On the Effect of Proportional Fairness in Energy Transfer for Wireless Powered Communication Networks

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***Abstract*—Wireless powered communication network (WPCN) is an emerging area of research where energy is transferred from the access point to the mobile terminals in the downlink and information is transferred in the uplink. In the context of WPCN, we study the effects of applying different downlink/uplink scheduling schemes on the system performance in terms of achieved system throughput and fairness. In contrast to conventional wireless networks, where data scheduling determines the system sum rate and fairness behaviour, downlink energy scheduling contributes equally in WPCNs. We propose fairness based downlink energy transfer and compare different combinations of downlink and uplink scheduling schemes. Furthermore, we propose a new metric for downlink energy transfer for the special case of finite energy buffer and evaluate its effect on the achieved system throughput and fairness. Our numerical results show that a complete throughput fairness cannot be achieved as long as fairness is not employed in energy transfer in downlink regardless of the uplink scheduling scheme.**

***Index Terms*—Proportional fair scheduling, wireless powered communication networks, energy harvesting, SWIPT.**

I. Introduction

Energy harvesting wireless communication has attracted a lot of research interest recently. Wireless sensor networks are one of the first applications of energy harvesting communication where energy harvested from the natural sources is used to prolong network life time [1]. Energy harvesting solutions have been applied to cellular networks, relay networks and cognitive radios in different settings, e.g., see [2]–[4].

Energy harvesting sources can be classified as deterministic or stochastic depending on the availability of the information about energy arrivals and can be modeled using different techniques such as Markov chain. Energy can also be harvested from radio frequency (RF) signals where energy arrival process is stochastic; but depends on channel distribution. Simultaneous wireless information and power transfer (SWIPT) is a promising technique to allow energy harvesting and information transfer from the RF signals [5]. SWIPT is performed using time sharing or power splitting techniques. Power splitting extracts information and harvest energy from the RF signal simultaneously by splitting power from the same RF signal, while time sharing dedicates a proportion of the time for energy harvesting and information retrieval [6].

Different communication schemes for energy harvesting systems have been addressed in literature in different settings. In [7], the authors study transmission completion time minimization problem where energy harvesting instants are known offline.

On one side, sum rate maximization is desirable by system point of view, e.g., Ju *et al*. propose a protocol termed "harvest-then-transmit" in [8], where wireless energy is broadcasted by the hybrid access point (AP) to all the users in the downlink. Then, the users send their independent information to the hybrid AP in the uplink using their individually harvested energy by time-division-multiple-access. The authors mainly focus on maximizing the uplink throughput of the wireless powered communication network by optimally allocating the time for the downlink wireless energy transfer by the AP and the uplink wireless information transmissions by different users. The solution of this problem reveals an interesting new phenomenon in the wireless powered communication networks termed as "doubly near-far". On one side, a far user receives less amount of wireless energy from the AP than a nearer user in the downlink and on the other side, it has to transmit with more power in the uplink for achieving the same information rate. It occurs due to doubly distance-dependent signal attenuation in both the downlink and the uplink. The authors propose a new performance metric referred to as *common-throughput* to overcome the doubly near-far problem. This metric consists of an additional constraint which indicates that all the users should be allocated an equal rate in their uplink wireless information transfers without considering the distance to the hybrid access point. This work has been extended to the case of multi-antenna systems in [9]. A similar work in [10] maximizes the transferred power to the users in downlink for a signal to noise and interference constraint for the multi-antenna settings.

On the other hand, maintaining fairness among the users is one of the goals for the network design and there is a tradeoff between rate maximization and fairness. Proportional fair scheduler (PFS) has been proposed to address this tradeoff in conventional wireless networks [11] and has been discussed in [12] for energy harvesting communications. The authors in [13] analyze the tradeoff between the users' capacity and the amount of energy transferred simultaneously in downlink.

