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MAXIMIZATION OF WEIGHTED SUM OF THE USER ENERGY EFFICIENCIES TO INCREASE ENERGY EFFICIENCY IN WIRELESS POWERED COMMUNICATION

Atiya Sultana[#1]

[#] *Dept. of Electronics and Communication Engineering, Navodaya Institute of Technology VTU,Karnataka,India*

***Abstract*— In this paper, we consider wireless powered communication networks (WPCNs) where multiple users harvest energy from a dedicated power station and then communicate with an information receiving station in a time-division manner. Thereby, our goal is to maximize the weighted sum of the user energy efficiencies (WSUEEs). In contrast to the existing system-centric approaches, the choice of the weights provides flexibility for balancing the individual user EEs via joint time allocation and power control. We first investigate the WSUEE maximization problem without the quality of service constraints. Closed form expressions for the WSUEE as well as the optimal time allocation and power control are derived. Based on this result, we characterize the EE tradeoff between the users in the WPCN. Subsequently, we study the WSUEE maximization problem in a generalized WPCN where each user is equipped with an initial amount of energy and also has a minimum throughput requirement. By exploiting the sum-of-ratios structure of the objective function, we transform the resulting nonconvex optimization problem into a two-layer subtractive-form optimization problem, which leads to an efficient approach for obtaining the optimal solution. The simulation results verify our theoretical findings and demonstrate the effectiveness of the proposed approach.**

***Index Terms*— User energy efficiency, wireless powered communication networks, resource allocation.**

I. INTRODUCTION

WIRELESS energy transfer (WET), where receivers harvest energy from radio frequency (RF) signals, is considered to be a promising solution for prolonging the lifetime of wireless devices. Combined with wireless information transmission (WIT), WET introduces a paradigm shift for the design of wireless communication. The authors established a “harvest-then-transmit” protocol for wireless powered communication networks (WPCNs), where the time allocated to the base station for downlink (DL) WET and the time allocated to the users for uplink (UL) WIT were jointly optimized for maximization of the system throughput. Similar problems were studied in the contexts of WPCNs with relays and massive multiple-input multiple-output (MIMO) . These works either focused on the spectral efficiency (SE) or the outage probability of WPCNs while the energy consumption of both energy transfer and information transmission was not considered, despite its importance for the design of future wireless communication systems.

The explosive growth of high-data-rate applications and services has triggered a dramatic increase in the energy consumption of wireless communications. Due to the rapidly rising energy costs and tremendous carbon footprints of communication systems , energy efficiency (EE), measured in bits-per-joule, has attracted considerable attention as a new performance metric in both academia and industry. In fact, EE is particularly important in WPCNs since the harvested RF energy is attenuated by signal propagation. Resource allocation for system-centric EE maximization was studied for simultaneous wireless information and power transfer (SWIPT) systems. Specifically, the subcarrier assignment, power allocation, and power splitting ratio were jointly optimized for maximization of the system EE, while guaranteeing both a minimum amount of harvested energy and also a minimum user data rate. Chen *et al.* investigated energyefficient power allocation for large-scale MIMO systems for a single-user setup. However, employing large numbers of antennas may not be energy efficient if the energy consumption

In system-centric EE maximization via joint time allocation and power control. We showed that from the system’s perspective, only users who have a better energy utilization efficiency than the system itself should be scheduled while the rest of the users should remain silent during UL WIT. However, such a resource allocation algorithm design may lead to starvation of some users and thus their quality of service (QoS) cannot be guaranteed in practice.

