Scheduling and Relay Selection for Full-Duplex Wireless Powered Cooperative Communication Networks

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***Abstract*—In this manuscript, we consider a full-duplex wireless powered cooperative communication system where the users communicate with a hybrid access point through relays. We formulate an optimization problem with the objective to minimize the total transmission time through user scheduling and relay selection while considering the traffic demand, energy causality and initial battery levels of the users. The formulated optimization problem is a mixed integer non-linear programming problem, hence difficult to solve for the global optimal solution. As a solution strategy, we decompose the problem into sub problems: time allocation, scheduling and relay selection. In the time allocation problem; the schedule and relays are assumed to be pre-known, we derive the optimal solution by using the optimality analysis. For the scheduling problem; we assume that users know their relays, we determine the optimal schedule. For the relay selection problem; users transmit their information in a pre-determined order, we determine the optimal relays for each user. For the overall scheduling and relay selection problem, we propose a heuristic algorithm which iteratively determines the scheduling and relay selection in polynomial time by using the optimal solutions of the individual relay selection and scheduling problems. Through simulations, we demonstrate that the scheduling length can be significantly reduced through proper scheduling and relay selection. The proposed algorithm performs very close to the optimal solution for different maximum user transmit power, network densities, initial battery levels and hybrid access point power levels.**

***Index Terms*—Total time minimization, wireless powered cooperative communication network, scheduling, Relay selection.**

I. INTRODUCTION

With the recent technological advances in the field of wireless sensor networks, the number of installed sensor nodes is continuously increasing. This requires sustainable solution to prolong the lifetime of such energy constrained nodes, therefore, avoid the battery replacement and make the system self sufficient. One solution is to harvest energy from the environment [1]. However, the energy harvested from conventional sources such as solar, vibration and wind depends on the weather conditions, hence, is un-predicted and uncontrollable. On the other hand, energy transfer through inductive and magnetic coupling has short range, large size and requires exact alignment, which makes it inappropriate for wireless sensor networks. Energy harvesting through radio frequency (RF) signals is a promising technology due to its long range, small form factor and full control on the transferred energy. In the literature, there are two operational models for RF energy harvesting (EH) known as simultaneous wireless information and power transfer (SWIPT) [2], [3] and wireless powered communication networks (WPCN) [4]. In SWIPT, the same RF signal is used for both wireless information and power transfer from the access point (AP) to multiple network nodes, whereas in WPCN, network nodes harvest energy in the downlink (DL) from the AP and send their information to the AP, using the harvested energy in the uplink (UL).

In conventional wireless networks without EH, relaying or cooperative communication technique has been utilized to improve the network coverage, system throughput and energy efficiency [5]. For the RF-EH networks recently, relays are being incorporated to assist the information transfer along with efficient energy management through cooperation [6]. There are two main categories of the relays: amplify-and-forward (AF), where a relay node amplifies the received signal from the source and sends it to the destination, and decode-and-forward (DF), where a relay node first decodes the signal received from the source and then sends it to the destination. Initially, researchers studied the three node relay based WPCN model, also known as wireless powered cooperative communication network (WPCCN). The authors in [7]–[9] study the WPCCN system, considering the half-duplex (HD) mode of transmission, where both relay and user need to harvest energy from the AP in the DL and then the user transmits the information to the AP in the UL, with or without relay. [7] also extends the three node model to multiple relay scenario and presents a relay selection problem, based on the available channel state information (CSI). [10] considers a multi-user multi-relay network model and presents a joint relay selection, scheduling and power control problem with the objective of minimizing the total duration of wireless power and information transfer for a HD system. To the best of our knowledge, only [7] and [10] present the relay selection problem for WPCCN systems, but they are limited to HD mode of transmission. In the HD system, the EH duration is fixed and all the users/relays get equal time to harvest the energy, therefore, scheduling is not important. However, in the full-duplex (FD) model, hybrid access point (HAP) transmits energy throughout the frame, which results in uneven EH times for the users and relays. For FD models, scheduling is important because the transmission of users with low energy levels can be delayed so that they can harvest more energy during the transmission of other users leading to smaller total transmission time.

