

In-Band Full-Duplex Wireless Powered Communication Networks

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Abstract—In this paper, we consider wireless powered communication network (WPCN) in which a hybrid access point (H-AP) and user equipments (UEs) all operate in in-band full-duplex (IFD) mode. FD ability of UE allows it to harvest energy from the received energy while it transmits information in uplink (UL) at the same time, as well as that of the H-AP allows it to broadcast energy in the downlink (DL) while it receives UEs' UL information. In the aforementioned network, we derived optimal UL time allocation to users to maximize the sum-throughput in the network. We show by simulation that the IFD WPCN has higher throughput than that of HD WPCN when the self-interference (SI) can be effectively cancelled thanks to more efficient use of UL time and increased harvested energy.

I. INTRODUCTION

Recently, harvesting energy from the far-field radio-frequency (RF) signal transmission has a great deal of attention as a viable new source for energy harvesting. One line of research to use RF energy energy harvesting is aimed to design a new type of wireless network termed wireless-powered communication network (WPCN) in which wireless user equipments (UEs) communicate using the energy harvested from wireless power transmissions. In particular, one particular WPCN model where a hybrid access-point (H-AP) coordinates wireless energy/information transmission to/from a set of distributed users in the downlink (DL) and uplink (UL) transmissions, respectively, has been proposed in [1]. It has been shown in [1] that there exists a fundamental trade-off in allocating DL time for wireless energy transfer and UL time for wireless information transmission in the half duplex (HD) WPCN, since increasing DL time increases the amount of harvested energy and hence the UL transmit power at each user, but also decreases users' UL time for information transmission given a total time constraint.

On the other hand, there has been recently a growing interest in in-band full duplex (IFD) based wireless systems, where the wireless node transmits and receives simultaneously in the same frequency band, thus potentially doubling the spectral efficiency. However, due to the simultaneous transmission and reception at the same node, IFD systems suffer from the self-interference (SI) that is part of the transmitted signal of an IFD node received by itself, thus interfering with the desired signal received at the same time. Self-interference cancellation (SIC)

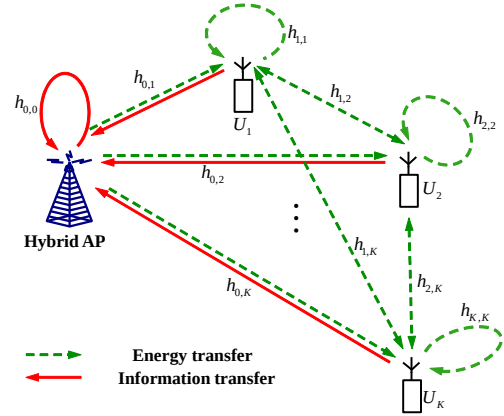


Fig. 1. A WPCN model with an IFD H-AP and IFD UEs.

is a key challenge for implementing IFD communication since the power of SI typically overwhelms that of the desired signal. Various SIC techniques have been proposed in the literature (see e.g., [2]-[4] and the references therein). By state-of-the-art SIC techniques today, it has been reported that SIC up to 110dB higher power of the desired signal can be implemented [2].

In this paper, we apply the IFD technique to the WPCN shown in Fig. 1, to further improve throughput. By allowing IFD operation, the H-AP is able to broadcast energy and receive information to/from the distributed users simultaneously over a given frequency band and thus significantly increases the time for wireless energy transfer, as compared to the half duplex HD considered in [1] in which DL time for energy transfer is limited. Furthermore, UEs operating in IFD mode are able to transmit their UL information while harvesting energy from the received signals at the same time. In addition, it also makes possible for UEs to harvest energy from the SI as well as other UEs' UL signals, so that the amount of harvested energy at each user increases. Taking IFD operations of both H-AP and UEs and increased harvested energy at each UE into consideration, we first study a time-division-multiple-access (TDMA) protocol that enables aforementioned operations of the H-AP and UEs. We then study UL time allocations to UEs to maximize the sum-throughput of the UEs in the UL.

