Energy-Efficient Transmission for Wireless Powered Multiuser Communication Networks

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***Abstract*—This paper considers wireless powered communication networks (WPCN). Our goal is to investigate the maximum network energy efficiency (EE) by joint time allocation and power control while taking account the initial battery energy level of each user. It is shown that the EE maximization problem for the WPCN can be cast into the EE maximization problems for two independent networks, i.e., purely wireless powered communication networks (PWPCN) or initial energy limited communication networks (IELCN). For the PWPCN, we find that: 1) in the wireless energy transfer (WET) stage, the power station always transmits with its maximum power; 2) it is not necessary for all users to transmit signals in the wireless information transmission (WIT) stage, but all scheduled users will deplete all of their energy; 3) the maximum system EE can always be achieved by exhausting all the available time. Based on these observations, we derive a closed-form expression for the system EE based on the user EE, which transforms the original problem into a user scheduling problem that can be solved efficiently. While for the IELCN, we reveal that the most energy-efficient transmission strategy is to only schedule the user who has the highest user EE. Simulation results validate our theoretical findings and demonstrate the effectiveness of the proposed scheme.**

I. Introduction

Wireless energy transfer techniques have drawn significant attention because of their capability to prolong the lifetime of wireless networks, especially for energy-constrained scenarios [1], [2]. There are basically two lines of research in this field. An earlier line of research focuses on simultaneous wireless information and power transfer (SWIPT) which has been investigated in various scenarios [3], [4]. Another related line of research aims at a paradigm shift on wireless networks, known as wireless powered communication network (WPCN) [5]. Specifically in [5], the energy transfer time and the information transmission time are jointly optimized to maximize the system throughput. Note that all the above works on energy transfer focus on improving the system throughput only.

Recently, *green-oriented technologies* have inevitably become the design components of future communication systems due to the rising energy costs and tremendous carbon footprints [6]. Energy efficiency (EE) defined as bits per joule has been accepted gradually as an important green indicator of practical systems. However, few works investigate the energy efficiency of energy transfer. The authors in [7] study the energy-efficient resource allocation for orthogonal frequency division multiple access (OFDMA) systems employing SWIPT. However, the conclusions and proposed methods in [7] are not applicable to the WPCN scenario due to the fundamental differences between these two systems. To our best knowledge, the energy efficiency of WPCN has not been investigated in the literature and designing energy-efficient transmission is also crucial to transforming the green concept into future communication systems.

In this paper, we consider a WPCN where multiple users harvest energy from a power station and then transmit signals using the harvested energy to a receiving station. The difference between this work and [5] is three-fold. First, the receiving base station in our system model does not need to be co-located with the power station and hence the near-far problem that appeared in [5] is naturally solved. Second, each user is allowed to store redundant energy harvested from the current transmission block which shall provide higher flexibility for the energy utilization. Third, we aim to maximize the system energy efficiency while guaranteeing the quality of service instead of only maximizing the system throughput

We formulate the EE maximization problem for multiuser WPCN with joint time allocation and power control while taking account the initial battery energy level of each user. Moreover, the circuit energy consumption of the power station and user terminals is explicitly considered. In particular, we reveal that the energy-efficient WPCN can be directly cast into either initial energy limited communication networks (IELCN) or purely wireless powered communication networks (PWPCN). By exploiting the special structure of the problem, we derive the optimal solution and provide the corresponding physical interpretation for each network.

II. Preliminaries

A. System Description

We consider a WPCN, as illustrated in Fig. 1, which consists of one power station, K wireless-powered users, denoted as U_k, for $k = 1, ..., K$, and one receiving base station, which can be or not be co-located with the power station. The "harvest and then transmit" protocol is employed for this network [5], i.e. all users first harvest energy from the RF signal sent by the

This work is supported by the National 973 Project #2012CB316106, by NSF China #61328101 and #61322102, by the STCSM Science and Technology Innovation Program #13510711200, by the SEU National Key Lab on Mobile Communications #2013D11.

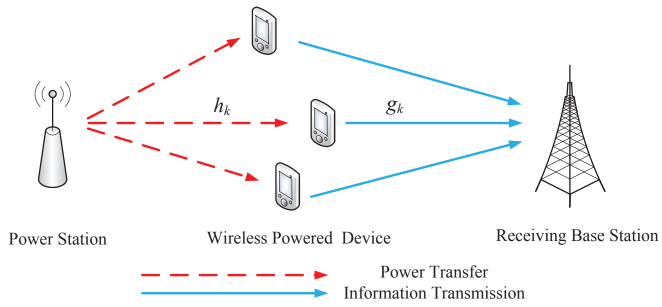

Fig. 1. The system model of a wireless powered multiuser communication network.

power station, referred to as downlink (DL), and then transmit the information signal to the receiving base station, referred to as uplink (UL). It is assumed that the power station and all users operate in the time division manner over the same frequency band for the ease of implementation. Without loss of generality, we also assume that U_k, for $k = 1, ..., K$, is configured with a rechargeable battery built-in with an initial energy level of Q_k, which may be the energy stored from previous transmission blocks and can be used for WIT in this transmission block.