In this work, we follow the system settings in [8] with the difference that the AP beamforms RF signals in downlink transmission using a single input single output (SISO) model[1]. In uplink transmission, a single user is selected for data transmission. Based on SISO system model, we study 'doubly near-far' problem and evaluate the throughput and fairness performance for the system using 'double proportionally fair' (DPF) criterion, i.e., the user selection on both the uplink and the downlink is made based on the proportional fairness criterion. The complete fairness can only be achieved by DPF at the cost of reduction in system sum rate. We evaluate the proposed scheme for the cases of finite and infinite energy buffer and show that PFS applied to uplink for data transmission solely cannot achieve certain fairness points.

The rest of the paper is organized as follows. Section II introduces system model used in this work. We discuss the proposed framework in Section III. The numerical results related to our scheme are presented in Section IV and we conclude with the summary of the main contributions of the work in Section V.

II. System Model

We consider a multiple access system with K users uniformly distributed in a single cell. The users are hybrid nodes with the ability to harvest energy and information from the RF signals. The AP is located at the center of the cell. Time is slotted such that the length of every slot is normalized to one. For simplicity, we assume a SISO scenario with both AP and the users equipped with a single antenna. In the downlink transmission, the AP beamforms (a random) signal to a single user which harvests energy from the RF signal as shown in Fig. 1. The users are equipped with a storage battery to store the harvested energy.

We assume block fading model on both downlink and uplink, i.e., the fading remains constant for the length of one time slot, but independently and identically distributed (iid) between the time slots and across the users. The users also experience long term path loss where each user is placed at a distance d.

All the users are assumed to be backlogged, i.e., have always data available for transmission. In contrast to [8], where the length of the time slot has been optimized for energy harvesting and making a transmission, we assume that even time slots are dedicated for downlink energy transfer and odd time slots are reserved for uplink data transmission where T is normalized to unity. Thus, the energy harvested by the selected user at downlink is given by

$$E_k^h(t) = \frac{\eta P |g_k|^2}{d^{\alpha_1}} \ , \tag{1}$$

where P is the fixed power transmitted by AP and $0 \leq \eta \leq 1$ is energy harvesting efficiency from the RF signal. g_k denotes downlink fading channel coefficient between the AP and the scheduled user k while α_1 is the path loss exponent for

[1]MISO beamforming improves energy transfer without changing the results. We consider SISO in this work to focus on the main idea.

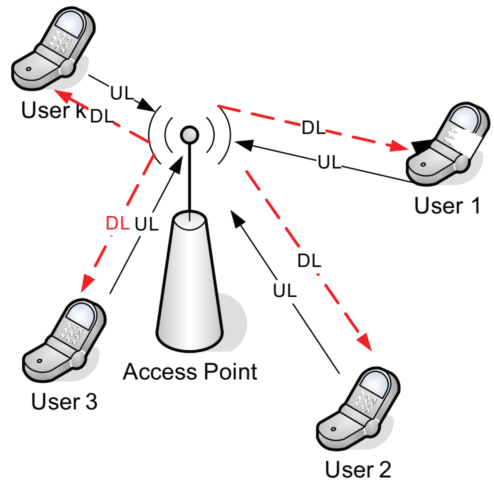


Fig. 1. The schematic diagram for the system model. Energy is transferred from the AP to the users in downlink and data is transmitted in uplink.

downlink. It is assumed that the channel state information (CSI) is known at AP for the downlink energy transfer and also at the users for uplink information scheduling.

At uplink, a single user is scheduled for transmission. The received signal for the scheduled user is given by

$$y = hx + n \ , \tag{2}$$

where h is the channel gain, x is channel input and n is Gaussian random noise with zero mean and unit variance.

The transmit power is not fixed for every scheduled user. Depending on the stored energy, it differs between the power generated from the stored energy at time slot t and the peak power constraint P_u. For the peak power constraint P_u, the rate $R_k(t)$ for the scheduled user is given by,

$$R_k(t) = \log_2\left(1 + \frac{\min(P^{\text{st}}, P_u)|h_k(t)|^2 d^{-\alpha_2}}{N_0}\right) \tag{3}$$

where P^{st} denotes the power from the battery with stored energy E^{st} which remains identical as $T = 1$. N_0 is additive white Gaussian noise power and α_2 is path loss exponent for uplink. For convenience, we assume α_1 and α_2 to be identical in this work. Thus, the rate not only depends on the uplink channel for user k, but also at the stored energy.

