# Power Allocation for Three-Phase Two-Way Relay Networks with Simultaneous Wireless Information and Power Transfer

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***Abstract*—This paper considers a three-phase two-way relay system in which two single-antenna transceivers exchange data with the help of a multi-antenna energy harvesting relay. An SNR maximization problem is formulated under fixed total power and fairness constraints. Given the fraction of energy harvested by the relay in the first two phases, a closed-form expression for the optimal power allocation between the transceivers is derived. Simulation results show that three-phase two-way relaying can have better performance than conventional two-phase two-way relaying, especially if the number of antennas at the relay is large.**

***Index Terms*—Two-way relay, simultaneous information and power transfer, energy harvesting, power allocation, signal to noise ratio maximization.**

## I. Introduction

Simultaneous wireless information and power transfer (SWIPT) has drawn a lot of recent attention because of its capability to increase the reliability of wireless networks with energy constraints [1]. Compared to the conventional power distribution in wireless networks [2]–[5], the role of SWIPT becomes more important in severe environments where it is difficult to share/provide energy for some distant nodes. *Power Splitting* (PS) and *Time Switching* (TS) protocols have been extensively considered for SWIPT in [6]–[8]. In the PS protocol, the received signal is fed into a power splitter. A fractional portion of the received power denoted by $0 \leq \theta < 1$ is fed into the energy harvester and the remaining portion $1-\theta$ is fed to the information receiver. The TS protocol is similar except, rather than simultaneously receiving information and harvesting energy, the receiver switches between information receiving and energy harvesting over time.

One potential application of SWIPT is in the area of relay-assisted bidirectional communication, also known as two-way relaying (TWR). One or more intermediate relays assist two transceivers A and B to exchange independent data with each other [9]–[12]. Exact expressions for the outage probability, ergodic capacity and diversity-multiplexing trade-off for a TWR with an energy harvesting (EH) amplify and forward relay were derived in [13]. The problem of beamforming design for sum-rate maximization under imperfect channel state information (CSI) in a scenario that the transceivers harvest energy from multiple relay nodes was considered in [14]. Power allocation at the transceivers to minimize the network outage probability was studied in [15]. The optimal beamforming design for a single multi-antenna EH relay was derived in [16]. Most of this prior work, however, has only considered *two-phase* TWR (2P-TWR), where A and B simultaneously transmit in the first phase and the relay(s) transmit in the second phase. Under the usual half-duplex assumptions, the transceivers A and B do not receive each other's signals in the first phase. Consequently, the 2P-TWR protocol does not utilize the direct link between A and B and relies entirely on the relay to facilitate communication between A and B.

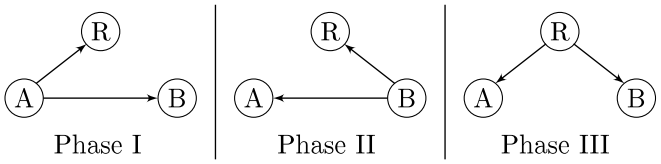


Fig. 1: System model for the three-phase two-way relaying (3P-TWR) with energy harvesting.

In this paper, we analyze the performance of the *three-phase* TWR (3P-TWR) system shown in Fig. 1 with a single multiantenna EH relay in terms of the received signal to noise ratio (SNR) at the transceivers. We assume the EH relay uses the PS protocol to continuously harvest a fraction of the energy while simultaneously receiving information from transceivers A and B. Under total transceiver power and equal SNR constraints, we derive closed-form expressions for the optimal power allocation to maximize the SNR at transceivers A and B. Our results show that 3P-TWR can outperform 2P-TWR in certain settings. Our results also show that the effect of the EH relay is only significant if the relay has a large number of antennas to facilitate efficient energy harvesting

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and directed transmission to the transceivers.

The following notation are used throughout the paper. Vectors, an $N \times N$ identical matrix and the transpose operation are denoted by bold lowercase letters, $\mathbf{I}_N$ and $(\cdot)^T$, respectively. The notation $x \sim \mathcal{CN}(\mu, \sigma^2)$ denotes that $x$ is a circularly symmetric complex Gaussian random variable with mean $\mu$ and variance $\sigma^2$.

