DEBIT: Distributed Energy Beamforming and Information Transfer for Multiway Relay Networks

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Abstract: In this paper, we propose a new distributed energy beamforming and information transfer (DEBIT) scheme for realizing simultaneous wireless information and power transfer (SWIPT) in multiway relay networks (MWRNs), where multiple single-antenna users exchange information via an energy-constrained single-antenna relay node. We investigate the optimal transceiver designs to maximize the achievable sum-rate or the harvested power. The resultant sum-rate maximization problem is non-convex and the global optimal solution can be obtained through a three-dimensional search in combination with conventional convex optimization. To reduce the computation complexity, a suboptimal DEBIT scheme is also proposed, for which the optimization problem becomes linear programming. The achievable sum-rate performance is analyzed and a closed-form lower bound is derived for the MWRN with a large number of users. Furthermore, we consider the harvested-power maximization problem under a target sum-rate constraint, and derive a lower bound of the average harvested power for MWRNs with a large number of users. Numerical results show that the DEBIT scheme significantly outperforms the conventional SWIPT and the derived lower bounds are tight.

1 Introduction

In many wireless networks, terminals are usually equipped with fixed power supplies and have a limited lifetime, e.g., sensor nodes embedded in buildings are equipped with batteries which are highly inconvenient to replace. Harvesting energy from the environment has emerged as a promising solution for prolonging the lifetime of energy-constrained devices in wireless communication systems [1–6]. Considering the fact that radio frequency (RF) signals carry information as well as energy at the same time, simultaneous wireless information and power transfer (SWIPT) technology has gained considerable attention in both academic and industrial fields [7–11].

The concept of SWIPT was first proposed in [3] and [4]. In a SWIPT-enabled wireless network, the relays can process information and harvest energy from received signals simultaneously. The SWIPT technique has been applied to various wireless networks, such as multi-input multi-output (MIMO) systems [11–13], orthogonal frequency division multiple access (OFDMA) systems [14], wireless relay networks [15–17], and cognitive radio networks [18].

In [19], the authors investigated the optimal resource allocation to maximize the energy efficiency for SWIPT OFDMA systems with power-splitting receivers. In [20], the authors analyzed the performance of SWIPT enabled two-way relay network (TWRN), where the relay harvests power from the sources’ transmit signal based on a time-switching protocol. In [21], the authors investigated the optimal transmission policy for the SWIPT TWRN where both the users and the relay node are able to process information and harvest power simultaneously.

A key observation is that, in wireless communications, the electromagnetic wave impinged upon a receiver is usually a mixture of the signals from multiple independent transmitters. As such, the harvested power at a receiver can be significantly enhanced if the transmit signals can be coordinated to superimpose each other coherently at the receiver. This is the basic idea of distributed energy beamforming and information transfer (DEBIT), which was introduced in [19], where the gain of DEBIT was studied in two-way relay networks. However, such distributed energy beamforming gain is quite limited since there are only two transmitters serving the energy-harvesting relay in a two-way relay network. It is of pressing interest to understand how this gain scales along with the number of transmitters, and how it fundamentally affects the tradeoff between information delivery and power transfer.

In this work, we apply DEBIT to multiway relay networks (MWRNs) [21–23] and study the transceiver design to optimize the system performance. For MWRNs with a large number of users, a large transmit power budget is usually required at the relay node, especially when AF protocol is adopted by the relay [21–22]. It has been shown in [20, 21] that the throughput of the MWRN over Gaussian channels will be bottlenecked by the relay if it has a limited power supply. With DEBIT, the relay node can harvest power from the RF signals to improve the network throughput, as well as to prolong the relay’s lifetime [20].

We study the sum-rate maximization and harvested power maximization problems for the proposed DEBIT scheme. For sum-rate maximization, the power splitting ratio, the time splitting ratio as well as the power allocations are jointly optimized to maximize the sum-rate of MWRNs under a target harvested power at the relay. The resultant optimization problem is non-convex, and we show that the global optimal solution can be obtained through a three-dimensional search in combination with conventional convex optimization. We also propose a suboptimal scheme to reduce the complexity, for which the sum-rate maximization problem becomes simple linear programming problem. We analyze the sum-rate performance of the proposed scheme and a closed-form expression of the sum-rate lower bound is derived for the MWRN with a large number of users. In addition, we also formulate the problem of maximizing the harvested power under the constraint of a target sum-rate for information delivery. We show that this harvested-power maximization problem can be solved by a three-dimensional exhaustive search on top of a convex program. We also propose a low-complexity suboptimal scheme, and show that the optimal resource allocation for such a simplified scheme can be efficiently obtained by a one-dimensional search over solutions of linear programs. We further establish an asymptotic lower bound of the average harvested power, and show that the lower bound increases quadratically in the number of users.
The rest of this paper is organized as follows. Section 2 describes the system model and Section 3 describes the DEBIT scheme. Section 4 investigates the sum-rate maximization problem. The achievable sum-rate performance is analyzed in Section 5. Section 6 investigates the harvested power maximization problem. The proposed schemes are tested and compared with the conventional SWIPT scheme in Section 7, followed by the conclusions in Section 8.