The average throughput $T_k(t)$ of a user k up to time slot t is defined as

$$T_k(t) = \lim_{t \to \infty} \frac{1}{t} \sum_{j=1}^{t} R_k(j) \ . \tag{4}$$

The system throughput is computed by normalizing the users' sum rate with the number of users.

To measure the fairness in resource allocation among different users, different criteria are used in literature, e.g. max-min fairness, variance, etc. We use a similar criterion, called Jain's fairness index, to compare the fairness of different schemes in this paper. Jain's index is mathematically defined as [14],

$$F = \frac{\left(\sum_{k=1}^{K} T_k\right)^2}{K \sum_{k=1}^{K} (T_k)^2} \tag{5}$$

The higher the Jain's fairness index, the more fair the scheme is.

III. Double Proportionally Fair Scheme (DPF)

We propose a scheme to deal with "doubly near-far" problem presented in [8]. In the downlink, energy harvesting (EH) is maximized if the user with the best channel is scheduled for EH. However, the probability that a user close to the AP has a better channel as compared to the user at the cell edge is much higher. Therefore, the users at the cell edge will not have energy to capitalize good channel for uplink transmission when scheduled for information transfer.

We propose a double proportionally fair scheme in this work. In the downlink energy transmission, a user is scheduled for energy transfer from the AP such that

$$k^* = \arg\max_k \frac{E_k^h(t)}{E_k^{\text{st}}(t)} \tag{6}$$

where $E_k^h(t)$ and $E_k^{\text{st}}(t)$ represent the harvested and stored energy for user k at time t, respectively. This metric is termed as fair energy transfer (FET) in rest of this paper. The stored energy for the scheduled user k^* is updated as

$$E_k^{\text{st}}(t) = E_k^{\text{st}}(t-1) + E_k^h(t), \quad k = k^* \tag{7}$$

where $E_k^h(t)$ is given by (1). For all the other users, $E_k^h(t) = 0$ and the stored energy remains the same as we assume no leakage in stored energy with time. The capacity of the battery is assumed to be infinite.

As a reference scenario, we consider the case when downlink energy transfer is scheduled such that

$$k^* = \arg\max_k E_k^h(t) \ . \tag{8}$$

We denote this criterion by maximum energy transfer (MET) in the rest of this paper. At system level, the downlink energy scheduling by (8) further deteriorates the performance of the users at the cell edge who suffer from the near far phenomenon.

Assuming a fully backlogged system at uplink, a user is scheduled following the PFS scheme such that

$$k^* = \arg\max_k \frac{R_k(t)}{T_k(t)} \ . \tag{9}$$

A. Finite Energy Buffer

In this section, we assume that the energy buffer for the users is finite. If the energy buffer for the users is finite, (6) is modified as,

$$k^* = \arg\max_k \frac{E_k^{\text{eff}}(t)}{\acute{E}_k^{\text{st}}(t)} \tag{10}$$

where $E_k^{\text{eff}}(t)$ is given by

$$E_k^{\text{eff}}(t) = \begin{cases} E_k^h(t) & \frac{E_k^h(t)+E_k^{\text{st}}(t-1)}{E_m} \leq 1 \\ E_m - E_k^{\text{st}}(t-1) & \frac{E_k^h h(t)+E_k^{\text{st}}(t-1)}{E_m} > 1 \end{cases} \tag{11}$$

and,

$$\acute{E}_k^{\text{st}}(t) = \min\left(E_k^h(t) + E_k^{\text{st}}(t-1), E_m\right) \tag{12}$$

with $\acute{E}_k^{\text{st}}(t)$ denoting the stored energy for a finite battery with capacity E_m in Joules.

The rational behind (11) is to have a 'fair' competition between the users for energy reception. For example, if a scheduled user has a very good downlink channel, but the battery is almost full, the user will not be able to make full use of the channel. Thus, the effective useful energy harvested by the user is given by (11) and the user should compete with other users on the effective energy metric. Following the same line of arguments, the $E_k^h(t)$ metric in (8) is also replaced by $E_k^{\text{eff}}(t)$ in (11) for the MET case.