Assume that both DL and UL channel are quasi-static block fading, where the channel coefficient remains constant during each block, but can vary from one to another. The DL channel gain between the power station A and user terminal k, and the UL channel gain between user terminal k and the receiving base station are denoted as h_k and g_k, respectively. We also assume that the power station can obtain perfect and global channel state information (CSI) through a dedicated channel so as to explore the EE upper bound of WPCN.

During the WET stage, the power station broadcasts the energy signal, denoted as x_0, which represents an arbitrary complex random signal. The corresponding transmit power is denoted as P_0, i.e. $E[|x_0|^2] = P_0$, and the transmission time is τ_0. Then the received signal y_k at U_k can be expressed as

$$y_k = \sqrt{h_k} x_0 + n_k, \qquad k = 1, \cdots K, \tag{1}$$

where n_k is the additive white Gaussian noise at U_k. Generally, the harvesting receiver at each user terminal will harvest energy from the whole signal. However, since the noise is negligible compared with the energy signal with large transmit power, and is thereby omitted in the harvested energy. Thus, the amount of energy harvested at U_k can be expressed as

$$E_k^h = \eta \tau_0 P_0 h_k, \qquad k = 1, \cdots K, \tag{2}$$

where $\eta \in (0, 1]$ is the energy conversion efficiency depending on the type of the receiver.

During the WIT stage, each user transmits its independent information signal x_k to the base station in a time division manner and the corresponding transmit power is denoted as p_k, i.e., $E[|x_k|^2] = p_k$. Then, at the receiving base bastion side, the signal from U_k can be expressed as

$$y_k^b = \sqrt{g_k} x_k + z_k, \tag{3}$$

where z_k represents the additive white Gaussian noise for x_k with zero mean and variance σ^2. Denote the information transmission time of user k as τ_k. Then, the achievable throughput of U_k can be expressed as

$$B_k = \tau_k W \log_2 \left(1 + \frac{p_k g_k}{\Gamma \sigma^2}\right), \tag{4}$$

where W is spectrum bandwidth of the considered system and Γ characterizes the gap between the achievable rate and the channel capacity due to a practical modulation and coding design. In the sequel, we use $\gamma_k = \frac{g_k}{\Gamma \sigma^2}$ to denote the the normalized channel gain in WIT. Thus, the total throughput of the WPCN, denote as B_{tot}, is given by

$$B_{\text{tot}} = \sum_{k=1}^{K} B_k = \sum_{k=1}^{K} \tau_k W \log_2(1 + p_k \gamma_k). \tag{5}$$

B. Power Consumption Model

The total energy consumption of WPCN consists of two parts: the energy consumed in WET and WIT, respectively. For each part, we adopt the similar energy consumption model as used widely in [7]–[10], namely, the power consumption of a transmitter includes not only the over-the-air transmit power but also the circuit power consumed by hardware processing.

During the WET stage, the system energy consumption, denoted as E_{WET}, is modeled as

$$E_{\text{WET}} = P_0 \tau_0 - \sum_{k=1}^{K} E_k^h + P_c \tau_0, \tag{6}$$

where the P_c is the circuit power of the power station. Note that $P_0 \tau_0 - \sum_{k=1}^{K} E_k^h$ is the energy loss due to channel propagation. In practice, it is always positive due to the law of energy conservation, and the non-ideal energy conversion efficiency. The third term $P_c \tau_0$ represents the energy consumed for circuits of the power station.

During the WIT stage, each user independently transmit its own signal with the transmit power p_k and the time τ_k. Thus, the energy consumed by U_k can be modeled as

$$E_k = p_k \tau_k + p_c \tau_k, \tag{7}$$

where p_c is the circuit power of the user terminal, and is assumed to be same for all users. Noth that E_k should satisfy $E_k \leq E_k^h + Q_k$, which is known as the energy causality constraint in energy harvesting systems.

Therefore, the total energy consumption of the whole system, denoted as E_{tot}, is given by

$$E_{\text{tot}} = E_{\text{WET}} + \sum_{k=1}^{K} E_k. \tag{8}$$

C. User Energy Efficiency

In our previous work, we introduced the concept of user EE and it was shown to be highly connected with the system EE. In this subsection, we review the definition of user EE in the context of WPCN.