2 System Model

Fig. 1 (a) shows a half-duplex MWRN with K single-antenna users and one single-antenna relay node. We assume there is no direct user-to-user links, and these users need to exchange information via the relay node. Full-data exchange is considered in this work, i.e., each user need to receive the messages from all the other users in two consecutive phases. Note that such a model corresponds to the case that multiple sensor nodes exchange information through an intermediate node. In the first phase (referred to as MAC phase), all the users send signals to the relay. In the second phase (referred to as BC phase), the relay harvests energy using a power splitter and then forwards the residual signal to the users using amplify-and-forward relaying protocol. The channel between the k-th user and the relay is denoted by $h_k$, which is Rayleigh distributed and keeps unchanged during the two phases. We also assume that each node has perfect knowledge of all the channels.

3 The Proposed DEBIT Scheme

3.1 MAC Phase

As shown in Fig. 1 (b), the MAC phase is in general divided into two subphases, and the duration of the two subphases are $\alpha T$ and $(1-\alpha)T$, respectively. Here, $\alpha \in [0, 1]$ and $T$ is the duration of the whole MAC phase. In the first subphase, as shown in Fig. 1 (b), each user sends superimposed energy symbols as well as information symbols to the relay. While in the second subphase, user $k$ transmits information symbols only.

Let $p_{k,E}$ and $p_{k,1}$ denote the transmit power of the energy and information symbols at the $k$-th user, respectively. In the first subphase, the transmit signal at user $k$ is given by

$$ x_{k,1}(t) = \sqrt{p_{k,E}} e^{-jkh_k}s_E(t) + \sqrt{p_{k,1}k_{k,1}}(t), t \in [0, \alpha T] \tag{1} $$

where $s_E(t)$ is the energy signal for power transfer, and $s_{k,1}(t)$ is the information signal.

In the second subphase, let $p_{k,2}$ denote the transmit power of user $k$. Then, the transmit signal of the $k$-th user is given by

$$ x_{k,2}(t) = \sqrt{p_{k,2}} s_{k,2}(t), t \in (\alpha T, T]. \tag{2} $$

Let $P_k$ denote the transmit power budget at user $k$ in the MAC phase, then $p_{k,E}$, $p_{k,1}$ and $p_{k,2}$ are subject to the following constraint:

$$ \alpha(p_{k,E} + p_{k,1}) + (1-\alpha)p_{k,2} = P_k, \forall k. \tag{3} $$

3.2 Relay Energy Harvesting and Information Processing

From (1), in the first subphase, the received signal at the relay is

$$ \tilde{y}_{R,1}(t) = \sum_{k=1}^{K} \sqrt{P_k E|h_k|s_E(t)} + \sum_{k=1}^{K} \sqrt{P_k,1|h_k|s_{k,1}(t)} + z_{R,1,a}(t), \tag{4} $$

where $z_{R,1,a}(t) \sim \mathcal{CN}(0, \sigma_{R,a}^2)$ is the additive white Gaussian noise (AWGN) at the relay’s antenna.

Fig. 1: (a) A K-user multiway relaying system. (b) Frame structure for the proposed DEBIT scheme. (c) Energy harvesting and information processing at the relay.

Then, the relay performs information receiving and energy harvesting based on power splitting [6]. Specifically, the received signal $\tilde{y}_{R,1}(t), t \in [0, \alpha T]$, is split into two parts: $\sqrt{\eta} \tilde{y}_{R,1}(t)$ and $\sqrt{1-\eta} \tilde{y}_{R,1}(t)$, where $\eta \in [0, 1]$ is the relay’s power splitting ratio. Here, $\sqrt{\eta} \tilde{y}_{R,1}(t)$ is used for energy harvesting, and $\sqrt{1-\eta} \tilde{y}_{R,1}(t)$ is for information forwarding. From (1), the harvested power in the first subphase is given by

$$ P_{EH}(\alpha, \eta, \tilde{p}_E, \tilde{p}_1) = \alpha \eta E(\tilde{y}_{R,1}(t)^2) = \alpha \eta \left[ \sum_{k=1}^{K} \sqrt{p_{k,E}|h_k|^2} \right]^2 + \sum_{k=1}^{K} p_{k,1}|h_k|^2, \tag{5} $$

where $\eta \in [0, 1]$ is the efficiency of energy conversion, $\tilde{p}_E \triangleq [p_{1,E}, \ldots, p_{K,E}]^T$, and $\tilde{p}_1 \triangleq [p_{1,1}, \ldots, p_{1,K}]^T$. Note that the first and second term on the right hand side of (5) denotes the energy harvested from the common signal $s_E(t)$ and the information signal $s_{k,1}(t)$, respectively.

