Optimal On-Off Transmission Schemes for Full Duplex Wireless Powered Communication Networks

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Abstract—In this paper, we consider a full duplex wireless powered communication network where multiple users with radio frequency energy harvesting capability communicate to an energy broadcasting hybrid access point. We investigate the minimum length scheduling and sum throughput maximization problems considering on-off transmission scheme in which users either transmit at a constant power or remain silent. For minimum length scheduling problem, we propose a polynomial-time optimal scheduling algorithm. For sum throughput maximization, we first derive the characteristics of an optimal schedule and then to avoid intractable complexity. We propose a polynomial-time heuristic algorithm which is illustrated to perform nearly optimal through numerical analysis.

Index Terms—WPCN, throughput maximization, schedule length minimization.

I. INTRODUCTION

The lifetime of a wireless sensor network is usually battery dependent requiring replacement or recharging while the former is either very difficult or infeasible. Recently, radio frequency (RF) energy harvesting arises as the most suitable technology to provide perpetual energy. Due to design of highly efficient RF energy harvesting hardware [1], the dream of wireless power transfer has become true. In wireless powered communication networks (WPCN), wireless users with RF energy harvesting capability; i.e., sensors and machine type communication (MTC) devices, communicate to a hybrid access point (HAP) in the uplink using the energy transferred by the HAP in the downlink [2].

The sum throughput maximization (STM) and minimum length scheduling (MLS) problems have been studied for WPCNs under various models and assumptions. In the half-duplex WPCN models, the users transmit information and harvest energy in non-overlapping time intervals. For half-duplex models, several studies such as [3]–[5] have considered the WPCN for common, minimum and weighted throughput maximization respectively. Whereas, [6]–[8] have considered single and multi-antenna WPCN systems for MLS problems. On the other hand, WPCN studies have recently incorporated full duplex technology allowing the access point and the users to achieve simultaneous energy transfer and data communication. Self-interference is the major setback for full-duplex transmission, however, due to recent advances in self-interference cancellation techniques and their practical implementations under the development of 5G and beyond networks, full-duplex has become realizable. The authors in [9]–[11] have considered the full duplex models for MLS and STM. Due to full duplex, a wireless user can harvest energy during both its own and other users transmission, making scheduling important which is missing in these works. Whereas, only few studies [12]–[14] have paid attention to scheduling but in either a limited context or employing a computationally-inefficient technique. In [12], the scheduling frame is divided into a fixed number of equal length time slots resulting in underutilization of the resources. In [13], authors have used Hungarian algorithm to find the schedule which is computationally very complex for such sequence dependent transmissions, whereas, [14] considered the discrete rate optimization problem to minimize the schedule length. Moreover, these studies have considered simplistic models compared to the system model discussed in this paper. Due to low processing cost and use of simple and cheap power amplifiers, on-off transmission scheme can be very useful for inexpensive sensor networks leading to affordable and widespread deployments of IoT applications. However, in the context of WPCN, no previous study have considered this scheme except [15], [16] where the authors have analysed the average error rate and outage probability for a single user system. In this paper, we incorporate on-off transmission scheme for a multi-user WPCN in which users either transmit with a constant power or remain silent if the user can not afford transmission at this power.

The goal of this paper is to revisit MLS and STM problems for determining the optimal time allocation and scheduling considering on-off transmission scheme and a realistic non-linear energy harvesting model in a full-duplex WPCN. The main contributions are listed as follows:

- We characterize the Minimum Length Scheduling Problem (MLSP) and Sum Throughput Maximization Problem (STMP) and mathematically formulate each as a mixed integer linear programming (MILP) problem.
- For MLSP, we propose an optimal polynomial-time algorithm incorporating optimal time allocation and scheduling.
II. System Model and Assumptions

We describe the WPCN architecture and the assumptions used throughout the paper as follows:

1) The WPCN architecture, as depicted in Fig. 1, consists of a HAP and N users; i.e., machine type communications devices and sensors. The HAP and the users are equipped with one full-duplex antenna for simultaneous wireless energy transfer and data transmission on downlink and uplink channels, respectively. The uplink channel gain from user \( i \) to the HAP and the downlink channel gain from the HAP to user \( i \) are denoted by \( g_i \) and \( h_i \), respectively.

2) The HAP has stable energy supply and continuously broadcasts wireless energy with a constant power \( P_h \). Each user \( i \) harvests the radiated energy from the HAP and stores it in a rechargeable battery. Each user has an initial energy \( B_i \) stored in its battery at the beginning of the scheduling frame which includes the harvested and unused energy in the previous scheduling frames.