Due to very large number of nodes and low energy harvesting rates, the relay and user architecture should be simple so that they can be used with low power consumption. Because of simple power amplifiers and low processing cost, on-off transmission scheme can be very useful for the inexpensive wireless sensor networks, leading to affordable and widespread deployments of IoT applications. In the context of WPCN, on-off transmission scheme has been incorporated in [11]–[13]. Specifically, [11] and [12] analyzes the average error rate and outage probability for a single user system whereas, [13] presents the minimum length scheduling and sum throughput maximization problems for a multi-user single hop system.

In this paper, we present an optimization framework for a FD-WPCCN system by considering the energy causality and a more practical non-linear energy harvesting model for an on-off transmission scheme, for the first time in the literature. We formulate a mixed integer non-linear programming (MINLP) problem with the objective of minimizing the total transmission time through relay selection and user scheduling, then, we decompose the problem into sub-problems, named as time allocation problem (TAP), scheduling problem, relay selection problem. For the first three problems, we derive an optimal solution. For the overall scheduling and relay selection problem, we present a polynomial time heuristic algorithm based on iterative calling of the optimal solutions.

II. SYSTEM MODEL AND ASSUMPTIONS

We consider a wireless powered communication network consisting of single HAP, N users and K decode-and-forward (DF) relays, as depicted in Fig. 1. The HAP operates in FD mode and is equipped with a single FD antenna, which is capable of simultaneous energy transmission and information reception. The HAP transmits at constant power P_h during the whole transmission frame. The users and relays are completely dependent on the harvested energy, which they store in their batteries. The initial battery level at the start of the frame is denoted by B_i, $i \in \{1,...,N\}$ and B_k, $k \in \{1,...,K\}$ for the users and relays, respectively. We assume that in each scheduling frame, user i has a traffic demand of D_i bits. All the channel gains are assumed to be block fading, i.e., channel gains remain same within a transmission frame. The DL channel gain from the HAP to relay k and from HAP to user i are denoted by h_k and h_i, respectively. The UL channel gain from user i to relay k and from relay k to the HAP are denoted by $g_{i,k}$ and g_k, respectively. We assume time division multiple access protocol as the medium access protocol. The total time in which system remains operational is divided into multiple slots of variable length and each slot is allocated to the users/relays for the information transmission or energy harvesting. We assume a more practical non-linear energy harvesting model based on a logistic function [14] and the energy harvesting rate of user i is given by

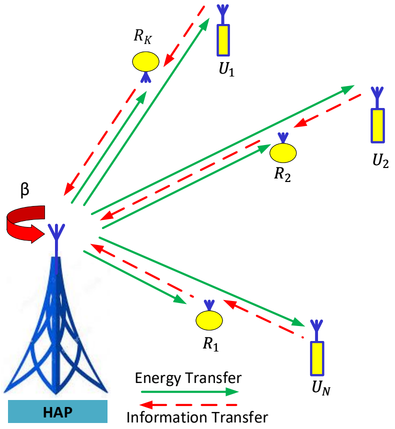

Fig. 1. System Model

$$C_i = \frac{P_s\left(\Psi_i - \Omega\right)}{\left(1-\Omega\right)}, \tag{1}$$

where Ψ_i=$(1+e^{-a_1(P_h h_i - a_2)})^{-1}$, and $\Omega = (1+e^{a_1 a_2})^{-1}$ is a constant to make sure zero-input zero-output response. The EH rate for relay k is given by

