Full-Duplex Wireless-Powered Relay with Self-Energy Recycling

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Abstract

This letter studies a wireless-powered amplify-and-forward relaying system, where an energy-constrained relay node assists the information transmission from the source to the destination using the energy harvested from the source. We propose a novel two-phase protocol for efficient energy transfer and information relaying, in which the relay operates in full-duplex mode with simultaneous energy harvesting and information transmission. Compared with the existing protocols, the proposed design possesses two main advantages: i) it ensures uninterrupted information transmission since no time switching or power splitting is needed at the relay for energy harvesting; ii) it enables the so-called self-energy recycling, i.e., part of the energy (loop energy) that is used for information transmission by the relay can be harvested and reused in addition to the dedicated energy sent by the source. Under the multiple-input single-output (MISO) channel setup, the optimal power allocation and beamforming design at the relay are derived. Numerical results show a significant throughput gain achieved by our proposed design over the existing time switching-based relay protocol.

Index Terms

Wireless energy transfer, full-duplex relay, SWIPT, energy recycling.

I. INTRODUCTION

Radio-frequency (RF) enabled wireless energy transfer (WET) has recently emerged as a promising solution to provide convenient and perpetual power supply for energy-constrained networks. Since RF signal is able to convey both information and energy, one appealing direction of research is to jointly investigate information and energy transfer to achieve simultaneous wireless information and power transfer (SWIPT) (see e.g. [1], [2] and references therein). An important application scenario for SWIPT lies in wireless-powered relaying (WPR), in which information is transmitted from the source to the destination via an energy-constrained relay node that is powered by means of WET. Existing studies on WPR mostly consider half-duplex relaying and adopt either time switching-based relaying (TSR) [3]–[5] or power...
splitting-based relaying (PSR) protocols \cite{5, 6}, by exploiting the time-switching and power-splitting receiver architectures for SWIPT proposed in \cite{7}. In \cite{8} and \cite{9}, a time switching-based full-duplex wireless-powered transmission/relaying system is studied, where the source/relay node operates in full-duplex mode with simultaneous \textit{information reception and energy/information transmission}.

In this letter, we propose a new two-phase protocol for amplify-and-forward (AF) based WPR. In the first phase, information is transmitted from the source to the relay. In the second phase, the received signal at the relay is amplified and forwarded to the destination, and concurrently, dedicated energy signals are sent from the source to the relay for energy harvesting. Hence, the relay operates in full-duplex mode in the second phase with simultaneous \textit{information transmission} and \textit{energy harvesting}. Compared with the existing TSR or PSR protocols, the proposed design possesses the advantage of uninterrupted information transmission since no time switching or power splitting is needed at the relay for energy harvesting. Besides, unlike the full-duplex relaying studied in \cite{9}, which suffers from severe self-interference and requires additional energy consumption at the relay in order to implement the sophisticated analog and/or digital interference-cancelation \cite{10}, in our proposed full-duplex protocol, the self-interfering link at the relay is in fact beneficial since it enables the so-called self-energy recycling, i.e., part of the energy (loop energy) that is used for information transmission by the relay can be harvested and reused in addition to the dedicated energy sent by the source. Under the multiple-input single-output (MISO) channel setup, we study the optimal power allocation and beamforming design at the relay to maximize the end-to-end throughput. We also study the optimal time division ratio for the existing TSR as a benchmark for performance comparison. Numerical results show a significant throughput gain achieved by our proposed design.

\section{System Model and Proposed Protocol}

As shown in Fig.\ref{fig:sysmodel}, we consider a WPR system where the source node $S$ transmits information to the destination node $D$ via an energy-constrained relay $R$, which is assumed to be solely powered by the energy harvested from $S$. We assume that $S$ and $R$ are equipped with $M$ and $N+1$ antennas, respectively,
and D has one single antenna. Furthermore, as illustrated in Fig. 2, we assume that R is equipped with N RF chains for information transmission, as well as one RF chain for information reception and one rectifier for energy harvesting. Therefore, at each time instance, a maximum of N antennas can be activated for information transmission and one antenna for information/energy reception. For simplicity, we assume that the direct link from S to D is negligible and thus is ignored in this letter. In addition, we assume a quasi-static channel model with perfect channel state information (CSI) at S and R. In practice, the CSI can be acquired by various methods, e.g., the pilot-assisted reverse-link channel training [11].

