Adaptive Proportional Fairness Scheduling for SWIPT-Enabled Multicell Downlink Networks

Yongjae Kim, Bang Chul Jung†, Inkyu Bang*, Youngnam Han
Dept. of EE, Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea
†Dept. EE, Chungnam National University, Daejeon, Korea
*Dept. CS, School of Computing, National University of Singapore (NUS), Singapore
Email: {yongjaekim, ynhan}@kaist.ac.kr, †bcjung@cnu.ac.kr, *inkyu@comp.nus.edu.sg

***Abstract*—Simultaneous wireless information and power transfer (SWIPT) has been considered one of the emerging techniques to overcome power limitation of wireless devices using batteries as well as to send information at the same time. Although the SWIPT techniques have been intensively investigated, the *fairness* among wireless-powered devices in the SWIPT-enabled multicell networks has not been studied yet. In this paper, we propose an adaptive proportional fairness (α-PF) scheduling algorithm in SWIPT-enabled multi-cell downlink networks. We define an adjustable weighted sum of achievable rate and harvested energy as the utility function of each user and investigate fairness among utilities of users. Through extensive simulations, we evaluate the proposed scheduling algorithm in terms of rate-energy (RE) tradeoff, the fairness of achievable rate and harvested energy. Compared to various existing scheduling algorithms such as random scheduling, maximum signal-to-interference-plus-noise (SINR) scheduling, and α-adaptive scheduling algorithms, the proposed scheduling algorithm achieves better fairness measure (e.g., Jain's fairness index). In addition, we can adaptively control parameters of the proposed scheduling algorithm to satisfy certain requirements of the system.**

***Index Terms*—Energy harvesting, simultaneous wireless information and power transfer (SWIPT), rate-energy tradeoff, user scheduling, proportional fairness.**

I. INTRODUCTION

Wireless networks are being expected to support a massive number of IoT devices such as smart-phones, tablet computers, smart home sensors, and RFID tags. It is forecasted that the total number of connected devices becomes more than tens of billions in the fifth generation (5G) wireless communication systems [1]. Most devices commonly operate in a battery-powered manner and thus they suffer from battery depletion problem. To prolong the lifetime of battery-powered devices, energy harvesting (EH) from various renewable resources and even radio frequency (RF) signals has received much attention from both academia and industry [2]. In particular, energy harvesting from the RF signals so-called wireless power transfer (WPT) has recently been highlighted as one of the possible solutions to power a massive number of devices in 5G scenarios due to its reliability compared to energy harvesting from renewable resources, which usually depend on environments (e.g., weather) [2], [3].

Interestingly, previous work [4], [5] showed that RF signals can transfer information and energy at the same time, which is called simultaneous wireless information and power transfer (SWIPT). Since the notion of SWIPT was introduced in [4], [5], various aspects of the SWIPT technique have been investigated [6]–[11]. In [6], the resource allocation algorithm that maximizes the energy efficiency was studied for orthogonal frequency division multiple access (OFDMA) SWIPT systems. In [7]–[9], several transmit beamforming technique were proposed for SWIPT-enabled multiple-input single-output (MISO) broadcast channels. In [7], a joint transmit beamforming and receive power splitting ratio optimization algorithm was proposed with the semidefinite relaxation technique. In [8], a joint information and energy transmit beamforming technique was investigated in SWIPT-enabled *multi-user* MISO downlink networks where the base station (BS) sends both information and energy to multiple users via spatial multiplexing. In [9], another joint information and energy transmit beamforming technique was proposed for a single-cell wiretap MISO downlink network with passive *eavesdroppers*. In [10], a relay selection algorithm was studied a SWIPT-enabled cooperative relay network, where the relay can send information and power to receiver simultaneously. In [11] and references therein, various potential emerging technologies was reviewed especially for SWIPT-enabled 5G wireless networks, and relevant research challenges was summarized.