Definition 1 (User Energy Efficiency): The EE of user k, for $k = 1, .., K$, is defined as the ratio of its achievable throughput over its consumed energy in the WIT stage, i.e.,

$$ee_k = \frac{\tau_k W \log_2(1 + p_k\gamma_k)}{\tau_k p_k + \tau_k p_c} = \frac{W \log_2(1 + p_k\gamma_k)}{p_k + p_c}, \qquad (9)$$

where the energy consumption includes both the transmit energy and the circuit energy.

The user EE ee_k is a strictly quasiconcave function of p_k and it is easy to prove that this fractional type function has the stationary point which is also the optimal point. Thus, by setting the derivative of ee_k with respect to p_k to zero, we obtain that the optimal power and the optimal user EE satisfies

$$p_k^\star = \left[\frac{W}{ee_k^\star \ln 2} - \frac{1}{\gamma_k}\right]^+, \forall\, k, \qquad (10)$$

where $[x]^+ \triangleq \max\{x, 0\}$. Based on (9) and (10), the numerical values of $ee_k^\star$ and $p_k^\star$ can be easily obtained by the bisection method [11].

III. Energy-Efficient Transmission For WPCN

In this section, we study the resource allocation in WPCN to maximize the system EE, which is defined by the ratio of the achieved system throughput over the consumed system energy, i.e.,

$$EE = \frac{B_{\rm tot}}{E_{\rm tot}}. \qquad (11)$$

Specifically, our goal is to jointly optimize the *time allocation* and *power control* in the *downlink* and the *uplink* for the EE of considered systems. Then, EE maximization can be formulated as

$$\begin{aligned}
\max_{\substack{\tau_0,\{\tau_k\},\\ P_0,\{p_k\}}} \quad & \frac{\sum_{k=1}^K \tau_k W \log_2(1 + p_k\gamma_k)}{P_0\tau_0(1 - \sum_{k=1}^K \eta h_k) + P_c\tau_0 + \sum_{k=1}^K (p_k\tau_k + p_c\tau_k)} \\
\text{s.t.} \quad & \text{C1: } P_0 \le P_{\max}, \quad \text{C3: } \tau_0 + \sum_{k=1}^K \tau_k \le T_{\max}, \\
& \text{C2: } p_k\tau_k + p_c\tau_k \le \eta P_0 \tau_0 h_k + Q_k, \ \forall\, k, \\
& \text{C4: } \tau_0 \ge 0, \ \tau_k \ge 0, \ \forall\, k, \\
& \text{C5: } P_0 \ge 0, \ p_k \ge 0, \ \forall\, k. \qquad (12)
\end{aligned}$$

In problem (12), constraint C1 imposes the maximum transmit power $P_{\max}$ for the power station in the DL. C2 ensures that the energy consumed for WIT in the UL does not exceed the total available energy which includes both the harvested energy $\eta P_0 \tau_0 h_k$ and the initial energy Q_k. In C3, $T_{\max}$ is the total available transmission time. C4 and C5 are non-negative constraints on time allocation and power control variables, respectively. Note that problem (12) is neither convex nor quasi-convex due to the fractional-form objective function and the non-linear inequality constraints in C2. Generally, there is no standard method for solving non-convex problems efficiently.

A. Equivalent Optimization Problems

First, we show that the EE maximization problem for W-PCN can be cast into two independent optimization problems for two simplified sub-systems. To facilitate the presentation, we define $\Phi_\mathcal{P}$ and $\Phi_\mathcal{I}$ as the set of users whose initial energy levels are zero and strictly positive, i.e., $Q_k = 0$ for $k \in \Phi_\mathcal{P}$ and $Q_k > 0$ for $k \in \Phi_\mathcal{I}$, respectively. The system EE of the WPCN is denoted as EE^*.

Theorem 1: Problem (12) is equivalent to one of the following two problems:

1) The EE maximization in a purely wireless powered communication network (PWPCN) (i.e. all the concerned users in $\Phi_\mathcal{P}$, are solely powered by WET without initial energy available):

$$\begin{aligned}
\max_{\substack{\tau_0,\{\tau_k\},\\ P_0,\{p_k\}}} \quad & \frac{\sum_{k\in\Phi_\mathcal{P}} \tau_k W \log_2(1 + p_k\gamma_k)}{P_0\tau_0(1 - \sum_{k=1}^K \eta h_k) + P_c\tau_0 + \sum_{k\in\Phi_\mathcal{P}} (p_k\tau_k + p_c\tau_k)} \\
\text{s.t.} \quad & \text{C4}, \ \text{C5}, \\
& P_0 \le P_{\max}, \\
& p_k\tau_k + p_c\tau_k \le \eta P_0 \tau_0 h_k, \quad k \in \Phi_\mathcal{P}, \\
& \tau_0 + \sum_{k\in\Phi_\mathcal{P}} \tau_k \le T_{\max}. \qquad (13)
\end{aligned}$$