As shown in Fig. 3, we propose a two-phase AF protocol for the WPR system. In the first phase of duration $T/2$, with $T$ denoting the total block duration, information is sent from S to R (with the switch shown in Fig. 2 connected to Information Receiver). In the second phase with the remaining time $T/2$, the received information signal at R is amplified and forwarded to D by its $N$ transmitting antennas, and concurrently, dedicated energy signals are sent from S to the receiving antenna of R for energy harvesting (with the switch shown in Fig. 2 connected to Energy Harvester). The proposed protocol is elaborated in more details in the following section.

III. RELAYING WITH SELF-ENERGY RECYCLING

Denote by $h \in \mathbb{C}^{M \times 1}$ the baseband equivalent MISO channel from S to the receiving antenna of R. With the CSI $h$ available at S, the maximal ratio transmission (MRT) with beamforming vector $v_s = h/\|h\|$ is known to be optimal for information transmission. The information signal received at R during the first phase is thus given by

$$y_{r,1}[k] = \sqrt{P_s}\|h\|x_{s,1}[k] + n_{r,1}[k],$$

(1)

where $k$ denotes the symbol index; $P_s$ represents the source transmission power; $x_{s,1}[k]$ denotes the information-bearing symbol sent by S, which is assumed to be independently circularly-symmetric com-
plex Gaussian (CSCG) distributed with zero mean and unit variance, i.e., $x_{s,1}[k] \sim \mathcal{C}\mathcal{N}(0, 1)$, $\forall k$; and $n_{r,1}[k] \sim \mathcal{C}\mathcal{N}(0, \sigma_r^2)$ denotes the receiver AWGN noise at $R$.

In the second phase, the received signal in (1) is amplified and forwarded to $D$ by the $N$ transmitting antennas of $R$ with power $P_r$ and beamforming vector $v_r \in \mathbb{C}^{N \times 1}$, where $\|v_r\| = 1$. Denote by $g \in \mathbb{C}^{N \times 1}$ the MISO channel from $R$ to $D$. The received signal at $D$ can be expressed as

$$y_d[k] = \sqrt{P_r}g^Hv_r \frac{y_{r,1}[k]}{\sqrt{A}} + n_d[k]$$

$$= \sqrt{P_r}P_f \frac{\|h\|g^Hv_rx_{s,1}[k]}{\sqrt{A}} + \frac{\sqrt{P_r}}{\sqrt{A}}g^Hv_r n_{r,1}[k] + n_d[k],$$

where $A \triangleq P_s\|h\|^2 + \sigma_r^2$ is the power of the received signal in (1); and $n_d[k] \sim \mathcal{C}\mathcal{N}(0, \sigma_d^2)$ denotes the AWGN noise at $D$. The end-to-end throughput from $S$ to $D$ can thus be expressed as

$$R = \frac{1}{2} \log_2(1 + \gamma_d)$$

in bps/Hz, with $\gamma_d$ denoting the received signal-to-noise ratio (SNR) at $D$, which is given by

$$\gamma_d = \frac{P_s\|h\|^2}{\sigma_r^2 + \frac{\sigma_d^2}{P_r\|g^Hv_r\|^2}}.$$  \hfill (2)

Concurrently with information transmission by the relay in the second phase, wireless energy is sent from $S$ to the receiving antenna of $R$ for energy harvesting. Particularly, the energy-harvesting circuitry at $R$ not only harvests the dedicated energy sent from $S$, but also recycles a portion of its own transmitted energy via a loop channel denoted by $f \in \mathbb{C}^{N \times 1}$. The received signal by the receiving antenna of $R$ is expressed as

$$y_{r,2}[k] = \sqrt{P_s}\|h\|x_{s,2}[k] + \sqrt{P_r}f^Hv_r \frac{y_{r,1}[k]}{\sqrt{A}} + n_{r,2}[k],$$