$$C_k = \frac{P_s\left(\Psi_k - \Omega\right)}{\left(1-\Omega\right)}, \tag{2}$$

where Ψ_k=$(1+e^{-a_1(P_h h_k - a_2)})^{-1}$, P_s represents the saturation power, a_1 and a_2 are the positive constants related to the non-linear charging rate with respect to the input power and turn-on threshold, respectively. We assume that users and relays can harvest energy throughout the frame except when they are transmitting or receiving the information. The information transmission time of user i to relay k is denoted by $\tau_{i,k}$ and the information transmission time of relay k is denoted by τ_k. The energy harvesting time of user i until it starts information transmission is given by $\sum_{j\in\mathcal{U}}(\tau_{0j}+\tau_j)+\sum_{m\in\mathcal{R}}(\tau_{0m}+\tau_m)$, where $\mathcal{U}$ is a set of users that are scheduled before user i and $\mathcal{R}$ is a set of relays that are used to forward the information to HAP before the information transmission of user i. The τ_{0j} is the required waiting time duration for the j^{th} user in $\mathcal{U}$ so that it can transmit its information in τ_j amount of time at power P_{max}. The τ_{0m} is the required waiting time of the m^{th} relay in set $\mathcal{R}$ so that it can forward the information in τ_m amount of time at power P_{max}. The total available energy for user i is given by

$$E_i = B_i + C_i\left(\sum_{j\in\mathcal{U}}(\tau_{0j}+\tau_j) + \sum_{m\in\mathcal{R}}(\tau_{0m}+\tau_m)\right) \tag{3}$$

Similarly, the energy harvesting time before the information transmission of relay k is $\sum_{j\in\mathcal{V}}(\tau_{0j}+\tau_j)+\sum_{m\in\mathcal{S}}(\tau_{0m}+\tau_m)$, where $\mathcal{V}$ and $\mathcal{S}$ are the set of users and relays which are used before relay k, respectively. The total available energy of relay k denoted by E_k is given as

$$E_k = B_k + C_k\left(\sum_{j\in\mathcal{V}}(\tau_{0j}+\tau_j) + \sum_{m\in\mathcal{S}}(\tau_{0m}+\tau_m)\right) \tag{4}$$

We use continuous transmission rate model and Shannon's channel capacity formula is used to determine the transmission rates of both users and relays.

III. PROBLEM FORMULATION

In this section, we formulate the joint optimization problem for the scheduling, time allocation and relay selection denoted by $\mathcal{SRSP}$. The objective of $\mathcal{SRSP}$ is to minimize the total transmission time subject to energy causality and users traffic demand which is given as

$\mathcal{SRSP}$

$$\textit{minimize} \quad \tau_0 + \sum_{i=1}^{N}\sum_{k=1}^{K}\tau_{i,k} + \sum_{k=1}^{K}\tau_k \tag{5a}$$

subject to

$$\sum_{k=1}^{K} s_{i,k}\tau_{i,k}Wlog_2\left(1+\frac{g_{i,k}P_{max}}{WN_0}\right) \geq D_i; \quad \forall i \tag{5b}$$

$$E_i - \tau_{i,k}P_{max} \geq 0 \quad \forall i \tag{5c}$$

$$\sum_{i=1}^{N} s_{i,k}\tau_i Wlog_2\left(1+\frac{g_iP_{max}}{\beta P_h + WN_0}\right) \geq \sum_{i=1}^{N} D_i s_{i,k}; \quad \forall k \tag{5d}$$

$$E_k - \tau_k P_{max} \geq 0 \quad \forall k \tag{5e}$$

$$\sum_{k=1}^{K} s_{i,k} = 1; \quad \forall i \tag{5f}$$

$$a_{ij} + a_{ji} = 1 \quad \forall i,j \tag{5g}$$

variables

$$\tau_{i,k}, \tau_k, \geq 0; \quad \forall i, \forall k; s_{i,k} \in \{0,1\}; a_{i,j} \in \{0,1\}; \tag{5h}$$

