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LETTER

Fairness-aware transmitter design for OFDMA-based full-duplex wireless powered communication networks

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Abstract This letter introduces a transmitter design algorithm that prioritizes user fairness for OFDMA-based full-duplex wireless powered communication networks. In the energy transmitter, beamforming is determined to efficiently transmit energy signals to user terminals while minimizing interference to the information receiver, and the transmit power is allocated according to a proportional fairness criterion. In user terminals, subbands are allocated based on minimum rate maximization for information transmission using the harvested power. The simulation results demonstrate that the proposed design algorithm achieves superior user fairness compared to the conventional sum-rate maximization algorithm.

Keywords: wireless energy transfer, energy beamforming, power allocation, subband allocation

Classification: Wireless communication technologies

1. Introduction

Future Internet of Things (IoT) networks must support numerous energy-constrained communication terminals with high energy efficiency. Wireless energy transmission (WET) using radio frequency (RF) signals, which efficiently and wirelessly supply energy to communication terminals, is a promising technology for IoT networks [1]. Wireless powered communication networks (WPCNs) have been extensively investigated as WET-enabled communication systems. In WPCNs, a user terminal harvests energy from an RF signal transmitted by an energy transmitter (ET) and uses the harvested energy for wireless information transmission (WIT) to an information receiver (IR) [2].

Most conventional WPCNs employ half-duplex transmissions based on the harvest-then-transmit protocol to perform WET and WIT in the same frequency band [3]. However, such half-duplex WPCNs suffer from spectral-efficiency loss because the user terminals cannot transmit information during the WET phase. Full-duplex WPCNs (FD WPCNs) have been considered to improve the spectral efficiency of half-duplex WPCNs [4], in which WET and WIT are performed simultaneously. A critical problem with FD WPCNs is that the signals sent by the ET to the user terminals for WET interfere with the signals sent by the user terminals to the IR for WIT. In [5], it was demonstrated that transmit beamforming (BF) using multiple antennas at the ET was effective in suppressing interference. However, the BF technique assumes a single-user system and cannot be applied to multi-user systems. In [6], multiple users were accommodated using orthogonal frequency-division multiple access (OFDMA), which has been widely used in narrowband IoT networks owing to its low complexity and efficient spectrum utilization in frequency-selective channels. OFDMA is also preferable for WPCNs because of its spectrum resource usage flexibility to meet power spectral density (PSD) requirements for safety and interference avoidance [2]. Although it is crucial to mitigate the interference from the ET to the IR, specific methods for suppressing it have not been described in [6]. In [7], an OFDMA-based multi-user FD WPCN utilizing a BF at the ET for interference suppression was considered, and a transmitter design algorithm that maximized the sum rate was proposed. However, the transmitter design allocates more resources to users with favorable channel conditions, resulting in unfair resource allocation among users. In WPCNs, the user fairness issue is more critical because users far away from ET and IR suffer from lower throughput than those in the vicinity, i.e., doubly near-far problem [2]. Thus, it is essential for WPCNs to enhance user fairness.

Some studies have been conducted on fairness-aware transmitter designs for multi-user WPCNs [8, 9]. In [8], three power and time allocation criteria were considered to achieve rate fairness. In [9], proportional-fairness-based resource allocation outperformed sum rate maximization in terms of fairness performance. However, despite the usefulness of OFDMA and FD transmission for WPCN, as shown in [7], previous studies have not employed them.

In this letter, we propose a transmitter design algorithm that considers user fairness in OFDMA-based multi-user FD WPCNs [10][1]. In the proposed algorithm, the BF at the ET is determined for efficient WET and interference suppression, and the transmit power at the ET is allocated to subbands based on the proportional fairness criterion. In addition, the subband allocation at the user terminals was determined based on the minimum rate maximization [11].

2. System model

Figure 1 depicts an OFDMA-based FD WPCN system consisting of an ET, K users, and an IR. The ET transmits energy signals to users using N subbands. Each user operates in

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[1] In [10], we only outlined the power allocation method. In this letter, we describe the entire transmitter design algorithm in detail and presents more numerical results.

