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Energy beamforming for full-duplex wireless-powered communication networks

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ABSTRACT

In this paper, we consider a full-duplex (FD) wireless-powered communication network (WPCN), where one FD hybrid access point (HAP) equipped with multiple antennas simultaneously transmits energy to and receives information from multiple users. Firstly, we propose a space division wireless energy allocation scheme and calculate the harvested energy in downlink wireless energy transfer (WET) for each user. Secondly, we derive an approximate closed-form expression of user's achievable ergodic rate in uplink wireless information transfer (WIT). Thirdly, the energy allocation for different users is optimized under the max–min user fairness constraint, and a closed-form solution is obtained. Numerical results show that the simulation and the approximation of achievable rates are well matched, and energy beamforming can effectively suppress self-interference (SI), and improve rates as well as fairness among users. Moreover, FD-WPCNs are shown to outperform half-duplex (HD) WPCNs in rates with same number of antennas.

1. Introduction

Nowadays, the performance of wireless devices are severely restricted by finite battery capacity. To prolong the lifetime of smart devices in wireless sensor networks (WSNs) and Internet of things (IoTs), we investigate wireless-powered communication networks (WPCNs) [1,2], where user equipment uses energy harvested from radio frequency (RF) signals to transmit information.

Full-duplex (FD) transmission is a potential technology for 5G communications. To improve the utilization of time and spectrum resources, FD technique has been investigated in multi-user WPCNs. In FD-WPCNs, hybrid information and energy access points (HAPs) simultaneously transmit energy and receive information, and users can keep on harvesting energy when other users are transmitting information, while in most existing works on WPCNs, HAPs operate in the half-duplex (HD) mode [3–7]. Multi-user FD-WPCN models considering single transmit block with energy causality were proposed in [8,9]. In [10], authors studied the optimal resource allocation of multi-user FD-WPCNs.

However, in [8–10], all the HAPs are equipped with only two antennas, one for wireless energy transfer (WET) and the other for wireless information transfer (WIT), and the resource allocation is achieved by adjusting the transmission time allocated to users. Multi-antenna can suppress self-interference (SI), which seriously affects the performance of FD system [11]. Upon invoking the advantages of multiple antennas, we adopt energy beamforming to allocate energy for different users through space division multiple access (SDMA). In [12], authors discussed full-duplex wireless-powered MIMO systems consisting of one multi-antenna HAP and one multi-antenna user, while our system including multiple single-antenna users.

Energy beamforming in simultaneous wireless information and power transfer (SWIPT) system was investigated in [13], and a novel energy borrowing technique was put forward in [14], in which energy harvesting nodes borrowed energy from the power grid and returned the energy back with additional energy interest. In a WPCN, users with poor channels harvest less energy in WET while they need more transmit power to overcome fading in uplink WIT, which causes the performance gap among users, a.k.a., the doubly near-far problem [1]. To ensure the fairness among users, in [3,4], HAPs allocate more power to users with poor channels by energy beamforming.

Taking user fairness into account, we investigate the effects of energy beamforming on FD-WPCNs. In this paper, we firstly propose an improved FD-WPCN model by equipping two groups of antennas on HAPs for downlink WET and uplink WIT, respectively. Secondly, we consider a space division energy allocation scheme

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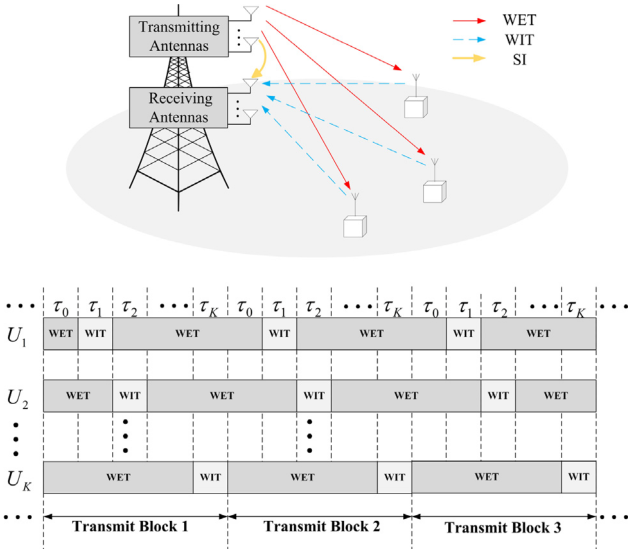