The variables of the $\mathcal{SRSP}$ are $\tau_{i,k}$, the transmission time of user i by using relay k; τ_k, transmission time of relay k; $a_{i,j}$, the scheduling variable, which takes value 1 if user i transmits data before user j and 0 otherwise; and $s_{i,k}$, the relay selection variable, which is a binary variable and takes value 1 if user i transmits information by using relay k and zero otherwise. Additionally, τ_0 is the time in which users/relays harvest energy only. The objective of the optimization problem is to minimize the schedule length given in Eq. (5a). Eqs. (5b) and Eq. (5d) represent the constraints on satisfying the traffic demand of the users. Eqs. (5c) and (5e) represent the energy causality constraints of the users and relays, respectively, i.e., consumed energy should be less than the available energy. Eq. (5f) guarantees that only one relay is selected for each user. Eq. (5g) represents the scheduling constraint, i.e., if user i transmits information before user j then user j can not transmit information before user i. The $\mathcal{SRSP}$ is a mixed integer non-linear programming problem (MINLP), which is generally hard to solve for the optimal solution. To solve the problem optimally, we decompose the $\mathcal{SRSP}$ into two sub-problems, namely, time allocation problem $\mathcal{TAP}$ and scheduling and relay selection (SRS) problem.

IV. TIME ALLOCATION PROBLEM

In this section, we formulate the time allocation problem in which all the users know their transmission order and the relay, i.e, $s_{i,k}$ and $a_{i,j}$ are known. Without loss of generality, we assume that user i transmits in the i^{th} transmission slot by using relay k. The TAP is formulated as follows:

$\mathcal{TAP}$

$$\textit{minimize} \quad \tau_0 + \sum_{i=1}^{N}\sum_{k=1}^{K}\tau_{i,k} + \sum_{k=1}^{K}\tau_k \tag{6a}$$

subject to

$$\tau_{i,k}Wlog_2\left(1+\frac{g_{i,k}P_{max}}{WN_0}\right) \geq D_i; \quad \forall i \tag{6b}$$

$$E_i - \tau_{i,k}P_{max} \geq 0 \tag{6c}$$

$$\tau_k Wlog_2\left(1+\frac{g_kP_{max}}{\beta P_h + WN_0}\right) \geq D_i; \quad \forall k \tag{6d}$$

$$E_k - \tau_k P_{max} \geq 0 \tag{6e}$$

variables

$$\tau_{i,k}, \tau_k, \geq 0; \quad \forall i, \forall k; \tag{6f}$$

The variables of the $\mathcal{TAP}$ are $\tau_{i,k}$, the transmission time of user i by using relay k, and τ_k, transmission time of relay k. It can be easily verified that the formulated problem (6) is a linear optimization problem, which can be solved for optimal solution.

Lemma 1. *In an optimal solution of $\mathcal{TAP}$, the constraints in Eqs. (6b) and (6d) should hold with equality.*

Proof. Suppose that in an optimal solution $\tau = \{\tau^*_{1,k}, \tau^*_{2,k}, \cdots, \tau^*_{N,k}\}$ are the allocated transmission times of users such that $\tau^*_{i,k}Wlog_2\left(1+\frac{g_{i,k}P_{max}}{WN_0}\right) > D_i$. The function $f(\tau^*_{i,k}) \triangleq x\tau^*_{i,k}$, where x is a constant, is a linearly increasing function of x for $x > 0$. Therefore, for any user i, we can always find a $\tau'_{i,k}$ such that $\tau'_{i,k}Wlog_2\left(1+\frac{g_{i,k}P_{max}}{WN_0}\right) = D_i$ and it is clear that $\tau'_{i,k} < \tau^*_{i,k}$. This is a contradiction. In a similar way, we can prove that Eq.(6d) should also hold with equality.

Due to Lemma 1, the optimal transmission time of user i by using relay k is given by

$$\tau_{i,k} = \frac{D_i}{Wlog_2\left(1+\frac{g_{i,k}P_{max}}{WN_0}\right)} \tag{7}$$

Similarly, the required energy for the data transmission in $\tau_{i,k}$ is

$$E_i^{req} = \tau_{i,k}P_{max} \tag{8}$$

As users transmit data by using a constant rate model, initially user may not afford the P_{max} for its complete transmission. Therefore, the users need to wait so that they can harvest enough energy for data transmission. The optimal waiting time for user i to reach the required energy level denoted by $\tau_{0,i}$ is given by

$$\tau_{0,i} = \frac{1}{C_i}(E_i^{req} - E_i) \tag{9}$$

Due to Lemma 1, the optimal transmission time of relay k to forward the information of user i is given by

$$\tau_k = \frac{D_i}{Wlog_2\left(1 + \frac{g_k P_{max}}{\beta P_h + W N_0}\right)} \tag{10}$$

