Joint Orthogonal Band and Power Allocation for Energy Fairness in WPT System with Nonlinear Logarithmic Energy Harvesting Model

Jaeseob Han, Student Member, IEEE, Gyeong Ho Lee, Student Member, IEEE, Sangdon Park, Member, IEEE, and Jun Kyun Choi, Senior Member, IEEE

Abstract—Wireless power transmission (WPT) is expected to play an important role in the Internet of Things services by providing the perpetual operation of IoT sensors. However, to prolong the IoT network’s lifetime, the efficient resource allocation algorithm is required, in particular, the energy fairness issue among IoT sensors has been a critical challenge of the WPT system. In this paper, considering energy fairness as the minimum received energy of all energy poverty IoT sensors (EPISs), we allocate orthogonal frequency bands to several EPISs and transfer the RF power on each orthogonal band, using energy beamforming. Based on the energy poverty, we propose orthogonal frequency bands assignment rule, granting the priority to the EPISs with less received energy. We also formulate two transmission power allocation problems, incorporated the nonlinear logarithm-energy harvesting (EH) model. First, the total received power maximization (TRPM) problem is presented and solved by combining the well-known Karush-Kuhn-Tucker (KKT) conditions with the modified water-filling algorithm. Second, the common received power maximization (CRPM) problem is formulated and the optimal solution is derived using the iterative bisection search method. To apply the bisection search method to the problem, this paper proposes a method of specifying the scope of the solution for the objective function defined by the sum of monotonous functions. In numerical results, assuming the mobility of EPISs by the one-dimensional random walk model, the effectiveness of the mobility of EPISs on the minimum received energy of all EPISs is presented. In addition, this paper analyzes the difference in performance among the nonlinear EH model and linear EH model in CRPM and TRPM problem. Finally, the performance of the proposed resource allocation schemes is verified by comparing other resources allocation schemes, such as Round robin and equal power distribution.

Index Terms—Energy beamforming, Internet-of-Things (IoT), nonlinear energy harvesting (EH) model, resource allocation, wireless power transmission (WPT).

I. INTRODUCTION

With the Internet of Things (IoT) emerging as a promising technology for the hyper-connected society, a large number of IoT sensors have been placed in various IoT application domains, such as the smart city and smart home. Consequently, the IoT technology will cover every part of our lives. However, since most of IoT sensors are battery-powered wireless devices, these devices have an energy poverty problem. To tackle this problem, the concept of radio-frequency (RF) wireless power transmission (WPT) technology has been extensively investigated. Since it can transmit power wirelessly to mobile IoT sensors that are difficult to be supplied power from the connecting cables, it has received a substantial interest for researchers.

One of the practical research related to RF-WPT is the Cota technology of Ossia company [2]. Cota technology used a beacon signal to detect energy-absorbing objects such as humans and utilized beamforming technology for transmitting the power wirelessly for a specific object while avoiding energy-absorbing objects. This company succeeded in transmitting 1 W (Watt) of Radio Frequency (RF) energy at 30 feet using 2.4GHz or 5.8GHz ISM band through Cota technology. The other company, which is called Energous, introduced a technology called WattUp. The technology uses a Wi-Fi frequency band from 5.7 GHz to 5.8 GHz to transmit 4 Watt to twelve devices at 20 feet away from the power transmitter, simultaneously. [1]. In addition, various RF-WPT research has been also conducted in academia. Two representative research topics are as follows: simultaneous wireless information and power transfer (SWIPT) network and the wireless powered communication network (WPCN).

In SWIPT, the power transmitter can provides both power and information simultaneously to multiple receivers by combining a WPT system with a wireless communication system. There have been various studies related to SWIPT, such as separated SWIPT [8], [11], [14], [33], [37], co-located SWIPT with power splitting (PS) mechanism [19], [24], [26], [31], [36], [37], [39], [40], and co-located SWIPT with time splitting (TS) mechanism [10], [11], [31], [37].

The other application technology of WPT, where the receivers are first powered by WPT and perform their information signal transmission using the harvested energy, is referred to as WPCN. According to the antenna technology in WPCN, a handful of research work has been reported such as single-input single-output (SISO) WPCN [5], [9], [35], multiple-input single-output (MISO) WPCN [13], [15], [23], [25], [32], multiple-input multiple-output (MIMO) WPCN [6].

These WPT technologies provide user-friendliness, convenience, and flexibility to IoT applications because there is no need to replace the battery of IoT sensors. Nevertheless, since WPT technology utilizes RF signal to transmit power, how to deal with the signal power attenuation, heavily dependent on the distance from the wireless power transmitter,
The main contribution of this paper is summarized as follows: results present the performance of our proposed algorithms. Mobility of EPISs by the random walk model, the numerical results present the performance of the proposed algorithms. In addition to the nonlinear EH model. In addition, when considering the mobility of EPISs by the random walk model, the numerical results present the performance of our proposed algorithms.

**A. Contribution**

In this paper, we consider a MISO-WPT system, where a single power transmitter (PT) with multiple antennas simultaneously transmits power to a number of single-antenna energy poverty IoT sensors (EPIS). We focus on energy fairness issues through the energy beamforming in orthogonal frequency bands and transmission power allocation under the nonlinear EH model. In addition, when considering the mobility of EPISs by the random walk model, the numerical results present the performance of our proposed algorithms. The main contribution of this paper is summarized as follows:

- To handle the energy fairness issue among the EPISs, the energy beamforming in orthogonal frequency bands is addressed. The EPISs located near the power transmitter receives a substantial amount of power due to their low power-signal attenuation, but relatively little power received for far away EPISs. Therefore, this paper considers the orthogonal frequency band allocation and the energy beamforming to EPISs, which received less energy.
- We consider the practical nonlinear EH model for the reduction of misleading optimization solutions. The conventional linear EH model was adopted in most WPT works, but the recent research found that it may be an ideal concept. Different from [4] which proposed a nonlinear EH model based on logistic function, this paper considers logarithmic nonlinear EH model with operating limits, resulting in a simpler optimization problem. Also, it allows for more accurate received power modeling.
- The problem of the total received power maximization (TRPM) is studied under the constraints of the limited transmission power on the orthogonal bands and the transmission power budget of PT. The closed-form solution is obtained by using the KKT optimality condition and modified water filling algorithm [21].
- The common-received power maximization (CRPM) problem is also presented under the same condition of TRPM and solved by applying the iterative bisection search method. To apply the bisection search method to the problem, this paper proposes a method of specifying the scope of the solution for the objective function which is the form of the sum of monotonic functions.
- Assuming the mobility of EPISs as the one-dimensional random walk model, the performance of the proposed resource allocation algorithms is demonstrated in the numerical results.