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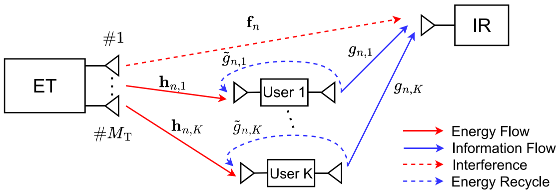

Fig. 1 OFDMA-based FD WPCN system.

FD mode to harvest energy from its received signal and transmit its information data to the IR using the harvested energy simultaneously. The IR receives signals from users and detects their information. The ET uses M_T transmitting antennas, and the IR uses a single receiving antenna. Each user uses a single transmitting antenna and receiving antenna. We assume perfect knowledge of all channels, which are frequency-selective.

The ET sends a random signal u_n in the nth subband for energy transmission, which is preferable because of its lower PSD [2]. Its transmitted signal in the nth subband is expressed as $\mathbf{x}_n^\mathrm{E} = \sqrt{P_n^\mathrm{E}}\mathbf{w}_n u_n$, where P_n^E is the transmission power of the ET and $\mathbf{w}_n \in \mathbb{C}^{M_\mathrm{T}\times 1}$ is the BF vector in the nth subband. We assume that $\mathbb{E}[u_n u_{n'}^*] = 1$ for $n = n'$; otherwise, 0, and $\|\mathbf{w}_n\| = 1, \forall n$. The total transmit power of the ET can then be expressed as $\sum_{n=0}^{N-1} \mathbb{E}\left[\|\mathbf{x}_n^\mathrm{E}\|^2\right] = \sum_{n=0}^{N-1} P_n^\mathrm{E}$.

Let $\mathcal{N}_k$ denote the set of subbands allocated to the kth user. The kth user sends the data symbol $v_{n,k}$ in the nth subband. Its transmitted signal in the nth subband is $x_{n,k}^\mathrm{U} = \sqrt{P_{n,k}^\mathrm{U}} v_{n,k},\ n \in \mathcal{N}_k$, where $P_{n,k}^\mathrm{U}$ is the transmit power of the kth user in the nth subband. We also assume that $\mathbb{E}[v_{n,k} v_{n',k'}^*] = 1$ for $n = n'$ and $k = k'$; otherwise, it is 0. The total transmit power of the kth user can then be expressed as $\sum_{n\in\mathcal{N}_k} P_{n,k}^\mathrm{U}$. The harvested power of the kth user is expressed as follows:

$$P_k^\mathrm{EH} = \eta\left(\sum_{n=0}^{N-1} P_n^\mathrm{E}|\mathbf{h}_{n,k}^T\mathbf{w}_n|^2 + \sum_{n\in\mathcal{N}_k} P_{n,k}^\mathrm{U}|\tilde{g}_{n,k}|^2\right), \tag{1}$$

where $\mathbf{h}_{n,k} \in \mathbb{C}^{M_\mathrm{T}\times 1}$ is the channel from the ET to the kth user in the nth subband, $\tilde{g}_{n,k} \in \mathbb{C}$ is the loopback channel of the kth user in the nth subband, and η is the energy-conversion efficiency. Eq. (1) implies that each user harvests energy from the signal transmitted by the ET and its own transmitted signal. Note that the reception of its own transmitted signal acts as energy self-recycling rather than self-interference. We assume that each user uses all the harvested power for data transmission. Subsequently, the relationship $\sum_{n\in\mathcal{N}_k} P_{n,k}^\mathrm{U} = P_k^\mathrm{EH}$ holds true. From this relationship, the transmit power of the kth user in the nth subband is expressed in closed form as

$$P_{n,k}^\mathrm{U} = \alpha_{n,k}\frac{\eta\sum_{n'=0}^{N-1} P_{n'}^\mathrm{E}|\mathbf{h}_{n',k}^T\mathbf{w}_{n'}|^2}{1-\eta|\tilde{g}_{n,k}|^2}, \tag{2}$$

where the power allocation parameter $\alpha_{n,k} \in \mathbb{R}$ is introduced instead of $P_{n,k}^\mathrm{U}$, subject to $\alpha_{n,k} \geq 0$ and $\sum_{n\in\mathcal{N}_k}\alpha_{n,k} = 1$.