For the uplink, PFS and Maximum throughput scheduling (MTS) [15] are applied. MTS schedules the user with the best instantaneous channel, regardless of the history while PFS schedules the user with the best channel normalized by its throughput. For the downlink energy transfer, maximum energy transfer based rule in (8) or (energy) proportional fairness based rule in (6) are studied.

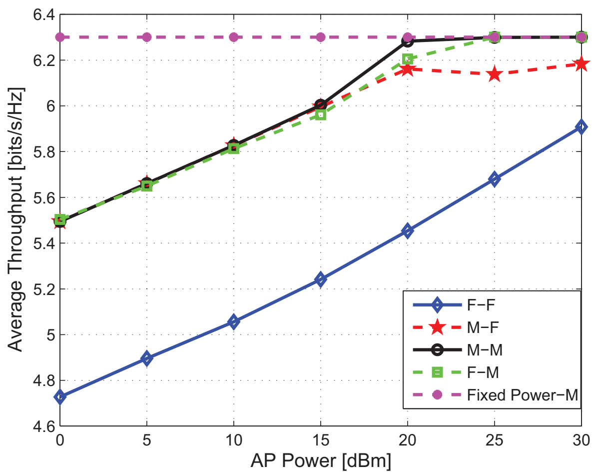
Based on the combinations of the mentioned uplink and downlink scheduling schemes, we define the following scenarios for numerical evaluation.

1) Max-downlink-Fair-uplink (M-F), where MET is applied at downlink while PFS is applied at uplink.
2) Max-downlink-Max-uplink (M-M), where MET is applied at downlink while maximum throughput scheduling (MTS) is applied at uplink.
3) Fair-downlink-Max-uplink (F-M), where FET is applied at downlink while MTS is applied at uplink.
4) Fair-downlink-Fair-uplink (F-F), where FET is applied at downlink while PFS is applied at uplink. This scenario is referred to as DPS in this paper.

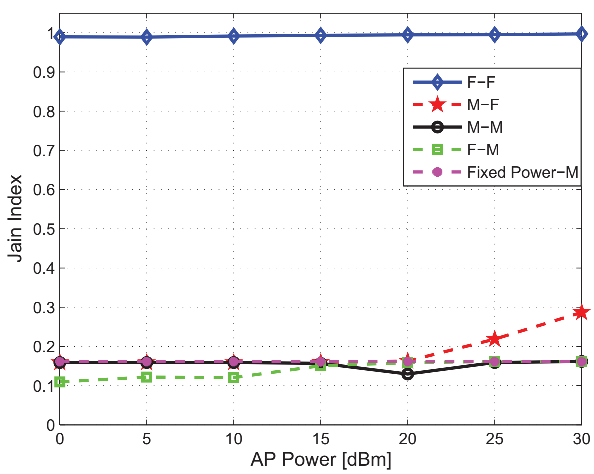
IV. Numerical Results and Discussion

For the above mentioned scenarios, we compute average system throughput and corresponding Jain's fairness index. First, we study the effect of our scheme on both achieved throughput and fairness index. Then, we apply finite buffer size constraint and evaluate the performance for our modified metric.

We assume that 10 users are distributed around the AP such that the nearest user is at a distance of $d = 0.5$ m and the farthest user is at $d = 5$ m. The other users are placed at equal spacing of 0.5 m between $[0.5\ 5]$ m. Path loss exponents α_1 and α_2 for both uplink and downlink transmissions are identical and equal 2. We assume iid rayleigh fading channel with unit mean for uplink and downlink where uplink (data) and downlink (energy) transmissions are performed in orthogonal time slots. Note that data can also be transferred along with energy on downlink using MISO or MIMO techniques as in [10], but we consider the simplified scenario where only energy is transferred on downlink to focus on the interaction of uplink and downlink scheduling schemes. For the numerical evaluations, we assume white noise power spectral density of