## II. System Model and Problem Formulation

We consider the 3P-TWR model depicted in Fig. 1, in which two transceivers A and B exchange independent data through a half-duplex relay R. Transceivers A and B are equipped with a single antenna, while relay R has $N$ antennas and is also powered by an EH device. A complete cycle of communication is performed in three consecutive phases. In the first and second phases, A and B take turns and broadcast their data to R and the other transceiver. During these two phases, R harvests a fraction of the energy from the received signals using the PS protocol [6]. It is assumed the energy received from the transmissions of A and B is the only source of energy for retransmissions by R. Also, it is assumed that the required power for signal processing at R is negligible compared to the transmit power in the third phase. In the third phase, R broadcasts a combination of its received signals during the first and second phases to A and B, using the harvested energy. After completing the three phases, each transceiver combines its received signals based on the maximal ratio combining (MRC) criterion.

The complex channels A $\rightarrow$ B, A $\rightarrow$ R and B $\rightarrow$ R are denoted by $h_{AB}$, $\mathbf{h}_{AR}$ and $\mathbf{h}_{BR}$, respectively. All of channels are assumed to be fixed during the three phases and reciprocal, i.e., $h_{AB} = h_{BA}$, $\mathbf{h}_{AR} = \mathbf{h}_{RA}^T$, and $\mathbf{h}_{BR} = \mathbf{h}_{RB}^T$.

*Phase I: A $\rightarrow$ R and B*

During this phase, the received signals at R and B are obtained as

$$\mathbf{y}_1^R = \sqrt{P_A}\mathbf{h}_{AR}x_1 + \mathbf{z}_1^R$$
$$y_1^B = \sqrt{P_A}h_{AB}x_1 + z_1^B$$

where $x_1$ and $P_A$ are the transmit data and power by A, $\mathbf{z}_1^R \sim \mathcal{CN}(\mathbf{0}_{N\times 1}, \sigma^2\mathbf{I}_N)$ and $z_1^B \sim \mathcal{CN}(0, \sigma^2)$ are additive white gaussian noise (AWGN) terms at R and B, respectively. Assuming unit length of time for each phase so that the power and energy terms can be used equivalently, R uses a fraction $\sqrt{\theta}$ $(0 \leq \theta < 1)$ of its received signal for harvesting energy according to the PS protocol. Hence, the harvested energy (power) in phase I is obtained as

$$Q_1 = \eta\theta||\mathbf{h}_{AR}||^2 P_A$$

where $\eta$ $(0 < \eta \leq 1)$ is the conversion efficiency factor [8].

*Phase II: B $\rightarrow$ R and A*

During this phase, the received signals at R and A are obtained as

$$\mathbf{y}_2^R = \sqrt{P_B}\mathbf{h}_{BR}x_2 + \mathbf{z}_2^R$$
$$y_1^A = \sqrt{P_B}h_{AB}x_2 + z_1^A$$

where $x_2$ and $P_B$ are the transmit data and power by B, $\mathbf{z}_2^R \sim \mathcal{CN}(\mathbf{0}_{N\times 1}, \sigma^2\mathbf{I}_N)$ and $z_1^A \sim \mathcal{CN}(0, \sigma^2)$ are AWGN terms at R and A, respectively. The harvested energy in phase II is obtained as

$$Q_2 = \eta\theta||\mathbf{h}_{BR}||^2 P_B.$$

*Phase III: R $\rightarrow$ A and B*

During this phase, the relay uses the harvested energy to broadcast a combination of the transceivers' signals. The total harvested energy in phases I and II is equal to $Q = Q_1 + Q_2$. The relay R is constrained to use only harvested energy for transmission in Phase III, averaged over the noise realizations. Depending on different noise realizations $\mathbf{z}_1^R$ and $\mathbf{z}_2^R$, R may use more or less instantaneous energy than the actual harvested energy $Q$ in a given frame. Nevertheless, the average energy expended by R is chosen to balance the harvested energy over a large number of frames.