In fact, most existing works focus on optimizing the system centric EE from the system’s perspective and little effort has been made to investigate the user-centric EE from the terminals’ perspective. Since the capacities of batteries are limited but the demand for heterogeneous user experience increases, the EEs of individual users become increasingly critical for the operation of practical wireless communication systems. However, a resource allocation aiming at optimizing the system-centric EE, which is defined as the ratio of the system throughput to the system energy consumption, is in general suboptimal as far as the EE of the individual users is concerned. In contrast, in WPCNs, where users harvest energy and transmit information signals independently, the user-centric EE focuses on the EE of each user and is thus more relevant for practical user-centric applications than the system-centric EE. In addition, user-centric EE optimization provides insights into the EE tradeoff between different users. For conventional SE optimization, the tradeoff between users is quite obvious and simple: the throughput of one user cannot be improved without decreasing the throughput of the other users. This is because utilizing more resources, such as transmit powerand transmission time, is always beneficial for increasing the data rate of a user. However, this simple relationship may not hold for EE optimization. It is well known that exceedingly large transmit power will lead to a lower individual user EE , which suggests that users may not always compete for resources with each other. In other words, it may be possible to maximize the EEs of all users simultaneously. Furthermore, if the users have high minimum throughput requirements, users that are allocated short transmission times have to transmit with larger powers in order to meet the throughput requirements which may result in lower user EEs. In contrast, users that are allocated longer transmission times have higher flexibility in adjusting their transmit powers which facilitates higher user EEs. In this case, the EEs of the users may not be maximized simultaneously. Therefore, it is interesting to study the EE tradeoff between different users in WPCNs and it is expected that the adopted resource allocation policy plays an important role in balancing the individual EEs.

II. OVERVIEW OF RELIABLE STRATEGY FOR USER CENTRIC INFRASTRUCTURE

A. EXISTING SYSTEM

In existing works, we study the energy-efficient resource allocation in WPCNs from a user-centric perspective. Time allocation and power control are jointly optimized to maximize the weighted sum of the user energy efficiencies (WSUEE).Thereby, our problem formulation takes also into account the circuit power consumption for WIT and WET. We first investigate the WSUEE maximization problem without minimum user throughput constraints, which provides useful insights into the EE tradeoff between the users of WPCNs. Subsequently, we extend the WSUEE maximization problem to a generalized WPCN where each user has a certain amount of initial energy and also a minimum throughput requirement. This generalization provides more flexibility for users to improve their EEs while guaranteeing QoS.

For WPCNs without QoS requirements, we reveal that it is optimal to let the power station transmit with the maximum allowed power while letting each user exhaust its own harvested energy using a fixed transmit power. Based on this insight, we derive closed-form expressions for the maximum WSUEE as well as the optimal time allocation and power control, which facilitates the characterization of the EE tradeoff between users in WPCNs. It is found that within a throughput region, all users can achieve their individual maximum EEs simultaneously while only beyond that region, there exists non-trivial tradeoff among user EEs. This is unlike the conventional user SE tradeoff in where users are always competing for resources and a non-trivial user SE tradeoff always exists.

For generalized WPCNs, the WSUEE maximization problem is more difficult to solve since in contrast to the case without QoS requirements, some users may not exhaust all of their available energies in order to save transmission time for users with high throughput requirements. Exploiting the sum-of-ratios structure of the objective function, we transform the original non-convex optimization problem into an equivalent parameterized optimization problem which can be solved iteratively via solving a two-layer optimization problem. For the inner-layer, we show that the joint time allocation and power control optimization problem in subtractive form is a standard convex optimization problem and can be efficiently solved using Lagrangian dual decomposition. For the outer-layer, the parameters for the equivalent parametric optimization problem are updated with the damped Newton method having a super linear convergence speed. The proposed two-layer algorithm is guaranteed to con-verge to the optimal solution.

B. PROPOSED SYSTEM

We propose the WPCN power consumption model for the wireless terminals is provided. The “harvest-then-transmit” protocol is employed all users first harvest energy from the RF signal broadcasted by the power station in the DL, and then transmit information signals individually to the information receiving station in the UL. We focus on user-centric EE maximization, it is important to properly model the energy consumption of the user terminals in WPCNs. We aim at balancing the EEs of the users in WPCNs. To achieve this goal, we adopt WSUEE as the objective function, which is in fact a scalarization of the EEs of multiple users. We investigate the WSUEE maximization problem when QoS constraints are not imposed, which provides useful design insights for energy-efficient transmission and characterization of the user EE trade off in WPCNs.

Our goal is to jointly optimize time allocation and power control for both DL WET and UL WIT for maximization of the WSUEE. The proposed optimization can account for the effects of various energy harvesting techniques when combined with WET. The system EE gain of the system-centric EE maximization approach over the WSUEE maximization approach is at the expense of sacrificing user fairness, which is not desirable from the perspective of the end users.