The other part of the received signal, $\sqrt{1-\eta} \tilde{y}_{R,1}(t), t \in [0, \alpha T]$, is then converted into baseband for information processing. It should be noted that the energy symbols $s_E(t)$ are known to the relay node. Hence, it can be canceled at the relay before information processing. After removing the signals related to $s_E(t)$ from $\sqrt{1-\eta} \tilde{y}_{R,1}(t)$, the relay obtains

$$ y_{R,1}(t) = \sqrt{1-\eta} \tilde{y}_{R,1}(t) - \sum_{k=1}^{K} \sqrt{(1-\eta)p_{k,E}|h_k|^2 s_E + z_{R,1,b}(t)} = \sum_{k=1}^{K} \sqrt{(1-\eta)p_{k,E}|h_k|^2 s_{k,1}(t) + z_{R,1,b}(t)} \tag{6} $$

Here, $z_{R,1,b}(t) \sim \mathcal{CN}(0, \sigma_{R,b}^2)$ is the AWGN introduced by the signal conversion from passband to baseband. $z_{R,1}(t) \triangleq $
\[ \sqrt{1 - \theta} z_{R,1,n}(t) + z_{R,1,s}(t) \text{ with a variance of } \sigma_{R,1}^2 = (1 - \theta)\sigma_{R,a}^2 + \sigma_{R,b}^2. \]

As mentioned before, no energy harvesting is involved at the relay in the second subphase, and the relay's received signal is given by

\[ y_{R,2}(t) = \sum_{k=1}^{K} \sqrt{p_k} h_k s_{k,2}(t) + z_{R,2}(t), \]

where \( t \in (\alpha T, T) \), and \( z_{R,2}(t) \sim \mathcal{CN}(0, \sigma_{R}^2) \) is the AWGN.

### 3.3 BC Phase

After energy harvesting and information processing, the relay broadcasts information symbols received in the MAC phase to all the users in the BC phase. Similarly to the MAC phase, the BC phase consists of two subphases, with the transmit signals at the relay expressed as

\[ x_{R,n}(t) = \sqrt{\omega} y_{R,n}(t), \quad n = 1, 2, \tag{8} \]

where \( n \) is a subphase index, and \( \omega \) is an amplification factor for power control at the relay:

\[ \omega \times \left[ \alpha \left( 1 - \theta \right) \sum_{k=1}^{K} p_{k,1} |h_k|^2 + \sigma_{R,1}^2 \right] + (1 - \alpha) \left( \sum_{k=1}^{K} p_{k,2} |h_k|^2 + \sigma_{R}^2 \right) \leq P_R, \tag{9} \]

where \( P_R \) denotes the relay power budget.

At user \( k \), the received signals in the BC phase can be expressed as

\[ y_{k,n}(t) = h_k x_{R,n}(t) + z_{k,n}(t), \tag{10} \]

where \( z_{k,n}(t) \sim \mathcal{CN}(0, \sigma^2) \) is the AWGN.

After removing the self-interference, user \( k \) obtains

\[ \tilde{y}_{k,n}(t) = \sum_{m=1, m \neq k}^{K} \sqrt{\omega} h_m s_{m,n}(t) + \sqrt{\omega} h_k z_{R,n}(t) + z_{k,n}(t), \tag{11} \]

where \( \delta_1 = (1 - \theta) \) for the first subphase, and \( \delta_2 = 1 \) for the second subphase.

### 4 Sum-Rate Maximization

In this section, we investigate the optimal transceiver design to maximize the achievable sum-rate of the DEBIT scheme over MWRNs.