This paper is composed as follows. Section II discusses the system model about the WPT mechanism, which this paper proposes. Section III formulates the total received power maximization and common received power maximization problems and derives the optimal solutions. The numerical results of the proposed algorithms are provided in Section IV. Finally, the conclusions are presented in Section V.

**Notation**: The following notation is used in this paper. The uppercase bold A represents a matrix, the lowercase bold a represents a vector, the uppercase A for set, and the lowercase a for scalar. For a square matrix S, tr(S) denotes the trace of S, S^H means Hermitian which denotes conjugate transpose of S, λ(S) denotes eigenvalues of S, and v_λ means eigenvector of eigenvalue of λ. The n(A) denotes the cardinality of a set A and ||a|| denotes the magnitude of a vector a.

**II. System Model**

As shown in Fig. I, this paper considers multi-input single-output (MISO) WPT system, consisted of one power transmitter (PT) with m antennas and n_e energy poverty IoT sensors (EPIS) with one antenna. The set of indices of orthogonal frequency bands are denoted by \( \Gamma = \{1, 2, \ldots, n_C\} \). Assuming perfect channel state information (CSI), PT transmits the power to the n_C targeted EPISs simultaneously. We suppose that all channels experience quasi-static flat fading.
In order to enhance power transfer efficiency, B. Energy beamforming

The whole procedure is expressed in Algorithm 1.

Algorithm 1 Sensor Selection rule based on Energy Poverty (SSEP)

1: Initialization The total received energy $U_k$ of EPIS$_k$, $\forall k \in \Gamma$, and the number of orthogonal bands $n_C$.
2: Arrange EPISs according to total received energy with ascending order.
3: Selects first $n_C$ EPISs.
4: return The information about selected EPISs such as total received energy, channel status, etc.

(i.e., channel power gain on each channel stay constant within the power transmission time) and without loss of generality, the power transmission time is set to be one. Therefore, energy and power would have the same meaning.

In this paper, a plurality of EPISs requires power transmission and PT decides which EPISs should be chosen for orthogonal bands assignment and how to allocate the amount of transmission power on each orthogonal band. We design the energy beamforming in each orthogonal bands for enhancing the power transfer efficiency and consider the practical non-linear EH model to reduce resource allocation mismatch.

### A. Sensors Selection rule based on Energy Poverty (SSEP)

If the number of the orthogonal bands $n_C$ is larger than $m$, which is the number of EPISs, every EPISs could receive power by PT. However, if $m$ becomes larger than $n_C$, it is impossible to transmit power to all of EPISs simultaneously. Currently, since massive IoT sensors have been distributed in various IoT application domains, the number of IoT devices are generally larger than the number of the orthogonal bands. Thus, the orthogonal bands’ assignment rule for EPISs is required. This paper considers IoT sensors selection rule on each orthogonal band based on energy poverty (SSEP), giving the priority to EPISs with less received energy, which allocates orthogonal band first and transmitting optimized power. In consequence, SSEP arranges EPISs according to the total received energy with ascending order and then group first $n_C$ EPISs. The EPIS’s index set in this group is expressed by $\Gamma_P$. The whole procedure is expressed in Algorithm 1.

### B. Energy beamforming

Once EPISs are assigned with orthogonal bands through SSEP, PT considers how to transmit the RF signals for the EPISs selected. In order to enhance power transfer efficiency, we consider the energy beamforming, where power is optimally transmitted to a specific EPIS by multiplying an appropriate weight vector to the power symbol [34]. At first, the baseband transmitted signal $s_k$ for EPIS$_k$ is defined as

$$ s_k = w_k s_0, \quad \forall k \in \Gamma_P, \quad (1) $$

where $w_k \in \mathbb{C}^{n_t \times 1}$ represents the beamforming weight vector for EPIS$_k$ and $s_0$ is the power symbol. It is assumed that $s_0$ is an independent and identically distributed(i.i.d.) random variable with zero mean and unit variance.

Then, the transmission power of the PT for EPIS$_k$ can be expressed as $p_k^t = E[|s_k|^2] = \|w_k\|^2 \text{tr}(w_k w_k^H)$. Assuming that all channels follow independent quasi-static flat fading, the channel gain vector $h_k \in \mathbb{C}^{n_t \times 1}$ is constant within power transmission time. The received baseband signal $y_k$ is expressed as

$$ y_k = h_k^T s_k + \epsilon_k, \quad \forall k \in \Gamma_P, \quad (2) $$

where $\epsilon_k \sim N(0, \sigma_k^2)$ is additive noise. This paper ignored the noise power in the EPIS$_k$, since it is actually a negligible amount in the EPIS$_k$ [14], [29]. Therefore, the amount of power transferred is expressed as

$$ p_k^r = \text{tr}(G_k W_k), \quad \forall k \in \Gamma_P, \quad (3) $$

where $G_k = h_k h_k^H \in \mathbb{C}^{n_t \times n_t}$ is a channel gain matrix for EPIS$_k$ and $W_k = w_k w_k^H \in \mathbb{C}^{n_t \times n_t}$ is a beamforming weight matrix. In [34], the optimal energy beamforming vector is obtained as

$$ w_k^* = v_{\text{max}}(h_k h_k^H), \quad \forall k \in \Gamma_P, \quad (4) $$

where $v_{\text{max}}$ denotes the eigenvector corresponding to the maximum eigenvalue. Since the rank of channel gain matrix $G_k$ is one, there exists only one eigenvalue. Therefore, The received power using energy beamforming is

$$ p_k^r = \lambda_k p_k^t, \quad \forall k \in \Gamma_P, \quad (5) $$

where $\lambda_k = \lambda(h_k h_k^H)$ denotes the eigenvalue of $h_k h_k^H$. Since the PT can eigen-decompose $G_k$ to obtain eigenvalue and eigenvector, PT sets an beamforming weight vector as an eigenvector that corresponds to an eigenvalue of $G_k$.

### C. Nonlinear EH model

When the RF signal is transmitted, it should be converted into DC power that can be used at EPISs. At this time, EPISs need the rectifier that converts the AC power into the
where operating in the 900 MHz frequency band and proposes a DC power. This paper considers nonlinear rectifiers model from [20]. The parameters between linear & nonlinear EH models and raw data extracted from [27] and (b) a comparison between linear & nonlinear EH models and raw data extracted from [20]. The parameters \(a_k, b_k\) are calculated by minimizing the sum of squared error.

DC power. This paper considers nonlinear rectifiers model operating in the 900 MHz frequency band and proposes a practical nonlinear EH model as

\[
r(x) = a_k \log(1 + b_k x), \quad \text{s.t.} \quad 0 \leq x \leq c_k,
\]

where \(a_k, b_k, \text{ and } c_k\) are parameters that vary depending on the detailed circuit characteristics such as capacitor and diode. The \(a_k, b_k\) are calculated by minimizing the sum of squared error between the data extracted using Engauge Digitizer [18] and the rectifier model and \(c_k\), which is rectifier’s operation limit, can be easily found by checking an extracted data.