II. SYSTEM MODEL

As shown in Fig. 1, this paper considers a WPCN consisting of one H-AP and K users (e.g., sensors) denoted by U_i ,

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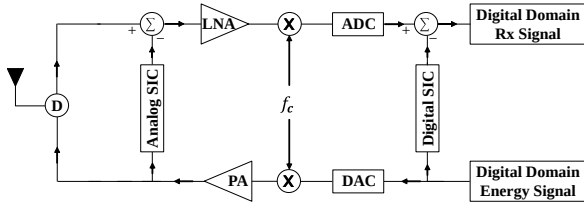


Fig. 2. Transceiver structure for H-AP.

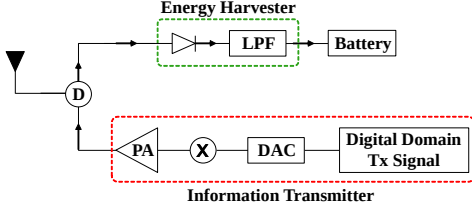


Fig. 3. Transceiver structure for UEs.

$i = 1, \dots, K$. The H-AP and UEs operate over the same frequency band, and are all equipped with a single full duplex antenna, e.g. [2]. The H-AP is assumed to have a stable energy supply, whereas each user terminal does not have any embedded energy sources. As a result, the users need to replenish energy from the received signal, which is then used to power operating circuit and transmit information. The H-AP broadcasts energy with constant power P_0 in the DL to power UEs and receive information in the UL, whereas UEs transmit information in the UL orthogonally over time using their respective harvested energy.

Thanks to IFD capability, at any given time the H-AP transmits energy signal in the DL while it receives information of a UE in the UL at the same time. Fig. 2 shows IFD transceiver structures for the H-AP. The transmitting and receiving ends of the H-AP are connected to a single antenna via, e.g., circulator [2] or electric balance duplex (EBD) [3] to enable IFD transmission and reception. Furthermore, SI cancellers are deployed in both analog and digital domains to prevent the energy signal from interfering with the received UL signal. In addition, Fig. 3 shows the IFD transceiver structure for UEs. Similarly to the H-AP, the transmitting and receiving ends of a UE are connected to a single antenna via circulator or EBD for IFD operation. In contrast to the H-AP, however, the receiving ends of UEs do not decode information, but harvest energy instead. Therefore, an energy harvester (e.g. rectifier [5]) is employed at the receiving end and any SI canceller is not deployed. UEs are also able to transmit information in the UL while it harvests energy from the received signals at the same time thanks to IFD capability.

Without loss of generality, we assume that the channels in this network all follow quasi-static flat-fading, and the channels remain constant during each block transmission time, denoted by T . The channel from U_i to U_j is denoted by a complex coefficient $h_{i,j}$ with channel power gain $H_{i,j} = |h_{i,j}|^2$, $i \in \{0, \dots, K\}$, $j \in \{0, \dots, K\}$ (U_0 denotes the H-AP in the sequel). Assuming channel reciprocity holds for both directions of transmissions, we have $h_{i,j} = h_{j,i}$. Furthermore,

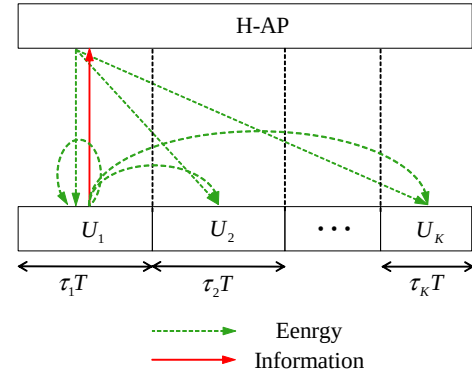


Fig. 4. Transmission protocol for WPCN with an IFD H-AP and IFD UEs.