where $EE^*_{\rm PWPCN}$ is the maximum EE of the WPCN. 2) The EE maximization in an initial-energy limited communication network (IELCN) (i.e. all the concerned users in $\Phi_\mathcal{I}$ are solely powered by the initial energy without harvesting energy):

$$\begin{aligned}
\max_{\{p_k\},\{\tau_k\}} \quad & \frac{\sum_{k\in\Phi_\mathcal{I}} \tau_k W \log_2(1 + p_k\gamma_k)}{\sum_{k\in\Phi_\mathcal{I}} (p_k\tau_k + p_c\tau_k)} \\
\text{s.t.} \quad & \text{C4}, \ \text{C5}, \\
& p_k\tau_k + p_c\tau_k \le Q_k, \quad k \in \Phi_\mathcal{I}, \\
& \sum_{k\in\Phi_\mathcal{I}} \tau_k \le T_{\max}, \quad k \in \Phi_\mathcal{I}. \qquad (14)
\end{aligned}$$

where $EE^*_{\rm IELCN}$ is the maximum EE of the IELCN. If $EE^*_{\rm PWPCN} \ge EE^*_{\rm IELCN}$, then $EE^* = EE^*_{\rm PWPCN}$; otherwise $EE^* = EE^*_{\rm IELCN}$.

Proof: Please refer to Appendix A. ■

Theorem 1 clearly reveals that the EE maximization problem of WPCN with initial stored energy can be reduced to the EE maximization in either of the two simplified systems, i.e., PWPCN and IELCN. In the following, we study the EE as well as characterizing the properties of each system independently.

B. Properties of Energy-Efficient PWPCN

The following lemma characterizes the operation of the power station for energy-efficient transmission.

Lemma 1: In the energy-efficient PWPCN, the power station always transmits with its maximum allowed power, i.e., $P_0 = P_{\max}$, for the WET in the DL.

Proof: Due to space limitation, Lemma 1, 2, and 3 will be put in the journal version of this paper. ■

This lemma seems contradictory to intuition at first thought. In conventional systems, since only the transmit power is optimized, the EE is generally first increasing and then decreasing with the transmit power when the circuit power is taken into account. Yet, in the PWPCN where the transmission time can also be optimized, letting the power station transmit with the maximum allowed power could reduce the allocated time for WET in the DL, and thereby reduce the energy consumed on circuits of the power station. Moreover, it also provides users more time to improve the system throughput during UL WIT.

The following lemma reveals the time utilization for energy-efficient transmission.

Lemma 2: In the energy-efficient PWPCN, the optimal system EE can always be achieved by using up all the available transmission time, i.e.,

$$\tau_0 + \sum_{k\in\Phi_{\mathcal{P}}} \tau_k = T_{\max}. \tag{15}$$

Moreover, the optimal system EE is independent of $T_{\max}$.

Lemma 2 indicates that in the PWPCN, there is only a certain relationship between the energy transfer time and the information transmission time of each user. If the total available time is not completely used up, increasing the time for WET and WIT at the same scale can at least maintain the system EE, while improving the system throughput.

Now, we study how the wireless powered users are scheduled for utilizing their harvested energy for energy-efficient transmission.

Lemma 3: In the energy-efficient PWPCN,
1) if $EE^*_{\mathrm{PWPCN}} < ee^\star_k$, then user k is scheduled, i.e., $\tau^*_k > 0$, and it will use up all of its energy, i.e., $\tau^*_k(p^*_k + p_c) = \eta P_{\max}\tau^*_0 h_k$;
2) if $EE^*_{\mathrm{PWPCN}} = ee^\star_k$, scheduling user k or not does not affect the maximum system EE, i.e., $0 \le \tau^*_k(p^*_k + p_c) \le \eta P_{\max}\tau^*_0 h_k$;
3) if $EE^*_{\mathrm{PWPCN}} > ee^\star_k$, then user k is not scheduled, i.e., $\tau^*_k = 0$, and it preserves all of its energy for the next transmission slot.

Although EE^*_{PWPCN} is still unknown, Lemma 3 reveals an important property related to the user scheduling and the energy utilization: users that are scheduled, should have a better or at least the same energy utilization efficiency as that of the system, and for the strictly better users, utilizing all of their energy can always benefit the system EE.

Remark 1: In [5], which focuses on the throughput maximization problem in the PWPCN, it has been shown that the transmission time of each user increases linearly with the equivalent channel gain. In other words, all users are scheduled no matter how poor their UL channels are. However, for EE oriented systems, it may not be cost effective any more to schedule all users, especially those with weak channels, since they also cause additional circuit energy consumption.