The required energy for the relay to forward the user information of user i is given by

$$E_k^{req} = \tau_k P_{max} \tag{11}$$

The waiting time for relay k, denoted by $\tau_{0,k}$, is given by

$$\tau_{0,k} = \frac{1}{C_k}(E_k^{req} - E_k) \tag{12}$$

Now once we have solved the TAP problem optimally, next we will analyze the SRS problem.

V. SCHEDULING AND RELAY SELECTION

To determine the optimal schedule and relay selection, first we analyze the problem for a pre-determined relay selection, i.e., $s_{i,k}$ are known, and we aim to determine the optimal $a_{i,j}$. Then, using the known optimal schedule of the users, we find the best relay for each user.

A. Scheduling Problem

Let us define the term $T_{i,k}$ as the total time for user i to transmit the information from user i to the HAP via relay k, which consist of both energy harvesting and information transmission, and is given by

$$T_{i,k} = \tau_{0,ik} + \tau_i, \tag{13}$$

where $\tau_{0,ik} = \tau_{0,i} + \tau_{0,k}$ is the required energy harvesting time for user i and corresponding relay; $\tau_i = \tau_{i,k} + \tau_k$ is the transmission time of user i and corresponding relay. The following lemma gives the optimal scheduling scheme for the predetermined relay selection.

Lemma 2. *In an optimal solution of scheduling problem, users are allocated in increasing order of their transmission completion time values.*

Proof. This can be proved by contradiction. Suppose that $\tau^* = [\tau_0^*, \tau_1^*, \tau_2^*, ..., \tau_N^*]$ is the set of optimal transmission times for the users with τ_0^* as the total energy harvesting duration. Let $t^* = [t_1^*, t_2^*, ..., t_N^*]$ denote the transmission completion time of the users such that $t_1^* < t_2^* < ... < t_N^*$ and schedule length $L^* = t_N^*$. Now let us interchange the order of any two successive users j and $j+1$ such that user $j+1$ transmits before user j. The schedule length of this new schedule will be $t_N^* + \tau_j > L^*$, which is a contradiction. $\square$

The foregoing lemma suggests that at any particular time instant t^{dec}, the optimal policy for the user scheduling is to allocate the user with minimum $T_{i,k}$. Based on this discussion, the scheduling algorithm presented in Algorithm 1 is described as follows. The algorithm starts by initializing $\mathcal{S}$, τ_0, $t(\mathcal{S})$ to an empty set (Line 3). For each user i of the system, the total time to transmit information to the HAP $T_{i,k}$ is evaluated (Line 5). Then, the user j with minimum $T_{i,k}$ is selected (Line 6) and the set $\mathcal{S}$ is updated with the user with minimum $T_{i,k}$ (Line 7). τ_0 is updated by adding the energy harvesting time of the user j (Line 9) and $t(\mathcal{S})$ by adding the total transmission time of user j (Line 10). Algorithm terminates when all the users in the system are being scheduled accordingly. The computational complexity of SA is $\mathcal{O}(N^2)$. In the following, we present the relay selection scheme for the users.

Algorithm 1 Scheduling Algorithm

```
1:  input: set of users $\mathcal{N}$ and a relay for each user
2:  output: transmission schedule $\mathcal{S}$, total energy harvesting time
        $\tau_0$, schedule length $t(\mathcal{S})$
3:  $\mathcal{S} \leftarrow \emptyset$, $t(\mathcal{S}) \quad 0$, $\tau_0 \quad 0$,
4:  while $\mathcal{N} \neq \emptyset$ do
5:      Evaluate $T_{i,k}$ for $\forall i \in \mathcal{N}$
6:      $j \quad \text{argmin}_{i \in \mathcal{N}} T_{i,k}$,
7:      $\mathcal{S} \leftarrow \mathcal{S}$ + $\{j\}$,
8:      $\mathcal{N} \leftarrow \mathcal{N}$ - $\{j\}$,
9:      $\tau_0 \quad \tau_0 + \tau_j^{EH}$,
10:     $t(\mathcal{S}) \quad t(\mathcal{S}) + T_{i,k}$,
11: end while
```