$h_{i,i}$, $i = 0, 1, \dots, K$, denotes the loopback channel through which SI of U_i passes, including the transmit signal leakage inside the transceiver as well as its reflected versions from outside environment. It is further assumed that the H-AP perfectly knows $h_{i,j}$, $\forall i \in \{0, \dots, K\}$, $\forall j \in \{0, \dots, K\}$.

Fig. 4 shows transmission protocol in this IFD WPCN. Each transmit block is divided into K slots each with duration of $\tau_i T$, $0 \leq \tau_i \leq 1$, $i = 1, \dots, K$, where

$$\sum_{i=1}^K \tau_i \leq 1. \quad (1)$$

UEs transmit their own independent information by TDMA in the UL, i.e., U_i transmits information during the i th slot with $\tau_i T$ amount of time, while the H-AP broadcasts energy in the DL during whole block duration with a constant power P_0 .

During the i th slot, the received signal at the H-AP is then expressed as

$$y_{0,i} = \sqrt{P_i} h_{0,i} x_i + \sqrt{P_0} h_{0,0} x_0 + n_0, \quad (2)$$

where x_0 and x_i denote the transmitted signal from the H-AP and U_i , respectively, with $\mathbb{E}[|x_0|^2] = \mathbb{E}[|x_i|^2] = 1$. In addition, P_i denotes the transmit power of U_i . Furthermore, n_0 denotes the receiver noise at the H-AP, which is assumed to be $n_0 \sim \mathcal{CN}(0, \sigma_0^2)$, where $\mathcal{CN}(\nu, \sigma^2)$ stands for a circularly symmetric complex Gaussian (CSCG) random variable with mean ν and variance σ^2 . Since the H-AP has to decode x_i , the term $\sqrt{P_0} h_{0,0} x_0$ in (2) is SI at the H-AP.

During the i th slot, in addition, U_i transmit its own uplink information while receiving energy from the H-AP in the DL. Therefore, the received signal at U_i is expressed as

$$y_{i,i} = \sqrt{P_0} h_{0,i} x_0 + \sqrt{P_i} h_{i,i} x_i + n_i, \quad (3)$$

where $n_i \sim \mathcal{CN}(0, \sigma_i^2)$ stands for the receiver noise at U_i . Furthermore, the energy signal broadcast by the H-AP and the UL transmit signal of U_i during this time slot are also received by inactive UEs, i.e., U_j 's, $j = 1, \dots, K$, $j \neq i$, since all the transmissions and receptions are performed in the same frequency band at the same time. Therefore, the received signal at an inactive UE U_j is expressed as

$$y_{j,i} = \sqrt{P_0} h_{0,j} x_0 + \sqrt{P_i} h_{i,j} x_i + n_j, \quad (4)$$

where $n_j \sim \mathcal{CN}(0, \sigma_j^2)$ stands for the receiver noise at U_j . It is worth noting that in (3) and (4), U_i and U_j do not have any

information to decode. Therefore, all the received signals, i.e., $\sqrt{P_0}h_{0,i}x_0$, $\sqrt{P_i}h_{i,i}x_i$, $\sqrt{P_0}h_{0,j}x_0$, and $\sqrt{P_i}h_{i,j}x_i$ in (3) and (4), can all be used to harvest energy. In particular, $\sqrt{P_i}h_{i,i}x_i$ in (3) is used as an energy source instead of being cancelled as opposed to the typical IFD communication systems where it acts as SI and thus should be cancelled.

III. ACHIEVABLE THROUGHPUT OF IFD WPCN

In this section, we study the achievable throughput of each user in the UL when the harvested energy is utilized. Furthermore, we also study the optimal time allocation to maximize the sum-rate throughput in UL transmissions.