#### 4.1 Optimal Designs

From (11), it can be seen that the signal model for the considered MWRN represents a multi-access channel with \( K - 1 \) users. Hence, the achievable rate region for the proposed DEBIT scheme is the convex hull of

\[ \bigcap_{k=1}^{K} \bigcap_{S \in \mathcal{S}_k} \left\{ (R_1, \ldots, R_K) \right\} \]

\[ \sum_{m \in S} R_m \leq R_{k,S}(\alpha, \theta, \omega, \bar{p}_1, \bar{p}_2), \tag{12} \]

where \( \mathcal{S}_k = \{ 1, \ldots, k-1, k+1, \ldots, K \} \), \( \bar{p}_2 = [p_{1,2}, \ldots, p_{K,2}]^T \), and

\[ R_{k,S}(\alpha, \theta, \omega, \bar{p}_1, \bar{p}_2) = \]

\[ \alpha \mathcal{C} \left( \frac{(1 - \theta) |\omega| h_k^2 \left( \sum_{m \in S} |h_m|^2 p_{m,1} \right) + \sigma_{R,1}^2}{|\omega| h_k^2 \left( \sum_{m \in S} |h_m|^2 p_{m,2} \right) + \sigma_{R}^2} \right) + (1 - \alpha) \mathcal{C} \left( \frac{|\omega| h_k^2 \left( \sum_{m \in S} |h_m|^2 p_{m,1} \right) + \sigma_{R,1}^2}{|\omega| h_k^2 \left( \sum_{m \in S} |h_m|^2 p_{m,2} \right) + \sigma_{R}^2} \right), \tag{13} \]

with \( \mathcal{C}(x) \equiv \frac{1}{2} \log_2(1 + x) \).

Let \( P_{EH}^0 \) denote the target harvested power at the relay. In the following, we aim to maximize the achievable sum-rate under peak power constraint at each user. The sum-rate maximization problem can be formulated as

\[ \text{P1} : \quad \max_{\alpha, \theta, \omega, \bar{p}_1, \bar{p}_2} R_{\text{sum}} = \sum_{k=1}^{K} R_k \]

s.t. (9), (12),

\[ 0 \leq \theta \leq 1, \tag{14} \]

\[ 0 \leq \alpha \leq 1, \tag{14} \]

\[ P_{EH}^0(\alpha, \theta, \omega, \bar{p} \in [0, P_{peak}, k = 1, \ldots, K], \]

\[ \bar{p}_{peak} \text{ denotes the peak power at each user.} \]

Note that the function \( f(\bar{p}_E) = \left( \sum_{k=1}^{K} \sqrt{\omega} h_k \right)^2 \) in (5) is concave in \( \bar{p}_E \in \mathbb{R}^K \). Furthermore, the other constraints in (14) are linear constraints when \( \alpha, \theta, \) and \( \omega \) are fixed. Based on these observations, we have the following result.

**Theorem 1.** For fixed \( \alpha, \theta, \) and \( \omega, \) the optimization problem P1 is convex.

**Remark 1.** Note that both the relay power constraint function (9) and the rate constraints (13) are monotonic increasing functions in terms of \( \omega. \) Hence, with Theorem 1, the global optimal solution for P1 can be obtained with a two-dimensional exhaustive search over \( \alpha, \theta, \) together with a one-dimensional bisection search over \( \omega. \)

### 4.2 Suboptimal Designs

Capitalizing on the distributed energy beamforming gain, the proposed DEBIT scheme can achieve superior performance over the conventional SWIPT. However, a three-dimensional search is required to find the optimal solution, and it is quite difficult to analyze its performance. In this subsection, we propose a suboptimal scheme with low-complexity. We show that the optimization problem for the suboptimal scheme becomes linear-programming problem which are much easier to solve as compared with the optimal scheme.

In this suboptimal scheme, the first subphase at each user is dedicated to power transfer, i.e., \( p_{k,1} = 0, \forall k \), and the powers used for energy transfer are equal to each other, i.e., \( p_{k,E} = p_{E}, \forall k \). At the relay node, the power splitting ratio is \( \theta_{sub} = 1 \), as each user transmits energy signals only in the first subphase. For such suboptimal scheme, the achievable rate region is the convex hull of

\[ \bigcap_{k=1}^{K} \bigcap_{S \in \mathcal{S}_k} \left\{ (R_1, \ldots, R_K) \right\} \]

\[ \sum_{m \in S} R_m \leq R_{k,S}(\alpha, \omega, \bar{p}_1, \bar{p}_2), \tag{15} \]

where

\[ R_{k,S}(\alpha, \omega, \bar{p}_1, \bar{p}_2) = \]

\[ (1 - \alpha) \mathcal{C} \left( \frac{|\omega| h_k^2 \left( \sum_{m \in S} |h_m|^2 p_{m,1} \right) + \sigma_{R,1}^2}{|\omega| h_k^2 \left( \sum_{m \in S} |h_m|^2 p_{m,2} \right) + \sigma_{R}^2} \right), \tag{16} \]
From [16], it can be seen that the time duration for energy transfer, \( \alpha_{\text{sub}} T \), should be minimized to maximize the achievable data rate in the second subphase. Hence, the power of the energy signal in the first subphase should be as high as possible, that is

\[
p_{k,E} = p_E = P_{\text{peak}} \quad \forall k. \tag{17}
\]

