A Hybrid Protocol for SWIPT in Cooperative Networks

Pradeep SETHU LAKSHMI, *Mangalathu Gopalakrishnan JIBUKUMAR*

Division of Electronics, School of Engineering, Cochin University of Science and Technology, University Road, 682 022 Cochin, India

sethuharipuram@gmail.com, jibukumar@cusat.ac.in

DOI: 10.15598/aeee.v19i1.3901

Article history: Received Aug 06, 2020; Revised Nov 13, 2020; Accepted Nov 14, 2020; Published Mar 31, 2021.

Abstract. *A promising technology for addressing network lifetime and energy bottlenecks in wireless networks is the Simultaneous Wireless Information and Power Transfer (SWIPT). In this paper, a Hybrid Time switching and Power splitting-based Relaying (HTPR) protocol for SWIPT in an Amplify-and-Forward (AF) network is proposed. The network consists of a source, relay, and destination in which the relay performs Energy Harvesting (EH) from the source signal and uses the harvested energy to transmit the signal to the destination. A direct link exists between the source and destination, and the signals from the source and relay are combined by the Maximum Ratio Combining (MRC) method at the destination. Closed-form expressions for outage probability are derived under delay-limited transmission to determine the achievable throughput at the destination in different transmission schemes. For a constant data rate, HTPR protocol with uniform and optimal EH ratios are considered for throughput maximization. To solve the optimization problem, the convex optimization technique Lagrange multiplier method and Karush-Kuhn-Tucker (KKT) conditions are used. Results show that the HTPR protocol has higher throughput than other SWIPT protocols at relatively high Signal-to-Noise Ratio (SNR).*

Keywords

Cooperative, energy harvesting, hybrid protocol, power splitting, SWIPT, time switching.

1. Introduction

Cooperative communication provides high throughput, good link reliability, and spatial diversity with the help of intermediate relays when the source-destination link fades significantly [1]. In cooperative networks, the relays are energy-constrained, and it is inconvenient to frequently recharge or replace relay batteries because of economic and physical constraints. Thus, EH techniques have been developed as a favourable solution for powering wireless networks. Apart from conventional energy harvesting methods, the use of Radio-Frequency (RF) signals for EH is more appealing since RF signals provide a more stable form of energy, and it could simultaneously transfer information and power. This is termed as simultaneous wireless information and power transfer [2], [3] and [4]. The nodes can perform Information Processing (IP) and EH from the same received RF signal with SWIPT, and this shows significant gains in energy consumption and bandwidth efficiency. Therefore, SWIPT may be of fundamental importance for wireless communication networks of the Fifth-Generation (5G) in the future.

In the framework of SWIPT, the conventional EH protocols are – Power Splitting-based Relaying (PSR) and Time Switching-based Relaying (TSR) [5]. In PSR protocol, the receiver is employed with a power splitter that splits the received signal power into two fractions aiming at EH and IP. In TSR protocol, the receiver is employed with a simple switch to have independent EH followed by IP. Both PSR and TSR protocols are given similar attention as they are equally important to the research. Further, there is no clear response about which one is better. Generally, the PSR protocol outperforms the TSR protocol at high SNR and the

TSR protocol outperforms the PSR protocol at low SNR [14].

In a network employing PSR or TSR protocol, we have to either optimize the Power Splitting (PS) ratio or Time Switching (TS) ratio accordingly. PSR protocol does not consider the TS ratio, while TSR protocol does not consider the PS ratio. Thus, throughput based on either power or time is regarded as the local optimum. Research works have shown that a Hybrid Protocol (HP) combining PSR and TSR schemes can achieve better network throughput [6] and [14]. Therefore, to improve the network performance, a hybrid protocol has been developed in this paper.

A Time Power Switching-based Relaying (TPSR) protocol is proposed in [6] and [7] that determines optimal values of EH ratios (PS and TS) for maximizing the throughput of an AF network. In [6], both the relay and destination nodes are assumed to be mobile, whereas all the nodes are static in [7]. This work is further extended to two-way AF and Decode-and-Forward (DF) relay networks in [8] and [9], respectively, in which two source nodes concurrently transmit their data via a relay employing TPSR protocol.