To maximize the transmission efficiency, R applies a beamforming matrix $\mathbf{W}_i$ to $\mathbf{y}_i^R$ for $i \in \{1, 2\}$, where

$$\mathbf{h}_{BR}^* = \mathbf{W}_1\mathbf{h}_{AR}$$
$$\mathbf{h}_{AR}^* = \mathbf{W}_2\mathbf{h}_{BR}.$$

The relay's transmitted signal can then be written as

$$\mathbf{x}_R = \sqrt{1-\theta}\left(\sqrt{P_A}\mathbf{h}_{BR}^* x_1 + \sqrt{P_B}\mathbf{h}_{AR}^* x_2\right) + \bar{\mathbf{z}}^R$$

where $\bar{\mathbf{z}}^R = \bar{\mathbf{z}}_1^R + \bar{\mathbf{z}}_2^R$ with $\bar{\mathbf{z}}_i^R = \mathbf{W}_i\mathbf{z}_i^R$ for $i \in \{1, 2\}$. The received signals at A and B are obtained as

$$y_2^A = \beta\mathbf{h}_{AR}^T\mathbf{x}_R + z_2^A$$
$$y_2^B = \beta\mathbf{h}_{BR}^T\mathbf{x}_R + z_2^B$$

where the energy scale factor $\beta$ chosen to ensure the average energy used for transmission is equal to the harvested energy $Q$ is defined as

$$\beta = \frac{\sqrt{Q}}{\mathrm{E}\{\|\mathbf{x}_R\|\}} = \sqrt{\frac{\eta\theta(||\mathbf{h}_{AR}||^2 P_A + ||\mathbf{h}_{BR}||^2 P_B)}{(1-\theta)(||\mathbf{h}_{AR}||^2 P_B + ||\mathbf{h}_{BR}||^2 P_A) + 2N\sigma^2}}. \quad (1)$$

Assuming availability of the perfect CSI of $\mathbf{h}_{AR}$ and $\mathbf{h}_{BR}$ at both A and B, the back propagated self-interference in $y_2^A$ and $y_2^B$ can be removed. The remaining signals at A and B can be written as

$$\tilde{y}_2^A = \beta\mathbf{h}_{AR}^T\left(\sqrt{1-\theta}\sqrt{P_B}\mathbf{h}_{AR}^* x_2 + \bar{\mathbf{z}}^R\right) + z_2^A$$
$$\tilde{y}_2^B = \beta\mathbf{h}_{BR}^T\left(\sqrt{1-\theta}\sqrt{P_A}\mathbf{h}_{BR}^* x_1 + \bar{\mathbf{z}}^R\right) + z_2^B.$$

Finally, transceiver $S \in \{A, B\}$ performs MRC between $y_1^S$ and $\tilde{y}_2^S$. Considering independence among the noise terms, the resulting SNRs for A and B (conditioned on the channel states) can be written as

$$\bar{\gamma}_A = \frac{|h_{AB}|^2 P_B}{\sigma^2} + \frac{\beta^2(1-\theta)P_B||\mathbf{h}_{AR}||^4}{\sigma^2\left(2N\beta^2||\mathbf{h}_{AR}||^2 + 1\right)} \quad (2)$$

$$\bar{\gamma}_B = \frac{|h_{AB}|^2 P_A}{\sigma^2} + \frac{\beta^2(1-\theta)P_A||\mathbf{h}_{BR}||^4}{\sigma^2\left(2N\beta^2||\mathbf{h}_{BR}||^2 + 1\right)} \quad (3)$$

To maximize the received SNR of the transceivers subject to a total power constraint and an SNR equality constraint, we pose the following optimization problem:

$$\begin{aligned} \underset{P_A,P_B,\theta}{\text{maximize}} \quad & \bar{\gamma}_A \\ \text{subject to:} \quad & \bar{\gamma}_A = \bar{\gamma}_B \\ & 0 \le \theta < 1 \\ & P_A + P_B = P. \end{aligned} \tag{4}$$

In other words, we wish to find the optimum power allocation between transceivers A and B and the optimum energy harvesting fraction $\theta$ at R to maximize the SNR subject to an equal SNR constraint and a total power constraint.