C. SYSTEM MODEL

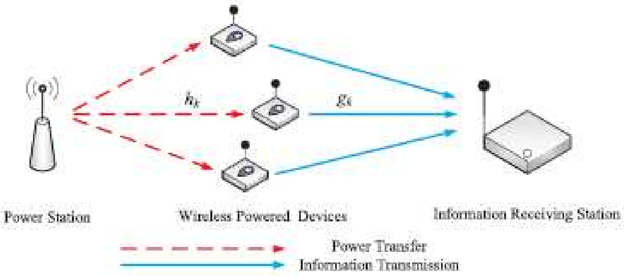


Fig. 1. The system model of a wireless powered communication network (WPCN).

In this section, we first introduce the WPCN system model.

Then, the WPCN power consumption model for the wireless terminals is provided. Finally, we define the objective function,i.e., the WSUEE.

D. *Signal and Energy Harvesting Models*

We consider a WPCN which consists of a power station, K wireless-powered users, and an information receiving station, as depicted in Fig. 1. The "harvest-then-transmit" protocol, i.e., all users first harvest energy from the RF signal broadcasted by the power station in the DL, and then transmit information signals individually to the information receiving station in the UL. For the ease of implementation, the power station and all users are equipped with a single antenna and use time division duplex to transmit in the same frequency band. Both the DL and the UL channels are modeled as quasi-static block fading channels,where the channel coefficients are assumed to be constant during each transmission time block (corresponding to e.g. one data packet), but vary independently from one block to the next. The DL channel gain between the power station and user terminal k and the UL channel gain between user terminal k and the information receiving station are denoted as hk and gk, respectively. We also assume that the channel state information (CSI) is perfectly known at the power station since our goal is to obtain an EE upper bound for practical WPCNs. Once calculated, the resource allocation policy is conveyed to the users to perform energyefficient transmission. Thereby, we assume that the energy consumed for estimating and exchanging CSI can be drawn from a dedicated battery which does not rely on the harvested

RF energy. In the DL WET stage, the power station broadcasts an energy signal with transmission power $P0$ during transmission time $\tau 0$. The energy harvested from the noise and the UL WIT signals received from other users is assumed to be negligible, since the thermal noise power and the user transmit powers are both much smaller than the transmit power of the power station in practice . Thus, the amount of energy harvested at user k can be modeled as

$$E_k^H = \eta_k \tau_0 P_0 h_k, \qquad (1)$$

where $\eta k \in (0, 1]$ is the energy conversion efficiency. In the UL WIT stage, user k transmits an independent information signal xk to the information receiving station with transmission power pk during transmission time τk . Then, the achievable throughput of user k, denoted as Bk, is given by

$$B_k = \tau_k W \log_2\left(1 + p_k \gamma_k\right), \qquad (2)$$

where $\gamma k = gk/\sigma 2$ denotes the channel-to-noise-power ratio for UL WIT. Constants W and $\sigma 2$ are the bandwidth of the considered system and the variance of the additive white Gaussian noise, respectively.

E. *Power Consumption Model for Wireless Terminals*

Since we focus on user-centric EE maximization, it is important to properly model the energy consumption of the user terminals in WPCNs. Here, we adopt the power consumption model from , which takes into account

the transmit power, transmit circuit power, and receive circuit power of the user terminals for system design.

In WPCNs, the overall energy consumption of each wireless

powered terminal consists of two parts: the energies consumed during DL WET and UL WIT, respectively. In the DL WET stage, as the terminal is in reception mode, only a constant circuit power is consumed for receive signal processing, i.e., pr,k . Thus, the energy consumption in this stage is $pr,k\tau 0$. Note that $EH\ k - pr,k\tau 0 = (\eta k\ P0\ hk - pr,k)\tau 0 > 0$ should always hold. If $EH\ k - pr,k\tau 0 \le 0$, it means that user k cannot store any energy during energy harvesting. This can be caused by a low energy conversion efficiency ηk, a small transmit power of the power station $P0$, a degraded DL channel gain hk , or a large receive circuit power consumption pr,k. In this case, user k should be shut down and not be considered for resource allocation. Hence, in the following, we onlyconsider those users which satisfy $EHk - pr,k\tau 0 \ge 0$. In the UL WIT stage, the wireless terminal is in the transmission mode, and the power consumption includes not only the over-the- air information transmit power, denoted as pk, but also the circuit power consumed for transmit signal processing,