where $x_{s,2}[k]$ denotes the energy-bearing signal sent by $S$, with $\mathbb{E}[|x_{s,2}[k]|^2] = 1$. By substituting $y_{r,1}[k]$ given in (1) into the above equation and ignoring the negligible energy harvested from the receiver noise $n_{r,1}[k]$ and $n_{r,2}[k]$, the total harvested energy at $R$ during each block is given by

$$E_r = \frac{T}{2} \eta P_s\|h\|^2 \mathbb{E} \left[ |x_{s,2}[k] + \frac{\sqrt{P_r}}{\sqrt{A}}f^Hv_rx_{s,1}[k]|^2 \right]$$

$$\leq \frac{T}{2} \eta P_s\|h\|^2 \left( 1 + \frac{\sqrt{P_r}}{\sqrt{A}}|f^Hv_r|^2 \right),$$  \hfill (3)

where $0 < \eta \leq 1$ denotes the energy harvesting efficiency at $R$. The upper bound of harvested energy
We then have

\[ \text{Theorem 1} \] indicates that the optimal relay beamforming is obtained as a linear combination of

\[ \medtext{and the maximum throughput from} \ S \饰 \ \text{is attained when} \ x_{s,2}[k] = x_{s,1}[k]e^{j\angle f^H v_r}, \ \forall k, \ \text{with} \ \angle z \ \text{denoting the phase of the complex number} \ z. \ \text{As will be shown in Theorem 1, with the optimal beamforming} \ v_r^*, \ \text{we have} \ \angle f^H v_r^* = 0; \ \text{hence, the above condition reduces to} \ x_{s,2}[k] = x_{s,1}[k], \ \forall k. \ \text{Furthermore, to ensure that the average energy used for transmission by} \ R \ \text{does not exceed that being harvested, we have} \ P_r T/2 \leq E_r. \ \text{Let} \ \gamma_1 \ \text{and} \ \gamma_2 \ \text{be the SNRs of the first and second hops, respectively, i.e.,} \ \gamma_1 \triangleq P_s \|h\|^2/\sigma_r^2, \ \text{and} \ \gamma_2 \triangleq P_r \|g^H v_r\|^2/\sigma_d^2. \ \text{Using} \ (2) \ \text{and} \ (4) \ \text{and by discarding the constant terms, the problem of maximizing} \ \gamma_2 \ \text{is equivalent to that of maximizing} \ \gamma_2, \ \text{which can be formulated as}

\[
(P1) : \max_{P_r, v_r} \ \gamma_2 \triangleq P_r \|g^H v_r\|^2/\sigma_d^2 \\
\text{s.t.} \ 0 \leq P_r \leq \eta P_s \|h\|^2 \left(1 + \frac{\sqrt{P_r}}{\sqrt{A}}\|f^H v_r\|\right)^2, \\
\|v_r\| = 1. 
\]

\[ (5) \]

Let \( 0 \leq \theta \leq \pi/2 \) be the effective angle between \( f \) and \( g \), which is defined as \( \cos(\theta) \triangleq \|f^H g\|/(\|f\|\|g\|) \).

We then have

**Theorem 1:** The optimal solution \( (P_r^*, v_r^*) \) to \( P1 \) is

\[
P_r^* = \|v^*\|^2, \ v_r^* = v^*/\|v^*\|,
\]

where \( v^* = \alpha_1 e^{j\angle g^H f} g + \alpha_2 f \), with

\[
\alpha_1 = \frac{\|h\|}{\|g\|} \sqrt{1 + \frac{1}{\gamma_1}} \eta P_s \sqrt{1 + \frac{1}{\gamma_1} - \eta \|f\|^2 \sin^2 \theta}, \ \text{and}
\]

\[
\alpha_2 = \frac{\eta \|h\|}{\|g\|} \sqrt{1 + \frac{1}{\gamma_1}} \frac{P_s}{\sqrt{\gamma_1} \|f\| \cos \theta} \left(1 + \frac{\sqrt{\gamma_1} \|f\| \cos \theta}{\sqrt{1 + \frac{1}{\gamma_1} - \eta \|f\|^2 \sin^2 \theta}}\right).
\]

The corresponding optimal value of \( P1 \) is

\[
\gamma_2^* = \left(1 + \frac{1}{\gamma_1}\right) \eta P_s \|h\|^2/\|g\|^2 \left(\sqrt{\gamma_1} \|f\| \cos \theta + \sqrt{1 + \frac{1}{\gamma_1} - \eta \|f\|^2 \sin^2 \theta}\right)^2,
\]

\[ (8) \]

and the maximum throughput from \( S \) to \( D \) is \( R^* = \frac{1}{2} \log_2 \left(1 + \frac{\gamma_1 \gamma_2}{\gamma_1 + \gamma_2 + 1}\right) \).