## III. Optimal Power Allocation

Considering the problem in (4), the Lagrange function $\mathcal{L}$ is defined as follows

$$\mathcal{L}(P_A, P_B) = \bar{\gamma}_A + \lambda_1(\bar{\gamma}_A - \bar{\gamma}_B) + \lambda_2(P_A + P_B - P) \tag{5}$$

By taking the partial derivatives of $\mathcal{L}$ with respect to the unknown parameters $P_A$, $P_B$, $\lambda_1$ and $\lambda_2$, the following set of equations are obtained:

$$\frac{\partial \mathcal{L}}{\partial P_A} = \frac{\partial \bar{\gamma}_A}{\partial P_A}(1+\lambda_1) - \lambda_1 \frac{\partial \bar{\gamma}_B}{\partial P_A} + \lambda_2 \tag{6}$$

$$\frac{\partial \mathcal{L}}{\partial P_B} = \frac{\partial \bar{\gamma}_A}{\partial P_B}(1+\lambda_1) - \lambda_1 \frac{\partial \bar{\gamma}_B}{\partial P_B} + \lambda_2 \tag{7}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_1} = \bar{\gamma}_A - \bar{\gamma}_B \tag{8}$$

$$\frac{\partial \mathcal{L}}{\partial \lambda_2} = P_A + P_B - P. \tag{9}$$

By setting the equations (6) to (9) equal to zero, these equations can be rewritten as

$$\begin{aligned} \frac{\partial \bar{\gamma}_A}{\partial P_A}(1+\lambda_1) - \lambda_1 \frac{\partial \bar{\gamma}_B}{\partial P_A} + \lambda_2 &= 0 \\ \frac{\partial \bar{\gamma}_A}{\partial P_B}(1+\lambda_1) - \lambda_1 \frac{\partial \bar{\gamma}_B}{\partial P_B} + \lambda_2 &= 0 \\ \bar{\gamma}_A - \bar{\gamma}_B &= 0 \\ P_A + P_B - P &= 0. \end{aligned}$$

To facilitate analysis, we define

$$\begin{aligned} \phi_{SN} &:= \beta^2(1-\theta)||\mathbf{h}_{SR}||^4 \\ \phi_{SD} &:= 2N\beta^2||\mathbf{h}_{SR}||^2 + 1 \end{aligned}$$

for $S \in \{A, B\}$. With this notation, the SNR terms can be rewritten as

$$\begin{aligned} \bar{\gamma}_A &= \frac{1}{\sigma^2}\left(|h_{AB}|^2 P_B + \frac{\phi_{AN}}{\phi_{AD}}\right) \\ \bar{\gamma}_B &= \frac{1}{\sigma^2}\left(|h_{AB}|^2 P_A + \frac{\phi_{BN}}{\phi_{BD}}\right). \end{aligned}$$

Replacing $P_B = \mathcal{P}$ and $P_A = P - \mathcal{P}$ in the equation $\bar{\gamma}_A - \bar{\gamma}_B = 0$, we can write

$$\mathcal{P}\frac{|h_{AB}|^2\phi_{AD} + \phi_{AN}}{\phi_{AD}} = (P-\mathcal{P})\frac{|h_{AB}|^2\phi_{BD} + \phi_{BN}}{\phi_{BD}}$$

or, equivalently

$$\mathcal{P}\phi_{BD}(|h_{AB}|^2\phi_{AD} + \phi_{AN}) = (P-\mathcal{P})\phi_{AD}(|h_{AB}|^2\phi_{BD} + \phi_{BN}).$$

Note that $\phi_{AN}$, $\phi_{AD}$, $\phi_{BN}$ and $\phi_{BD}$ are also functions of $\mathcal{P}$. After substituting for these quantities and collecting terms, we can write

$$\mathcal{A}(\theta)\mathcal{P}^3 + \mathcal{B}(\theta)\mathcal{P}^2 + \mathcal{C}(\theta)\mathcal{P} + \mathcal{D}(\theta) = 0 \tag{10}$$