Different from above studies, Morsi *et al.* focused on multi-user scheduling problem for the SWIPT-enabled network [12], [13]. In [12], [13], two order-based scheduling algorithms were proposed for a single-cell SWIPT-enabled downlink network with the time switching receiver at users: order-based normalized-signal-to-noise ratio (N-SNR) and order-based equal throughput (ET) scheduling algorithms. In addition, the average per-user harvested energy and achievable rate are derived in closed-forms under several fading channels such as Rayleigh, Rician, Nakagami-m, and Weibull fading channels. However, the analysis is done only in the single-cell environment. Subsequently, Bang *et al.* [14] proposed an α-adaptive scheduler for SWIPT-enabled multi-cell networks with a power splitting receiver at users. The basic idea of the α-adaptive scheduler is to balance maximizing achievable rate and maximizing harvested energy of the scheduled user by changing a parameter defined as α. However, the proposed scheduler in [14] did not fully consider the fairness issue

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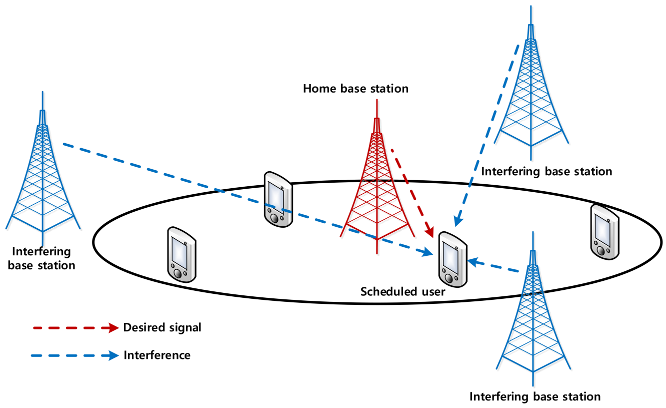

Fig. 1. A SWIPT-enabled multicell downlink network

among users.

There have been a few studies to consider fairness issues in SWIPT systems [15], [16]. Hadzi-Velkov *et al.* [15] considered time-division multiple access (TDMA), and derived an optimal time ratio between information transmission and EH when the proportional fairness (PF) scheduling criterion was adopted. Diamantoulakis *et al.* [16] also investigated the optimal time ratio for non-orthogonal multiple access with time-sharing (NOMA-TS) [17] as well as TDMA from the resource allocation point of view. However, previous work [15], [16] only focused on maximizing fairness in terms of achievable rate with the energy constraint in a single-cell environment. To the best our knowledge, there have been few studies related to scheduling/fairness problems in single/multicell SWIPT networks ,still, the fairness issues have not been thoroughly investigated.

In this paper, we propose an adaptive proportional fairness (α-PF) user scheduling algorithm for SWIPT-enabled multicell downlink networks with the power splitting receiver to guarantee a fairness among users' utilities defined as the weighted sum of achievable rate and harvested energy. We evaluate the performance of the proposed scheduling algorithm including achievable rate, harvested energy, and fairness among users by changing the parameter α (weighting factor). Through simulations, we verify that the proposed scheduling algorithm significantly outperforms the existing scheduling algorithms in terms of fairness of achievable rate of users at the cost of a slightly reduced achievable sum-rate of the network.

The rest of this paper is organized as follows. In Section II, the system model is described. In Section III, the power splitting receiver architecture and corresponding signal processing are introduced. In Section IV, the adaptive PF scheduling is proposed. The performance of the proposed scheduling algorithm is evaluated and compared with the conventional scheduling algorithms in Section V. Finally, conclusive remarks are drawn in Section VI.