**Proof:** Please refer to Appendix A.

Theorem 1 indicates that the optimal relay beamforming is obtained as a linear combination of \( g \) and \( f \) so as to achieve a good balance between information transmission and self-energy recycling. Furthermore, \( (8) \) shows that \( \gamma_2^* \) monotonically increases with \( \cos(\theta) \), i.e., as the MISO channels \( f \) and \( g \) are better aligned.
Corollary 1: In the special case when $R$ has one single transmitting antenna ($N = 1$) and the MISO channel $f$ becomes a complex scalar $f$, the solution to (P1) reduces to

$$P^r_\star = \frac{\eta P_s \|h\|^2}{\left(1 - \sqrt{\eta} |f| / \sqrt{1 + \frac{1}{\gamma_1}}\right)^2}. \quad (9)$$

It follows from (9) that $P^r_\star > \eta P_s \|h\|^2$, i.e., thanks to the self-energy recycling in the proposed protocol, the relay can transmit with larger power than that using the directly harvested energy from the source.

IV. TIME-SWITCHING BASED RELAYING

In this section, we consider the existing TSR protocol [5] for our studied WPR system, which serves as a benchmark for performance comparison. As shown in Fig. 4, the TSR protocol in general consists of three phases. In the first phase of duration $\alpha T$, with $0 < \alpha < 1$, energy signal is sent from $S$ to $R$ for energy harvesting. In the second and third phases each with equal duration $(1 - \alpha)T/2$, information is sent from $S$ to $R$ and then forwarded from $R$ to $D$ via AF relaying, respectively. With this protocol, the total energy harvested by $R$ during each block is $E_r = \alpha T \eta P_s \|h\|^2$, and the transmit power of $R$ can be obtained as $P_r = E_r / ((1 - \alpha)T/2) = 2\alpha \eta P_s \|h\|^2 / (1 - \alpha)$. Using (2) as well as the fact that the optimal transmit beamforming at $R$ should match to the MISO channel $g$ in this case, i.e., $\mathbf{v}_r = g / \|g\|$, the received SNR at $D$ can be expressed as

$$\gamma_d = \frac{\gamma_1}{1 + \frac{C(1 - \alpha)}{\alpha}}, \quad (10)$$

where $C \triangleq (1 + \gamma_1)\sigma_d^2 / (2\eta P_s \|h\|^2 \|g\|^2)$. The throughput maximization problem in this case is then formulated as

$$(P2) : \max_{0 \leq \alpha \leq 1} R(\alpha) \triangleq \frac{1 - \alpha}{2} \log \left(1 + \frac{\gamma_1}{1 + \frac{C(1 - \alpha)}{\alpha}}\right).$$

Theorem 2: The optimal solution to (P2) is

$$\alpha^\star = \frac{(z^\star - 1)C}{(z^\star - 1)C + 1 + \gamma_1 - z^\star}, \quad (11)$$

where $1 < z^\star < 1 + \gamma_1$ is the unique solution of the equation $f(z) = 0$ in the interval $(1, 1 + \gamma_1)$, with
Fig. 5: Throughput versus source transmission power $P_s$.

$f(z)$ given by

\[
f(z) \triangleq \gamma_1 C z \ln z + (C - 1) z^2 - z(\gamma_1 C + 2C - 2\gamma_1 - 2) \\
- (\gamma_1 + 1)(\gamma_1 + 1 - C),
\]

which is a monotonically increasing function over $z \in (1, 1 + \gamma_1)$ with $f(1) = -\gamma_1^2$ and $f(1 + \gamma_1) = \gamma_1 C(1 + \gamma_1) \ln(1 + \gamma_1)$.