where

$$\begin{aligned} \mathcal{A} \triangleq\ & (Y-Z)(U(||\mathbf{h}_{AR}||^2 - ||\mathbf{h}_{BR}||^2) \\ & + (|h_{AB}|^2(V-W))/\sigma^2) - (V-W)(X \\ & (||\mathbf{h}_{AR}||^2 - ||\mathbf{h}_{BR}||^2) - (|h_{AB}|^2(Y-Z))/\sigma^2) \\ \mathcal{B} \triangleq\ & (Y-Z)(PU||\mathbf{h}_{BR}||^2 - PU(||\mathbf{h}_{AR}||^2 - ||\mathbf{h}_{BR}||^2) \\ & + (PW|h_{AB}|^2)/\sigma^2 - (P|h_{AB}|^2(V-W))/\sigma^2) \\ & - (PX||\mathbf{h}_{BR}||^2 + (PY|h_{AB}|^2)/\sigma^2)(V-W) \\ & - PY(U(||\mathbf{h}_{AR}||^2 - ||\mathbf{h}_{BR}||^2) + (|h_{AB}|^2(V-W))/\sigma^2) \\ & - PW(X(||\mathbf{h}_{AR}||^2 - ||\mathbf{h}_{BR}||^2) - (|h_{AB}|^2(Y-Z))/\sigma^2) \\ \mathcal{C} \triangleq\ & -(Y-Z)(P^2U||\mathbf{h}_{BR}||^2 + (P^2W|h_{AB}|^2)/\sigma^2) \\ & - PW(PX||\mathbf{h}_{BR}||^2 + (PY|h_{AB}|^2)/\sigma^2) \\ & - PY(PU||\mathbf{h}_{BR}||^2 - PU(||\mathbf{h}_{AR}||^2 - ||\mathbf{h}_{BR}||^2) \\ & + (PW|h_{AB}|^2)/\sigma^2 - (P|h_{AB}|^2(V-W))/\sigma^2) \\ \mathcal{D} \triangleq\ & PY(P^2U||\mathbf{h}_{BR}||^2 + (P^2W|h_{AB}|^2)/\sigma^2) \end{aligned}$$

and

$$\begin{aligned} U &\triangleq \eta\theta(1-\theta)||\mathbf{h}_{AR}||^4 \\ V &\triangleq 2\eta\theta N\sigma^2||\mathbf{h}_{AR}||^4 + \sigma^2(1-\theta)||\mathbf{h}_{BR}||^2 \\ W &\triangleq 2\eta\theta N\sigma^2||\mathbf{h}_{AR}||^2||\mathbf{h}_{BR}||^2 + \sigma^2(1-\theta)||\mathbf{h}_{AR}||^2 \\ X &\triangleq \eta\theta(1-\theta)||\mathbf{h}_{BR}||^4 \\ Y &\triangleq 2\eta\theta N\sigma^2||\mathbf{h}_{BR}||^4 + \sigma^2(1-\theta)||\mathbf{h}_{AR}||^2 \\ Z &\triangleq 2\eta\theta N\sigma^2||\mathbf{h}_{AR}||^2||\mathbf{h}_{BR}||^2 + \sigma^2(1-\theta)||\mathbf{h}_{BR}||^2. \end{aligned}$$

Observe that, given the power splitting parameter $\theta$ and the channel states, (10) is a cubic equation in $\mathcal{P} = P_B$. Hence, (10) can be straightforwardly solved for $\mathcal{P}^{\text{opt}} \in (0, P)$ to compute the optimum power allocation. The optimum power allocation follows as

$$P_B^{\text{opt}} \triangleq \mathcal{P}^{\text{opt}} \tag{11}$$

$$P_A^{\text{opt}} \triangleq P - \mathcal{P}^{\text{opt}}. \tag{12}$$

Note that for $\mathcal{P} = 0$, we get $\bar{\gamma}_A - \bar{\gamma}_B < 0$ and for $\mathcal{P} = P$, we get $\bar{\gamma}_A - \bar{\gamma}_B > 0$, so since the function $f(\mathcal{P}) = \bar{\gamma}_A - \bar{\gamma}_B$ is continuous, there is at least 1 solution for $f(\mathcal{P}) = 0$ over the interval $(0, P)$. Computing the optimum value for $\theta$ requires using numerical methods such as a line search over discrete values in the interval $0 \le \theta < 1$.

## IV. Simulation Results

This section presents several simulation results to demonstrate the performance of 3P-TWR with an energy harvesting relay. All of the results in this section assume a carrier

frequency $f = 1$ GHz, a power harvesting efficiency of $\eta = 0.5$, and a noise variance of $\sigma^2 = -70$ dBm. To obtain the power splitting parameter $\theta$, the interval $0 \leq \theta < 1$ is divided into equal parts with length $0.05$, and the $\theta$ that maximizes (4) is chosen as an approximation of the optimal value.