The optimal values of EH ratios and the impact of channel information are taken into account in [10], [11] and [12] to maximize the throughput of AF and DF networks using TPSR protocol. The channel capacity of a DF network employing TPSR protocol with optimal power allocation is analysed in [13]. Subsequently, the study is extended to a multi-relay scenario, where a max-min relay selection scheme is used to pick an optimal relay from the available multiple relays.

A hybrid protocol that maximizes the AF and DF network throughput in both indoor and outdoor environments is proposed in [14], [15] and [16]. A versatile version of this is suggested for an AF network in [17], named as Adaptive Relaying (AR) protocol. The AR protocol works as TSR protocol when TSR is the best, and as PSR protocol when PSR is the best. The AF relay in [18] uses AR protocol for EH from the information signal and Co-Channel Interferences (CCIs). The performance of AR protocol over the Rician fading channel in two-way AF networks is examined in [19]. The outage probability of AF and DF networks employing HP, having non-linear EH behaviour is studied in [20] and [21], whereas having multiple relays is discussed in [22] and [23]. On the contrary, the outage of HP in AF and DF networks over asymmetric fading channels is investigated in [24] and [25], respectively. A Time Switching Protocol with Adaptive Power Splitting (TS-APS) for multi-relay DF network is discussed in [26]. The same is considered for a single relay AF network in [27], and multi-relay AF network in [28] and [29].

In all the papers reviewed above, the authors have optimized both the PS and TS ratios of the HP to maximize the network throughput, and most of the works consider SWIPT cooperative networks in the absence of source-destination Direct Link (DL). A direct link can enhance the throughput of the network [30] and [31], but a DL is seldom considered except [21]. Moreover, using a multi-antenna array architecture for SWIPT enhances the efficiency and allows EH even for low-power signals. However, several issues that arise and need to be addressed in multi-antenna transmissions are antenna selection, synchronization, channel estimation, CCIs, etc. [32] and [33]. This will increase the complexity of the network, spatial implementation, etc and the power allocation across the relays should be addressed in such cases to fix the problem [34] and [35], so MIMO techniques are not discussed in this study.

Motivated by the above considerations, a novel hybrid protocol for SWIPT in an AF network that shows better performance even for the unoptimized case is proposed in this paper, which is named as Hybrid Time switching and Power splitting-based Relaying (HTPR) protocol. The network model comprises a source, relay and destination. Using the HTPR protocol, the relay harvests energy from the source signal and then use the harvested energy for Information Transmission (IT) to the destination. A direct link is also taken into account, and the signals received at the destination are combined by the MRC method. The performance of HTPR protocol, specifically outage probability and throughput, is evaluated in Delay-Limited Transmission (DLT) mode [32] for different transmission schemes at the destination and is also compared with the existing SWIPT protocols having conventional and hybrid nature [5] and [14]. For a constant data rate, we consider two cases of HTPR protocol for throughput maximization:

- Uniform EH ratios at the relay – HTPR_U,
- Optimal EH ratios at the relay – HTPR_opt.

Comparing the SWIPT protocols, our numerical results showed that HTPR protocol outperforms other protocols at high SNR, and TSR protocol outperforms other protocols at low SNR. In addition, the joint optimization of EH ratios in HTPR_opt achieves better throughput than HTPR_U with uniform EH ratios. The rest of this paper is organized as: Sec. 2. describes the network model with proper explanation of assumptions taken and system parameters. Section 3. investigates the outage probability and throughput of network in different transmission schemes at the destination. Section 4. describes the convex optimization method adopted for throughput maximization in HTPR protocol. The numerical results are presented in Sec. 5. , and the paper concludes with future directions in Sec. 6.