denoted as pc,k. Therefore, the overall energy consumption of user k can be expressed as

$$E_k = \tau_0 p_{r,k} + \tau_k \frac{p_k}{\varepsilon_k} + \tau_k p_{c,k}, \qquad (3)$$

where $\varepsilon k \in (0, 1]$ is a constant which accounts for the power amplifier (PA) efficiency of user terminal k.

C. Objective Function: User-Centric EE

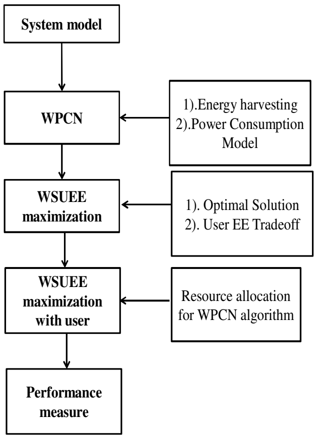
The EE of each user in WPCNs is defined as the ratio of its achievable throughput during UL WIT and its overall energy consumption during both DL WET and UL WIT, i.e.,

$$EE_k = \frac{B_k}{E_k} = \frac{\tau_k W \log_2\left(1 + p_k \gamma_k\right)}{\tau_0 p_{r,k} + \tau_k \frac{p_k}{\varepsilon_k} + \tau_k p_{c,k}}. \qquad (4)$$

In this paper, we aim at balancing the EEs of the users in WPCNs. To achieve this goal, we adopt WSUEE as the objective function, which is in fact a scalarization of the EEs of multiple users. This metholodolgy is commonly used for the investigation of possibly conflictling design objectives. The WSUEE of WPCNs can be expressed as

$$EE_{\text{sum}} = \sum_{k=1}^{K} \omega_k EE_k, \qquad (5)$$

where the constant weight factors $\omega k \ge 0$, $\forall\ k$, are provided by upper layers and reflect the priorities of the different users. These predefined weights introduce a flexibility for customizing the performance of different users. For example, the system designer can assign higher weights to users with less energy storage but higher throughput requirements to make them more energy efficient.



Flow chart 1

III. SIMULATION RESULTS

In this section, simulation results to validate our theoretical findings is presented to demonstrate the user EE.

Four users are randomly and uniformly distributed on the right hand side of the power station with a reference distance of 2 meters and a maximum service distance of 10 meters.

The information receiving station is located 100 meters away from the power station. The system bandwidth is set to 20 kHz and the time duration is set as 1 s . The path loss exponent is 2.4 and the thermal noise power is -110 dBm. The small scale fading for WET and WIT is Rician fading with Rician factor 7 dB and Rayleigh fading, respectively. For the purpose of comparison, the maximum transmit powers of the power stations are set as 30 dBm and 46 dBm. Unless specified otherwise, it is assumed that all users have the same receive and transmit circuit power consumption as well as the same weight, the same energy conversion efficiency, and the same PA efficiency. The corresponding values are set to $pr,k = pr = 30$ mW, $\omega k = \omega = 1$, $pc,k = pc = 50$ mW, $\eta k = \eta = 0.9$, and $\varepsilon k = \varepsilon = 0.9$, $\forall\ k$, respectively.