The IR receives information signals from each user and interference from the ET. Assuming that the signals from the ET and users arrive at the ET within a cyclic prefix interval, the received signal of the IR in the nth subband is given by

$$y_n^\mathrm{I} = \sqrt{P_{n,k}^\mathrm{U}} g_{n,k}\, v_{n,k} + \sqrt{P_n^\mathrm{E}}\mathbf{f}_n^T\mathbf{w}_n u_n + z_n,\ n \in \mathcal{N}_k, \tag{3}$$

where $g_{n,k} \in \mathbb{C}$ is the channel from the kth user to the IR in the nth subband, $\mathbf{f}_n \in \mathbb{C}^{M_\mathrm{T}\times 1}$ is the channel vector from the ET to the IR in the nth subband, and z_n is the additive white Gaussian noise in the nth subband at the IR. In (3), the first term is the desired data component of the kth user, and the second term is the interference component that must be suppressed. From (2) and (3), we obtain the signal-to-interference-plus-noise ratio (SINR) for the kth user in the nth subband of the IR as follows:

$$\gamma_{n,k} = \frac{\alpha_{n,k}\sum_{n'=0}^{N-1} P_{n'}^\mathrm{E}|\mathbf{h}_{n',k}^T\mathbf{w}_{n'}|^2}{P_n^\mathrm{E}|\mathbf{f}_n^T\mathbf{w}_n|^2 + \sigma_z^2} G_{n,k}, \tag{4}$$

where $G_{n,k} = \frac{\eta|g_{n,k}|^2}{1-\eta|\tilde{g}_{n,k}|^2}$, The achievable user rate for the kth user is given by:

$$R_k = \sum_{n\in\mathcal{N}_k}\log_2(1+\gamma_{n,k}). \tag{5}$$

3. Transmitter design

The purpose of the transmitter design is to determine the variables $\{\mathbf{w}_n\}$, $\{P_n^\mathrm{E}\}$, $\{\alpha_{n,k}\}$, and $\{\mathcal{N}_k\}$. Determining the optimal variables is cumbersome because the variables are coupled. In the proposed algorithm, we take the approach of determining each variable separately.

First, we determine the power allocation $\{P_n^\mathrm{E}\}$ at ET when $\{\mathbf{w}_n\}$, $\{\alpha_{n,k}\}$, and $\{\mathcal{N}_k\}$ are given. To ensure user fairness, we employ a proportional-fairness-based power allocation that maximizes the sum of the logarithms of the user's rate R_k. The power allocation problem for P_n^E can be formulated as

$$\max_{\{P_n^\mathrm{E}\}}\sum_{k=1}^{K}\log(R_k)\ \text{s.t.}\ \sum_{n=0}^{N-1} P_n^\mathrm{E} \leq P_{\max},\ P_n^\mathrm{E} \geq 0, \forall n, \tag{6}$$

where $P_{\max}$ is the maximum transmission power at the ET. Because of the existence of P_n^E in the denominator of $\gamma_{n,k}$ in (4), the problem (6) is nonconvex, making it difficult to solve. To solve this problem, we assume that the interference can be sufficiently suppressed by an appropriate BF, that is, $|\mathbf{f}_n^T\mathbf{w}_n|^2 \approx 0$. Then, the problem (6) can be reformulated as

$$\begin{aligned}&\max_{\{P_n^\mathrm{E}\}}\sum_{k=1}^{K}\log\left\{\sum_{n\in\mathcal{N}_k}\log_2\left(1+\frac{\alpha_{n,k}\sum_{n'=0}^{N-1}P_{n'}^\mathrm{E}|\mathbf{h}_{n',k}^T\mathbf{w}_{n'}|^2}{\sigma_z^2}G_{n,k}\right)\right\}\\ &\quad\text{s.t.}\ \sum_{n=0}^{N-1}P_n^\mathrm{E} \leq P_{\max},\ P_n^\mathrm{E} \geq 0, \forall n.\end{aligned} \tag{7}$$

Problem (7) is concave and can be solved in a computationally efficient manner using convex solvers, such as CVXPY.