A. Achievable Throughput in IFD WPCN

Note that the harvested energy from receiver noise can be neglected due to its small amount [1]. From (3) and (4), the received energy of U_i during a block duration T , E_i , can thus be expressed as

$$E_i = \zeta_i \left(P_0|h_{0,i}|^2 + \tau_i P_i|h_{i,i}|^2 + \sum_{\substack{j=1 \\ j \neq i}}^K \tau_j P_j|h_{j,i}|^2 \right) T, \quad (5)$$

where ζ_i denotes the energy harvesting efficiency at U_i . We denote $0 < \eta_i < 1$ as the portion of the harvested energy used for wireless information transmission by U_i in steady state, which are assumed to be given constants. We then have

$$\tau_i P_i T = \theta_i E_i, \quad i = 1, \dots, K, \quad (6)$$

where $\theta_i = \zeta_i \eta_i$. From (5) and (6), it follows that

$$\mathbf{A} \mathbf{\Upsilon} \mathbf{P} = P_0 \mathbf{\beta}, \quad (7)$$

where $\mathbf{P} = [P_1 \ P_2 \ \dots \ P_K]^T$ and $\mathbf{\Upsilon} = \text{diag}\{\tau_1 \ \tau_2 \ \dots \ \tau_K\}$ with $\text{diag}\{\mathbf{v}\}$ denoting a diagonal matrix with $\mathbf{v}$ consisting of its diagonal entries. Furthermore, $\mathbf{A}$ is a matrix where

$$A_{i,j} = \begin{cases} 1 - \theta_i |h_{i,i}|^2 & , \text{ if } j = i \\ -\theta_i |h_{i,j}|^2 & , \text{ otherwise,} \end{cases} \quad (8)$$

with $A_{i,j}$ denoting the element of matrix $\mathbf{A}$ on the i th row and j th column. Finally, $\mathbf{\beta}$ is a vector given by

$$\mathbf{\beta} = [\theta_1 |h_{1,0}|^2 \ \theta_2 |h_{2,0}|^2 \ \dots \ \theta_K |h_{K,0}|^2]^T. \quad (9)$$

From (7)-(9), P_i is given by

$$P_i = \rho_i \frac{P_0}{\tau_i}, \quad i = 1, \dots, K, \quad (10)$$

where ρ_i , $i = 1, \dots, K$, is given by

$$[\rho_1 \ \rho_2 \ \dots \ \rho_K] = \mathbf{A}^{-1} \mathbf{\beta}. \quad (11)$$

It is worth noting that after SIC, the residual SI at the H-AP can be approximated as $I_0 \sim \mathcal{CN}(0, \alpha P_0)$, where $\alpha \ll 1$. Given time allocation to users $\boldsymbol{\tau} = [\tau_1 \ \dots \ \tau_K]$, achievable throughput of U_i in the UL during the i th slot is then expressed from (2) and (10) as

$$\begin{aligned} R_i(\boldsymbol{\tau}) &= \tau_i \log_2 \left(1 + \frac{|h_{0,i}|^2 P_i}{\sigma_0^2 + \alpha P_0} \right) \\ &= \tau_i \log_2 \left(1 + \frac{\gamma_i(P_0)}{\tau_i} \right), \quad i = 1, \dots, K, \end{aligned} \quad (12)$$

where γ_i is given by

$$\gamma_i(P_0) = \frac{\rho_i |h_{i,0}|^2 P_0}{(\sigma_0^2 + \alpha P_0)}, \quad i = 1, \dots, K, \quad (13)$$

with ρ_i , $i = 1, \dots, K$, given in (11).

B. Time Allocation to Maximize Sum-Throughput

To maximize sum-throughput in this network, optimal time allocation, denoted by $\boldsymbol{\tau}^*$, can be obtained by solving the following problem:

$$\begin{aligned} \text{(P1): } \max_{\boldsymbol{\tau}} \quad & \sum_{i=1}^K R_i(\boldsymbol{\tau}) \\ \text{s.t.} \quad & \sum_{i=1}^K \tau_i \leq 1, \end{aligned} \quad (14)$$

$$\tau_i > 0, \quad i = 1, \dots, K. \quad (15)$$

It can be easily shown that $R_i(\boldsymbol{\tau})$ is a concave function of $\boldsymbol{\tau}$. Since the constraint in (14) is an affine function of $\boldsymbol{\tau}$, problem (P1) is a convex optimization problem. The optimal time allocation for (P1), $\boldsymbol{\tau}^*$, is then given in the following proposition.