Fig. 1. System model and structure of transmit block.

using energy beamforming, and derive users' harvested energy. Thirdly, the approximate close-form expression of each user's achievable ergodic rate is derived to show the effects of residual SI and the number of antennas. Further, We derive a closed-form energy allocation solution under the max–min user fairness constraint. Finally, through numerical results, we verify that the approximation of rates is well matched with the simulation results. Numerical results also show that exploiting energy beamforming in FD-WPCN provides the following benefits: (1) improving overall rates of FD-WPCNs; (2) ensuring fairness among users; (3) Suppressing SI. Moreover, under a realizable SI cancellation, FD-WPCNs are shown to outperform HD-WPCNs in rates with same number of antennas.

The rest of this paper is organized as follows. Section 2 introduces the FD-WPCN model and formulates the optimization problem. Section 3 presents the approximation and analysis of achievable ergodic rates. In Section 4, we optimize the power allocation. Numerical results and conclusion are given in Sections 5 and 6, respectively.

Notations : Lower and upper case boldfaced letters represent vectors and matrices, respectively. $\mathbb{C}^{X\times Y}$ denotes a $X \times Y$ complex valued matrices. The Euclidean norm, the variance and the expectation are denoted by $\|\cdot\|_2$, $Var[\cdot]$ and $\mathbb{E}[\cdot]$, respectively. $\mathbf{H}^H$ denotes the Hermitian of matrix $\mathbf{H}$. $\mathcal{CN}(0,\sigma^2)$ denotes the set of complex Gaussian variables with zero mean and covariance σ^2.

2. System model and problem formulation

2.1. System model and block structure

We consider a multi-user FD-WPCN, where a FD HAP simultaneously transmits energy to and receive information from K single-antenna users (denoted by U_k, $k = 1,\ldots,K$) by employing N_t transmitting antennas and N_r receiving antennas, as shown in Fig. 1. All users operate in the time division duplex (TDD) mode over the same frequency band. Assume that the users can only harvest energy from the HAP and then use the harvested energy to transmit information in the uplink.

Fig. 1 also shows the transmit block structure of the system. In traditional WPCNs, one block is usually divided into two phases for WET and WIT, respectively. However, in our proposed FD model, one block of duration T is divided into $K+1$ time slices denoted by τ_k, $i = 0, 1, \ldots, K$. We assume that all time slices are of the same duration, i.e. $\forall k$, $\tau_k = T/(K+1) = \tau$. Without loss of generality, we assume $T = 1$. User U_k transmits information in the kth slice and harvests energy in the other K slices. In addition, the 0th slice is a dedicated WET slice, which ensures the system working properly even with only one user [10]. What should be noted is that in [8,9], users stop harvesting energy after WIT phase considering single transmit block and energy causality, while in our FD model, users harvest energy after the WIT phase and use the harvested energy for information transfer in next block, thus avoiding wasting energy.