Next, we determine the BF vector $\{\mathbf{w}_n\}$ when $\{P_n^\mathrm{E}\}$, $\{\alpha_{n,k}\}$, and $\{\mathcal{N}_k\}$ are given. The BF vector should sufficiently suppress interference to hold the assumption made in (7). To achieve this, we employ the SINR maximization approach. Specifically, the problem solving for $\mathbf{w}_n$ is expressed as:

$$\max_{\mathbf{w}_n} \frac{\mathbf{w}_n^H \mathbf{H}_{n,k} \mathbf{w}_n}{\mathbf{w}_n^H \mathbf{F}_n \mathbf{w}_n} \quad \text{s.t.} \quad \|\mathbf{w}_n\| = 1,\ n \in \mathcal{N}_k. \tag{8}$$

where

$$\mathbf{H}_{n,k} = \alpha_{n,k} G_{n,k} \left(P_n^{\mathrm{E}} \mathbf{h}_{n,k}^* \mathbf{h}_{n,k}^T + \sum_{\substack{i=0 \\ i \neq n}}^{N-1} P_i^{\mathrm{E}} |\mathbf{h}_{i,k}^T \mathbf{w}_i|^2 \mathbf{I}_{M_\mathrm{T}} \right) \in \mathbb{C}^{M_\mathrm{T} \times M_\mathrm{T}}, \tag{9}$$

$$\mathbf{F}_n = P_n^{\mathrm{E}} \mathbf{f}_n^* \mathbf{f}_n^T + \sigma_z^2 \mathbf{I}_{M_\mathrm{T}} \in \mathbb{C}^{M_\mathrm{T} \times M_\mathrm{T}}. \tag{10}$$

Problem (8) cannot be solved directly because $\mathbf{H}_{n,k}$ in (9) depends on $\mathbf{w}_i (i \neq n)$. To avoid this dependence, we empirically set $\mathbf{w}_i = 1/\sqrt{M_\mathrm{T}}\mathbf{1}$ in (9), where $\mathbf{1} = [1 \cdots 1]^T$. Subsequently, because problem (8) results in a generalized eigenvalue problem, $\mathbf{w}_n$ which maximizes $\gamma_{n,k}$ is given by

$$\mathbf{w}_n = \mathcal{L}\{\mathbf{H}_{n,k}, \mathbf{F}_n\},\ n \in \mathcal{N}_k, \tag{11}$$

where $\mathcal{L}\{\mathbf{A}, \mathbf{B}\}$ denotes the normalized eigenvector corresponding to the largest generalized eigenvalue of the matrix pair $(\mathbf{A}, \mathbf{B})$.

Next, we consider determining the power allocation parameters $\{\alpha_{n,k}\}$ for users. When $\{\mathbf{w}_n\}$, $\{P_n^{\mathrm{E}}\}$, and $\{\mathcal{N}_k\}$ are given, $\{\alpha_{n,k}\}$ can be determined independently for each user. A reasonable strategy is to maximize R_k for $\{\alpha_{n,k}\}$, which can be formulated as:

$$\max_{\{\alpha_{n,k}\}} R_k \ \text{s.t.} \sum_{n \in \mathcal{N}_k} \alpha_{n,k} = 1,\ \alpha_{n,k} \geq 0, \forall k. \tag{12}$$

The water-filling algorithm can solve this problem, and its solution can be expressed as:

$$\alpha_{n,k} = \max\left\{0, \mu_k - \frac{1}{G'_{n,k}}\right\},\ n \in \mathcal{N}_k, \tag{13}$$

where the water level μ_k is chosen to satisfy the constraint and

$$G'_{n,k} = \frac{\sum_{n'=0}^{N-1} P_{n'}^{\mathrm{E}} |\mathbf{h}_{n',k}^T \mathbf{w}_{n'}|^2}{P_n^{\mathrm{E}} |\mathbf{f}_n^T \mathbf{w}_n|^2 + \sigma_z^2} G_{n,k}. \tag{14}$$

Finally, we explain the subband allocation $\{\mathcal{N}_k\}$. When $\{\mathbf{w}_n\}$, $\{P_n^{\mathrm{E}}\}$, and $\{\alpha_{n,k}\}$ are given, the problem to be solved is the same as the subband allocation problem in OFDMA-based communication systems. Here, we employ the simple subband allocation algorithm of [11], which maximizes the minimum rate among users to ensure user fairness. Using this algorithm, each user is allocated at least one subband, and lower-rate users are allocated more subbands.