Proof: Please refer to Appendix B.

V. Numerical Results

We assume that the available bandwidth for the WPR system is 10MHz, and the AWGN power spectrum density at both the receivers of R and D is $-160$dBm/Hz. Hence, the total noise power is $\sigma_r^2 = \sigma_d^2 = -90$dBm. The energy harvesting efficiency at R is assumed to be $\eta = 0.8$. We also assume that the transmitting antennas at both S and R form a 2-element ($M = N = 2$) uniform linear array (ULA) with elements separated by distance $d = \lambda/2$, where $\lambda$ denotes the carrier wavelength. Furthermore, we assume that the receiving antenna at R has the same distance $\lambda/2$ to its two transmitting antennas, so that the loop channel can be modelled as $f = \sqrt{\beta_{rr}}[1 \ 1]^T$, where $\beta_{rr} = -15$dB denotes the loop-link path loss \[12\]. We assume that both h and g are modelled by line-of-sight (LoS) channels with angle-of-departure (AoD) $\theta_h = 10^\circ$ and $\theta_g = 5^\circ$, respectively. Thus, we have $h = \sqrt{\beta_{sr}}[1, e^{j2\pi d/\lambda \sin \theta_h}]^T$ and $g = \sqrt{\beta_{rd}}[1, e^{j2\pi d/\lambda \sin \theta_g}]^T$, with $\beta_{sr}$ and $\beta_{rd}$ denoting the path loss from S to R and from R to D, respectively. We set $\beta_{sr} = \beta_{rd} = -60$dB, which may correspond to a separation distance around 30 meters with carrier frequency at 900 MHz.
In Fig. 5, the throughput in bps/Hz is plotted against the source transmission power $P_s$ for both the proposed design and the TSR protocol [5] with optimal time allocation $\alpha^\star$. It is observed that significant throughput gains are achieved by our proposed protocol with sufficiently large $P_s$, thanks to the self-energy recycling as well as the simultaneous energy harvesting and information transmission at the relay, which ensures continuous information transmission without any interruption due to energy transfer.

VI. CONCLUSION

In this letter, we propose a new protocol for wireless-powered relaying system with simultaneous energy harvesting and information transmission at the relay, which achieves uninterrupted information transmission and also self-energy recycling. The optimal power allocation and beamforming design at the relay are obtained under the MISO channel setup and assuming AF relaying. Numerical results show significant throughput gains with the proposed design over the existing scheme.

APPENDIX A

PROOF OF THEOREM

By discarding the term $\sigma_d^2$, and defining $v \triangleq \sqrt{P_r}v_r$, $a \triangleq \eta P_s\|h\|^2$, and $\hat{f} = f/\sqrt{A}$, (P1) can be recast as

$$(P1.1) : \max_v |g^H v|^2 \quad \text{s.t.} \quad \|v\|^2 \leq a\left(1 + |\hat{f}^H v|\right)^2.$$  

Lemma 1: (P1.1) is equivalent to the following problem

$$(P1.2) : \max_v |g^H v|^2$$

$$\text{s.t.} \quad \|v\|^2 \leq a\left(1 + |\hat{f}^H v|^2 + 2\text{Re}(\hat{f}^H v)\right). \quad (13)$$

Proof: First, it is observed that if $v$ is an optimal solution to (P1.1), so does $ve^{j\omega}$ for arbitrary phase rotation $\omega$. Thus, without loss of generality, we can restrict that $\hat{f}^H v$ in (P1.1) is a real number. As a result, (P1.1) is equivalent to

