Amplify-and-Forward Full-Duplex Relay with Power Splitting-Based SWIPT

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Abstract—This paper proposes a virtual harvest-transmit model and a harvest-transmit-store model for amplify-and-forward full-duplex relay (FDR) networks with power splitting-based simultaneous wireless information and power transfer. The relay node employs a battery group consisting of two rechargeable batteries. By switching periodically between two batteries for charging and discharging in two consecutive time slots of each transmission block, all the harvested energy in each block has been applied for full duplex transmission in the virtual harvest-transmit model. By employing energy scheduling, the relay node switches among the harvesting, relaying, harvesting-relaying, and idle behaviors at a block level, so that a part of the harvested energy in a block can be scheduled for future usage in the harvest-transmit-store model. A greedy switching policy is implemented to operate the harvest-transmit-store model, where the FDR node transmits when its residual energy ensures decoding at the destination. Numerical results verify the outage performance of the proposed schemes.

I. INTRODUCTION

Energy harvesting (EH) has emerged as a new technology for wireless relaying networks [1], [2]. By harvesting energy from ambient radio-frequency (RF) signals, periodic battery replacement or recharging can be alleviated for energy-constrained relay nodes. Since RF signals can carry both information and energy, simultaneous wireless information and power transfer (SWIPT) has gained a lot of interest from academic institutions and industry [2]–[5]. Recently, two practical receiver architectures, namely, time switching (TS) and power splitting (PS) [6], have been adopted in various SWIPT systems [4], [7], [8]. In TS-based SWIPT (TS-SWIPT), the receiver harvests power from an energy signal sent by the source and then receives the source transmitted information signal in a time-division manner. In PS-based SWIPT (PS-SWIPT), the receiver extracts energy from the received source signal with the aid of PS. In general, PS-SWIPT reduces the time slots consumed compared with TS-SWIPT, so that the information transmission time, as well as the spectral efficiency, can be increased.

By employing TS-based and PS-based protocols for amplify-and-forward (AF) relay networks [2], SWIPT not only keeps energy-constrained relay nodes active, but also enables information relaying across barriers or over long distance. In [9], the outage and diversity performances of SWIPT in cooperative networks with spatially random relays have been investigated. In [10], the distributed PS-based SWIPT has been designed for interference-limited relay networks. Several power allocation schemes for EH relay networks with multiple source-destination pairs were investigated in [11]. Furthermore, antenna switching and antenna selection have also been applied for SWIPT relaying networks [12], [13]. In [14], PS-SWIPT has been investigated for AF relaying networks by employing full and partial channel state information. All the aforementioned relay-assisted SWIPT employ half-duplex relay (HDR) nodes, so that two time phases are needed to accomplish one time of transmission.

Since full-duplex relay (FDR) can receive and transmit simultaneously, the spectral efficiency of an FDR network can be significantly improved over its HDR counterpart. Recently, the applications of SWIPT in FDR networks have drawn much attention [15]–[17]. By employing separated relay receive antennas and transmit antennas for EH and information relaying, respectively, the authors of [15] proposed a self-interference immunizing FDR scheme. In [16], the throughput has been analyzed for FDR networks with TS-SWIPT. Then, MIMO antennas have been employed at the relay to enhance the performance of TS-SWIPT in FDR networks [17]. Due to TS implementation, all the aforementioned TS-SWIPT schemes in FDR networks are not strictly operated in FDR mode, so that the reduction of information transmission time is unavoidable. On the other hand, PS-SWIPT has shown its performance improvement over TS-SWIPT in HDR networks [2]. Since PS-SWIPT does not change the effective information transmission time in relay networks [2], it is suitable to employ PS-SWIPT in FDR networks, so that the effective information transmission time can be doubled compared to that of HDR networks.

To the best of our knowledge, how to deploy PS-SWIPT in FDR networks is still an open problem. The technical challenge of implementing PS-SWIPT in FDR network is how to realize full-duplex energy harvesting and information relaying, i.e., charging and discharging simultaneously at the relay node besides the full-duplex information processing. In this paper, we propose to employ a battery group consisting of two batteries at the relay node to realize the full-duplex operation. By periodically switching between two rechargeable batteries for charging and discharging during two consecutive time slots of each block, the energy-constrained relay can be self-powered in a virtual harvest-transmit model. The harvest-
transmit-store model along with its greedy switching (GS) policy has also been designed.