Algorithm 1 Proposed Transmitter Design Algorithm

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1: $\mathcal{N} = \{0, 1, \ldots, N-1\}$, $\mathcal{N}_k = \mathcal{N}, \forall k$, $P_n^{\mathrm{E}} = P_{\max}/N, \forall n$, $\alpha_{n,k} = 1/N, \forall n, k$
2: for $k = 1$ to $K$ do
3:     for $n = 0$ to $N-1$ do
4:         Determine $\mathbf{H}_{n,k}$ using (9) with $\mathbf{w}_i = 1/\sqrt{M_\mathrm{T}}\mathbf{1}, \forall i \neq n$
5:         Determine $\mathbf{w}_n$ using (11) and set $\mathbf{w}_n^{(k)} = \mathbf{w}_n$
6:     end for
7:     for $n = 0$ to $N-1$ do
8:         Determine $G'_{n,k}$ using (14)
9:         $R_{n,k} = \log_2(1 + \alpha_{n,k} G'_{n,k})$
10:    end for
11: end for
12: $\mathcal{N}_k = \emptyset, \forall k$
13: for $k = 1$ to $K$ do
14:     Find $n$ satisfying $R_{n,k} \geq R_{m,k}, \forall m \in \mathcal{N}$
          $\rightarrow \mathcal{N}_k = \mathcal{N}_k + \{n\}$, $\mathcal{N} = \mathcal{N} - \{n\}$, $R_k = \sum_{n \in \mathcal{N}_k} R_{n,k}$
15: end for
16: while $\mathcal{N} \neq \emptyset$ do
17:     Find $k$ satisfying $R_k \leq R_l, \forall l \in \{1, 2, \ldots, K\}$
18:     For the found $k$, find $n$ satisfying $R_{n,k} \geq R_{m,k}, \forall m \in \mathcal{N}$
          $\rightarrow \mathcal{N}_k = \mathcal{N}_k + \{n\}$, $\mathcal{N} = \mathcal{N} - \{n\}$, $R_k = \sum_{n \in \mathcal{N}_k} R_{n,k}$
19: end while
20: $\mathbf{w}_n = \mathbf{w}_n^{(k)}, \forall k, n \in \mathcal{N}_k$
21: $\alpha_{n,k} = 1/|\mathcal{N}_k|, \forall k, n \in \mathcal{N}_k$
22: Determine $P_n^{\mathrm{E}}$ by solving (7), $\forall n$
23: Determine $\alpha_{n,k}$ using (13), $\forall k, n \in \mathcal{N}_k$
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The proposed algorithm is summarized in Algorithm 1. From steps 2 to 11, the tentative rates $R_{n,k}$ are computed by assuming that each user can use all subbands $\mathcal{N}_k = \mathcal{N}$, and equal power allocations are applied $P_n^{\mathrm{E}} = P_{\max}/N$ and $\alpha_{n,k} = 1/N$. From steps 12 to 19, the subband allocation $\{\mathcal{N}_k\}$ is determined by the algorithm in [11] using the tentative rates. In step 20, the BF vectors $\{\mathbf{w}_n\}$ are determined. In step 22, the power allocation at the ET $\{P_n^{\mathrm{E}}\}$ is determined under an equal power allocation of $\alpha_{n,k}$. In step 23, the power allocation for users $\{\alpha_{n,k}\}$ is determined. Note that we confirmed in our preliminary simulation that iteratively running this algorithm did not improve performance. The computational complexity of the proposed algorithm is dominated by the computation of the BF vector $\mathbf{w}_n$ in steps 2–11, which is $O(NKM_\mathrm{T}^3)$.