B. Relay selection algorithm

Similar to the scheduling problem for a known relay selection, it is optimal to allocate the relay which gives minimum $T_{i,k}$ to each user for a predetermined transmission order and the optimality can be easily proved just like Lemma 2. The Relay Selection Algorithm (RSA) takes a set of users $\mathcal{N}$ and a schedule as input, and returns the optimal relay selection, transmission and waiting times of users and relays, and optimal schedule length. RSA starts by initializing relays $\mathcal{R}$, transmission times and waiting times to an empty set and schedule length to 0 (Line 3). For each scheduled user i, the algorithm evaluates $T_{i,k}$ and finds the relay with minimum $T_{i,k}$ (Lines $5-6$). Then, this relay is allocated to user i for relaying its information to the HAP (Line 7). The algorithm updates the schedule length, transmission and waiting times of the users and relays (Lines $8-12$). The algorithm terminates when all the users are assigned a relay (Line 4). The computational complexity of RSA is $\mathcal{O}(N \times K)$.

Algorithm 2 Relay Selection Algorithm (RSA)

```
1:  input: set of user $\mathcal{N}$, schedule $\mathcal{S}$
2:  output: Relay selection $\mathcal{R}$, user transmission times $\tau_{\mathbf{i,k}}$, user
        waiting times $\tau_{\mathbf{0,i}}$, relay transmission times $\tau_{\mathbf{k}}$, relay waiting
        times $\tau_{\mathbf{0,k}}$, schedule length $t(\mathcal{S})$
3:  $\mathcal{R} \leftarrow \emptyset$, $\tau_{\mathbf{i,k}}(\mathcal{R}) \leftarrow \emptyset$, $\tau_{\mathbf{0,i}}(\mathcal{R}) \leftarrow \emptyset$, $\tau_{\mathbf{k}}(\mathcal{R}) \leftarrow \emptyset$, $\tau_{\mathbf{0,k}}(\mathcal{R}) \leftarrow$
        $\emptyset$, $t \leftarrow 0$
4:  for $i = 1 : |\mathcal{N}|$ do
5:      Evaluate $T_{i,k}$ for $\forall i \in \mathcal{K}$
6:      $j \leftarrow \text{argmin}_{i \in \mathcal{N}} T_{i,k}$,
7:      $\mathcal{R} \leftarrow \mathcal{R}$ + $\{j\}$,
8:      $t \leftarrow t + T_{i,k}(j)$,
9:      $\tau_{\mathbf{0,i}} \leftarrow \tau_{\mathbf{0,i}}$ + $\{\tau_{0,i}\}$,
10:     $\tau_{\mathbf{i,k}} \leftarrow \tau_{\mathbf{i,k}}$ + $\{\tau_{i,m}\}$,
11:     $\tau_{\mathbf{0,k}} \leftarrow \tau_{\mathbf{0,k}}$ + $\{\tau_{0,m}\}$,
12:     $\tau_{\mathbf{k}} \leftarrow \tau_{\mathbf{k}}$ + $\{\tau_m\}$,
13: end for
```

C. Scheduling and Relay Selection Problem

The purpose of this section is to determine the schedule and relay selection which minimizes the overall transmission time of the network. As in the last section we have solved the scheduling problem and relay selection problem optimally, one straight forward solution to the scheduling and relay selection problem is to enumerate all the possible schedule and relay combinations and pick the one which gives the minimum transmission time. However, this brute-force scheme has an exponential computational complexity and it is intractable even for a medium size networks. Therefore, in the following, we will present a polynomial-time heuristic algorithm.