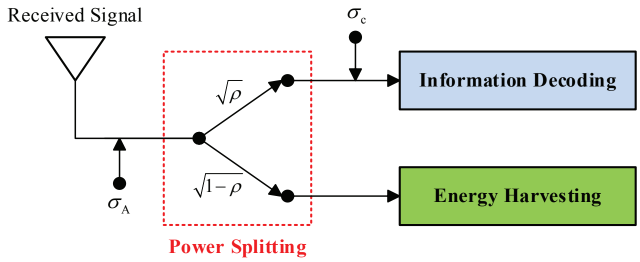

Fig. 2. Power Splitting Receiver Architecture

II. System Model

Fig. 1 shows a SWIPT-enabled multicell downlink network where a home BS serving N users and K interfering BSs are deployed. We assume that all BSs and users are equipped with a single antenna and BSs always have packets to transmit to their scheduled users at each time slot. During one symbol time duration (i.e., one time slot), only a single user is scheduled among N users by the home BS. The users are randomly deployed within the range of home BS and they equip with power splitting receivers for EH. Additionally, we assume a block fading channel that the channel coefficient remains constant during one time slot and changes independently in the next time slot.

For user n, $n \in \{1, \cdots, N\}$, h_n denotes the channel coefficient between the home BS and user n. Similarly, $g_{n,k}$ denotes the channel coefficient between the interfering BS k, $k \in \{1, \cdots, K\}$, and user n. We assume that both h_n and $g_{n,k}$ are complex Gaussian random variables with zero means and variance $\sigma^2_{h_n}$ and $\sigma^2_{g_{n,k}}$, respectively.

When user m is scheduled by the home BS at a certain time slot, the received signal at user n is given by

$$y_n = h_n s_m + \sum_{k=1}^{K} g_{n,k} x_k + w_A, \tag{1}$$

where s_m denotes the desired signal for user m, x_k denotes the interference signal from the interfering BS k, and w_A denotes the additive white Gaussian noise (AWGN) with zero mean and variance σ^2_A. All BSs have the transmit power constraint P, i.e., $|s_m|^2 = P$, and $|x_k|^2 = P$.

III. Basic Operations of Power Splitting Receiver

In this section, we briefly introduce basic operations of SWIPT systems when the power splitting receivers are considered [18]. Fig. 2 shows a power splitting receiver architecture in which the received signal is split into two separate signals with power splitting ratio $\rho \in [0, 1]$. A portion of the signal is used for information decoding (ID) and the other is used for EH[1]. Note that, in the multicell downlink SWIPT system, interference from other BSs (i.e., interfering BSs) can be exploited as an additional energy harvesting source for all users (scheduled and non-scheduled users).

[1]In this paper, the terms "energy" and "power" are used interchangeably under an assumption of unit length of symbol time duration.

A. Information Decoding

When we consider ID at the power splitting receiver, additional conversion noise has to be taken into account [18]. As a result, the received signal for ID at user m (scheduled user) is given by

$$\begin{aligned} y_{\mathrm{ID},m} &= \sqrt{\rho} y_m + w_{\mathrm{c}} \\ &= \sqrt{\rho}\left(h_m s_m + \sum_{k=1}^{K} g_{m,k} x_k + w_{\mathrm{A}}\right) + w_{\mathrm{c}}, \end{aligned} \quad (2)$$

where y_m is the total received signal obtained in (1) and w_{c} denotes the conversion noise introduced by converting RF passband signal into baseband signal. Similarly to w_{A}, w_{c} is assumed to be a complex Gaussian random variable with zero mean and variance σ_{c}^2. From (2), the received signal-to-interference-plus-noise-ratio (SINR) for user m is obtained by

$$\lambda_m(\rho) = \frac{\rho |h_m|^2 P}{\rho\left(\sum_{k=1}^{K} |g_{m,k}|^2 P + \sigma_{\mathrm{A}}^2\right) + \sigma_{\mathrm{c}}^2}. \quad (3)$$

Accordingly, the achievable rate according to ρ for user n at a certain time slot is obtained by

$$R_n(\rho) = \begin{cases} \log_2\left(1 + \lambda_n(\rho)\right) & n = m, \\ 0 & n \neq m, \end{cases} \quad (4)$$

where only the scheduled device achieves positive data rate and the other devices have zero data rate, since we assume that a single device is scheduled during a time slot.