3) A realistic non-linear energy harvesting model is assumed which is based on the logistic function \([17],[18]\) due to its close performance to the experimental results proposed in \([19]–[21]\). For such a non-linear energy harvesting model the energy harvesting rate for user \( i \) is given as:

\[
C_i = \frac{P_i(\Psi_i - \Omega_i)}{1 - \Psi_i} \tag{1}
\]

Where, \( \Omega_i = \frac{1}{1 + e^{A_i(B_i - B_i)}} \) is a constant to make sure that zero-input will generate zero-output response, \( P_i \) is the maximum harvested power in the saturation state and \( \Psi_i \) is a logistic function related to user \( i \) which is defined by:

\[
\Psi_i = \frac{1}{1 + e^{-A_i(h_iP_h - B_i)}} \tag{2}
\]

Where, \( A_i \) and \( B_i \) are the input power and turn-on threshold constants of user \( i \) for the non-linear charging rate respectively. For a given energy harvesting circuit, the parameters \( P_i, A_i \) and \( B_i \), \( i \in \{1, \ldots, N\} \) can be determined by curve fitting.

4) We consider time division multiple access as medium access control for the uplink data transmissions from the users to the HAP. The time is partitioned into scheduling frames which are further divided into variable-length time slots each of which is allocated to a particular user.

5) We use constant power model in which all users have a constant transmit power \( P_{max} \) during their data transmissions which is imposed to limit the interference to nearby systems.

6) We use constant rate transmission model, in which Shannon capacity formulation for an AWGN channel is used in the calculation of transmission rate \( r_i \) of user \( i \) as

\[
r_i = W \log_2(1 + k_i P_{max}), i \in \{1, \ldots, N\} \tag{3}
\]

where \( W \) is the channel bandwidth and \( k_i \) is defined as \( g_i/(N_0W + \beta P_h) \). The term \( \beta P_h \) is the self interference at the HAP and \( N_0 \) is the noise power density.

III. Minimum Length Scheduling Problem

In this section, we introduce the minimum length scheduling problem, denoted by MLSP. The joint optimization of the time allocation and scheduling with the objective of minimizing the schedule length is formulated as follows:

MLSP:

\[
\text{minimize} \quad \sum_{i=0}^{N} \tau_i \tag{4a}
\]

\[
\text{subject to} \quad W \tau_i \log_2(1 + k_i P_{max}) \geq D_i, i \in \{1, \ldots, N\} \tag{4b}
\]

\[
B_i + C_i(\tau_0 + \sum_{j=1}^{N} a_{ji} \tau_j + \tau_i) - P_{max} \tau_i \geq 0, \quad i \in \{1, \ldots, N\} \tag{4c}
\]

\[
a_{ij} + a_{ji} = 1, i \neq j, i, j \in \{1, ..., N\} \tag{4d}
\]

\[
\text{variables} \quad \tau_i \geq 0, \quad a_{ij} \in \{0, 1\}. \tag{4e}
\]
The variables of the problem are \( \tau_i \), the transmission time of user \( i \), and \( a_{ij} \), a binary variable that takes value 1 if user \( i \) is scheduled before user \( j \) and 0 otherwise. In addition, \( \tau_0 \) denotes an initial unallocated time in which all users harvest energy without transmitting data. The objective of the problem is to minimize the schedule length which is equal to the completion time of the transmissions of all users, as given by Eq. (4a).

In an optimal solution of MLSP, users are allocated the amount of data that should be transmitted by user \( i \) during data transmission cannot exceed the total amount of available energy including both the initial battery level and the harvested energy until and during the transmission of a user.

The foregoing lemma suggests that at any particular time instant \( t \), it is an optimal policy to schedule any user \( i \) with \( s_i^{min} - t \) is nonpositive and minimum among all \( i \in [1,N] \). Then, the optimal schedule should start with an initial unallocated time \( \tau_0 = \min_{i \in [1,N]} s_i^{min} \) and schedule the user with minimum \( s_i^{min} \). Then, it needs to schedule all users in increasing order of \( s_i^{min} \) values. Based on the foregoing discussion, we next introduce the Minimum Length Scheduling Algorithm (MLSA), given in Algorithm 1, for MLSP.