4. Simulation results

We evaluated the performance of the proposed transmitter design algorithm by comparing it with that of the sum rate maximization (SRM) design algorithm in [7]. The simulation settings were as follows: $N = 16, M_\mathrm{T} = 5, \eta = 0.6, P_{\max} = 40$ dBm, the loopback gain of users was -10 dB, and the noise power of z_n is $\sigma_z^2 = -90$ dBm. The distance attenuation was $(c/4\pi f_c)^2 d^{-2.4}$, where c is the speed of light, d is the distance, and the carrier frequency was $f_c = 900$ MHz. The ET and IR were located at $(-6$ m$, 0$ m$)$ and $(6$ m$, 0$ m$)$, respectively, and the users were uniformly distributed in a circle centered at the origin and with a radius 3 m. The Rayleigh fading channels were modeled as linear FIR filters with a 6 tap exponentially decaying power profile. To evaluate the user fairness, we defined the fairness index as $\frac{(\sum_{k=1}^K R_k)^2}{K \sum_{k=1}^K R_k^2}$. The simulation results were averaged over 10^3 channel realizations.

Figure 2 shows fairness performance comparisons as a function of the ET transmission power $P_{\max}$ for two cases of K. The fairness index of the proposed algorithm increases with $P_{\max}$, whereas that of SRM does not increase for a larger $P_{\max}$. The proposed algorithm provides superior fairness performance compared to the SRM in both cases.

Figure 3 illustrates the effect of the number of users on the fairness index. We observed that the fairness index of SRM

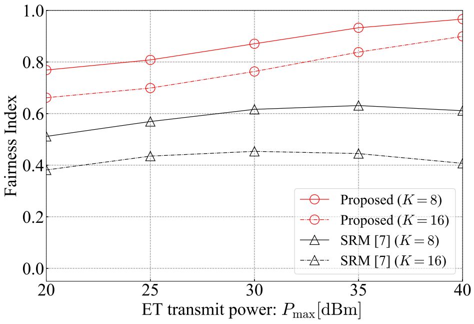

Fig. 2 Fairness performance comparisons.

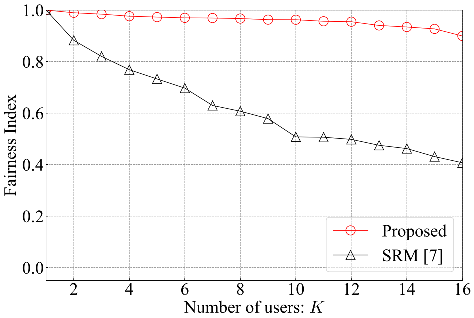

Fig. 3 Effect of the number of users on fairness performance.

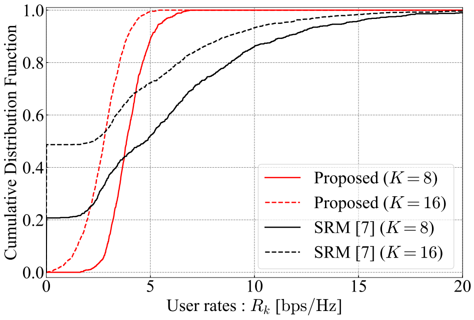

Fig. 4 CDFs of user rates.

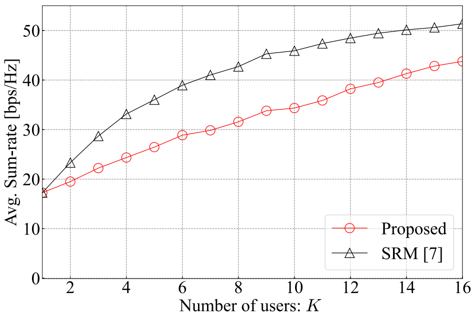

Fig. 5 Sum rate performance comparison.

significantly decreased as the number of users increased, whereas the proposed method maintained a higher fairness performance.