B. Energy Harvesting

At an EH module, the harvested energy is proportional to the power of the received signal and thus it is expressed as follows when we consider user n:

$$Q_n(\rho) = \begin{cases} \zeta\left(1-\rho\right)\left(P_{\mathcal{D}} + P_{\mathcal{I}} + \sigma_{\mathrm{A}}^2\right) & \text{for } n = m, \\ \zeta\left(P_{\mathcal{D}} + P_{\mathcal{I}} + \sigma_{\mathrm{A}}^2\right) & \text{for } n \neq m, \end{cases} \quad (5)$$

where ζ denotes the conversion efficiency with range $0 \leq \zeta \leq 1$, $P_{\mathcal{D}} = |h_n|^2 P$ and $P_{\mathcal{I}} = \sum_{k=1}^{K} |g_{n,k}|^2 P$ denotes the received power from the home BS and K interfering BSs, respectively. Note that ρ is set to zero for the non-scheduled device, since the entire received signal power will be utilized at the EH module if $n \neq m$. Throughout this paper, we assume $\zeta = 1$, since ζ only affects the linear scaling of the harvested energy.

C. Rate-Energy Tradeoff Region

As defined in [18], the rate-energy tradeoff region of user n can be written as follows:

$$C_n(N, K, P) = \bigcup_{\rho \in [0,1]} \{(r, q) : r \leq r_n(\rho),\, q \leq q_n(\rho)\}, \quad (6)$$

where $r_n(\rho)$ and $q_n(\rho)$ are defined in (4) and (5), respectively.

IV. Proposed Adaptive Proportional Fairness Scheduling Algorithm

In this section, we introduce the proposed scheduling algorithm which can adaptively achieve fairness in the multicell downlink SWIPT system. Although a notion of the adaptive scheduling including the closed-form analytic results was investigated in [14], fairness among the users has not been carefully considered. Accordingly, we develop a novel scheduling algorithm, called α-PF scheduler, which guarantees the fairness in terms of EH as well as ID. In addition, the α-PF scheduler is designed by considering the entire harvested energy over the network than that of the scheduled user as in [14] since all users always can harvest the energy regardless of scheduling decision by the home BS.

In the proposed scheduling algorithm, the home BS selects one of the users within cell range based on the utility function composed of the achievable rate of each user and harvested energy. Similar to [14], the α-PF scheduler uses a weighting factor α to properly adjust preference between the achievable rate and the amount of harvested energy, in the utility function. Interestingly, this results in achieving better fairness compared to conventional scheduling schemes. Specifically, the utility function of α-PF scheduler at time t is described in (7) shown at the top of next page. In (7), the first term denotes the SINR of user n and it is multiplied by the weighting factor α. The second term related to EH is divided by the scaling factor $N \cdot \sigma_{g,\max}^2$ to match the level of the first term. $\sigma_{g,\max}^2$ is the average channel gain of the strongest interfering BS. Although the second term is same among the users, it is meaningful since the average criterion value, as well as the instantaneous criterion value, are used for the PF scheduling. Therefore, the proposed α-PF scheduling scheme is described as follows:

$$m = \underset{n \in \{1, \cdots, N\}}{\arg\max} \frac{z_n(t)}{Z_n}, \quad (8)$$

where Z_n denotes the average of instantaneous criterion over several time slots.