In the FD-WPCN, the HAP employs multi-antenna technology to communicate with single-antenna users. We define $\mathbf{G}_d^H \in \mathbb{C}^{K\times N_t}$ and $\mathbf{G}_u \in \mathbb{C}^{N_r\times K}$ as the channel matrices from the HAP's transmitting antennas to the K users, and from the K users to the HAP's receiving antennas, respectively. We can express $\mathbf{G}_d$ and $\mathbf{G}_u$ as $\mathbf{G}_d = \mathbf{H}_d\mathbf{D}_d^{1/2}$ and $\mathbf{G}_u = \mathbf{H}_u\mathbf{D}_u^{1/2}$, where $\mathbf{H}_d^H \in \mathbb{C}^{K\times N_t}$ and $\mathbf{H}_u \in \mathbb{C}^{N_r\times K}$ are the small-scale fading matrices and have i.i.d. $\mathcal{CN}(0,1)$ elements. Here $\mathbf{g}_{d,k}$, $\mathbf{g}_{u,k}$, $\mathbf{h}_{d,k}$ and $\mathbf{h}_{u,k}$ denote the kth column of $\mathbf{G}_d$, $\mathbf{G}_u$, $\mathbf{H}_d$ and $\mathbf{H}_u$, respectively. $\mathbf{D}_d$ and $\mathbf{D}_u$ are K order diagonal matrices with $[\mathbf{D}_d]_{kk} = \beta_{d,k}$ and $[\mathbf{D}_u]_{kk} = \beta_{u,k}$, respectively. Here, $\beta_{d,k}$ and $\beta_{u,k}$ represent downlink and uplink large-scale fading coefficients, respectively. All users send pilot sequences L to the FD HAP before the beginning of their energy transfer. By exploiting those pilot sequences, the FD HAP estimates the uplink and downlink channel matrices as $\widehat{\mathbf{G}}_d$ and $\widehat{\mathbf{G}}_u$, respectively. Here we assume perfect channel estimation, i.e. $\widehat{\mathbf{G}}_d = \mathbf{G}_d$, $\widehat{\mathbf{G}}_u = \mathbf{G}_u$.

In a FD-WPCN system, the HAP's transmit power is much greater than the power of the received signal at HAP, which will cause serious SI. Since transmitting antennas are close to receiving antennas, the propagation delay is small. Therefore, the SI signal's light-of-sight component can be efficiently reduced by RF domain self-interference cancellation (SIC) technology [11]. As a result, the residual SI channel denoted by $\mathbf{G}_s \in \mathbb{C}^{N_t\times N_r}$ is assumed as Rayleigh fading [11] and the elements of $\mathbf{G}_s$ are i.i.d. following $\mathcal{CN}(0,\sigma_s^2)$, where σ_s^2 is defined as the SIC capability of FD-WPCN system.

2.2. Downlink wireless energy transfer

The energy that U_k uses for WIT is harvested from last transmit block's $(k+1)$th time slice to current transmit block's $(k-1)$th time slice. Since users do not need to demodulate the WET signal, we assume that all users share the same symbol x_d in WET with $|x_d| = 1$. The received signal over the downlink at U_k during τ_j, $k \neq j$ denoted by $y_{d,k}$, is given by

$$y_{d,k} = \sqrt{P_d}\mathbf{g}_{d,k}^H\mathbf{w}(\mathbf{G}_d)x_d + n_{d,k}, \tag{1}$$

where P_d is the HAP's downlink transmit power, and $\mathbf{w}(\mathbf{G}_d)$ is given by

$$\mathbf{w}(\mathbf{G}_d) = \sum_{k=1}^{K}\sqrt{\alpha_k}\frac{\mathbf{g}_{d,k}}{\|\mathbf{g}_{d,k}\|_2}, \tag{2}$$

where α_k, the kth element of $\boldsymbol{\alpha}$, represents the power allocation weight for U_k, satisfying $\sum_{k=1}^{K}\alpha_k = 1$.

In (1) and (2), $\mathbf{w}(\mathbf{G}_d)$ is the $N_t \times 1$ beamformer vector. The HAP broadcasts energy to all users with K energy beams to facilitate efficient energy transmission with the aid of energy beamforming. The beamforming vector is generated based on the downlink channel state $\mathbf{G}_d$, and has been proved asymptotical optimal for energy transfer [4].

Assume that the energy harvested from ambient noise and other users' uplink WIT signals can be neglected. Thus, the expected energy harvested by U_k in any slice $\tau_i, i \neq k$, can be