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Optimal time allocation for multi-antenna wireless powered heterogeneous sensor network communications under imperfect CSI

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ABSTRACT

Energy harvesting is a promising technology to overcome the energy bottleneck in battery-powered heterogeneous sensor networks (HSNs). In an energy harvesting HSN, heterogeneous sensor nodes harvest energy to power themselves, and use the harvested energy for data transmission. This paper investigates a multiple-input single-output wireless powered HSN with imperfect channel state information (CSI). The receiver harvests energy from the power transmitter via radio-frequency wireless power transfer (WPT) in the downlink to support wireless information transfer (WIT) in the uplink. To improve WPT efficiency, the power transmitter employs energy beamforming by using instantaneous CSI. Under imperfect CSI, the receiver performs channel estimation and feeds the CSI back to the transmitter. We focus on balancing the time duration for channel estimation, WPT, and WIT, so as to maximize the throughput while satisfying the time duration constraint. By solving this optimizing problem, we derive the optimal time resource allocation scheme. Numerical simulation results demonstrate the effectiveness of the proposed scheme.

1. Introduction

Recently, energy harvesting wireless communications has been viewed as a safe and promising technique [1–3], which is especially important for energy-constrained wireless communication systems such as HSNs. A radio-frequency (RF) signal is a viable new source for wireless energy harvesting, since it has clear advantage in effective energy transfer distance. Therefore, the RF energy harvesting technique has applied in various areas, such as wireless sensor networks [4,5], body area networks [6,7]. In addition, RF energy harvesting should be used to provide charging capability for a variety of low-power mobile devices [8].

Since a RF signal carry energy and information at the same time, the topic of simultaneous wireless information and power transfer (SWIPT) has drawn significant attention in recent years. Varshney first proposed the idea of SWIPT in [9], where a capacity-energy function was proposed to characterize the fundamental performance tradeoff for SWIPT in single-input single-output (SISO) systems. It was done under additive white Gaussian noise (AWGN) channel with amplitude-constrained input. Ref. [10] investigated a coupled-inductor circuit in a special case of average power-constrained AWGN channel with frequency-selective fading, and presented an optimal tradeoff between the information and power transfer. In order to address that practical circuits for harvesting energy from radio signals are not yet able to decode the carried information directly in SWIPT, [11] proposed a dynamic power splitting scheme. This scheme considered that the received signal is dynamically splitted into two streams, while one portion is for energy harvesting and the remaining part is for information decoding. Different from [9–11] which studied the

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fundamental tradeoff for SWIPT in a point-to-point single-antenna system, in [12,13], SWIPT has been further studied in multiple-input single-output (MISO) and multiple-input multiple-output (MIMO) systems, respectively. In addition, SWIPT has also been studied in an uplink cellular network [14], where randomly deployed power beacons charge mobile users wirelessly. Moreover, a similar setup in cooperative networks was studied in [15].

Except for SWIPT, there is another research topic on energy harvesting, referred to as wireless powered communication network (WPCN) [16,17], which consider the joint design of downlink (DL) WPT and uplink (UL) WIT. In [16], an access point (AP) with a single antenna first transfers energy to multiple single-antenna users via DL energy beamforming, then the users perform UL WIT to the AP based on time-division-multiple-access (TDMA) by using the harvested energy. Then a "harvest-then-transmit" protocol was proposed. Moreover, the study in [16] was extended in [17], where the users transmitted information to the multi-antenna AP via space-division-multiple-access (SDMA).