Recall that \( \theta_{\text{sub}} = 1 \) for energy harvesting at the relay node. Then the corresponding harvested power is given by

\[
P_{\text{EH,sub}}(\alpha_{\text{sub}}) = \alpha_{\text{sub}} \eta P_{\text{peak}} \left( \sum_{k=1}^{K} |h_k|^2 \right)^2. \tag{18}
\]

For a target harvested power \( P_{\text{EH}}^0 \), we have

\[
\alpha_{\text{sub}} = \frac{P_{\text{EH}}^0}{\eta P_{\text{peak}} \left( \sum_{k=1}^{K} |h_k|^2 \right)^2}. \tag{19}
\]

As a result, the power of \( s_{k,2}(t) \) at user \( k \) is

\[
p_{k,2} = \frac{P_k - \alpha_{\text{sub}} P_{\text{peak}}}{1 - \alpha_{\text{sub}}}, \quad \forall k. \tag{20}
\]

From [16, 19] and [20], the coefficient \( \omega \) for the suboptimal DEBIT scheme can be determined by

\[
\omega_{\text{sub}} = \frac{P_R}{(1 - \alpha_{\text{sub}}) \left( \sum_{k=1}^{K} P_{k,2} \right) \left( 2 + \sigma_R^2 \right)}. \tag{21}
\]

With closed-form expressions of \( \alpha_{\text{sub}}, P_{k,2} \), and \( \omega_{\text{sub}} \) given by [19, 20] and [21], respectively, the sum-rate maximization problem for the suboptimal DEBIT scheme can be formulated as

\[
\text{P2:} \quad \max_{\left( R_n \right)_{n=1}^{K}} \quad R_{\text{sum,sub}} = \sum_{n=1}^{K} R_n \quad \text{s.t.} \quad \sum_{m \in S} R_m \leq R_{K, S, \text{sub}}, \forall S \subseteq \mathcal{S}, \forall k. \tag{22}
\]

From [22], we see that P2 is a linear program, and can be solved efficiently in polynomial time [23].

### 5 Sum-Rate Performance Analysis

In this section, we focus on analyzing the suboptimal DEBIT scheme, which serves as the performance lower bound of the optimal DEBIT scheme.

#### 5.1 Sum-Rate Performance Lower Bound

We consider a symmetric MWRN in which the power budgets are the same for all users: \( P_k = P \), which implies that \( P_{k,2} = p_{\text{sub}}, \forall k \), for the suboptimal DEBIT. We also assume \( \sigma_R^2 = \sigma^2 \), and that the channels are independent and identically distributed (i.i.d.) Rayleigh fading with an average gain of \( G \), i.e., \( E(|h_k|^2) = G, \forall k \).

Recall that the signal model in [11] represents a MAC with \( K - 1 \) users, and there are \( K \) such multi-access channels in the AF MWRN. Sort the channels in an ascending order as \( |h_{(1)}| \leq \cdots \leq |h_{(K)}| \).

For the AF MWRN, the achievable rates of users \( \pi(2), \ldots, \pi(K) \), are bottlenecked by the worst-channel user \( \pi(1) \), while the data rate of user \( \pi(1) \) is bottlenecked by the second worst user \( \pi(2) \). Based on these observations, we are able to obtain a sum-rate lower bound for the DEBIT scheme.

**Theorem 2.** For a symmetric MWRN with a target harvested power of \( P_{\text{EH}}^0 \), the achievable sum-rate of the proposed suboptimal DEBIT scheme is lower bounded by

\[
P_{\text{sum,sub}}^L(P_{\text{EH}}^0) = (1 - \alpha_{\text{sub}}) C \left( \frac{\omega_{\text{sub}} |h_{(1)}|^2 \sum_{k=1}^{K} |h_{k}|^2 p_{\text{sub}}}{\omega_{\text{sub}} |h_{(1)}|^2 \sigma^2 + \sigma^2} \right). \tag{23}
\]

**Proof:** See Appendix A.

**Remark 2.** As a sum-rate lower bound for the suboptimal scheme, the bound [23] also serves as the lower bound of the optimal DEBIT scheme described in the previous Section.

Based on Theorem 2, we are able to obtain a closed-form lower bound on the average sum-rate of the DEBIT scheme.