Figure 4 shows the cumulative distribution functions (CDF) of user rates R_k for two cases of K. In the proposed algorithm, R_ks are distributed within a narrow range, whereas in SRM, R_ks are distributed over a wide range. Furthermore, in the SRM, 20% of the users have a rate of 0 bps/Hz for $K = 8$ and 50% for $K = 16$. These results show that the proposed algorithm has higher user fairness than SRM.

Figure 5 presents a sum-rate performance comparison as a function of the number of users. The sum rate of SRM is higher than that of the proposed algorithm for any number of users, except $K = 1$. The performance difference is up to 11 bps/Hz at $K = 8$ and decreases when the number of users is small or large.

5. Conclusion

In this letter, we proposed a transmitter design algorithm that considers user fairness in OFDMA-based multi-user FD WPCNs. The proposed transmitter design achieved high user fairness by preferentially allocating resources to users at lower rates. The simulation results showed that the proposed method has higher user fairness than the sum-rate maximization algorithm at the expense of a slight sum-rate degradation.

References

[1] X. Lu, P. Wang, D. Niyato, D.I. Kim, and Z. Han, “ Wireless charging technologies: Fundamentals, standards, and network applications,” *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1413–1452, 2016. DOI: 10.1109/COMST.2015.2499783

[2] S. Bi, C.K. Ho, and R. Zhang. “Wireless powered communication: Opportunities and challenges,” *IEEE Commun. Mag.*, vol. 53, no. 4, pp. 117–125, April 2015. DOI: 10.1109/MCOM.2015.7081084

[3] H. Ju and R. Zhang, “Throughput maximization in wireless powered communication networks,” *IEEE Trans. Wireless Commun.*, vol. 13, no. 1, pp. 418–428, Jan. 2014. DOI: 10.1109/TWC.2013.112513.130760

[4] H. Ju, K. Chang, and M.-S. Lee, “In-band full-duplex wireless powered communication networks,” Proc. 2015 17th Int. Conf. Adv. Commun. Technol. (ICACT), Pyeong Chang, pp. 23–27, July 2015. DOI: 10.1109/ICACT.2015.7224751

[5] Y. Che, J. Xu, L. Duan, and R. Zhang, “Multiantenna wireless powered communication with cochannel energy and information transfer,” *IEEE Commun. Lett.*, vol. 19, no. 12, pp. 2266–2269, Dec. 2015. DOI: 10.1109/LCOMM.2015.2495187

[6] F. Wang and X. Zhang, “Resource allocation for wireless power transmission enabled full-duplex OFDMA mobile wireless networks,” Proc. IEEE Global Commun. Conf. (GLOBECOM), Abu Dhabi, UAE, pp. 1–6, Dec. 2018. DOI: 10.1109/GLOCOM.2018.8647388

[7] K. Hirashima and T. Miyajima, “Sum rate maximization for multi-user full-duplex wireless powered communication networks,” *IEICE Trans. Commun.*, pp. 1–10, 2024, in print. DOI: 10.23919/transcom.2023EBP3165

[8] C. Guo, B. Liao, L. Huang, Q. Li, and X. Lin, “Convexity of fairness-aware resource allocation in wireless powered communication networks,” *IEEE Commun. Lett.*, vol. 20, no. 3, pp. 474–477, March 2016. DOI: 10.1109/LCOMM.2016.2519344

[9] S. Pejoski, Z. Hadzi-Velkov, T.Q. Duong, and C. Zhong, “ Wireless-powered communication networks with non-ideal circuit power consumption,” *IEEE Commun. Lett.*, vol. 21, no. 6, pp. 1429–1432, June 2017. DOI: 10.1109/LCOMM.2017.2680446

[10] K. Hirashima and T. Miyajima, “User fairness power allocation in OFDMA-based wireless powered communication network,” Proc. ICETC 2023, no. P1-30, Nov. 2023. DOI: 10.34385/proc.79.P1-30

[11] W. Rhee and J.M. Cioffi, “Increase in the capacity of multi-user OFDM system using dynamic subchannel allocation,” Proc. IEEE VTC2000-Spring, vol. 2, pp 1085–1089, Tokyo, Japan, 2000. DOI: 10.1109/VETECS.2000.851292