Proposition 3.1: The optimal time allocation solution for (P1) to maximize sum-throughput is given by $\boldsymbol{\tau} = [\tau_1^* \ \dots \ \tau_K^*]$, where

$$\tau_i^* = \frac{\gamma_i(P_0)}{\sum_{j=1}^K \gamma_j(P_0)}, \quad i = 1, \dots, K. \quad (16)$$

Proof: Please refer to Appendix. ■

From (16) in Proposition 3.1, it is observed that $\tau_i \propto \gamma_i$. It is worth noting that $\rho_i h_{i,0} P_0$ in (13) is the received signal power at the H-AP during the i th slot, expressed with respect to P_0 . Therefore, γ_i is equivalent to the received signal-to-noise plus interference ratio (SINR) at the H-AP during the i th slot, expressed as a function of transmit power of the H-AP, P_0 . Given P_0 , the optimal UL time allocated to U_i is thus proportional to the received SINR of its UL signal at the H-AP during the i th slot.

IV. SIMULATION RESULT

In this section, we compare the maximum sum-throughput of IFD WPCN by (P1) versus that of HD WPCN studied in [1]. Neglecting short-term fading for convenience, the channel power gains in the network are modeled as $H_{i,j} = 10^{-3} D_{i,j}^{-\delta}$, $\forall i \in \{1, \dots, K\}$, $\forall j \in \{1, \dots, K\}$, $i \neq j$, for distance $D_{i,j}$ in meter, with the path-loss exponent $\delta = 2$ and 30dB signal power attenuation at a reference distance of 1m. For SI channels, we set $h_{i,i} = 0.03$, $\forall i = 1, \dots, K$, assuming that 15dB isolation of SI signal is achieved at UEs with circulators [2]. Moreover, it is assumed that the bandwidth is 1MHz and the AWGN at the receivers of the H-AP and UEs is assumed to have a white power spectral density of -160dBm/Hz . For each user, further it is assumed that $\eta_i = 0.75$, $\forall i$, and $\zeta_i = 0.67$, $\forall i$. Finally, UEs are assumed to be randomly located between two concentric circles centered at the origin with diameters 3m

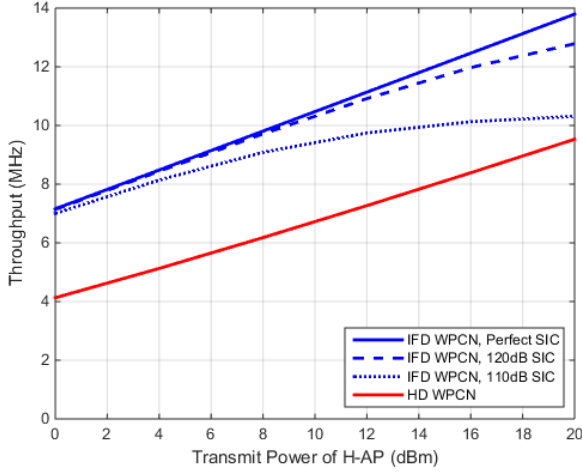


Fig. 5. Throughput comparison for HD versus IFD WPCN.

and 7m, respectively, where the coordination of U_i is given by $(D_{i,0} \cos \varphi_i, D_{i,0} \sin \varphi_i)$ with $D_{i,j}$'s and φ_i 's distributed uniformly in $[3, 7]$ and $[0, 2\pi]$, respectively.