**Proposition 1.** For a symmetric MWRN with a target harvested power \( P_{\text{EH}}^0 \), when the number of users are sufficiently large, the average sum-rate of the DEBIT scheme is lower bounded by

\[
P_{\text{sum,sub}}^L(P_{\text{EH}}^0) = P_{f_s}(P_{\text{EH}}^0)(1 - \alpha_{\text{sub}}^0) C \left( \frac{GP_R}{(K + \alpha_{\text{sub}}^0)(1 - \alpha_{\text{sub}}^0)\sigma^2} \right), \tag{24}
\]

where

\[
P_{f_s}(P_{\text{EH}}^0) = 1 - \Phi \left( \frac{\sqrt{K} \mu_H}{\sigma_H} \right), \tag{25a}
\]

\[
\alpha_{\text{sub}}^0 = \frac{P_{\text{EH}}^0}{\eta P_{\text{peak}} K^2 G^2} = \frac{P_R}{(P - 0.5 S P_{\text{peak}}) \sqrt{K G^2}} \tag{25b},
\]

\[
\omega_{\text{sub}} = \frac{P_R}{(P - 0.5 S P_{\text{peak}}) \sqrt{K G^2}} \tag{25c},
\]

\[
c_0 = \sqrt{\frac{1 - \Phi(z)}{G}}, \mu_H = \frac{\mu_H \sqrt{G}}{G}, \sigma^2 = \frac{\sigma^2}{G}, \Phi(z) \mbox{ is the cumulative distribution function (CDF) of the standard normal distribution } N(0, 1), \mbox{ and } g(\zeta, \mu, \sigma) \mbox{ is defined as}
\]

\[
g(\zeta, \mu, \sigma) \triangleq \mu + \frac{\sigma}{\sqrt{2\pi}} \left[ 1 - \Phi \left( \frac{\zeta - \mu}{\sigma} \right) \right] e^{-\frac{(\zeta - \mu)^2}{2\sigma^2}}. \tag{26}
\]

**Proof:** See Appendix B.

#### 5.2 Discussion

For the symmetric MWRN with a larger number of users, when the target harvested power satisfies \( P_{\text{EH}} \ll \pi K^2 \sigma^2 / 4 \), we have \( P_{\text{EH}} / \pi K^2 \approx 1 \), \( \alpha_{\text{sub}} \approx 0 \), and \( \omega_{\text{sub}} \approx \frac{P_R}{K P_{\text{peak}}} \). The lower bound in [24] can be further approximated as

\[
R_{\text{sum,sub}}^L(P_{\text{EH}}^0) \approx C \left( \frac{K G P R}{(K^2 P + P_{\text{peak}}) \sigma^2} \right). \tag{27}
\]

If the relay’s power budget scales with the number of users, that is, \( P_R = K P \), then from [27] we have

\[
\lim_{K \to \infty} R_{\text{sum,sub}}^L(P_{\text{EH}}^0) = \mathcal{O} \left( \frac{PC}{\sigma^2} \right). \tag{28}
\]

In this case, the sum-rate lower bound tends to a constant for a large number of users.
Proposition 2.

For the considered symmetric MWRN with a sufficiently large number of users, the average harvested power of DEBIT under a feasible target sum-rate \( P_{\text{sum}}^0 \) is lower bounded by

\[
P_{\text{sum}}^\text{avg,LB} (P_{\text{EH}}^0) \leq \frac{\pi}{4} \eta G P \left( K^2 - \nu_0 \left( 1 + \nu_0 E_1 \left( \frac{\nu_0}{K} \right) \right) K \right) e^{-\nu_0},
\]

where \( E_1(x) = \int_{\nu_0}^{\infty} t^{-1} e^{-t} dt \) is the exponential integral function, \( \xi_0 = K^2 \nu_0 \), and \( \nu_0 = D \sigma^2 / G P \).

Proof: The proof is similar to that of Proposition 1 and is omitted here.

Remark 3. Using the inequality that \( E_1(x) \leq e^{-x / x} < 1 / x \), the lower bound in (32) can be further bounded by

\[
P_{\text{sum}}^\text{avg,LB} (P_{\text{sum}}^0) \geq \frac{\pi}{4} \eta G P \left( (1 - \nu_0) K^2 - \nu_0 K \right) e^{-\nu_0},
\]

From the above result, we see that the harvested power lower bound increases with the number of users for a fixed feasible target sum-rate.

6 Harvested Power Maximization

In this section, we investigate the transceiver design for harvested power maximization of the proposed scheme under a predetermined sum-rate constraint.