In Lemma 1, 2, and 3, we have successively revealed several basic properties of the EE oriented PWPCN. In the following, we derive the expression of the system EE and also the optimal solution based on properties above.

Theorem 2: In the energy-efficient PWPCN, the optimal system EE can be expressed as

$$EE^* = \frac{\sum_{k\in S^*} ee^\star_k h_k}{\frac{1}{\eta}\left(\frac{P_c}{P_{\max}} + 1 - \sum_{k=1}^{K}\eta h_k\right) + \sum_{k\in S^*} h_k}, \tag{16}$$

where S^* is the optimal scheduled user set. The optimal power and time solution can be expressed as

$$\tau^*_0 = \frac{T_{\max}}{1 + P_{\max}\sum_{k\in S^*}\frac{h_k}{\log_2(\frac{g_k}{ee^\star_k})}}, \tag{17}$$

$$p^*_k = \left[\frac{W}{ee^*_k \ln 2} - \frac{1}{\gamma_k}\right]^+, \tag{18}$$

$$\tau^*_k = P_{\max}\tau_0 \frac{h_k ee^\star_k}{\log_2(\frac{g_k}{ee^\star_k})}. \tag{19}$$

Proof: Please refer to Appendix B . ■

Theorem 2 provides a very clear expression of the system EE by using the user EE and other system parameters. In (16), since $P_{\max}$ and P_c are the maximal allowed transmit power and the circuit power, which are anticipated to be larger and smaller for practical systems, respectively, their ratio $\frac{P_c}{P_{\max}}$ can be interpreted as the inefficiency of the power station. The term $1 - \sum_{k=1}^{K}\eta h_k$ represents the energy loss per unit transmit energy due to wireless channels and non-ideal energy harvesting devices.

Note that $\frac{1}{\eta}\left(\frac{P_c}{P_{\max}} + 1 - \sum_{k=1}^{K}\eta h_k\right)$ only consists of initial system parameters and is thereby a constant. This means that once S^* is given, the optimal solution can be obtained by (16). Therefore, the problem is simplified to finding the optimal user set S^*. In [9], we have proposed an efficient algorithm to tackle a scheduling problem with the similar structure as (16). The details of this algorithm are omitted here and we refer the readers to [9] for more information.

C. Properties of Energy-Efficient IELCN

Theorem 3: Problem (14) is equivalent to the following problem

$$\begin{aligned} \max_{k\in\Phi_{\mathcal{I}}} \ \max_{p_k,\tau_k} \ & \frac{\tau_k W \log_2(1 + p_k\gamma_k)}{p_k\tau_k + p_c\tau_k} \\ \text{s.t.} \ & p_k\tau_k + p_c\tau_k \le Q_k, \quad k\in\Phi_{\mathcal{I}}, \\ & \tau_k \le T_{\max}, \quad k\in\Phi_{\mathcal{I}}, \end{aligned} \tag{20}$$

and the corresponding optimal solution is given by

$$p_k = \begin{cases} p^\star_k, & \text{if } k = \arg\max_{i\in\Phi_{\mathcal{I}}} ee^\star_i, \\ 0, & \text{otherwise}, \ \forall i, \end{cases} \tag{21}$$

$$\tau_k = \begin{cases} (0, \frac{Q_k}{p_k + p_c}], & \text{if } k = \arg\max_{i\in\Phi_{\mathcal{I}}} ee^\star_i, \\ 0, & \text{otherwise}, \ \forall i. \end{cases} \tag{22}$$

Proof: Please refer to Appendix C. ■

Theorem 3 indicates that the optimal transmission strategy of IELCN is to schedule only the user with the highest user EE, i.e., time division multiplexing access (TDMA) is the optimal. Thus, based on Theorem 3, EE^*_{IELCN} can be easily obtained with the introduced user EE in Section II-C.

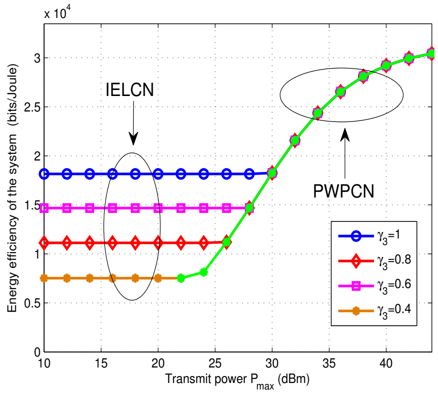

Fig. 2. System switching from PWPCN to IELCN.