V. Performance Evaluation

In this section, we evaluate the performance of the proposed scheduling algorithm in terms of RE tradeoff, the fairness measure of achievable rate (i.e., Jain's index) and harvested energy, through simulations. We also compare the performance of the proposed scheduling algorithm with the conventional scheduling algorithms, such as random scheduling, max SINR scheduling, and α-adaptive scheduling. The random scheduler randomly selects one of the users regardless of any user information. Since there is few processing for scheduling, it has low complexity while the high data rate is not achievable. The max SINR scheduler chooses one user who has the highest SINR value among the users and therefore the network can achieve the highest sum rate. However, the fairness is considerably degraded due to the *doubly near-far* problem [19]. The α-adaptive scheduler is to balance maximizing achievable rate and maximizing harvested energy

$$z_n(t) \triangleq \alpha \left[\frac{|h_n(t)|^2 P}{\sum\limits_{k=1}^{K} |g_{n,k}(t)|^2 P + \sigma_A^2 + \sigma_c^2} \right] + (1-\alpha) \left[\frac{\sum\limits_{n=1}^{N} \left\{ |h_n(t)|^2 + \sum\limits_{k=1}^{K} |g_{n,k}(t)|^2 \right\}}{N \cdot \sigma_{g,\max}^2} \right] \text{ for } \alpha \in [0,1]. \tag{7}$$

of the scheduled user by adjusting the controllable variable α. It also do not fully consider fairness.

A. Fairness Measure of Achievable Rate and Harvested Energy

To evaluate the fairness, we use the concept of Jain's fairness index [20] commonly used as a fairness measure for the acheivable rate. The fairness measure in terms of the achievable rate is given by

$$J_R\left(\overline{R_1}, \cdots, \overline{R_N}\right) = \frac{\left(\sum\limits_{n=1}^{N} \overline{R_n}\right)^2}{N \cdot \sum\limits_{n=1}^{N} \overline{R_n}^2}, \tag{9}$$

where $\overline{R_n}$ is the average achieved data rate of user n.

Similarly, the fairness measure in terms of the harvested energy is given by

$$J_Q\left(\overline{Q_1}, \cdots, \overline{Q_N}\right) = \frac{\left(\sum\limits_{n=1}^{N} \overline{Q_n}\right)^2}{N \cdot \sum\limits_{n=1}^{N} \overline{Q_n}^2}, \tag{10}$$

where $\overline{Q_n}$ is the average harvested energy of user n.

It is worth to note that the value of fairness measure ($\mathcal{J}$) ranges from $1/N$ to 1. When the value of fairness measure approaches $1/N$ (i.e., $\mathcal{J} \to 1/N$), it represents that resources are unfairly utilized to only one user. On contrary to this, we consider that resources are fairly utilized for all users if $\mathcal{J} \to 1$.

B. Simulation Environment

In this paper, we consider an indoor environment operating in the ISM band at a center frequency of 915 MHz, a bandwidth of 26 MHz, and a noise spectral density of -174 dBm/Hz, i.e., the noise power $\sigma_A^2 = -99$ dBm that are same as [14]. Also, we assume the conversion noise $\sigma_c^2 = -32$ dBm. The indoor path loss model in [21] is adopted with a path loss exponent of 2.76.

$$P_L(d) = 31.7 + 27.6 \log\left(\frac{d}{d_0}\right) [dB], \tag{11}$$

where $P_L(d)$ is the path loss at distance d in dB, d is a distance between a transmitter and a receiver, and d_0 is a reference distance.

In the indoor environment, we consider 8 users and 4 interfering BSs, i.e., $N = 8$ and $K = 4$. The cell range of home BS is set to 5 m, and the users are randomly deployed within the cell range. Also, the interfering BSs are uniformly