Table I: A RMSE value comparison between the proposed logarithmic model, linear, and nonlinear model from [4]

| Rectifier model                        | RMSE value from data [27] | RMSE value from data [20] |
|----------------------------------------|---------------------------|---------------------------|
| Logarithmic nonlinear model            | 0.00967                   | 0.0098                    |
| Linear model                           | 0.0042                    | 0.0027                    |
| Nonlinear model from [4]               | 0.0027                    | 0.0020                    |

Fig. 2 shows how well matches between the rectifier models and the data extracted from [27], [20]. Table I illustrates that the logarithmic nonlinear model best matches from the data extracted [27], [20] in RMSE value.

III. PROBLEM FORMULATION AND SOLUTION

A. Total Received Power Maximization (TRPM)

Considering the energy beamforming and the nonlinear EH model, PT should decide how much power needs to be transmitted for each EPISs. This part focus on maximizing the total received power of all EPIS \(k \in \Gamma_P\). The following total received power maximization (TRPM) problem can be mathematically formulated as

Algorithm 2 Total Received Power Maximization (TRPM)

1: **Initialization** Arrange the set of EPISs \(\Gamma_P\) by the value of \(\frac{1}{a_k b_k}\) in ascending order, the parameter indexes \(j = 1, k = 2\), the waterfilling width \(C_w = a_1\), the remaining energy \(E_r = E_c\), the energy height \(h = \frac{1}{a_1 b_1 c_1}\), the allocated power vector of EPISs \(p^t = 0\), \(a_{n_c+1}, b_{n_c+1} = 1\), and \(\lambda_{n_c+1} = \infty\).

2: **while** \(E_r > 0\) **do**

3:   **if** \(\min\left(\frac{b_k}{a_k} P_k\right) > \frac{1}{a_k b_k c_k}\) \(\& \left(C_w \left(\frac{1}{a_k b_k c_k} - h\right) \right) < E_r\) **then**

4:     **Update** \(E_r = E_r - C_w \left(\frac{1}{a_k b_k c_k} - h\right)\), \(C_w = C_w + a_k\), \(h = \frac{1}{a_k b_k c_k}\), and \(k = k + 1\).

5: **else if** \(\min\left(\frac{b_k}{a_k} P_k\right) \leq \frac{1}{a_k b_k c_k}\) \(\& \left(C_w \left(\frac{b_k}{a_k} P_k - h\right) \right) < E_r\) **then**

6:     **Update** \(E_r = E_r - C_w \left(\frac{b_k}{a_k} P_k - h\right)\), \(C_w = C_w + a_j\), \(h = \frac{c_k}{a_k a_j}\), and \(j = j + 1\).

7: **else**

8:     **Set** \(p^t_j = \frac{b_k}{a_k} P_k\).

9: **end if**

10: **for** \(i = j : k\) **do**

11:     **Set** \(p^t_i = a_i \left(h - \frac{1}{a_i b_i c_i}\right)\).

12: **end for**

13: **end if**

14: **end while**

15: **return** Set of allocated transmission power of EPISs \(p^t\), after reaggraged by the original order.
Algorithm 3 Bisection method for $\alpha$

1: **Initialization** the rectifier parameters $a_k, b_k$ for $k \in \Gamma_P$, the allocated eigenvalue $\lambda_k$ for $k \in \Gamma_P$, the total received power $U_k$ for $k \in \Gamma_P$, the remaining energy $E_r$, 
\[
\alpha_{\text{min}} = \min_k \left( U_k + a_k \log(1 + \frac{b_k \lambda_k E_r}{|P_k|^2}) \right),
\]
\[
\alpha_{\text{max}} = \max_k \left( U_k + a_k \log(1 + \frac{b_k \lambda_k E_r}{|P_k|^2}) \right),
\]
\[\epsilon = \text{stopping criterion, and } \alpha = \frac{\alpha_{\text{min}} + \alpha_{\text{max}}}{2}.
\]

2: while $\{\left\{ \sum_k \frac{1}{b_k \lambda_k} \left( \exp(\frac{\alpha - U_k}{a_k}) - 1 \right) - E_r \right\} \geq \epsilon \}$ do
3: if $\sum_k \frac{1}{b_k \lambda_k} \left( \exp(\frac{\alpha - U_k}{a_k}) - 1 \right) > E_r$ then
4: $\alpha_{\text{max}} \leftarrow \frac{\alpha_{\text{min}} + \alpha_{\text{max}}}{2}$.
5: else
6: $\alpha_{\text{min}} \leftarrow \frac{\alpha_{\text{min}} + \alpha_{\text{max}}}{2}$.
7: end if
8: $\alpha \leftarrow \frac{\alpha_{\text{min}} + \alpha_{\text{max}}}{2}$.
9: end while
10: return The parameter $\alpha$ satisfying the condition $\sum_k \frac{1}{b_k \lambda_k} \left( \exp(\frac{\alpha - U_k}{a_k}) - 1 \right) = E_r$.

\[
\max_{p_k} \sum_{k \in \Gamma_P} r(p_k^*) = \sum_{k \in \Gamma_P} a_k \log(1 + b_k \lambda_k p_k^*)
\]
\[\text{s.t. } 0 \leq p_k^* \leq \min \left( \frac{c_k}{\lambda_k}, P_c \right), \forall k \in \Gamma_P, \quad (8)
\]
\[\sum_{k \in \Gamma_P} p_k^* \leq E_c, \quad (9)
\]

where $E_c$ is the transmission power budget which PT has, $P_c$ is transmission power constraint under each orthogonal band, and $c_k$ is the rectifier’s operation limit of EPIS$_k$. Solving the above optimization problem, we can obtain the closed-form solution given by the following theorem.

**Theorem 1:** The optimal power value $p_k^*$ to be sent to EPIS$_k$ in the TRPM problem is expressed as follows
\[
p_k^* = \begin{cases} 
    h a_k - \frac{1}{b_k \lambda_k}, & \text{if this is } > 0 \text{ or } < \min(P_c, \frac{c_k}{\lambda_k}), \\
    \frac{c_k}{\lambda_k}, & \text{if the above value is } \geq \min(P_c, \frac{c_k}{\lambda_k}), \\
    0, & \text{Otherwise},
\end{cases}
\]
\[\text{where } h \text{ is the lagrange multiplier satisfying } \sum_{k \in \Gamma_P} p_k^* = E_c.
\]

**Proof:** See the Appendix [A].

Through the Theorem 1 the optimal power value $p_k^*$ for EPIS$_k$ is obtained. The $h$ is calculated by Algorithm 2 which is the modified waterfilling algorithm [21]. If PT transmits power $p_k^*$ to EPIS$_k$, $\forall k \in \Gamma_P$, then total received power for all EPIS$_k$, $\forall k \in \Gamma_P$, is maximized.