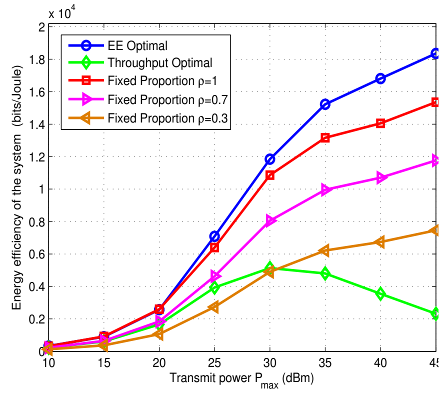

Fig. 3. The system EE versus the transmit power.

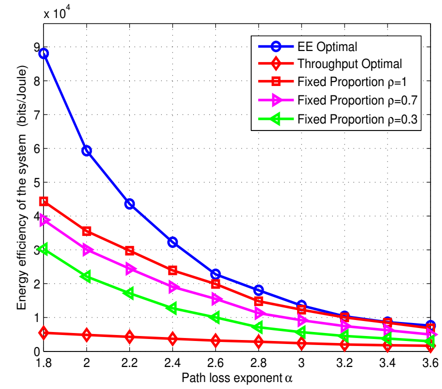

Fig. 4. System EE versus the path loss exponent.

IV. Numerical Results

In this section, we present comprehensive simulation results to validate the theoretical findings, and demonstrate the system EE of the proposed methods. Five users are randomly and uniformly distributed on the right side of the power station with the reference of 2 meters and the maximum service distance of 15 meters, respectively. The receiving BS is located 300 meters away from the power station. The system bandwidth is set as 15 kHz and then SNR gap is $\Gamma = 0$ dB. The path loss exponent for large scale fading is 2.8 and the thermal noise power is -110 dBm. The small scale fading for WET is the Rician fading with Rician factor 7 dB while that of for WIT is the normalized Rayleigh fading. The circuit powers at the power station and the user terminal are assumed as 500 mW and 5 mW, respectively. The energy harvesting efficiency is set to $\eta = 0.9$ unless specified otherwise.

A. System EE of WPCN: PWPCN versus IELCN

Here, we provides a concrete example to detailedly illustrate Theorem 1. We assume that P_c and p_c are 500 mW and 5 mW, respectively. Specifically, we set $\boldsymbol{Q} = [0, 0, 1, 1, 1]$, $\boldsymbol{h} = [0.1, 0.1, 0.1, 0.1, 0.1]$, and $\boldsymbol{\gamma} = \frac{\boldsymbol{g}}{\sigma^2} = [8, 6, \gamma_3, 0.3, 0.2]$, respectively. Note that only the last three users have the initial energy. Therefore, from Theorem 3 for ELCN, we know that only the third user would be scheduled provided $\gamma_3 > 0.3$ and its EE is independent of $P_{\max}$ while increasing with γ_3. However, from Theorem 2, we know that the EE of PWPCN is increasing with $P_{\max}$. Therefore, we can adjust γ_3 and $P_{\max}$ to observe the system switching from IELCN to PWPCN, which is shown in Fig. 2. In the low transmit power regime, the system is in the IELCN mode, but as $P_{\max}$ increases, when the EE of PWPCN supasses that of IELCN, the system switches to the PWPCN mode.

B. System EE versus Transmit Power of Power Station

We compare the EE of following methods: 1) EE Optimal: proposed approach; 2) Throughput Optimal: based on the conventional throughput maximization [5]; 3) Fixed Proportion: each user consume the same fixed proportion of its harvested energy, denoted as ρ, which can be adjusted.

In Fig. 3, as $P_{\max}$ increases, we observe that the performance of the EE Optimal scheme first increases and then only have marginal increase while that of a Throughput Optimal scheme first increases and then decreases, which is due to its greedy use of power. Moreover, for fixed proportion schemes, with ρ increases, the system EE also increases. However, even $\rho = 1$, the EE Optimal scheme still outperforms the fixed proportion scheme. The performance gap comes from that the proposed scheme only schedule users which is beneficial to the system EE while the fixed proportion scheme imprudently schedules all users without any selection.

C. System EE versus Path Loss Exponent of WET Channel

In Fig. 4, the system EE of all schemes decreases with an increasing path loss exponent α. Moreover, the performance gap between those schemes also decreases as α increases. As we know that a larger path loss exponent leads to more energy loss in signal propagation. This enforces the energy-efficient designs to schedule more users and utilize more energy to increase the system throughput so as to improve the system EE, which makes the proposed algorithm behave similar to the Throughput Optimal scheme.

V. Conclusions

In this paper, we have investigated the joint time allocation and power control of DL WET and UL WIT to maximize the system EE of the WPCN. For the basic case of best-effort WPCN, we have shown that the EE maximization problem can be cast into the EE maximization of two independent systems. For each system, we derive the optimal solution directly by exploiting the fractional-form structure of the problem, which serves as building blocks for obtaining the system EE. Simulation results demonstrate our theoretical findings and show that the propose scheme outperforms the throughput optimal scheme and fixed energy consuming scheme.