Input of MLSA algorithm is a set of users, denoted by \( \mathcal{F} \), with the characteristics specified in Section II. It starts by initializing the schedule \( \mathcal{S} \) where the \( i^{th} \) element of \( \mathcal{S} \) is the index of the user scheduled in the \( i^{th} \) time slot and the schedule length \( t(\mathcal{S}) \). At each step, MLSA picks the user with minimum \( s_i^{min} \) value among the unscheduled users. Then, the next time slot is allocated to this user at earliest possible time instant by updating \( \tau_0 \) accordingly. MLSA terminates when all users in \( \mathcal{F} \) are scheduled and outputs schedule \( \mathcal{S} \) and corresponding set of transmission times \( \tau \) including minimum possible \( \tau_0 \) value required for the successive and continuous transmissions of the users in \( \mathcal{F} \). The computational complexity of MLSA is \( O(N^2) \).

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**Algorithm 1 Minimum Length Scheduling Algorithm**

1: **input:** set of users \( \mathcal{F} \)
2: **output:** schedule \( \mathcal{S} \), set of transmission times \( \tau \), schedule length \( t(\mathcal{S}) \)
3: \( \mathcal{S} \leftarrow \emptyset \), \( t(\mathcal{S}) \leftarrow 0 \), \( \tau_0 \leftarrow 0 \),
4: **while** \( \mathcal{F} \neq \emptyset \) **do**
5: \( m \leftarrow \arg \min_{i \in \mathcal{F}} s_i^{min} \),
6: \( \mathcal{S} \leftarrow \mathcal{S} + \{ m \} \),
7: \( \mathcal{F} \leftarrow \mathcal{F} - \{ m \} \),
8: \( \tau_m \leftarrow D_m/(Wlog_2(1 + k_m P_{max})) \),
9: \( \tau_m^{waiting} \leftarrow \max \{ 0, s_m^{min} - t(\mathcal{S}) \} \),
10: \( \tau_0 \leftarrow \tau_0 + \tau_m^{waiting} \),
11: \( t(\mathcal{S}) \leftarrow t(\mathcal{S}) + \tau_m + \tau_m^{waiting} \),
12: **end while**

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**IV. Sum Throughput Maximization Problem**

In this section, we introduce the sum throughput maximization problem, denoted by STMP. The joint optimization of the time allocation and scheduling is formulated as follows:
Proof. Suppose that mission time for a set of users such that 
and \( i \) violates the energy causality requirement of user \( j \), transmission 
time of user \( j \) can be divided into two slots of lengths \( \tau_j^* - \tau' \) 
and \( \tau' \), each allocated to users \( j \) and \( i \), respectively. Then, sum 
throughput is increased by \( \tau (r_i - r_j) \) which is strictly positive. 
This is a contradiction.

While Lemma 3 indicates that high rate users should be priori-
torized for sum throughput maximization, an optimal schedule 
does not necessarily contain all users as long as maximum 
throughput is achieved using a subset of users. However, the 
following corollary of Lemma 3 states that the maximum rate 
user should be given a nonzero transmission time.

Corollary 1. Let user \( m \) has \( r_m = \max_i r_i \). Then, in an 
onimal solution, \( \tau_m > 0 \).

Moreover, if the maximum rate user has enough initial 
battery level to transmit with \( P_{\text{max}} \) during the entire scheduling 
frame, then, it needs to be allocated to the entire scheduling 
frame in the optimal schedule. Next, based on the foregoing 
analysis, we propose the Max-Rate First Scheduling Algorithm 
(MRSA), given in Algorithm 2. Input of MRSA algorithm is 
a set of users, denoted by \( F \), sorted in decreasing order of 
transmission rates. It starts by initializing the unallocated time 
duration to 1. At each step, MRSA picks the user with maximum 
rate and determines the maximum feasible transmission 
time it can allocate to that user. MRSA performs allocation 
starting from the end of the scheduling frame to allow higher 
rate users to harvest more energy. Then, it updates the unal-
located time duration accordingly and continues with the next 
user. If the unallocated time duration is 0 at any step, MRSA 
terminates by not scheduling the remaining users. Otherwise 
it schedules all users and the remaining unallocated time is 
specified as \( \tau_0 \). Upon termination, MLSA outputs the schedule 
\( S \) consisting of the allocated users and the corresponding sum 
throughput \( R(S) \). The computational complexity of MRSA is 
\( O(N) \).