**B. Common Received Power Maximization (CRPM)**

PT could utilize the TRPM algorithm to optimize the total received power of all EPIS$_k$, $\forall k \in \Gamma_P$. However, it can cause the energy unfairness issue among the EPISs.

Through SSEP, EPISs with less received energy are given the opportunity to receive power, but in TRPM, most of the power is transmitted to the EPIS, which is the nearest PT, causing an energy imbalance. Therefore, it is required that a sophisticated resource allocation algorithm without causing an energy imbalance among EPISs. This part considers Common Received Power Maximization (CRPM) problem to solve this energy unfairness issue. It can be formulated as
\[
\max_{p_k^*} \sum_{k \in \Gamma_P} r(p_k^*)
\]
\[\text{s.t. } U_k + a_k \log(1 + b_k \lambda_k p_k^*) \geq \bar{P}, \forall k \in \Gamma_P, \quad (12)
\]
\[0 \leq p_k^* \leq \min \left( \frac{c_k}{\lambda_k}, P_c \right), \forall k \in \Gamma_P, \quad (13)
\]
\[\sum_{k \in \Gamma_P} p_k^* = E_c, \quad (14)
\]
where $\bar{P}$ is the common received power for all EPISs. Here, the transmission power budget condition (14) has equal value to the constraint $E_c$. It is natural to consume all of the transmission power budgets at PT because it can improve the performance of common received power $\bar{P}$ of EPISs. Since (12) constraint is increasing about $p_k^*$, when all these conditions have equal value, the optimal solution of CRPM problem can be obtained as follows
\[
U_k + a_k \log(1 + b_k \lambda_k p_k^*) = \alpha, \quad \forall k \in \Gamma_P.
\]
Then,
\[
p_k^* = \frac{1}{b_k \lambda_k} \left( \exp(\frac{\alpha - U_k}{a_k}) - 1 \right).
\]

Since $p_k^*$ is increasing and continuous function over $\alpha$, we can find $\alpha$ by using bisection search method. The interval in which solution $\alpha$ exists is defined by following lemma.

**Lemma 1:** The solution $\alpha$ satisfying the condition (14) exists in the following interval $\alpha \in [\alpha_{\text{min}}, \alpha_{\text{max}}]$ where
\[
\alpha_{\text{min}} = \min_{k \in \Gamma_P} \left( U_k + a_k \log(1 + \frac{b_k \lambda_k E_r}{|P_k|^2}) \right),
\]
\[
\alpha_{\text{max}} = \max_{k \in \Gamma_P} \left( U_k + a_k \log(1 + \frac{b_k \lambda_k E_r}{|P_k|^2}) \right).
\]

**Proof:** See the Appendix [B].

Since we should consider the constraints about $p_k^*$ such as (12) and (13), the solution of the problem is composed of the iterative bisection search algorithm. The whole procedure is summarized in Algorithm 4.

**IV. Numerical Results**

**A. Simulation Setup**

In this section, we provide a numerical example to identify the performance of the proposed resource allocation algorithms. We consider a WPT system of 16-mobile energy poverty IoT sensors (EPISs) with a single antenna and one-power transmitter (PT) with four-antennas. We assume the following a few numerical simulation settings: the PT performed a total ten-thousand iteration of wireless power transmissions and at each time the maximum transmission power $E_c$ of the PT and the limited transmission power constraint $P_c$ in each orthogonal band is assumed to be 4W (Watt). The transmission power constraints are determined by reflecting the power regulation of the 900MHz band, which is the frequency...
Algorithm 4 Common Received Power Maximization (CRPM)

1: Initialization The number of iteration $I = 0$, the limit of iteration $I_{\text{lim}}$, the remaining energy $E_r = E_c$, the allocated power vector $p^I = 0$, and the index set of EPISs $\Gamma_P$.
2: while $\{E_r > 0\}$ and $\{I < I_{\text{lim}}\}$ do
3: Calculate $\alpha$ by Algorithm 5
4: for $k \in \Gamma_P$ do
5: Set $p_k^I = p_k^I + \frac{1}{a_k} \exp(\frac{a_k}{\lambda_k} \cdot \frac{1}{2})$.
6: end for
7: Set $E_r = 0$.
8: for $k \in \Gamma_P$ do
9: if $p_k > \min(\frac{a_k}{\lambda_k}, P_c)$ then
10: Set $E_r = E_r + \min(\frac{a_k}{\lambda_k}, P_c)$.
11: $p_k^I = \min(\frac{a_k}{\lambda_k}, P_c)$, and $\Gamma_P \leftarrow \Gamma_P \setminus k$.
12: end if
13: end for
14: $I = I + 1$.
15: end while
16: return Allocated transmission power vector $p^I$.

band used for IoT communication. The nonlinear rectifier parameters $a_k, b_k$ of the k-th EPIS are determined randomly between two values, $a = 0.0319, b = 3.6169$ from [27] and $a = 0.2411$ and $b = 0.4566$ from [20]. The paired values in $a$ and $b$ are obtained by minimizing the mean squared error (MSE) between the nonlinear EH model and extracted data from [27] and [20], respectively. The $c_k$, which denotes the operation limit of the rectifier, is fixed to 3 mW for both options. Within a 5 to 15 meter from PT, each EPIS is uniformly distributed in the WPT system and randomly moves with fixed-length walk-steps (0.03 m or 0.2 m) in each iteration. At each iteration of power transmission, we consider a one-dimensional random walk model of EPISs. It has three options to stop, move forward, and move backward based on PT, and the options have an equal probability, which is $1/3$. The distance-dependent signal pathloss model is given by following equation.

$$ L_k = L_0 \left( \frac{d_k}{d_0} \right)^{-\alpha}, \forall k \in \Gamma_P, $$

where $L_0$ is set to be $10^{-3}$, $d_k$ denotes the distance between PT and EPIS$k$, $\forall k \in \Gamma_P$, $d_0$ is a reference distance, which is 1 meter, and $\alpha$ is the path loss exponent set to be 3. The channel vector $h_k$ is obtained by averaging over 1,000 randomized independent and identically distributed (i.i.d.) Rayleigh fading channel generations and the average power of $h_k$ is normalized by $L_k$. Assuming that all channels follow independent quasi-static flat fading, the channel gain vector $h_k$ is constant within the power transmission time.

In this paper, we compare the proposed SSEP with the Round-robin scheduling algorithm, where the orthogonal bands are assigned to each EPIS in equal portions and in sequential order without priority. It guarantees the fairness for the number of the power receiving opportunities among EPISs. In addition, we validate the performance of the proposed power allocation algorithms by comparing the equal power distribution (EPD) algorithm additionally, where transmission power is divided equally on each orthogonal band.