Appendix A: Proof of Theorem 1

Let $\mathcal{S}^* = \{P_0^*, \tau_0^*, \{p_k^*\}, \{\tau_k^*\}\}$, $\widehat{\mathcal{S}} = \{\widehat{P}_0, \hat{\tau}_0, \{\hat{p}_k\}, \{\hat{\tau}_k\}\}$, and $\check{\mathcal{S}} = \{\check{P}_0, 0, \{\check{p}_k\}, \{\check{\tau}_k\}\}$ denote the optimal solutions of EE^*, EE^*_{PWPCN}, and EE^*_{IELCN} which have been defined in

Theorem 1, respectively. The corresponding energy loss during DL WET are E^*_{WET}, $\widehat{E}_{\mathrm{WET}}$, and 0, respectively. The feasible sets of problems (12), (13), and (14) are denoted as D, $D_{\mathcal{P}}$, and $D_{\mathcal{I}}$, respectively. By exploiting their fractional structures, we have the following inequalities

$$\begin{aligned}
& EE^* \\
= & \frac{\sum_{k=1}^{K} \tau_k^* r_k(p_k^*)}{E^*_{\mathrm{WET}} + \sum_{k=1}^{K} \tau_k^*(p_k^* + p_c)} \\
= & \frac{\sum_{k\in\Phi_{\mathcal{P}}} \tau_k^* r_k(p_k^*) + \sum_{k\in\Phi_{\mathcal{I}}} \tau_k^* r_k(p_k^*)}{E^*_{\mathrm{WET}} + \sum_{k\in\Phi_{\mathcal{P}}} \tau_k^*(p_k^* + p_c) + \sum_{k\in\Phi_{\mathcal{I}}} \tau_k^*(p_k^* + p_c)} \\
\overset{a}{\leq} & \max\left\{ \left.\frac{\sum_{k\in\Phi_{\mathcal{P}}} \tau_k^* r_k(p_k^*)}{E^*_{\mathrm{WET}} + \sum_{k\in\Phi_{\mathcal{P}}} \tau_k^*(p_k^* + p_c)}\right|_{S^*\in D}, \right. \\
& \left. \left.\frac{\sum_{k\in\Phi_{\mathcal{I}}} \tau_k^* r_k(p_k^*)}{\sum_{k\in\Phi_{\mathcal{I}}} \tau_k^*(p_k^* + p_c)}\right|_{S^*\in D} \right\} \\
\overset{b}{\leq} & \max\left\{ \left.\frac{\sum_{k\in\Phi_{\mathcal{P}}} \hat{\tau}_k r_k(\hat{p}_k)}{\widehat{E}_{\mathrm{WET}} + \sum_{k\in\Phi_{\mathcal{P}}} \hat{\tau}_k(\hat{p}_k + p_c)}\right|_{\widehat{S}\in D_{\mathcal{P}}}, \right. \\
& \left. \left.\frac{\sum_{k\in\Phi_{\mathcal{I}}} \check{\tau}_k r_k(\check{p}_k)}{\sum_{k\in\Phi_{\mathcal{I}}} \check{\tau}_k(\check{p}_k + p_c)}\right|_{\check{S}\in D_{\mathcal{I}}} \right\} \\
= & \max\left\{EE^*_{\mathrm{PWPCN}}, EE^*_{\mathrm{IELCN}}\right\}. \qquad (23)
\end{aligned}$$

where the inequality "a" holds true due to the property of the fractional structure, which can be easily verified. In the next, we analyze "b" can holds with strict equality, i.e., EE^*_{PWPCN} or EE^*_{IELCN} can be achieved without violating the feasible domain of original problem (12), which results in the following two cases:

- For $k \in \Phi_{\mathcal{P}}$, it is easy to verify the equivalence of $\{P_0, \tau_0, p_k, \tau_k\} \in D$ and $\{P_0, \tau_0, p_k, \tau_k\} \in D_{\mathcal{P}}$. As $\{\widehat{P}_0, \hat{\tau}_0, \hat{p}_k, \hat{\tau}_k\}$ is the optimal solution of maximizing EE_{PWPCN}, "b" holds true for the first term inside the bracket.
- For $k \in \Phi_{\mathcal{I}}$, $\{p_k^*, \tau_k^*\} \in D$ means that $\tau_k^*(p_k^* + p_c) \leq P_0^*\tau_0^* h_k + Q_k$ and $\tau_0^* + \sum_{k=1}^{K} \tau_k^* \leq T_{\max}$. Then, we can construct another solution $\{\widetilde{P}_0, 0, \widetilde{p}_k, \widetilde{\tau}_k\}$ with $\widetilde{P}_0 = P_0^*$, $\widetilde{p}_k = p_k^*$ and $\widetilde{\tau}_k = \alpha\tau_k^*$, where $\alpha = \min\limits_{k\in\Phi_{\mathcal{I}}} \frac{Q_k}{Q_k + P_0^*\tau_0^* h_k} \leq 1$ such that $\widetilde{\tau}_k(\widetilde{p}_k + p_c) \leq Q_k$ for $\forall\, k$. It can verified that $\{\widetilde{P}_0, 0, \widetilde{p}_k, \widetilde{\tau}_k\}$ is a feasible point in $D_{\mathcal{I}}$, but can achieve the same EE as $\{P_0^*, \tau_0^*, p_k^*, \tau_k^*\} \in D$, i.e.,
$$\begin{aligned}
\frac{\sum_{k\in\Phi_{\mathcal{I}}} \widetilde{\tau}_k r_k(\widetilde{p}_k)}{\sum_{k\in\Phi_{\mathcal{I}}} \widetilde{\tau}_k(\widetilde{p}_k + p_c)} &= \frac{\sum_{k\in\Phi_{\mathcal{I}}} \alpha\tau_k^* r_k(p_k^*)}{\sum_{k\in\Phi_{\mathcal{I}}} \alpha\tau_k^*(p_k^* + p_c)} \\
&= \frac{\sum_{k\in\Phi_{\mathcal{I}}} \tau_k^* r_k(p_k^*)}{\sum_{k\in\Phi_{\mathcal{I}}} \tau_k^*(p_k^* + p_c)}. \qquad (24)
\end{aligned}$$
  On other hand, since $\{\check{P}_0, 0, \check{p}_k, \check{\tau}_k\} \in D_{\mathcal{I}}$ is the optimal solution of maximizing EE_{IELCN}, "b" holds true for the second term inside the bracket.

Based on the above analysis, Theorem 1 is proved.

Appendix B: Proof of Theorem 2

Denote S^* as the set of users which are scheduled. Substituting $P_0 = P_{\max}$ and $\tau_k = \frac{\eta P_{\max} h_k \tau_0}{p_k + p_c}$ into the objective function of problem (13), we have

$$\begin{aligned}
EE &= \frac{\sum_{k\in S^*} \frac{\eta P_{\max} h_k \tau_0}{p_k + p_c} W\left(1 + p_k\gamma_k\right)}{E_{\mathrm{WET}} + \sum_{k\in S^*} \frac{\eta P_{\max} h_k \tau_0}{p_k + p_c}(p_k + p_c)} \qquad (25) \\
&= \frac{\eta P_{\max} \sum_{k\in S^*} h_k ee_k}{P_{\max}(1 - \sum_{k=1}^{K} \eta h_k) + P_c + \eta P_{\max} \sum_{k\in S^*} h_k},
\end{aligned}$$

Given S^*, we only have to maximize each ee_k which is solely determined by p_k, and its maximal value $ee_k^\star$ can be computed by (9) and (10). After some manipulations, we obtain

$$EE^* = \frac{\sum_{k\in S^*} h_k ee_k^\star}{\frac{1}{\eta}\left(\frac{P_c}{P_{\max}} + 1 - \sum_{k=1}^{K} \eta h_k\right) + \sum_{k\in S^*} h_k}. \qquad (26)$$

Since the transmit power of each scheduled user k is $p_k^\star$ from (26), τ_0^* and τ_k^* can be easily derived from Lemma 2 and Lemma 3.

Appendix C: Proof of Theorem 3

From (14), we can have

$$\begin{aligned}
EE^*_{\mathrm{IELCN}} &= \frac{\sum_{k\in\Phi_{\mathcal{I}}} \tau_k^* W \log_2\left(1 + p_k^*\gamma_k\right)}{\sum_{k\in\Phi_{\mathcal{I}}} \tau_k^*(p_k^* + p_c)} \\
&\overset{c}{\leq} \max_{k\in\Phi_{\mathcal{I}}} \frac{\tau_k^* W \log_2\left(1 + p_k^*\gamma_k\right)}{\tau_k^*(p_k^* + p_c)} \\
&\overset{d}{\leq} \max_{k\in\Phi_{\mathcal{I}}} \frac{W \log_2\left(1 + p_k^\star\gamma_k\right)}{p_k^\star + p_c} = ee_k^\star \qquad (27)
\end{aligned}$$

where the inequality "c" holds true due to the same argument as (23), and "d" follows from the optimality of $p_k^\star$ for ee_k^*. Then, putting the optimal power $p^\star$ into the time and energy harvesting constraints, we obtain (21) and (22).

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