A. *WSUEE Versus The Maximum Allowed Transmit Power Of The Power Station*

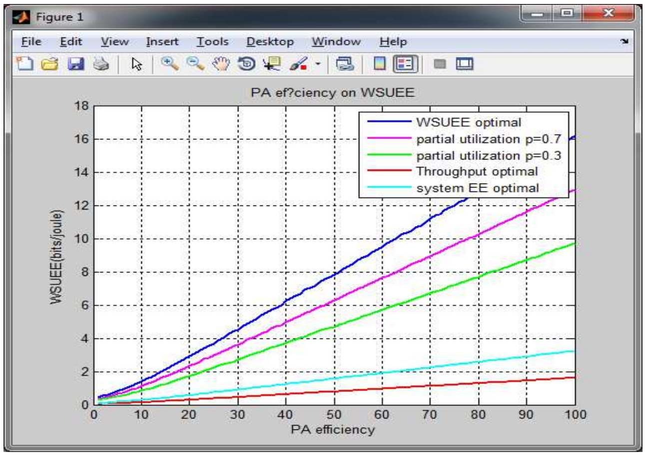


Fig 2:WSUEE Versus The Maximum Allowed Transmit Power Of The Power Station

In figure 2 the performance of the following schemes are compared:

1) WSUEE optimal: proposed approach;

2) System EE optimal: maximization of the system EE which is defined as a ratio of the system throughput and the system energy consumption

3) Throughput optimal: conventional throughput maximization;

4) Partial utilization: each user consumes only part of its harvested energy, i.e., $\tau kpk\varepsilon k+\tau k\, pc,k = \rho(\eta kP\max hk - pr,k)\tau 0$, where ρ $(0 < \rho < 1)$ can be adjusted to strike a balance between the energy consumed in the current transmission block and the energy stored for the next transmission block.

From above Figure 2, it is observed that the WSUEE of the proposed approach first increases quickly with the transmit power of the power station and then experiences marginal increases in the high transmit power region. This is because when $P\max$ is low, to transfer a certain amount of energy, a small increase of $P\max$ can significantly reduce the time needed for DL WET and thus reduce the receive circuit energy consumption. Therefore, the user EE improves quickly. On the other hand, in the high $P\max$ region, the time needed for DL WET is already so short that the receive circuit energy consumption does no longer have a large impact on the total user energy consumption, and thus, further increasing the transmit power leads only to a marginal increase in the WSUEE.

B. *WSUEE Versus PA Efficiency*

Figure 3 illustrates the impact of the user PA efficiency on the WSUEE of the considered schemes. As can be observed, the performance of all schemes increases with the PA efficiency,In addition, the performance gains of the proposed approach compared to the other schemes are also enhanced as the PA efficiency increases. This can be attributed to the fact that a higher PA efficiency allows a user to have more energy for information transmission, which provides the proposed optimization approach with more degrees of freedom for improving the user-centric EE.