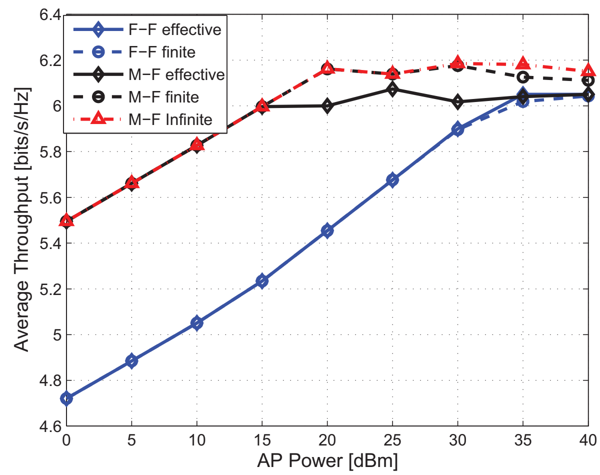


(a) Throughput vs AP Power



(b) Jain Index vs AP Power

Fig. 2. Throughput and Jain index comparison for different AP transmit power for different uplink and downlink scheduling scenarios.



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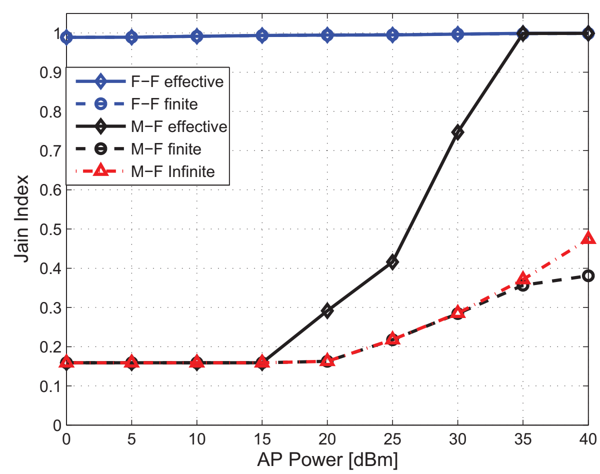

(b) Jain Index vs AP Power

Fig. 3. Throughput and Jain's index comparison for different AP transmit power for different uplink and downlink scheduling scenarios when battery capacity is finite and equals 2 Joules. For reference, the curves for M-F infinite case are plotted as well.

160 dbm/Hz while energy harvesting efficiency at the receiver η equals 0.8. The results are averages over 50,000 numerical simulations. The peak uplink power is set to 25 dbm.

Fig. 2 shows the comparisons of four scenarios described in Section III in terms of achieved throughput and Jain's index. As shown in Fig. 2(a), the throughput increases with increasing AP downlink transmit power. The throughput for all scenarios saturate at high AP power due to peak power constraint of 25 dbm. Different scenarios achieve this saturation at different AP power levels. The saturation is fast when downlink energy transfer is based on MET. Throughput for M-M scenario is higher than M-F scenario due to use of MTS at uplink but the opposite holds for fairness. For the baseline scenario, we plot the case when the users are connected to power supply and use MTS at uplink with a fixed uplink power 25 dbm. It is clear that both the scenarios which use MTS at uplink converge to this baseline case at high AP power and saturate afterwards.

The corresponding Jain's index for all the scenarios is plotted in Fig. 2(b). The F-F scenario (DPF) shows the highest fairness among all the scenarios at the cost of reduced throughput while Jain's index for all other scenarios is quite low. It is interesting to note that M-F scenario also shows poor fairness in spite of using PFS at uplink. We conclude from this comparison that overall fairness performance is more dominant by the downlink energy scheduling. If downlink energy transfer is not fair, rate fairness cannot be achieved regardless of the uplink rate scheduling scheme.

Fig. 3 compares the performance of different scenarios when battery capacity for the nodes is finite. For the finite storage capacity case when the stored energy is updated by (12), we distinguish two cases.