The rest of this paper is organized as follows. Section II describes the system model and the virtual harvest-transmit model of the considered AF FDR-assisted PS-SWIPT. Section III presents the harvest-transmit-store model and proposes the GS policy for its implementation. Section IV presents numerical results and discusses the system performance of our proposed scheme. Section V summarizes this study.

II. SYSTEM MODEL

In the considered wireless FDR network, a source intends to transmit its information to a destination. Due to physical isolation between the source and destination, an AF FDR node is employed to realize the dual-hop relay transmission. The source and destination are equipped with a single antenna, respectively, whereas the relay node is equipped with a single receive antenna and a single transmit antenna. All the channels are assumed to be quasi-static block fading, i.e., the channel coefficients keep constant during one block and vary independently from block to block. The channels of the source-to-relay and relay-to-destination links are denoted by \( h_1 = \sqrt{L_1} h_{11} \) and \( h_2 = \sqrt{L_2} h_{22} \), respectively, where \( L_1 \) and \( L_i \) \((i = 1, 2)\) are the large-scale path-loss and small-scale fading of two-hop links, respectively. For the sake of exposition, the channel gain of \( h_i \) is denoted by \( g_i = |h_i|^2 \) for \( i \in \{1, 2\} \). The small-scale channel magnitude, \( |\tilde{h}_i| \) \((i = 1, 2)\), is modeled as Nakagami-\(m\) fading with the unit mean such that \( g_i \) \((i = 1, 2)\) is distributed according to the gamma distribution with the shape factor \( m_i \) and the scale factor \( \theta_i = \frac{g_i}{m_i} \). Further, the normalized transmitted signals of the source and relay are denoted by \( x_s(t) \) and \( x_r(t) \), respectively. The transmission powers at the source and relay are denoted by \( p_s \) and \( p_r \), respectively.

In order to enable charging and discharging simultaneously, the energy-constrained relay deploys a battery group consisting of two rechargeable batteries, as depicted in Fig. 1. The two batteries are assumed having the same initial state. The duration of each block, \( T \), is divided equally into two time slots (odd and even slots). The two batteries are activated for EH and power supplying alternately in the odd and even slots during each block. In the odd (even) slot of a block, battery #1 (battery #2) functions in discharging, while battery #2 (battery #1) switches to the EH receiver for charging. Further, in each block, the consumed energy quantum of battery #1 (battery #2) in the odd (even) slot is set to equal to that of the relay-harvested energy during the even (odd) slot. Following the above procedures, the full-duplex relaying is powered in a self-sustainable way. Since this charging/discharging behavior mimics the harvest-transmit model of PS-SWIPT in HDR networks [2], where a single battery has been applied, we call it the virtual harvest-transmit model. With the aid of channel estimation designed for energy-constrained networks [13], we assume that the relay has the capability to access full channel state information.

In each slot, the incident signal at the relay receive antenna can be expressed as

\[
y_r(t) = \sqrt{p_r} h_1 x_s(t) + \sqrt{p_r} h_a x_r(t) + n_a(t), \tag{1}
\]

where \( h_a \) is the residual self-interference (RSI) channel incident on the receive antenna and \( n_a(t) \sim \mathcal{CN}(0, \sigma_a^2) \) is the additive noise at the receive antenna. The power of the relay-received signal is split in \( \rho : 1 - \rho \) proportion for EH and information processing, where \( \rho \) is the power splitting ratio. Due to a negligible power of antenna noise, the harvested energy at the end of a time slot can be written as

\[
E_h = \eta \rho (p_s g_1 + p_r g_0) \frac{T}{2}, \tag{2}
\]

where \( \eta (0 < \eta < 1) \) is the energy conversion efficiency and \( g_0 \equiv |h_a|^2 \) is the RSI channel incident on the relay receive antenna. Note that \( E_h \) has been sent to battery #2 (battery #1) for charging in the odd (even) slot. Simultaneously, the relay transmission in the current slot is powered by the battery that is not switched for EH. When \( E_h \) is adopted as the transmission energy quantum, the relay transmission power can be characterized by

\[
p_r = \frac{E_h}{T/2} = \eta \rho (p_s g_1 + p_r g_0). \tag{3}
\]

Based on (3), the relay transmission power can be expressed as

\[
p_r = \frac{\eta \rho p_s g_1}{1 - \eta \rho g_0}. \tag{4}
\]