As we know, the knowledge of accurate CSI at the power transmitter is especially important. More accurate CSI contributes to higher efficiency of DL power transfer and higher UL information rate. The CSI is an essential prerequisite for both energy beamforming and information decoding. In [18], the authors studied the tradeoff between WPT and WIT by optimizing the time allocation. In [19], the authors investigated the robust beamformer design with imperfect CSI to maximize the harvested energy for SWIPT. In [20], the authors studied the topic of joint time allocation and beamforming design with perfect/imperfect CSI to maximize the sum throughput. Furthermore, energy beamforming with one-bit feedback in a MIMO WPT system was studied in [21]. In practice, it is hard to obtain the perfect CSI at the transmitter due to various factors such as time-varying channel, inaccurate channel estimation, and so on. Although the above literature has considered the tradeoff between WPT and WIT under imperfect CSI, it does not take into account the time allocation for channel estimation. Typically, the transmitter needs to obtain CSI by performing channel estimation (CE) first. Note that the tradeoff in resource allocation between CE and energy transfer in multi-antenna systems without considering information transfer has been studied in [22,23]. In [22], the authors investigated the dynamic allocation of time resource for CE and energy resource for WET in a MISO system, and then obtain the optimal preamble length by solving a dynamic programming problem. The study was further investigated in [23]. The authors in [24] considered the optimal training design under the Rician fading channel by training the energy receiver antennas, as well as the training time and power allocation. In addition, the tradeoff in resource allocation between CE, data detection, and energy harvesting in a training-based SWIPT system has been investigated in [25]. Moreover, [26] studied a WPT-enabled massive MIMO system with imperfect CSI in a WPCN.

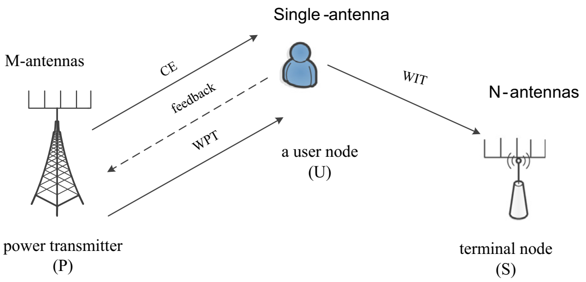

Fig. 1. Wireless-powered communication in a heterogeneous sensor network.

In this paper, we study MISO wireless powered communication in a HSN with energy beamforming, as shown in Fig. 1. We propose a three-phase (for simplicity, the time for CSI feedback from the receiver to the power transmitter is ignored) transmission protocol which contains the CE phase, the WPT phase, and the WIT phase. As we know, longer time duration for the CE phase leads to more accurate CSI available at the transmitter, and contributes to higher efficiency of power transfer, while shorter time duration for WPT and WIT will be left. In this case, there should be less harvested energy and less throughput. To maximize the throughput, we optimally design the time allocation for the CE phase, the WPT phase and the WIT phase.

The rest of this paper is organized as follows. In Section 2, we describe the system model. In Section 3, we introduce the optimization problem and formulate it. Section 4 focuses on analyzing and solving the optimal problem. Section 5 presents several simulation results to validate the performance of the propose algorithm. Finally, Section 6 concludes this paper.

2. System model

With reference to Fig. 1, we consider MISO wireless powered communication in a HSN, which consists of a wireless power transmitter (P) with M antennas, a user node (U) with single antenna, and a N-antenna terminal node (S). Note that the power transmitter can be a sink which has sufficient power supply. The user node and the terminal node are normal sensor nodes. The user node does not have enough energy for data transmission and should harvest energy via WPT.

The transmission process is divided into frames, as shown in Fig. 2. The length of each frame is fixed at T symbol durations. Each frame consists of four phases. In the first CE phase of t_1 symbol durations, P sends preambles in the DL and U performs channel estimation. In the second feedback phase of τ symbol durations, U feeds the CSI back to P in the UL. We assume that the feedback time is $\tau = 0$ for simplicity. In the third WPT phase of t_2 symbol durations, P delivers wireless energy via energy beamforming and U harvests energy from the received RF signal. In the final WIT phase, with the harvested energy, U transmits the information to S in the remaining symbol durations $T - t_1 - t_2$. In other words, U plays the roles as both power receiver and information transmitter. For convenience, we normalize $T = 1$ in the following, without loss of generality.

2.1. Channel estimation phase

During the channel estimation phase, we employ the least squares (LS) channel estimation method [27]. Similar to [23], we assume the duration of frame T consists of k time slots, and each of which is divided into M successive symbol durations, i.e., $T = kM$. It is further assumed that