Figure 2 shows the sum-rate performance of the 3P-TWR compared with the two-phase two-way relaying (2P-TWR) without energy harvesting [3], for different values of $P/\sigma^2$ assuming a single-antenna relay ($N = 1$). The sum-rate can be expressed as $\mathrm{E}\{\log_2(1+\bar{\gamma})\}$ and $2/3\mathrm{E}\{\log_2(1+\bar{\gamma})\}$ for 2P-TWR and 3P-TWR, respectively where $\bar{\gamma} = \bar{\gamma}_A = \bar{\gamma}_B$. The channel gains are assumed to be $|h_{AB}| = |h_{AR}| = |h_{BR}| = -25$ dB, corresponding to a free-space channel distance of $5$ m and a path loss exponent of $\alpha = 2$. The same total transmit power $P$ is considered for all schemes, i.e., for the 3P-TWR with EH, $P_A + P_B = P$ and for the 2P-TWR, $P_A + P_B + P_R = P$. The results in Figure 2 show that the sum-rate performance of the 3P-TWR with EH is better than the 2P-TWR in low transmit power regime (which is realistic in short range transmission), but as $P/\sigma^2$ increases, 2P-TWR performs better. This is due to the fact that it takes a total of two phases for a complete round of transmission in 2P-TWR compared to the three phases in 3P-TWR.

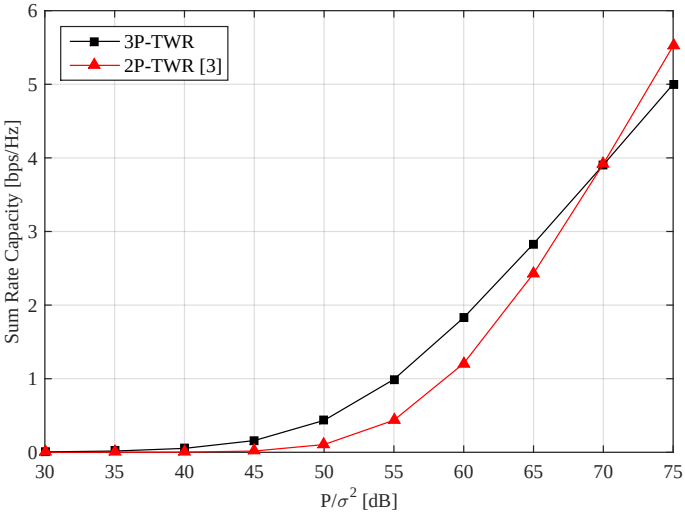


Fig. 2: Sum-rate performance of the network vs. different noise power values. The relay in this example has $N = 1$ antennas.

Figure 3 shows the effect of the number of antennas at R and the total transmit power $P$ over the sum-rate performance of the network with and without considering the direct link. In the cases with the direct link, the channel gains are the same as the previous example. In the cases without the direct link, we set $|h_{AB}| = 0$. We can observe that for large $N = 1000$, the sum rate capacity of the case without considering the direct link increases faster than the ones with the direct link. This happens because the former needs two phases for a complete round of transmission and also for large $N$, the the harvested energy at the relay becomes large.

In Figure 4 the relay channel gains are fixed to $|h_{AR}| = |h_{BR}| = -20$ dB and the direct channel's gain changes from $-60$ dB, i.e., almost completely blocked, to $-20$ dB. The results show that even when the direct channel is $40$ dB weaker, the 3P-TWR has a better sum-rate performance. This shows that because the relay uses an attenuated version of the total power in the network, if the number of antennas at the relay is not enough to harvest considerable energy, it will not be effective to improve the overall power of the received signal at the transceivers.

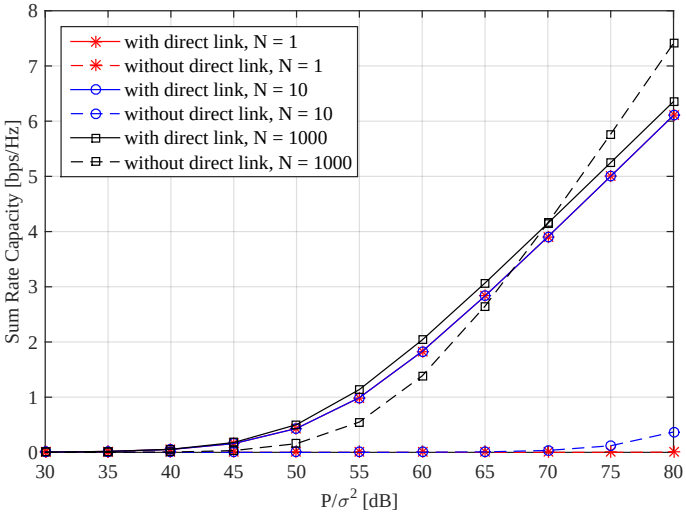


Fig. 3: Sum-rate performance of the network vs. total transmit power values and different number of antennas at the relay.