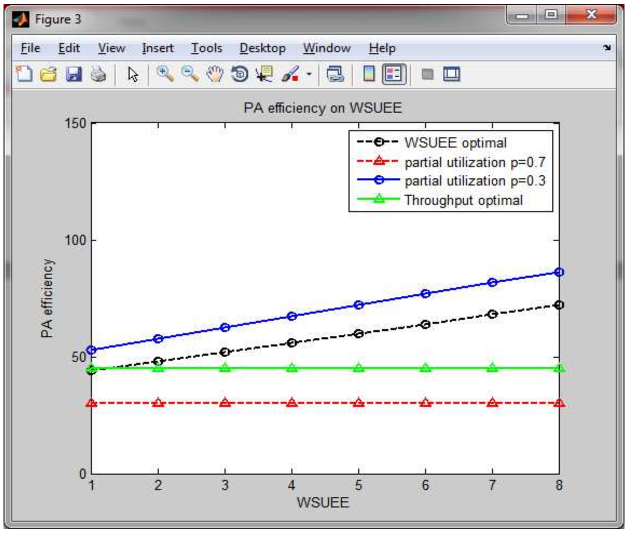


Fig 3:WSUEE Versus PA Efficiency

C. WSUEE Optimal Scheme And Average System EE Performance

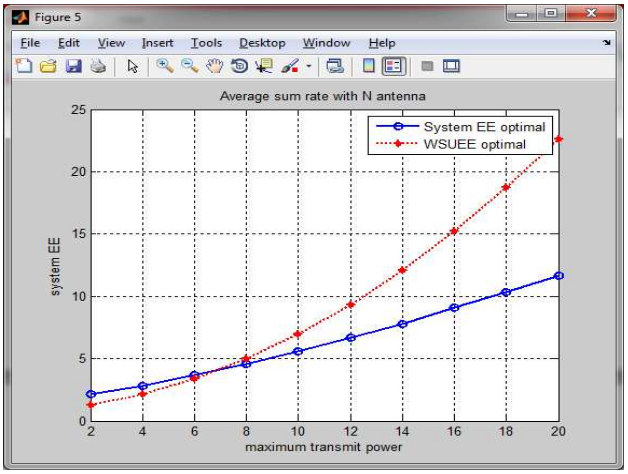


Fig 4: WSUEE Optimal Scheme And Average System EE Performance

Figure 4 illustrates the achieved system EE of the proposed WSUEE optimal resource allocation, which is generated by taking the result of the WSUEE optimal approach into the system EE expression. As can be seen, WSUEE maximization incurs a performance loss in terms of system EE compared to system-centric EE maximization and the performance loss increases with increasing maximum transmit power. This is due to the following two reasons. First, WSUEE maximization does not take into account the energy loss caused by signal attenuation during DL WET and thus, the obtained time allocation between DL WET and UL WIT is not optimal in terms of the system EE. Second, as revealed in for WUSEE maximization, each user is assigned a non-zero time interval for UL WIT, which is not beneficial for the overall system throughput and limits the system's ability to exploit multi-user diversity. In contrast, system-centric EE maximization selectively schedules only those users whose user EEs are higher than the system EE while forcing the rest of the users to be silent. Therefore, the system EE gain of the system-centric EE maximization approach over the WSUEE maximization approach is at the expense of sacrificing user fairness, which is not desirable from the perspective of the end users.

D. User EE Versus Min Throughput Requirement For Different Weights

Figure 5 shows the nontradeoff and tradeoff regions in terms of the user throughput when Rmin = Rk min, $k = 1, 2$. Specifically, for $\boldsymbol{\omega} = [5\ 1]$, it is observed that the EE of user 1 decreases slowly while the EE of user 2 decreases sharply as Rmin increases. In contrast, for $\boldsymbol{\omega} = [1\ 5]$, the EEs of user 1 and user 2 show the opposite behaviours. In particular, for Rmin = 4.5 ×104 bits, user 1 and user 2 achieve almost identical EEs. This suggests that in the user EE tradeoff region, assigning different weights to different users can indeed enforce a certain notion of fairness among users and help improve the individual EEs of users having degraded channels.