D. Scheduling and Relay Selection algorithm

The scheduling and relay selection algorithm $\mathcal{SRS}$ presented in Algorithm 3, is described as follows. The algorithm starts by taking set of users $\mathcal{N}$ with a predetermined relays $\mathcal{K}$ and optimal schedule length $t_{op}(\mathcal{S})$ obtained by brute-force as inputs. Then, the transmission schedule $\mathcal{S}$ and corresponding relays $\mathcal{R}$ are initialized by empty set. The algorithm also initializes the schedule length $t_{SRS}(\mathcal{S})$ to 0 and tolerance ϵ to value 0.03 (Line 3). The algorithm evaluates the schedule for the given relay selection by using the Algorithm 1 (Line 5). Then, this schedule is passed to the relay selection algorithm which evaluates the schedule length and optimal relay selection for this schedule (Line 6). The algorithm executes iteratively until the difference between the optimal schedule length and $t_{SRS}(\mathcal{S})$ is greater than the tolerance ϵ. The algorithm terminates when desired tolerance is achieved (Line 7).

Algorithm 3 Scheduling and Relay Selection Algorithm (SRS)

```
1: Input: set of users $\mathcal{N}$, set of predetermined relays $\mathcal{R}$, optimal schedule length $t_{op}$
2: Output: transmission schedule $\mathcal{S}$, schedule length $t_{SRS}(\mathcal{S})$, relay selection $\mathcal{R}$
3: $\mathcal{S} \leftarrow \emptyset$, $\mathcal{R} \leftarrow \emptyset$, $t_{SRS} \leftarrow 0$, $\epsilon \leftarrow 0.03$,
4: while $t_{op}$-$t_{SRS} > \epsilon$ do
5:     obtain schedule $\mathcal{S}$ by using $SA$ for relays $\mathcal{R}$,
6:     obtain schedule length $t_{SRS}$ and optimal relay selection $\mathcal{R}$ by using $RSA$ for schedule $\mathcal{S}$
7: end while
```

VI. PERFORMANCE ANALYSIS

The purpose of this section is to compare the performance of $\mathcal{TAP}$, scheduling algorithm denoted by $Scheduling$ and the scheduling and relay section algorithm denoted by SRS in comparison to the optimal solution denoted by BFA. Simulation results are obtained by averaging over 1000 independent random network realizations. The attenuation of the links considering large-scale statistics are determined using the path loss model given by $PL(d) = PL(d_0) + 10\alpha log_{10}\left(\frac{d}{d_0}\right) + Z$ where $PL(d)$ is the path loss at distance d in dB, d_0 is the reference distance, α is the path loss exponent, and Z is a zero mean Gaussian random variable with standard deviation σ. The small-scale fading has been modelled by using Rayleigh fading with scale parameter Ω_i set to mean power level obtained from the large-scale path loss model. The parameters used in the simulations are $\eta_i = 1$ for $i \in \{1, \cdots, N\}$; D_i is assumed to be 100 for $i \in \{1, \cdots, N\}$; $W = 1$ MHz; $d_0 = 1$ m; $PL(d_0) = 30$ dB; $\alpha = 2.76$, and $\sigma = 4$ [15]. The self interference coefficient β is taken as -80 dBm. For non-linear energy harvesting model, $P_s = 7mW$, $A = 1500$ and $B = .0022$.

Fig. 2 illustrates the performance of the algorithms for different HAP power levels, P_{max} levels and number of users. The schedule length decreases as the HAP power increases because higher HAP power increases the energy harvesting rate, which results in smaller waiting time for all the users. Above a certain value of P_h, the schedule length is almost constant due to the saturation region of all the users and relays and any further increase in the HAP power does not improve the energy harvesting rate. For lower values of the HAP power, scheduling performs significantly better than the TAP algorithm because delaying the users with low initial energy level gives them time to harvest more energy, hence, reduces their waiting time. However, the higher values of the HAP power, the smaller the scheduling impact due to higher energy harvesting rate and very low waiting times. The proposed SRS algorithm performs very close to the optimal solution for all the values of HAP power. For the P_{max} analysis, initially the total transmission time decreases as the P_{max} increases since users have higher energy level and they can utilize more energy by using higher power level. However, above a certain value of P_{max}, the schedule length starts increasing because users/relays are not allowed to transmit below P_{max}, therefore, higher P_{max} value requires more waiting time to reach this particular P_{max} value. The proposed solution performs significantly better than TAP and $Scheduling$ algorithm and performs very close to the optimal solution for all the range of P_{max} values. The last graph shows the impact of number of users on the total transmission length. For small number of users, the scheduling is not important however, as the network size increases, the scheduling becomes more important. In a larger network, it is more probable to find a user with very small waiting time, which makes scheduling more important. Initially, schedule length increases linearly, however, as the network sizes increases, any further addition of a user results in very small increase in the total transmission time.