In order to identify the performance of the proposed power allocation algorithms in the nonlinear EH model, we study the problems in the linear EH model as follows: the Linear Total Received Power Maximization (LTRPMP) problem and the Linear Common Received Power Maximization (LCRPM) problem. First, the LTRPMP problem is defined as

$$ \max_{p^I} \sum_{k \in \Gamma} h_k \lambda_k p_k^I \quad \text{s.t.} \quad 0 \leq p_k^I \leq \min(\frac{c_k}{\lambda_k}, P_c), \forall k \in \Gamma_P, \quad \sum_{k \in \Gamma_P} p_k^I = E_c, \quad (17) $$

where $h_k$ is a linear rectifier parameter derived by minimizing the mean square error between the data and linear rectifier model and $E_c$ is total transmission power constraint. Since this is a linear optimization problem, it can be solved by applying the sequential power allocation method. First, sorting the $h_k \lambda_k \lambda_k$ by descending order, and then allocating power $p_k^I = \min(\bar{P}_c, \frac{c_k}{\lambda_k}, E_c), \forall k \in \Gamma_P$, in sequential order until the remaining energy $E_c$ equals to zero. It can be expressed as the Algorithm 5 in Appendix C.

Next, the LCRPM problem is defined as

$$ \max_{p^I, P} \tilde{P} \quad \text{s.t.} \quad \tilde{U}_k + h_k \lambda_k p_k^I \geq \bar{P}, \forall k \in \Gamma_P, \quad 0 \leq p_k^I \leq \min(\frac{c_k}{\lambda_k}, P_c), \forall k \in \Gamma_P, \quad \sum_{k \in \Gamma_P} p_k^I = E_c. \quad (20) $$

As described above, the LCRPM problem can be solved by following the same process in the CRPM problem as follows

$$ h_k \lambda_k p_k^I = \alpha \iff p_k^I = \frac{\alpha}{h_k \lambda_k}, \forall k \in \Gamma_P. \quad (24) $$

The optimal solution can be obtained by applying the iterative bisection search algorithm, until $\sum_{k \in \Gamma_P} p_k^I = E_c$. The whole procedure is summarized as Algorithm 6 in Appendix D.

B. Performance Comparison with walk-step: 0.03 m/iteration

Fig. 3 compares the performance of resource allocation schemes, in terms of the minimum received energy of all EPISs, versus the iteration of the power transmission in 0.03 m/iteration walk-step. It can be observed that the SSEP has always a higher minimum received energy value than the Round-robin scheduling, and CRPM also outperforms the
other power allocation methods, TRPM, EPD. Therefore, the SSEP&CRPM showed the best performance in the minimum received energy. The reason for this result is that CRPM & SSEP allocates more resources, such as transmission power and the number of transmission power received, for the EPIs with poor wireless link state. In TRPM, regardless of whether SSEP or Round-robin is used, the minimum received energy value is zero, since the power transmission has not occurred to several EPIs with a poor channel condition to maximize the total received power. In both the CRPM and EPD, it can be seen that the minimum received energy value increases stably without significant changes.

In Fig. 4 we make a comparison of the performance in terms of the minimum received energy between the proposed CRPM and TRPM with considering the linear energy harvesting (EH) model and nonlinear EH model. In the case of CRPM, it shows the nonlinear EH model achieves 1.39% higher minimum received energy value than the linear model at the 86th batch iteration. As the number of power transmission increases, it can be seen that the gap of the minimum received energy, between the nonlinear and linear model, widens slighter than before. In TRPM, the nonlinear EH model is not comparable with linear EH model, since an EPI that have not received power exists.

Fig. 5 shows the total and minimum energy received by all EPIs under different transmission power and orthogonal bands allocation schemes, for the number of 10,000 power transmission iteration. In power allocation algorithms comparison, the TRPM shows the best performance in terms of the total received energy of all EPIs, regardless of whether SSEP or Round-robin. However, when observing the performance of minimum received energy, it can be easily found that certain EPIs should be sacrificed to maximize the total received energy of all EPIs in TRPM. In contrast to the TRPM, the total received energy for all EPIs represents the smallest value, but the best performance for the minimum received energy is detected for CRPM. In orthogonal bands allocation schemes comparison, the SSEP shows smaller performance in terms of the total received energy of all EPIs compared to the Round-robin, but better with respect to minimum received energy.
energy. In particular, the SSEP&CRPM shows 9.4% better performance in the minimum received energy compared to the Round robin&CRPM, and 1.31% less in total received energy. This trade-off result comes from that the Round-robin equally distributed the number of power transfer iteration to EPISs. It increases the probability of obtaining the energy of some EPISs that can harvest a large amount of power, but on the contrary, not elaborately takes into account EPISs, which cannot harvest large power due to the poor wireless link state. When comparing nonlinear and linear models in the SSEP&CRPM scheme, the minimum received energy of the nonlinear model was 1.36% higher than the linear model and the total energy was 1.37% higher. This result comes from the more sophisticated received power modeling achieved in the nonlinear model for each EPIS.

Fig. 6 displays the total received energy among all EPISs with 0.03 m/iteration power transmission iteration, under different transmission power and orthogonal bands allocation schemes. In Round-robin&CRPM, the EPISs are grouped into the number of orthogonal bands and the grouped EPISs receive the same power. Thus, the different pattern of received energy which the two groups get is observed as shown in Fig. 6(a). In TRPM, since it maximizes the total received energy of all EPISs, a huge difference in total received energy between EPISs is observed. In particular, Fig. 6(f) and (h) show that the 12th EPIS cannot receive power on the nonlinear model, but it receives a certain amount of power from the linear model. This can be seen as a result of misleading optimized power allocation, due to the lack of accurate modeling in received power. When comparing nonlinear and linear EH models in CRPM, significant performance degradation is not observed in the linear EH model.

C. Performance Comparison with walk-step: 0.2 m/iteration

Fig. 7 compares the performance of resource allocation schemes, in terms of the minimum received energy of all EPISs, versus the iteration of the power transmission in 0.2 m/iteration walk-step. In TRPM, the minimum received energy value ascends like stepwise as the number of power transmission increases. In addition, in SSEP, it is observed that CRPM had lower minimum received energy than the other two power allocation algorithms, TRPM and EPD, unlike the result of 0.03 m walk-step. The reason for this result is that the EPISs, which received less energy due to the poor channel state, gain more improved wireless link-state by moving more dynamically than 0.03 m/iteration walk-step and it leads to enhancing the probability of obtaining a substantial power. Nevertheless, there are no significant performance differences between different power allocation algorithms, except TRPM.