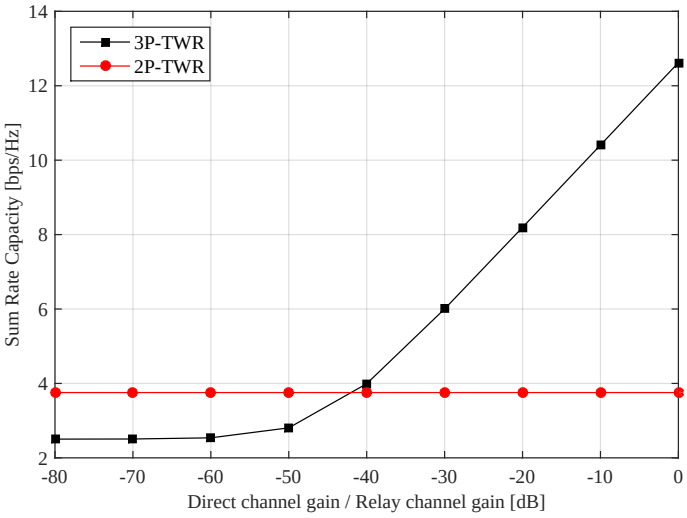


Fig. 4: Sum-rate performance of the network vs. different values for the ratio of the direct and the relay channel gains. The relay in this example has $N = 1$ antennas.

Figure 5 demonstrates the effect of the power splitting parameter $\theta$ on the received SNR. We assume a total power constraint of $P = 0$ dBm with the remaining parameters identical to those in Figure 2. The results show that for small $N$, the received SNR is not sensitive to variations of $\theta$. This is

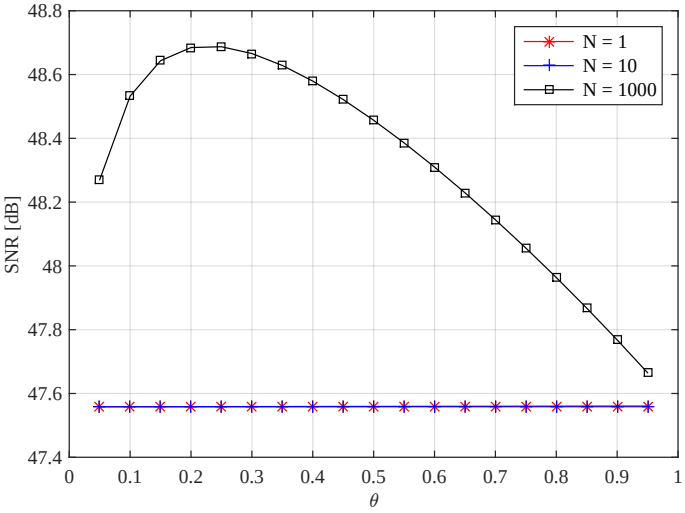


Fig. 5: SNR vs. $\theta$ for different values of $N$.

due to the fact that the relay provides negligible assistance in this case since it only harvests a small amount of energy and is unable to provide a significant signal to the transceivers in the third phase. In fact, if the relay channels are set to zero, the received SNR is equal to $\approx 17.55$ dB, which is approximately the same SNR for $N = 1$ and $N = 10$ in Figure 5. When $N = 1000$, however, the relay is able to harvest more energy and is more efficient at directing the energy to the transceivers in the third phase. In this case, a power splitting parameter of $\theta \approx 0.25$ maximizes the SNR. Moreover, the $N = 1000$ antenna relay provides a significant SNR gain over the full range of power splitting parameters tested.

## V. Conclusions

Three-phase two-way relay communication with an energy harvesting relay has been considered. A closed-form solution for the optimal power allocation between the transceivers which maximizes the received SNR subject to SNR equality and total power constraints was derived. Simulation results show that the optimal power allocation with a line search for the optimal energy harvesting ratio in the 3P-TWR with EH setup can have better performance than the conventional 2P-TWR in terms of the received SNR, especially if the number of antennas at the relay is large.

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