Finally, we analyse the runtime of the proposed algorithms in Fig. 3 for different number of nodes. The runtime of the optimal algorithm achieved by brute force increases exponentially with the addition of every new node, whereas the addition of new nodes adds minimal computational burden to the proposed algorithms. The runtime of the proposed algorithm is one thousandth time smaller than the optimal algorithm. It is important to note that the proposed algorithm performs very close to the optimal solution for all the ranges of different parameters as shown in Fig. 2.

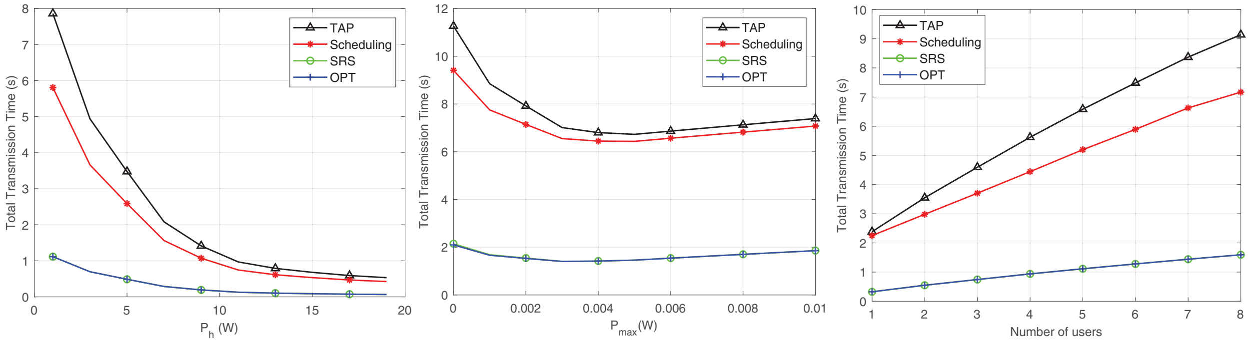

Fig. 2. Total transmission time of proposed algorithms for different P_h levels, P_{max} values and number of users in the network.

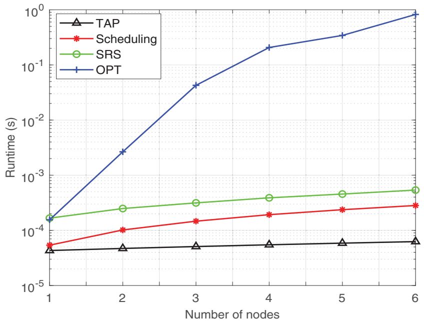

Fig. 3. Runtime of the proposed algorithms for different number of nodes

VII. CONCLUSION

In this paper, we investigate the total transmission time minimization problem through user scheduling and relay selection for a full-duplex WPCCN system considering on-off transmission scheme. First, we mathematically formulate the optimization problem as MINLP problem, which is difficult to solve in polynomial time. To solve the problem efficiently, we analyze the problem for time allocation, scheduling and relay selection individually and derive the optimal solution for each based on the optimality analysis. Then, for the overall scheduling and relay selection problem, we propose a heuristic algorithm which determines the schedule and corresponding relays by iteratively calling the optimal algorithms of the scheduling and relay selection. For future work, we aim to extend this study for discrete transmission rate and discrete power level models in which users can select a transmission rate/power from a finite set of discrete rate/power levels for their information transmission.

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