We further conduct the performance comparison of the minimum received energy versus the iteration number of power transmission, in the CRPM and TRPM algorithms, between the linear and nonlinear EH model, as shown in Fig. 8. It is observed that although the performance of the linear EH model is close to that of the nonlinear EH model in CRPM, the nonlinear EH model always outperforms the linear EH model slightly, in terms of the minimum received energy. When x is 85 batch iteration, the minimum received energy is about 0.6% higher in the nonlinear EH model of CRPM. Furthermore, in both nonlinear and linear EH models
in TRPM, it can be seen that the minimum received energy value ascends like stepwise, due to the movement of EPISs. As the number of power transmission increases, the nonlinear EH model outperforms the linear model.

Fig. 9 shows the total and minimum received energy by all EPISs for the number of 10,000 power transmission iteration, under different transmission power and orthogonal bands allocation schemes, at 0.2 m/iteration walk-step. In SSEP, TRPM shows the best performance in both total and the minimum received energy among all proposed power allocation algorithms. TRPM is shown to be 42% higher than CRPM at minimum received energy and 61% higher at total received energy. Although Round robin & TRPM is approximately 175% higher than SSEP & TRPM at total energy, at minimum received energy, SSEP & TRPM showed approximately 422% higher performance than Round robin & TRPM. SSEP & TRPM achieves the best performance in minimum received energy at the expense of total received energy. Compared to the linear EH model of SSEP & TRPM, the nonlinear EH model of SSEP & TRPM is approximately 24% higher at the minimum received energy and 6% higher at the total energy, which shows that both performance improvements are achieved by considering the nonlinear EH model.

Fig. 10 represents the total received energy among all EPISs with 0.2 m/iteration walk-step for the number of 10,000 power transmission iteration, under different transmission power and orthogonal bands allocation schemes. In SSEP, although some performance variations among EPISs appear when SSEP & TRPM is used, it is relatively small than Round robin as shown in Fig. 10(c) and (f). Thus, we can verify the effectiveness in energy fairness issue of our proposed SSEP scheme, when providing power to EPISs with high mobility.
particular, when SSEP&TRPM is used, EPISs have received similar energy between them, as opposed to 0.03 m/iteration walk-step. It indicates that if the EPIS’s mobility is high, the EPISs with poor wireless link-status may move closer to PT sometimes, giving them chances for receiving a substantial amount of energy. Therefore, when SSEP&TRPM is used, the EPISs with high mobility can receive energy in a balanced way, even in the case of TRPM.

V. CONCLUSION

We investigate a MISO-WPT system comprising of a multi-antenna power transmitter and multiple single-antenna EPISs. To handle energy fairness issues, we consider orthogonal bands allocation to the EPISs and energy beamforming technique on each orthogonal band. We propose orthogonal bands assignment rule based on the energy poverty of EPISs, granting the priority to the EPISs with less received energy. In addition, we formulate the common received power maximization (CRPM) problem that equalizes the received power of EPISs and the total received power maximization (TRPM) problem that maximizes the received power of EPISs. By considering the nonlinear EH model in optimization problems, it prevents the misleading optimized solution and reducing performance degradation. To solve the CRPM problem, the iterative bisection search method is adopted. For the sake of applying the bisection search method to the problem, this paper proposes a method of specifying the scope of the solution for the objective function defined by the sum of monotonous functions. A modified water-filling algorithm is applied to the closed-form solution obtained by using the KKT condition in the TRPM problem. Our extensive numerical results verify the importance of the proposed algorithms. Based on a comparison with Round robin scheduling algorithm, we validate the performance of our proposed SSEP scheme. In addition, we compare the proposed power allocation algorithms with an equal power distribution algorithm. Considering the mobility of EPISs as the one-dimensional random walk model, the effects of the mobility of EPISs on the minimum received energy of EPISs are presented. Unlike our belief, TRPM algorithms can achieve the mobility of EPISs on the minimum received energy of EPISs.

focus on resource allocation on the WPT system. Simultaneous wireless information and power transmission system can be implemented in the proposed system to support various IoT services.

- Other practical setups in the system model can be considered, such as relay channel, imperfect channel state information, interference channel, etc.

APPENDIX A

PROOF OF THEOREM 1

This appendix shows the proof of Theorem 1. Since the objective function is concave and constraints are convex form, we can apply KKT condition by reformulating this problem as minimizing convex problem. Then, we can simplify the original problem as following equation using KKT condition.

\[
\begin{align*}
\frac{a_k b_k \lambda_k}{1 + b_k \lambda_k P_k^*} &+ \mu_k - \zeta_k - \nu = 0, \quad \forall k \in \Gamma_p, \\
\zeta_k \left( p_k^* - \min \left( \frac{c_k}{h_k}, P_c \right) \right) &+ \mu_k p_k^* = 0, \quad \forall k \in \Gamma_p, \\
\sum_{k \in \Gamma_p} p_k^* - E_c &+ \mu_k = 0, \quad \forall k \in \Gamma_p, \\
0 &\leq p_k^* \leq \min \left( \frac{c_k}{h_k}, P_c \right), \quad \forall k \in \Gamma_p,
\end{align*}
\]

where \( \mu_k, \zeta_k, \) and \( \nu \) is Lagrange multipliers. There are three possible cases for \( p_k^* \).

1. In first case, \( 0 < p_k^* < \min \left( \frac{c_k}{h_k}, P_c \right) \), it is clear that \( \mu_k = 0 \) and \( \zeta_k = 0 \). From the stationary condition (25), we have \( p_k^* = h a_k - \frac{1}{b_k \lambda_k} \) where \( h = \frac{1}{\gamma} \).

2. In second case, \( p_k^* = 0 \), the complementary slackness condition (26) gives \( \zeta_k = 0 \) and from the stationary condition (25), we have \( h = \frac{1}{a_k b_k \lambda_k + \mu_k} \). It represents that \( h a_k - \frac{1}{b_k \lambda_k} = \frac{a_k b_k \lambda_k}{a_k b_k \lambda_k + \mu_k} \leq 0 \).

3. In third case, \( p_k^* = \min \left( \frac{c_k}{h_k}, P_c \right) \), we have \( \mu_k = 0 \) from the complementary slackness condition (27) and \( h = \frac{a_k \left( b_k \lambda_k - \frac{1}{\gamma} \left( 1 + b_k \lambda_k \min \left( \frac{c_k}{h_k}, P_c \right) \right) \right)}{b_k \lambda_k - \frac{1}{\gamma} \left( 1 + b_k \lambda_k \min \left( \frac{c_k}{h_k}, P_c \right) \right)} \) from the stationary condition (25). Since \( a_k, b_k, \lambda_k > 0 \), we have \( h > 0 \). By using the above conditions, it yields that \( h a_k - \frac{1}{b_k \lambda_k} = \frac{b_k \lambda_k \min \left( \frac{c_k}{h_k}, P_c \right)}{b_k \lambda_k - \frac{1}{\gamma} \left( 1 + b_k \lambda_k \min \left( \frac{c_k}{h_k}, P_c \right) \right)} \geq \min \left( \frac{c_k}{h_k}, P_c \right) \).