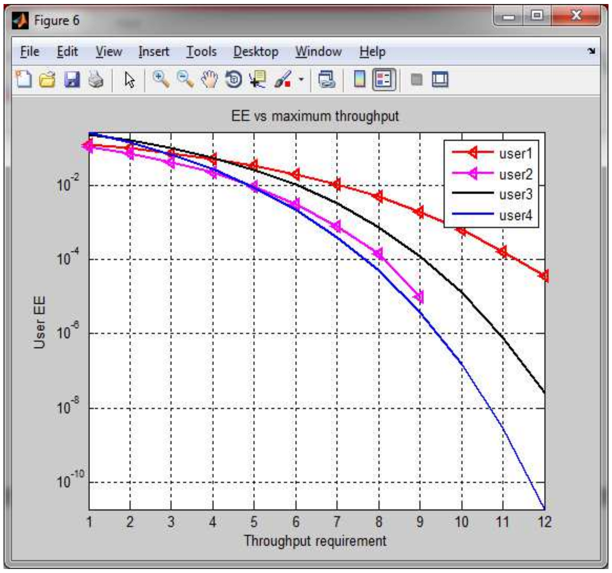


Fig 5: User EE Versus Min Throughput Requirement For Different Weights

E. User EE Versus Weight Of User 1

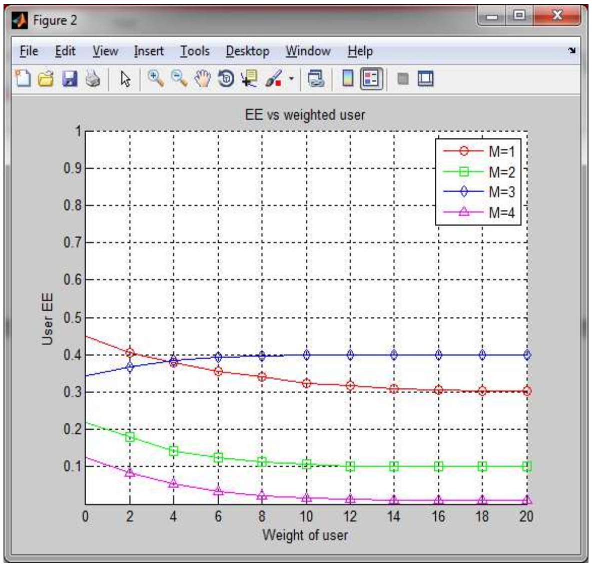


Fig 6: User EE Versus Weight Of User 1

F. *User EE Trade Off*

Below Figure 7 illustrates the tradeoff between four users where users 1, 2, 3, and 4 are located at distances of 80 m, 70 m, 90 m, and 95 m from the power station, respectively. Without loss of generality, it is assumed that all users have the same minimum throughput requirement, i.e., *Rk* min= *R*min =2 × 104 bits, ∀ *k*. Same weights are assigned to users 2, 3, and 4, i.e., $\omega2 = \omega3 = \omega4 = 1$, and vary the weight of user 1, $\omega1$, between 1 and 15. As can be seen from Figure as $\omega1$ increases, the EE of user 1 increases while the EEs of users 2, 3, and 4, decrease, which further demonstrates that assigning higher weights to some users indeed helps improve their EEs. In addition, it is worth noting that as $\omega1$ increases, the EE of user 1 first gradually increases and finally approaches a constant value, which is the maximum EE that user 1 can achieve. The user EE tradeoff is further studied in Figure where the EEs of users 2, 3, and 4 versus the EE of user 1 are depicted. As the EE of user 1 increases, the EE of the other users strictly decreases, which illustrates the non-trivial tradeoff between the EEs of individual users.

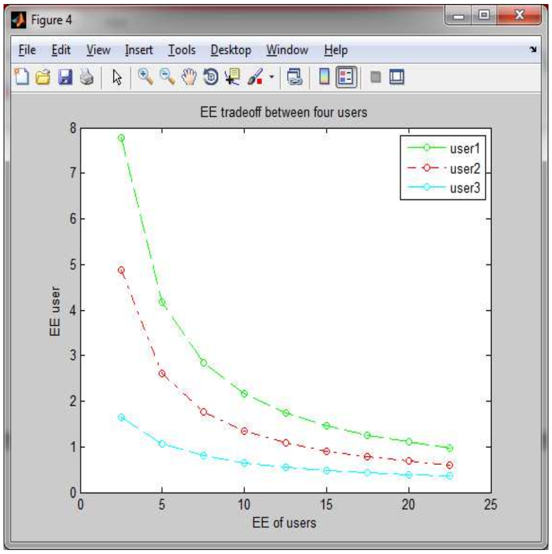


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Fig 7: User EE Trade Off

IV. CONCLUSION

In this paper, we investigated the energy-efficient resource allocation in WPCNs from a user-centric perspective. The time allocation and power control of DL WET and UL WIT were jointly optimized to maximize the WSUEE. For the WUSEE maximization problem without minimum user throughput requirements, we derived a closed-form expression for the WSUEE by carefully studying the properties of energy efficient transmission. For the WUSEE maximization problem with minimum user throughput requirements, we proposed a computationally efficient resource allocation algorithm to obtain the optimal solution by exploiting the sum-of-ratios structure of the objective function. Simulation results demonstrated the gains in EE achieved by the proposed joint optimization approach and also unveiled the tradeoff between the EEs of different users in WPCNs. In particular, for low user throughput requirements, all users can achieve their individual maximum EEs simultaneously; For high user throughput requirements, the individual user EEs can be balanced by assigning different weights to different users; Neither the system-centric EE scheme nor the throughput optimal scheme are user-centric EE optimal and the performance loss caused by adopting traditional schemes for user-centric EE systems is higher for larger power station transmit powers and for smaller user receive circuit powers.

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