6.1 Optimal and Suboptimal Designs

Let \( P_{\text{sum}}^0 \) denote the target sum-rate for the MWRN. The harvested power maximization problem can be formulated as

\[
P_3: \max_{\alpha, \theta, \omega, \mathbf{p}_E, \mathbf{p}_1} P_{\text{EH}}(\alpha, \theta, \mathbf{p}_E, \mathbf{p}_1) \quad \text{s.t.} \quad \begin{cases} \ \mathbf{x}, \ \mathbf{y} \ \text{as in (12)}, \\ \sum_{k=1}^K R_k \geq P_{\text{sum}}^0, \\ p_k, E + p_k, 1 \leq P_{\text{peak}}, \forall k. \end{cases}
\]

Similar to P1, the global optimal solution for P3 can be obtained as follows.

Theorem 3. For fixed \( \alpha, \theta, \) and \( \omega \), the harvested power maximization problem P3 is a convex problem. That is, the optimal solution to P3 can be found by three-dimensional searching over the associated convex optimization solutions.

To reduce complexity, we consider the suboptimal scheme as described in Section 4. Then, the harvested-power maximization problem can be formulated as

\[
P_4: \max_{\alpha_{\text{sub}}, \{ R_k \}} P_{\text{EH,sub}}(\alpha_{\text{sub}}) \quad \text{s.t.} \quad \begin{cases} \ \mathbf{x} \ \text{as in (12)}, \\ \sum_{m \in S} R_m \leq R_{k, S}, \forall S \in S_k, \forall k, \\ \sum_{k=1}^K R_k \geq P_{\text{sum}}^0. \end{cases}
\]

For fixed \( \alpha_{\text{sub}} \), the above optimization problem is a linear program. Hence, the optimal solution of (33) can be efficiently obtained by one-dimension search over \( \alpha_{\text{sub}} \).

6.2 Performance Analysis

Based on Theorem 2, we are able to obtain an lower bound on the average harvested power of DEBIT when there are a large number of users in the MWRN.

Proposition 2. For the considered symmetric MWRN with a sufficiently large number of users, the average harvested power of DEBIT under
instance, in a MWRN with \( K = 10 \) users, the harvested power of DEBIT is about eight times as that of the conventional SWIPT scheme.

8 Conclusion

This paper proposed a novel DEBIT scheme for efficient energy transfer and information delivery in MWRNs. The sum-rate maximization and harvest power maximization problems were investigated and it was shown that the global optimal solutions for these problems can be obtained with a three-dimensional search on top of a convex program. We also proposed suboptimal schemes to reduce the complexity. In addition, we analyzed the performance of the DEBIT scheme and derived closed-form lower bounds of the average sum-rate and the harvested power. Numerical results showed the tightness of the derived lower bounds. The DEBIT scheme establishes a novel joint energy harvesting and information delivery framework, and can be applied to various wireless relay networks or smart-grid powered wireless networks [26–28].

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ordered as \(\pi(1), \pi(3), \ldots, \pi(K)\) at user \(\pi(2)\), the achievable rate of user \(\pi(1)\) is
\[
R_{\text{sIC}}^{\pi(1)} = (1 - \alpha_{\text{sub}}) \times C \left( \frac{\omega_{\text{sub}} |h_{\pi(2)}|^2 |h_{\pi(1)}|^2 P_{2,\text{sub}}}{\omega_{\text{sub}} |h_{\pi(2)}|^2 \left( \frac{1}{K} \sum_{n=3}^{K} |h_{\pi(n)}|^2 P_{2,\text{sub}} + \sigma^2 \right) + \sigma^2} \right).
\]

From the above two equations, the achievable sum-rate of the proposed suboptimal DEBIT scheme is lower bounded by
\[
R_{\text{sum,sub}} \geq R_{\pi(1),S_1(\cdot),\text{sub}} + R_{\text{sIC}}^{\pi(1)}.
\]

Since \(|h_{\pi(2)}| \geq |h_{\pi(1)}|\) and \(|h_{\pi(2)}| \geq 0\), then \(P_{2,\text{sub}}^{\pi(1)}\) can be lower bounded by
\[
R_{\text{sIC}}^{\pi(1)} \geq (1 - \alpha_{\text{sub}}) \times C \left( \frac{\omega_{\text{sub}} |h_{\pi(2)}|^4 P_{2,\text{sub}}}{\omega_{\text{sub}} |h_{\pi(2)}|^2 \left( \frac{1}{K} \sum_{n=2}^{K} |h_{\pi(n)}|^2 P_{2,\text{sub}} + \sigma^2 \right) + \sigma^2} \right).
\]

From (35) and (37), we obtain the sum-rate lower bound in (23).