Therefore, the optimal solution (10) is obtained by considering the above three cases and the primal feasibility condition (29).

APPENDIX B

PROOF OF LEMMA 1

This appendix shows the proof of Lemma 1. First, the \( \alpha_{\min} = \min_k a_k \log \left( 1 + b_k \lambda_k \frac{E_c}{n(1+P)} \right) \) is obtained by substituting following \( p_k^* = \frac{E_c}{n(1+P)} \) and minimizing the \( \alpha \). Since \( p_k^* (\alpha) \) is increasing and continuous function over \( \alpha, p_k^* (\alpha_{\min}) \) has
lower value than \( \frac{E_c}{n(\Gamma_P)} \). Therefore, we can derive the following relationship:

\[
\sum_{k \in \Gamma_P} \alpha_k (\alpha_{\text{min}}) = p_1^i (\alpha_{\text{min}}) + p_2^i (\alpha_{\text{min}}) + \ldots + p_n(\Gamma_P) (\alpha_{\text{min}}) 
\leq \frac{E_c}{n(\Gamma_P)} + \frac{E_c}{n(\Gamma_P)} + \ldots + \frac{E_c}{n(\Gamma_P)} = E_c.
\]

Second, repeat the same process about \( \alpha_{\text{max}} \) relationship:

\[
\sum_{k \in \Gamma_P} \alpha_k (\alpha_{\text{max}}) = p_1^i (\alpha_{\text{max}}) + p_2^i (\alpha_{\text{max}}) + \ldots + p_n(\Gamma_P) (\alpha_{\text{max}}) 
\geq \frac{E_c}{n(\Gamma_P)} + \frac{E_c}{n(\Gamma_P)} + \ldots + \frac{E_c}{n(\Gamma_P)} = E_c.
\]

Since \( p_1^i (\alpha_{\text{max}}) \) has larger value than \( \frac{E_c}{n(\Gamma_P)} \), the above relationship is satisfied. Therefore, \( \alpha \) satisfying the condition (14) exists in the interval \([\alpha_{\text{min}}, \alpha_{\text{max}}]\).

### Appendix C

Pseudo-code for LTRPM

This appendix shows the pseudo-code for the Linear Total Received Power Maximization algorithm. The algorithm is based on sequential resource allocation algorithm.

#### Algorithm 5 Linear Total Received Power Maximization Algorithm

1. **Initialization** Arrange the set of EPISs \( \Gamma_P \) by the value of \( h_k \lambda_k \) in descending order.
   - the remaining energy \( E_r = E_c \).
   - the allocated power vector of EPISs \( p^t = 0 \).
2. **for** \( i = 1 : |\Gamma_P| \) **do**
   3. **if** \( E_r > \min \left( \frac{c_k}{\lambda_k}, P_c \right) \) **then**
   4. Set \( p^t_i = \min \left( \frac{c_k}{\lambda_k}, P_c \right) \).
   5. **else**
   6. Set \( p^t_i \leftarrow E_r \).
   7. **end if**
8. **end for**
9. **return** Set of allocated transmission power of EPISs \( p^t \), after reaggregated by the original order.

### Appendix D

Pseudo-code for LCRPM

This appendix shows the pseudo-code for the Linear Common Received Power Maximization algorithm. The algorithm is based on iterative resource allocation algorithm.

#### Algorithm 6 Linear Common Received Power Maximization Algorithm

1. **Initialization** The number of iteration \( I = 0 \).
   - the limit of iteration \( I_{\text{lim}} \).
   - the remaining energy \( E_r = E_c \).
   - the allocated power vector \( p^t = 0 \).
   - and the index set of EPISs \( \Gamma_P \).
2. **while** \( \{ E_r > 0 \} \) and \( \{ I < I_{\text{lim}} \} \) **do**
3. Set \( \alpha = \frac{\sum_{k \in \Gamma_P} E_c}{n(\Gamma_P) \lambda k} \).
4. **for** \( k \in \Gamma_P \) **do**
5. Set \( p^t_k \leftarrow p^t_k + \frac{n k}{\lambda_k} \).
6. **end for**
7. Set \( E_r = 0 \).
8. **for** \( k \in \Gamma_P \) **do**
9. **if** \( p^t_k > \min \left( \frac{c_k}{\lambda_k}, P_c \right) \) **then**
10. Set \( E_r = E_r + p^t_k - \min \left( \frac{c_k}{\lambda_k}, P_c \right) \).
11. **end if**
12. **end for**
13. \( I = I + 1 \).
14. **end while**
15. **return** Allocated transmission power vector \( p^t \).