Fig. 5 shows the maximum sum-throughput of IFD-WPCN versus HD-WPCN for different values of P_{avg} in dBm by averaging over 1000 randomly generated user locations, with $K = 10$. As shown in this figure, the average sum-throughput of IFD WPCN is always larger than that of HD-WPCN when SI is perfectly eliminated. However, it is observed that when SI at the H-AP is not perfectly cancelled, throughput of IFD WPCN is degraded. In this typical example, in particular, the H-AP should cancel more than 110dB SI for IFD WPCN to have higher throughput than that of HD WPCN. The improvement of throughput in IFD WPCN is first because more time is allocated to each UE for UL since no time is used for DL, and also because harvested energy at each UE is increased thanks to IFD capability.

V. CONCLUSION

This paper studied resource allocation and throughput of IFD WPCN in which H-AP and UEs all operate in IFD mode. By allowing UEs to operate in IFD, UEs can harvest energy from the received energy while it transmits information in UL at the same time, as well as the H-AP broadcasts energy in the DL while it receives UEs' UL information. In the aforementioned network, we derived optimal UL time allocation to users to maximize the sum-throughput in the network. Simulation results revealed that the IFD WPCN has higher throughput than that of HD WPCN when the SI can be effectively cancelled.

APPENDIX

The Lagrangian of (P1) is given by

$$\mathcal{L}(\tau, \lambda) = \sum_{i=1}^K R_i(\tau) - \lambda \left(\sum_{i=1}^K \tau_i - 1 \right), \quad (17)$$

where $\lambda \geq 0$ denotes the Lagrange multiplier associated with the constraint in (1). The dual function of (P1) is thus given

by

$$\mathcal{G}(\nu) = \min_{\tau \in \mathcal{D}} \mathcal{L}(\tau, \lambda), \quad (18)$$

where $\mathcal{D}$ is the feasible set of τ specified by (14) and (15).

It can be shown from (14) and (15) that there exists an $\tau \in \mathcal{D}$ with $\tau_i > 0$, $i = 1, \dots, K$, satisfying $\sum_{i=1}^K \tau_i < 1$, and thus strong duality holds for this problem thanks to the Slater's condition [6]. Since (P1) is a convex optimization problem for which the strong duality holds, the Karush-Kuhn-Tucker (KKT) conditions are both necessary and sufficient for the global optimality of (P1), which are given by

$$\sum_{i=1}^K \tau_i^* \leq 1, \quad (19)$$

$$\lambda^* \left(\sum_{i=1}^K \tau_i^* - 1 \right) = 0, \quad (20)$$

$$\frac{\partial}{\partial \tau_i} \sum_{i=1}^K R_i(\tau) - \lambda^* = 0, \quad i = 0, \dots, K, \quad (21)$$

where τ_i^* 's and λ^* denote the optimal primal and dual solutions of (P1), respectively. It can be easily verified that $\sum_{i=1}^K \tau_i = 1$ must hold for (P1) and thus from (20) without loss of generality, we assume $\lambda^* > 0$. From (21), it follows that

$$\ln \left(1 + \frac{\gamma_i(P_0)}{\tau_i^*} \right) - \frac{\frac{\gamma_i(P_0)}{\tau_i^*}}{1 + \frac{\gamma_i(P_0)}{\tau_i^*}} = \bar{\lambda}^*, \quad i = 1, \dots, K, \quad (22)$$

where $\bar{\lambda}^* = \lambda^* \ln 2$. For equality in (22) to hold for all the values of i for given P_0 , we should have

$$\frac{\gamma_1(P_0)}{\tau_1^*} = \frac{\gamma_2(P_0)}{\tau_2^*} = \dots = \frac{\gamma_K(P_0)}{\tau_K^*}, \quad (23)$$

It then follows from (20) and (23) that

$$\sum_{i=1}^K \tau_i^* = \frac{\tau_i^*}{\gamma_i} \sum_{j=1}^K \gamma_j = 1, \quad (24)$$

from which we have the optimal time allocation solution for (P1) given in (16).

This thus proves Proposition 3.1.

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