$$\max_v |g^H v|^2$$

$$\text{s.t.} \quad \|v\|^2 \leq a\left(1 + \text{Re}(\hat{f}^H v)\right)^2,$$

$$\text{Im}(\hat{f}^H v) = 0. \quad (14)$$

Next, we prove that the last constraint of problem (14) is redundant by showing that the optimal solution $v^\star$ to the relaxed problem without this constraint always satisfy $\text{Im}(\hat{f}^H v^\star) = 0$. Suppose, on the contrary,
that $\text{Im}(\hat{f}^Hv^*) \neq 0$. Let $\phi = \angle \hat{f}^Hv^*$. We then have
\[
\|v^*\|^2 \leq a \left(1 + \text{Re}(\hat{f}^Hv^*)\right)^2 < a \left(1 + \text{Re}(\hat{f}^Hv^*e^{-j\phi})\right)^2,
\] (15)
where the strict inequality follows from the fact that $\text{Re}(z) < |z|$ for any non-real complex number $z$. Define a new vector $v' = (1 + \epsilon)v^*e^{-j\phi}$, with $\epsilon > 0$ and arbitrarily small. The strict inequality in (15) implies that $v'$ is also feasible to the relaxed problem of (14). Furthermore, it obviously achieves a larger objective value than $v^*$. This thus contradicts the assumption that $v^*$ is the optimal solution. Therefore, the constraint $\text{Im}(\hat{f}^Hv) = 0$ is guaranteed by the relaxed problem of (14) and hence it is redundant. Furthermore, (P1.2) follows from a simple reformulation of the relaxed problem of (14).

With Lemma 1, finding the optimal solution to (P1.1) is tantamount to solving (P1.2), which can be reformulated as
\[
\max_v |g^Hv|^2, \quad \text{s.t.} \quad \|F^{1/2}v - b\|^2 \leq \beta,
\] (16)
where $F \triangleq I - a\hat{f}\hat{f}^H$, $b \triangleq aF^{-1/2}\hat{f}$, and $\beta \triangleq a + \|b\|^2$. By defining a new optimization vector $\hat{v} \triangleq (F^{1/2}v - b)/\sqrt{\beta}$, problem (16) is then equivalent to
\[
\max_{\hat{v}} |g^HF^{-1/2}(b + \sqrt{\beta}\hat{v})|^2, \quad \text{s.t.} \quad \|\hat{v}\|^2 \leq 1.
\] (17)
The optimal solution to problem (17) can be obtained with the following inequalities:
\[
|g^HF^{-1/2}(b + \sqrt{\beta}\hat{v})| \leq |g^HF^{-1/2}b| + \sqrt{\beta}|g^HF^{-1/2}\hat{v}|
\]
\[
\leq |g^HF^{-1/2}b| + \sqrt{\beta}\|F^{-1/2}g\|,
\]
where the upper bound is attained by setting $\hat{v}^* = F^{-1/2}ge^{j\psi}/\|F^{-1/2}g\|$, with $\psi = \angle g^HF^{-1/2}b$. As a result, the optimal solution to problem (16), and hence that to the original problem (P1.1) can be obtained as
\[
v^* = F^{-1/2}(b + \sqrt{\beta}\hat{v}^*) = aF^{-1}\hat{f} + \frac{\sqrt{\beta}F^{-1}ge^{j\psi}}{\|F^{-1/2}g\|}.
\] (18)
By evaluating (18) with the identity $F^{-1} = I + a\hat{f}\hat{f}^H/(1 - a\|\hat{f}\|^2)$ and after some manipulations, the results given in Theorem 1 can be obtained.

**APPENDIX B**

**PROOF OF THEOREM 2**

The second-order derivative of $R(\alpha)$ can be obtained as
\[
R''(\alpha) = \frac{-\gamma_1 C(1 - \alpha)(\gamma_1 + 2) + 2\alpha(1 + \gamma_1)}{2\ln 2(\alpha + C(1 - \alpha) + \gamma_1\alpha)^2(\alpha + C(1 - \alpha))^2} < 0.
\]
Thus, (P2) is a convex optimization problem, whose solution is given by the stationary point in the interval $(0, 1)$ satisfying $R'(\alpha) = 0$, or

$$
\frac{\gamma_1 C(1 - \alpha)}{\alpha + C(1 - \alpha) + \gamma_1 \alpha} = \ln \left( 1 + \frac{\gamma_1 \alpha}{\alpha + C(1 - \alpha)} \right).
$$

(19)

By letting $z = 1 + \frac{\gamma_1 \alpha}{\alpha + C(1 - \alpha)}$, we then have $1 < z < 1 + \gamma_1$. Furthermore, it can be shown that equation (19) is equivalent to $f(z) = 0$, with $f(z)$ defined in (12). The properties of $f(z)$ given in Theorem 2 can then be verified.

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