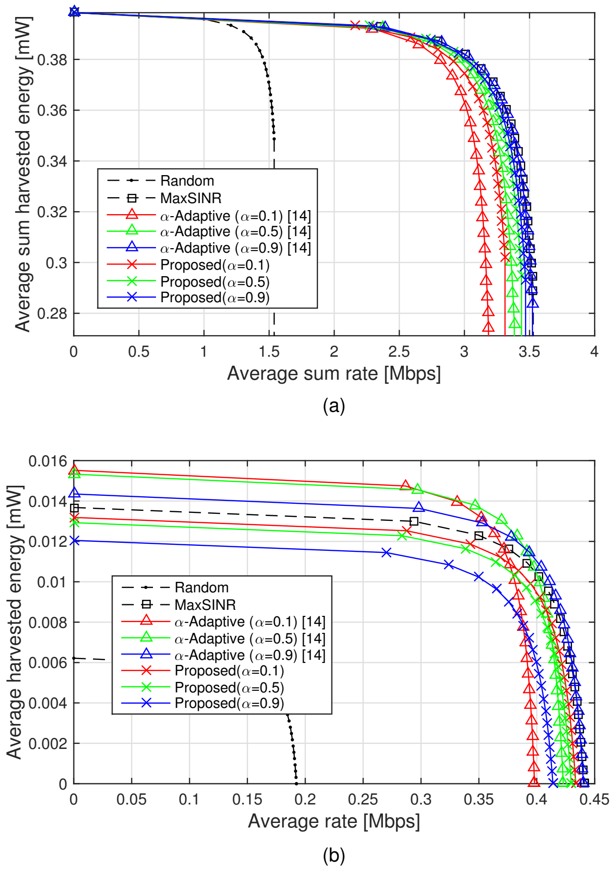

Fig. 3. R-E tradeoff region of (a) the entire network, (b) the scheduled user

distributed with a constant distance of 15 m from the home BS. As we consider 4 interfering BSs, the distance between interfering BSs is $15\sqrt{2}$ m. The transmit power of BSs is set to be 1 W, i.e., $P = 1$ W.

C. Numerical Results

Based on the above simulation environment, Fig. 3 describes the random scheduling, max SINR scheduling, and α-adaptive scheduling [14], including the proposed α-PF scheduling. The RE tradeoff region of the entire network is illustrated in Fig. 3 (a). When $\rho = 0$, the users cannot achieve the rate from the received signals, because the total received signals are used for EH. Therefore, the maximum energy can be harvested with zero data rate regardless of the scheduling schemes. In the other region except for $\rho = 0$, the random scheduling shows lower achievable sum rate than the others. In

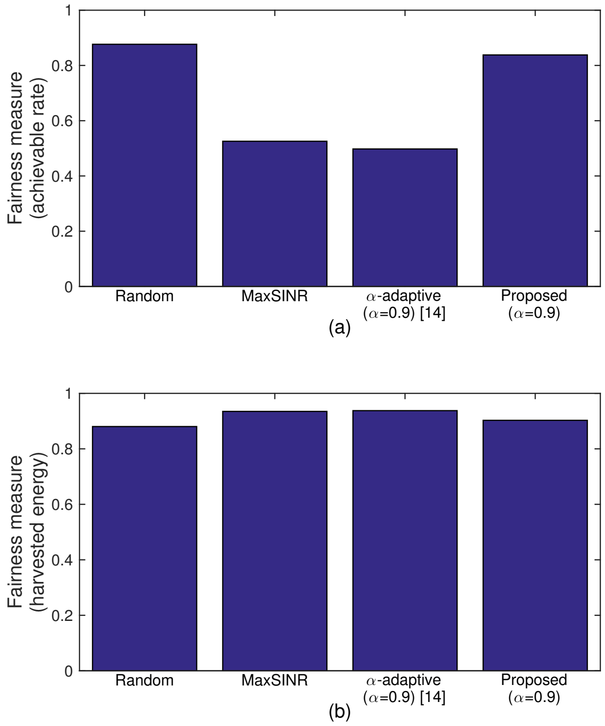

Fig. 4. (a) fairness measure of achievable rate (Jain's index), (b) fairness measure of harvested energy, when $\alpha = 0.9$