- The battery capacity is finite but the metric for down-

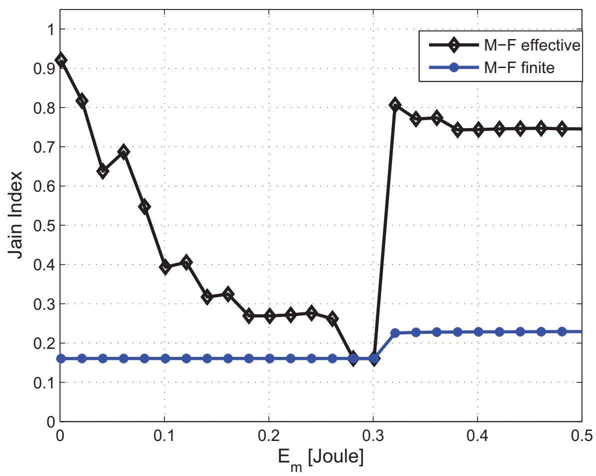

Fig. 4. The effect of buffer size on fairness for fixed downlink and uplink peak uplink powers. The downlink power is fixed to 30 dbm.

link energy transfer scheduling is based on $E_k^h(t)$. This implies that energy transfer process is transparent of the battery storage state and its capacity. We denote this case by appending 'finite' to the scenario.

- The battery capacity is finite and the metric for downlink scheduling is based on effective harvested energy, stored energy $\acute{E}_{\rm st}$ and maximum battery capacity via (11). We append 'effective' to the the scenario to denote it.

As a reference scenario, we include the curves for the infinite battery cases as well. Uplink scheduling scheme is fixed to PFS and we study the effect of finite energy buffer on the downlink energy transfer. We find no visible performance difference in terms of both throughput and fairness for finite or infinite cases for the 'F-F' scenario. When finite buffer constraint is applied to 'M-F' case, the difference is visible. As shown in Fig. 3(b), the fairness for the M-F effective case improves enormously as compared to other cases and it actually shows the same performance as 'F-F' scenario at AP power 35 dbm. Thus, the improved metric in (11) helps to enforce fairness regardless of the downlink energy transfer scheme. On the other side, the throughput for the M-F finite case is lower than M-F infinite case at high AP power due to waste of energy courtesy of finite buffer size as shown in 3(a). As M-F finite still applies the E_k^h metric without looking at the stored battery, some of the users scheduled for energy are not able to store the harvested energy and it is wasted.

We illustrate the effect of energy buffer limit on the fairness behaviour of the schemes in Fig. 4. In general, 'M-F finite' scheme is marginally affected by energy buffer size in terms of fairness. When effective metric is applied, the fairness decreases with the increase in energy buffer capacity in the beginning. At buffer size $E_m \simeq 0.3$, there is a sharp increase in fairness. Afterwards, Jain's index remains constant for increasing buffer size. This behaviour is explained as follows. At small energy buffer size, the near users are more affected by the lack of energy storage capacity as the harvested energy is wasted and they are not able to schedule a lot of data at uplink when scheduled. As the storage capacity increases, the users harvest more energy and throughput for the near users increases. However, fairness index decreases correspondingly as mismatch between the energy distribution of the near and far users increases while the metric in (11) does not help as $E_h > E_m$ mostly for the near users. At 0.3 Joule, the battery capacity becomes large enough that metric in (11) becomes fully effective and helps to increase Jain's fairness index. A further increase in buffer size does not help to increase fairness. It should be noted that value of $E_m \simeq 0.3$ depends at the downlink AP transmit power and uplink peak power constraint and a change in the powers shifts the transition point.

V. Conclusions

In this work, we address downlink energy transfer scheduling mechanism for wireless powered communication networks. We study 'double near-far' problem and propose proportional fairness based energy transfer at downlink. Through numerical evaluation, we show that regardless of the scheduling mechanism used for data transmission at uplink, throughput fairness cannot be achieved if the energy transfer is not fair. Then, we extend our framework to finite energy storage case and propose a modified metric for the downlink energy transfer. The modified metric provides better fairness even if the best channel based energy transfer rule is employed at downlink and achieves the same performance as the fair energy transfer rule at high AP power levels.

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