12 Appendix B: Proof of Proposition 1

From (3) and (5), the maximum harvested power of the suboptimal DEBIT scheme is
\[
P_{\text{EH,max}} = \eta P \left( \sum_{k=1}^{K} |h_k|^2 \right).
\]

The proposed suboptimal DEBIT scheme is feasible only when \(P_{\text{EH,max}} \geq P_{\text{EH}}^0\), that is
\[
\sum_{k=1}^{K} |h_k|^2 \geq c_0 \approx \sqrt{\frac{P_{\text{EH}}^0}{\eta P}}.
\]

Let \(X = \frac{1}{\sqrt{K}} \sum_{k=1}^{K} |h_k|\), \(\mu_H = E[|h_k|] = \sqrt{\frac{c_0}{K}}\) and \(\sigma_H^2 = \text{Var}[|h_k|] = \frac{c_0^2}{2K}\). According to the central limit theorem, \((X - \sqrt{K}\mu_H)\) will converge in distribution to a normal \(N(0, \sigma_H^2)\) for large \(K\), i.e.,
\[
\lim_{K \to +\infty} \Pr \left[ X - \sqrt{K}\mu_H \leq z \right] = \Phi(z/\sigma_H).
\]

where \(\Phi(x)\) is the CDF of the standard normal distribution \(N(0,1)\). Hence, the feasible probability of the suboptimal DEBIT scheme can be approximated by
\[
P_{\text{feas}}(P_{\text{EH}}^0) = P \left( X \geq \frac{c_0}{\sqrt{K}} \right) = 1 - \Phi \left( \frac{c_0}{\sqrt{K}\sigma_H} - \frac{\sqrt{K}\mu_H}{\sigma_H} \right).
\]

Next, we consider the achievable sum-rate lower bound when the proposed suboptimal DEBIT scheme is feasible, i.e., \(\sum_{k=1}^{K} |h_k|^2 \geq c_0\). For larger \(K\), and under the feasible condition \(\sum_{k=1}^{K} |h_k|^2 \geq c_0\), \(D_1 \approx \left( \sum_{k=1}^{K} |h_k|^2 \right)^2\) can be well approximated by its mean value:
\[
D_1 \approx \left( E \sum_{k=1}^{K} |h_k|^2 \right) \left( \sum_{k=1}^{K} |h_k|^2 \geq c_0 \right)^2.
\]

Since \(X = \frac{1}{\sqrt{K}} \sum_{k=1}^{K} |h_k|\) is approximately normally distributed for large \(K\), \(D_1\) can be approximated as \(D_1 \approx\)
$Kg^2 \left( \sqrt{\frac{c_0^2}{K}} \sqrt{\frac{\sqrt{\frac{\pi G}{4}}}{K}}, \sqrt{\frac{(4-\pi)G}{4}} \right)$, where $g(\zeta, \mu, \sigma)$ is defined in (26). Similarly, $D_2 \triangleq \sum_{k=1}^{K} |h_k|^2$ can be well approximated as $D_2 = \sqrt{Kg} \left( \frac{c_0^2}{K}, \sqrt{\frac{\pi G}{4}} \right)$ for large $K$. As a result, for large $K$, the parameters for the suboptimal DEBIT scheme can be well approximated as:

$$a_{\sub} \simeq a_0 = \frac{P_0^{EH}}{\eta P_{\text{peak}} D_1}, \quad (43)$$

$$\omega_{\sub} \simeq \omega_0 = \frac{P_{RH}}{(P - a_0 P_{\text{peak}}) D_2}, \quad (44)$$

and

$$P_{2,\sub} \simeq P_{2,TS} = \frac{P - a_0 P_{\text{peak}}}{1 - a_0}. \quad (45)$$

Consequently, the sum-rate lower bound can be approximated as

$$R_{\text{LB, sum, sub}}(P_0^{EH}) \simeq (1 - a_0)C \left( \frac{\omega_0^2 |h_{\pi(1)}|^2 D_1 P_{2,sub}^0}{\omega_{\sub}^2 |h_{\pi(1)}|^2 \sigma^2 + \sigma^2} \right). \quad (46)$$

From (41) and (46), the average sum-rate lower bound for a given target harvested power $P_0^{EH}$ can be approximated as

$$R_{\text{avg, LB, sum, sub}}(P_0^{EH}) \simeq P_{FS}(P_0^{EH}) E_{|h_{\pi(1)}|^2} \left[ R_{\text{LB, sum, sub}}(P_0^{EH}) \right]. \quad (47)$$

Note that the PDF of $|h_{\pi(1)}|^2$ is given by $f_{|h_{\pi(1)}|^2}(x) = K e^{-Kx/G}$. From (46), (47) and after tedious calculation, we can obtain the result in (24).