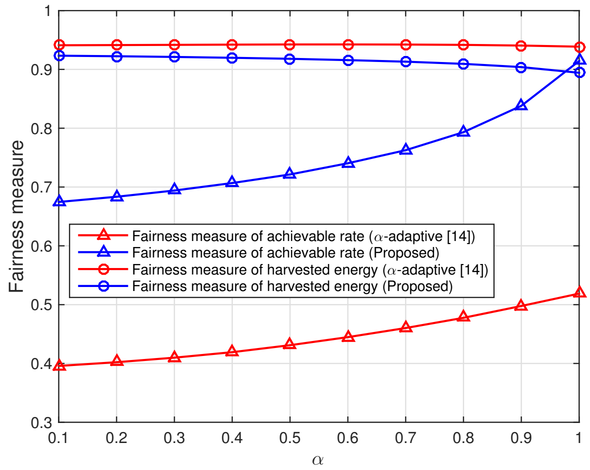

Fig. 5. Fairness measure in terms of achievable rate and harvested energy of the α-adpative scheduling algorithm and the proposed α-PF scheduling algorithm

the α-adaptive scheduling, the scheduling criterion is same as that of max SINR scheduler, when $\alpha = 1$. Therefore, the RE region of max SINR is similar to that of α-adaptive scheduling by increasing α. Since not only interference signals but also the desired signal can be exploited for EH in SWIPT, the max SINR scheduler shows the best achievable rate and EH performance among the various schedulers. However, the max SINR scheduler cannot guarantee the fairness performance among the users. Fig. 3 (b) shows the RE tradeoff region of the scheduled user. The results of RE region according to the scheduling schemes are similar to Fig. 3 (a). When $\alpha = 0.1$, the proposed α-PF scheduler shows the best RE performance compared to RE of the proposed scheduler with different values of α.

Fig. 4 depicts fairness measure in terms of achievable rate and harvested energy. In Fig. 4 (a), the α-PF scheduler shows better fairness measure than the max SINR, and α-adaptive scheduler of 59.5% and 68.4%, respectively, when $\alpha = 0.9$. Since the max SINR and α-adaptive scheduler select a user with the highest SINR and the highest utility consisted of SINR and harvested energies, the *doubly near-far* problem can have a serious impact on fairness in practice. The fairness index of harvested energy of α-PF scheduler is 3.87% lower than that of the α-adaptive scheduler, as shown in Fig. 4 (b). Since all users have EH ability and they can harvest the energy regardless of whether they are scheduled or not, each fairness index in energy aspect of the scheduling schemes has similar results.

Fig. 5 illustrates the fairness measures of the α-adaptive scheduler and the proposed α-PF scheduler when $\rho = 0.5$. Compared to the α-adaptive scheduler, the average fairness measure of achievable rate for α is improved by 69.1% and the average fairness measure of harvested energy for α is reduced by 3.34%. In addition, for all α and ρ, the average fairness measure of achievable rate is improved by 40.8% and the average fairness measure of harvested energy is degraded by 2.9%. Therefore, we show that the proposed α-PF scheduler greatly improves the fairness between users for achievable rate without significant degradation of other performance.

VI. Conclusion

In this paper, we proposed an adaptive proportional fairness scheduling algorithm, called α-PF scheduling, for simultaneous wireless information and power transfer (SWIPT)-enabled multi-cell downlink networks. we modified the existing α-adaptive scheduling algorithm for improving fairness of the achievable rate of users. By controlling α, the proposed scheduling algorithm can achieve various performance requirements flexibly. Through extensive simulations, we evaluated the performance of the proposed α-PF scheduling algorithm in terms of rate-energy tradeoff, achievable rate, harvested energy, and fairness among users. It was shown that the proposed scheduling algorithm significantly improve the fairness of achievable rate among users without much degradation of achievable sum-rate of the network. As a further study, we will mathematically analyze the fairness, achievable rate, and harvested energy of the SWIPT-enabled multi-cell downlink networks with the proposed scheduling algorithm.

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