The sampled signal at the relay for information processing can be expressed as

\[
y_r(k) = \sqrt{(1 - \rho)p_s h_1 x_s(k)} + \sqrt{(1 - \rho)p_r h_0 x_r(k)} + n_r(k), \tag{5}
\]

where \( k \) denotes the symbol index, \( h_k \) is the RSI channel remained in the digital-domain after some stages of interference cancellation, \( n_r(k) \equiv \sqrt{1 - \rho} n_a(k) + n_p(k) \) is the additive noise with the zero mean, \( n_a(k) \) is the sampled version of the antenna noise \( n_a(t) \mathcal{CN}(0, \sigma_a^2) \), \( n_p(k) \sim \mathcal{CN}(0, \sigma_p^2) \) is the processing noise. Since \( n_r(k) \) is dominated by the processing noise rather than the antenna noise, we approximate that \( n_r(k) \) has the variance \( \sigma_r^2 \approx \sigma_p^2 \). The signal \( x_r(k) \) in (5) is expressed as \( x_r(k) = G y_r(k - \tau) \), where \( G = 1/\sqrt{(1 - \rho)p_s g_1 + (1 - \rho)p_r g_0 + \sigma_e^2} \) is the amplification coefficient and \( \tau \) is an amount of delayed symbols due to signal processing at the relay. The received signal at the destination is given by

\[
y_d(k) = \sqrt{p_r} h_2 x_r(k) + n_d(k), \tag{6}
\]
where \( n_d(k) \sim CN(0, \sigma_d^2) \) is the noise at the destination. For this system, the instantaneous end-to-end (e2e) signal to interference plus noise ratio (SINR) is expressed as
\[
\gamma_{e2e} = \frac{\gamma_r \gamma_d}{\gamma_r + \gamma_d + 1} \approx \min\{\gamma_r, \gamma_d\} \quad \text{for intermediate/high SINRs, (7)}
\]
where \( \gamma_r \triangleq \frac{(1-\rho)g_1 + s_d}{\sigma_r^2} \), \( \gamma_d \triangleq \frac{\rho g_2}{\sigma_r^2} \), and \( g_0 \triangleq |h_b|^2 \) is the RSI channel gain in the digital-domain after some stages of interference cancellation.

III. PS-SWIPT WITH ENERGY SCHEDULING

In order to decode the relaying signal received at the destination, it requires that the e2e SINR at least equals to a target value \( \gamma_{th} \). In the virtual harvest-transmit model, the harvested energy in each block is directly used for relay transmission, without considering energy scheduling across channel realizations. Although the virtual harvest-transmit model is easy to implement, it would perform better if energy scheduling is allowed to store a part of the harvested energy for future usage. In this section, we propose the harvest-transmit-store model with its GS implementation for the considered network.

Based on PS operation and time-switching between two batteries, the relay can simultaneously charge one battery and forward its received signal with the stored energy of another battery. According to the channel condition, the relay can also perform only EH or relaying. Thus, the relay can switch among four operational modes: a) \( \mu_i \): the two batteries harvest energy from the relay-received signal during the odd and even slots, respectively, b) \( \mu_r \): the relay transmits data with its power being supplied by the two batteries in the odd and even slots, respectively, c) \( \mu_{hr} \): the relay harvests energy and forward data as that of the virtual harvest-transmit model, and d) \( \mu_0 \): the relay neither harvests nor transmits when both EH and transmission are impossible. In the t-th block, the operational mode of the relay is denoted by \( \mu(t) \in \{ \mu_i, \mu_r, \mu_{hr}, \mu_0 \} \).

Since the decoding at the destination depends on whether the relay transmits or not, the relay transmission power can be expressed as
\[
p_r = \begin{cases} 
\frac{\gamma_i \sigma_i^2}{\sigma_i^2}, & \text{if } \gamma_i > C_1 \text{ and } \mu(t) = \mu_{hr} \\
\frac{\gamma_i \sigma_i^2}{\sigma_i^2}, & \text{if } \gamma_i \leq \frac{\rho g_2}{\sigma_r^2} \leq C_1 \text{ and } \mu(t) = \mu_r \\
\text{does not exist,} & \text{otherwise}
\end{cases}
\]

where \( C_1 = \gamma_i \frac{(1-\rho)g_1 + s_d}{\sigma_i^2} + 2\sigma_i^2 \) is obtained by substituting \( p_r = \frac{\gamma_i \sigma_i^2}{\sigma_i^2} \) into \( \gamma_r = \gamma_{th} \).