Algorithm 2 Max-Rate First Scheduling Algorithm

1: input: set of users \( F \) sorted in decreasing order of rates 
2: output: set of transmission times \( \tau \), sum 
3: \( t^u \leftarrow 1 \), 
4: for \( i = 1 : |F| \) do 
5: \( E_i \leftarrow B_i + C_i t^u \), 
6: \( \tau_i \leftarrow \min \{ E_i / P_{\text{max}}, t^u \} \), 
7: \( t^u \leftarrow t^u - \tau_i \), 
8: if \( t^u = 0 \) then 
9: break, 
10: end if 
11: end for 
12: \( \tau_0 \leftarrow t^u \), 
13: \( S \leftarrow \{1, 2, \ldots, i\} \) 
14: \( R(S) \leftarrow \sum_{n=1}^m \tau_n r_n \)

V. Performance Evaluation

The goal of this section is to evaluate the performance of 
the proposed algorithms. Simulation results are obtained by 
averaging 1000 independent random network realizations. The 
users are uniformly distributed within a circle with radius 
of 10m. The attenuation of the links considering large-scale 
statistics are determined using the path loss model given by 

\[
\text{PL}(d) = \text{PL}(d_0) + 10 \alpha \log_{10} \left( \frac{d}{d_0} \right) + Z
\]

where \( \text{PL}(d) \) is the path loss at distance \( d \), \( d_0 \) is the reference 
distance, \( \alpha \) is the path loss exponent, and \( Z \) is a zero-mean

\[ (8a) \]

\[ (8b) \]

\[ (8c) \]

\[ (8d) \]

\[ (8e) \]
A Gaussian random variable with standard deviation $\sigma$. The small-scale fading has been modeled by using Rayleigh fading with scale parameter $\Omega$ set to mean power level obtained from the large-scale path loss model. The parameters used in the simulations are $\eta_i = 1$ for $i \in [1,N]$; $D_i = 100$ bits for $i \in [1,N]$; $W = 1$ MHz; $d_0 = 1$ m; $PL(d_0) = 30$ dB; $\alpha = 2.76$, $\sigma = 4$ [23]. The self interference coefficient $\beta$ is taken as $-70$ dBm.

A. Minimum Length Scheduling

In Fig. 2, we illustrate the performance of the proposed optimal algorithm MLSA in comparison to a predetermined scheduling order based algorithm, denoted by PDO, for different scenarios. PDO simply allocates the users in a given arbitrary order and thus does not exploit the benefit of optimal scheduling to decrease the length of the scheduling frame. We first illustrate the scheduling performance for different $P_h$ values. Schedule length decreases with the increasing $P_h$ since higher HAP power indicates that users can start and thus complete their transmissions earlier in the scheduling frame since any user will be able to afford $P_{max}$ transmit power earlier via harvesting more energy from the HAP. While for large values, optimal scheduling loses its importance on the performance, for relatively small and practical values of $P_h$, MLSA outperforms PDO significantly. A similar superiority of MLSA can be observed from the figure for increasing $P_{max}$ values. As $P_{max}$ increases, performance of both algorithms initially improve since users continue to afford $P_{max}$ transmit power using their initial battery levels at the very beginning of the scheduling frame. However, above a critical value of $P_{max}$, increasing transmit power leads to increasing initial unallocated time $\tau_0$ in the scheduling frame. This results in a performance degradation for PDO while MLSA accommodates this effect by optimally determining the scheduling order. Finally, MLSA outperforms PDO for increasing number of users in the WPCN. While the schedule length almost increases linearly for PDO as the number of users increases, the increase in the schedule length diminishes for MLSA again indicating the significance of determining optimal transmission order.

B. Sum Throughput Maximization

In Fig. 3, we illustrate the throughput performance of the proposed algorithm MRSA in comparison to the optimal solution, denoted by OPT. Optimal solution is obtained by enumerating all possible transmission orders and picking the one yielding the highest throughput via solving a convex optimization problem for each transmission order. One clear observation is that MRSA performs nearly optimal on average while achieving exact optimal solutions in most network realizations. As HAP power $P_h$ increases, sum throughput yielded by MRSA increases while it saturates for large values of $P_h$ since the energy that can be used by the users in a scheduling frame...
is limited. For increasing $P_{\text{max}}$, sum throughput first increases since users can have higher transmission rates. Then, above certain $P_{\text{max}}$ values, users cannot afford $P_{\text{max}}$ in the beginning of the scheduling frame resulting an increase in the initial unallocated time and thus decrease in the total allocated time by the users. As the number of users increases, sum throughput achieved by the users almost increases linearly as expected ideally.

VI. CONCLUDING REMARKS

In this paper, we have investigated minimum length scheduling and sum throughput maximization problems for a full-duplex WPCN considering on-off transmission scheme. For both problems, we have derived the characteristics of the optimal solution and proposed polynomial-time solution schemes. As future work, we plan extending this study for discrete rate based transmission rate model in which users can select a transmission rate from a finite set based on their SNR levels. Moreover, the WPCN architecture for multiple hybrid access points will also be investigated.

REFERENCES


