.0, 3.0, 1.0)$, $(1.0, 3.0, 1.0)$
Positions of protected devices	$(x, y, z) = (-3.0, 3.0, 1.0)$, $(-2.0, 3.0, 1.0)$, $(-1.0, 3.0, 1.0)$

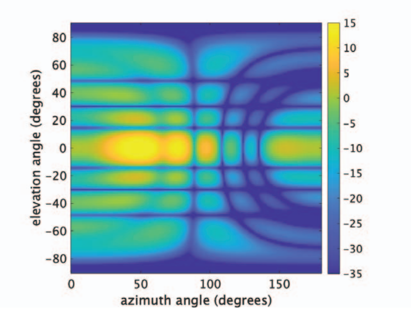

Fig. 6 Two-dimensional directivity based on the SLNR for MPT for simulation setting #2. (azimuth,elevation)=(45°,0°) is for receiver #1, (56.3°,0°) is for receiver #2, and (71.6°,0°) is for receiver #3. (azimuth,elevation)=(135°,0°) is for protected device #1, (123.7°,0°) is for protected device #2 and (108.4°,0°) is for protected device #3.

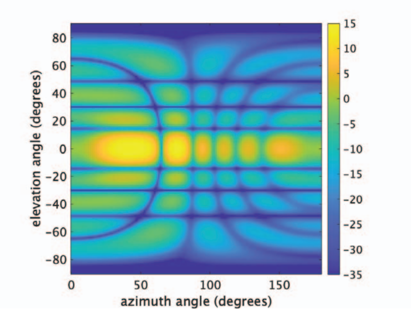

Fig. 7 Two-dimensional directivity based on the conventional method for simulation setting #2. (azimuth,elevation)=(45°,0°) is for receiver #1, (56.3°,0°) is for receiver #2, and (71.6°,0°) is for receiver #3. (azimuth,elevation)=(135°,0°) is for protected device #1, (123.7°,0°) is for protected device #2, and (108.4°,0°) is for protected device #3.

the receiver and protected device, indicating the simultaneous leakage suppression capability of our proposed method on protected devices and maintenance of the received power at the receivers irrespective of the increase in the number of receivers and protected devices is shown in Fig.8. Because the beamforming weights for the three receivers are summed, each received power differed slightly from 30 dBm. It is also shown that the received power is larger than the noise power -11.93 dBm (6.4×10^{-5}W) in Fig.5 and Fig.8. In our simulation environment, the CPU time in simulation settings #1 and #2 were 7.0×10^{-3} s and 1.5×10^{-2} s, respectively.

4. Conclusions

This study introduced a criterion called SLNR into MPT. We extended the concept of SLNR for MIMO downlink communication to SLNR for MPT. We obtained beamforming weights to realize high transfer efficiency while suppressing leakage power toward the protected devices by maximizing SLNR for MPT. The validity of our proposed method was confirmed through simulations. In the future, we will conduct experimental evaluations by implementing the proposed beamforming scheme using software-defined radio equipment.

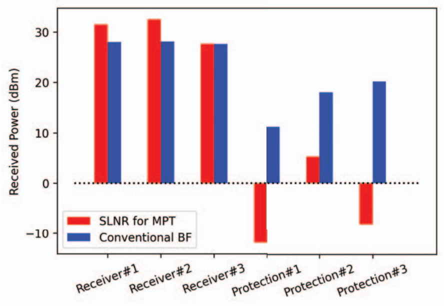

Fig. 8 Power comparison for simulation setting #2. The total transmitting power is 50.4 dBm using SLNR for MPT and 48.3 dBm using conventional beamforming.

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