We assume that the two batteries at the relay have the same size \( p_b = \alpha p_s \) with \( \alpha > 0 \). Each battery is discretized into \( L + 2 \) energy levels \( \varepsilon_i \triangleq ip_b/(L+1) \), where \( i = 0, 1, \ldots, L + 1 \). We define \( s_i, i = 0, 1, \ldots, L + 1 \) as the energy states for each battery, so that each battery is in state \( s_i \) when its stored energy equals to \( \varepsilon_i \). Further, \( P_{i,j} \) denotes the transition probability \( P_T(s_i \rightarrow s_j) \) and \( E_0(t) \in \{ \varepsilon_0 : 0 \leq i \leq L + 1 \} \) denotes the residual energy of each battery at the beginning of the t-th block. Also, we assume that the two batteries at the relay have the same initial state. In each block, the battery #1 (battery #2) duplicates in the even (odd) slot the operational mode that is operated by the battery #2 (battery #1) in the odd (even) slot, so that the two batteries have the same energy state at the beginning (end) of each block. Based on the considered discretized battery model, we define the energy that can be harvested from the received signal to be equal to \( \varepsilon \triangleq \varepsilon_{i^*} \), where
\[
i_{i^*} = \arg\max_{i \in \{0, \ldots, L+1\}} \{ \varepsilon_i : \varepsilon < \varepsilon_{i^*}, \mu(t) = \mu_h \}.
\]

As for the relay transmission, the relay also uses the \( L + 2 \) discrete energy levels. Corresponding to \( p_r \) of (8), the transmitted energy level is given by
\[
\varepsilon' = \varepsilon_{i^*}, \quad \text{if } \mu(t) = \mu_r, \quad \text{and } \varepsilon < \varepsilon_{i^*},
\]
\[
\varepsilon'' = \varepsilon_{i^*}, \quad \text{if } \mu(t) = \mu_{hr}, \quad \text{and } \varepsilon \leq \varepsilon_{i^*}.
\]

Since an outage event occurs when the source signal cannot be decoded at the destination or equivalently when the relay operates in the mode of \( \mu_i \) or \( \mu_{hr} \), the main optimization target is to minimize the number of times that the relay does not transmit. To this end, the GS policy prioritizes the operation modes \( \mu_r \) and \( \mu_{hr} \). When the residual energy in the two batteries can support the required transmitted energy, the GS policy switch the relay to transmission, otherwise it switch the relay to EH. Further, when the relay is allowed to transmit, the GS policy prefers \( \mu_r \) more than \( \mu_r \) in order to harvest the self-emitted energy whenever it is possible. For the t-th block, the GS policy can be expressed as
\[
\mu^{(GS)}(t) = \begin{cases} 
\mu_{hr}, & E_0(t-1) \geq \varepsilon' \text{ and } \varepsilon \geq \varepsilon_1 \\
\mu_r, & E_0(t-1) \geq \varepsilon' \text{ and } \varepsilon < \varepsilon_1 \\
\mu_h, & E_0(t-1) < \varepsilon' \text{ and } \varepsilon \geq \varepsilon_1 \\
\mu_0, & \text{otherwise}
\end{cases}
\]

and
\[
E_0(t) = \min\{p_r, E_0(t-1) - w_1(t-1)\varepsilon' + w_2(t-1)\varepsilon'' \},
\]
where \( w_1(t) \triangleq \mathbb{I}\{\mu(t) = \mu_r, \mu_{hr}\} \) and \( w_2(t) \triangleq \mathbb{I}\{\mu(t) = \mu_h, \mu_{hr}\} \) are the binary variables and \( \mathbb{I} \) denotes the indicator function.

By employing the GS policy, the relay’s battery group transits among the harvesting, relaying, harvesting-relaying, and idle behaviors, which can be represented by a finite Markov chain. Due to the complicated forms of the considered fading distribution, it is hard to derive the outage probability in a closed-form and we use simulations to verify the outage performance of the GS policy.

IV. SIMULATION RESULTS

In this section, we consider a single carrier system working with the carrier frequency 868 MHz and a bandwidth 200 kHz. The required SINR threshold at the destination for decoding
model is superior to the virtual harvest-transmit model in the low source transmission power region.

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