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### References

[1] "https://www.energous.com/"
[2] "https://www.ossia.com/"
[3] E. Boshkovska, D. W. K. Ng, L. Dai, and R. Schober, “Power-efficient and secure wcpcs with hardware impairments and non-linear eh circuit,” *IEEE Transactions on Communications*, vol. 66, no. 6, pp. 2642–2657, June 2018.
[4] E. Boshkovska, D. W. K. Ng, N. Zlatanov, and R. Schober, “Practical non-linear energy harvesting model and resource allocation for swit systems,” *IEEE Communications Letters*, vol. 19, no. 12, pp. 2082–2085, Dec 2015.
[5] J. Chen, L. Zhang, Y.-C. Liang, X. Kang, and R. Zhang, “Resource allocation for wireless-powered iot networks with short packet communication,” *IEEE Transactions on Wireless Communications*, vol. 18, no. 2, pp. 1447–1461, 2019.
[6] X. Chen, X. Wang, and X. Chen, “Energy-efficient optimization for wireless information and power transfer in large-scale mimo systems employing energy beamforming,” *IEEE Wireless Communications Letters*, vol. 2, no. 6, pp. 667–670, 2013.
[7] Z. Dai, Z. Fang, H. Huang, Y. He, and J. Wang, “Selective omnidirectional magnetic resonant coupling wireless power transfer with multiple-receiver system,” *IEEE Access*, vol. 6, pp. 19 287–19 294, 2018.
[8] R. Feng, M. Dai, and H. Wang, “Distributed beamforming in mimo swit system,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 6, pp. 5440–5445, 2016.
[9] H. Ju and R. Zhang, “Throughput maximization in wireless powered communication networks,” *IEEE Transactions on Wireless Communications*, vol. 13, no. 1, pp. 418–428, 2013.
[10] H. Lee, K.-J. Lee, H. Kim, and I. Lee, “Joint transceiver optimization for mimo swit systems with time switching,” *IEEE Transactions on Wireless Communications*, vol. 17, no. 5, pp. 3298–3312, 2018.
[11] S. Lee, L. Liu, and R. Zhang, “Collaborative wireless energy and information transfer in interference channel,” IEEE Transactions on Wireless Communications, vol. 14, no. 1, pp. 545–557, 2014.
[12] J. Li and G. AlRegib, “Network lifetime maximization for estimation in multi-hop wireless sensor networks,” IEEE Transactions on Signal Processing, vol. 57, no. 7, pp. 2456–2466, 2009.
[13] L. Liu, R. Zhang, and K. Chua, “Multi-antenna wireless powered communication with energy beamforming,” IEEE Transactions on Communications, vol. 62, no. 12, pp. 4349–4361, Dec 2014.
[14] L. Liu, R. Zhang, and K.-C. Chua, “Secrecy wireless information and power transfer with mimo beamforming,” IEEE Transactions on Signal Processing, vol. 62, no. 7, pp. 1850–1863, 2014.
[15] X. Liu, Y. Gao, M. Guo, and N. Sha, “Secrecy throughput optimization for the wpns with non-linear eh model,” IEEE Access, vol. 7, pp. 59477–59490, 2019.
[16] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, “Wireless charging technologies: Fundamentals, standards, and network applications,” IEEE Communications Surveys & Tutorials, vol. 18, no. 2, pp. 1413–1452, 2015.
[17] D. Mishra, G. C. Alexandropoulos, and S. De, “Energy sustainable iot with individual qos constraints through mimo swipt multicasting,” IEEE Internet of Things Journal, vol. 5, no. 4, pp. 2856–2867, 2018.
[18] M. Mitchell, B. Mutfakhtinov, T. Winchen et al., “Engauge digitizer software,” Webpage: http://markummitchell.github.io/engauge-digitizer. Accessed, vol. 11, 2017.
[19] D. W. K. Ng, E. S. Lo, and R. Schober, “Wireless information and power transfer: Energy efficiency optimization in ofdma systems,” IEEE Transactions on Wireless Communications, vol. 12, no. 12, pp. 6352–6370, 2013.
[20] G. Papotto, F. Carrara, and G. Palmisano, “A 90-nm cmos threshold-compensated rf energy harvester,” IEEE Journal of solid-state circuits, vol. 46, no. 9, pp. 1985–1997, 2011.
[21] S. Park, J. Lee, S. Bae, G. Hwang, and J. K. Choi, “Contribution-based energy-trading mechanism in microgrids for future smart grid: A game theoretic approach,” IEEE Transactions on Industrial Electronics, vol. 63, no. 7, pp. 4255–4265, 2016.
[22] M. M. Rana, W. Xiang, E. Wang, X. Li, and B. J. Choi, “Internet of things infrastructure for wireless power transfer systems,” IEEE Access, vol. 6, pp. 19295–19303, 2018.
[23] R. Rezaei, S. Sun, X. Kang, Y. L. Guan, and M. R. Pakravan, “Secrecy throughput maximization for full-duplex wireless powered iot networks under fairness constraints,” IEEE Internet of Things Journal, 2019.
[24] Q. Shi, L. Liu, W. Xu, and R. Zhang, “Joint transmit beamforming and receive power splitting for mimo swipt systems,” IEEE Transactions on Wireless Communications, vol. 13, no. 6, pp. 3269–3280, June 2014.
[25] Q. Sun, G. Zhu, C. Shen, X. Li, and Z. Zhong, “Joint beamforming design and time allocation for wireless powered communication networks,” IEEE Communications Letters, vol. 18, no. 10, pp. 1783–1786, 2014.
[26] P. V. Tuan and I. Koo, “Optimal multiuser mimo beamforming for power-splitting swipt cognitive radio networks,” IEEE Access, vol. 5, pp. 14141–14153, 2017.
[27] T. Umeda, H. Yoshida, S. Sekine, Y. Fujita, T. Suzuki, and S. Otaka, “A 950-mhz rectifier circuit for sensor network tags with 10-m distance,” IEEE Journal of Solid-State Circuits, vol. 41, no. 1, pp. 35–41, 2006.
[28] C. R. Valenta and G. D. Durgin, “Harvesting wireless power: Survey of energy-harvester conversion efficiency in far-field, wireless power transfer systems,” IEEE Microwave Magazine, vol. 15, no. 4, pp. 108–120, 2014.
[29] L. Wang, M. Elkashlan, R. W. Heath, M. Di Renzo, and K.-K. Wong, “Millimeter wave power transfer and information transmission,” in 2015 IEEE Global Communications Conference (GLOBECOM). IEEE, 2015, pp. 1–6.
[30] M. Xiong, M. Liu, Q. Zhang, Q. Liu, J. Wu, and P. Xia, “Tdma in adaptive resonant beam charging for iot devices,” IEEE Internet of Things Journal, vol. 6, no. 1, pp. 867–877, 2018.
[31] D. Xu and H. Zhu, “Outage minimized resource allocation for multiuser ofdm systems with swipt,” IEEE Access, vol. 7, pp. 79714–79725, 2019.
[32] D. Xu, Z. Zhong, and B. Ai, “Wireless powered sensor networks: Collaborative energy beamforming considering sensing and circuit power consumption,” IEEE Wireless Communications Letters, vol. 5, no. 4, pp. 344–347, Aug 2016.
[33] S. Yin and Z. Qu, “Resource allocation in multiuser ofdm systems with wireless information and power transfer,” IEEE Communications Letters, vol. 20, no. 3, pp. 594–597, 2016.
[34] Y. Zeng, B. Clerckx, and R. Zhang, “Communications and signals design for wireless power transmission,” IEEE Transactions on Communications, vol. 65, no. 5, pp. 2264–2290, May 2017.
[35] D. Zhai, H. Chen, Z. Lin, Y. Li, and B. Vucetic, “Accumulate then transmit: Multiuser scheduling in full-duplex wireless-powered iot systems,” IEEE Internet of Things Journal, vol. 5, no. 4, pp. 2753–2767, 2018.
[36] H. Zhang, C. Li, Y. Huang, and L. Yang, “Secure beamforming for swipt in multiuser mimo broadcast channel with confidential messages,” IEEE Communications Letters, vol. 19, no. 8, pp. 1347–1350, 2015.
[37] R. Zhang and C. K. Ho, “Mimo broadcasting for simultaneous wireless information and power transfer,” IEEE Transactions on Wireless Communications, vol. 12, no. 5, pp. 1989–2001, 2013.
[38] X. Zhang, X. Zhang, and L. Han, “An energy efficient internet of things network using restart artificial bee colony and wireless power transfer,” IEEE Access, vol. 7, pp. 12686–12695, 2019.
[39] X. Zhou, “Training-based swipt: Optimal power splitting at the receiver,” IEEE Transactions on Vehicular Technology, vol. 64, no. 9, pp. 4377–4382, 2014.
[40] Z. Zong, H. Feng, F. R. Yu, N. Zhao, T. Yang, and B. Hu, “Optimal transceiver design for swipt in k-user mimo interference channels,” IEEE Transactions on Wireless Communications, vol. 15, no. 1, pp. 430–445, 2015.