2. Network Model

Consider an amplify-and-forward network, as shown in Fig. 1. The source S communicates with the destination D through an intermediate relay R. A direct link also exists between source and destination. The source and destination are non-EH nodes with limitless power supply but the relay is energy-constrained. The relay first harvests energy from the source signal, and then transmits the source information to the destination using the harvested energy. Here, information flow exists between $S-D$, $S-R$ and $R-D$, but energy can only be transmitted by the source and harvested by the relay. The relay owns a harvest-and-use architecture [36]. Here, all nodes are equipped with a single antenna and communication takes place in half-duplex mode. The channels are modelled as quasi-static block fading channels which are assumed to be constant over a block time yet varying independently and identically from one block time to another following a Rayleigh distribution. Thus, for the $S-D$, $S-R$ and $R-D$ links, the corresponding channel coefficients and inter-node distances are $\{h_{sd}, h_{sr}, h_{rd}\}$ and $\{d, d_1, d_2\}$, respectively.

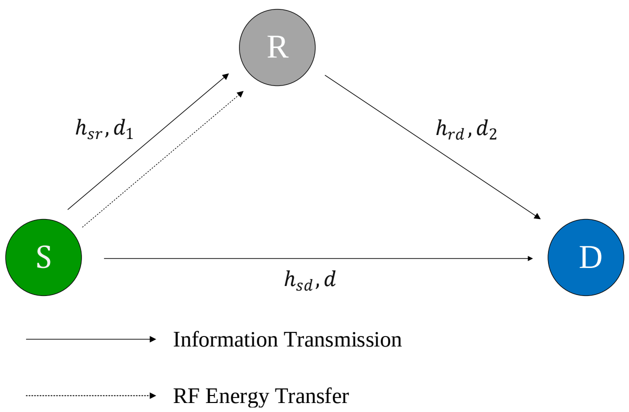

Fig. 1: Network model.

It is assumed that only the receivers know the channel state information via pilot transmission, i.e., the source does not know any channel information, but the relay knows h_{sr}, and the destination knows h_{sd} and h_{rd}. The signals received by the nodes are corrupted with Additive White Gaussian Noise (AWGN) having zero mean and variance σ^2, i.e. $\mathcal{CN}\left(0,\sigma^2\right)$. Throughout this paper, $n_{ar} \sim \mathcal{CN}\left(0,\sigma_{ar}^2\right)$ and $n_{cr} \sim \mathcal{CN}\left(0,\sigma_{cr}^2\right)$ denote the AWGN at the relay because of the receiving antenna and the RF band to baseband signal transformation, respectively. Similarly, for the AWGN at the destination, the subscript r is replaced with d. Moreover, the processing power required by the relay's transceiver circuitry is assumed to be negligible as compared with the signal transmission power from the relay to the destination [37].

2.1. HTPR Protocol

The relay block diagram and timing structure of HTPR protocol is shown in Fig. 2. HTPR protocol is a hybrid version of conventional EH protocols – TSR and PSR. The block time T for information transmission between source and destination consists of three time slots: $\frac{\alpha T}{2}$, $\frac{(1-\alpha)T}{2}$ and $\frac{T}{2}$, which is divided equally between $S-R$ and $R-D$ as in [38]. The source has no energy constraints, so the transfer of information between $S-R$ has taken less time $\frac{(1-\alpha)T}{2}$. On the other hand, the relay is energy-constrained, so the transfer of information between $R-D$ takes longer time $\frac{T}{2}$, which use energy-efficient modulation schemes.

The functions of the EH receiver and information receiver are the same as described in [37], and [39]. During the time slot $\frac{\alpha T}{2}$, the relay performs EH from the source signal as in the TSR protocol, and the next time slot $\frac{(1-\alpha)T}{2}$ works on the basis of PSR protocol. HTPR protocol splits the received source signal power P_s in the ratio $\beta : 1-\beta$, where βP_s fraction of the signal power is used for EH and $(1-\beta)P_s$ is used for $S-R$ information transmission. The remaining block time $\frac{T}{2}$ is used for $R-D$ information transmission. The terms α and β are the EH ratios in HTPR protocol, α is the time fraction and β is the power fraction utilized for SWIPT at the relay (α is similar to the TS ratio in TSR protocol and β is similar to the PS ratio in PSR protocol). The values of α and β affect the amount of energy harvested at the relay and total achievable throughput at the destination. The following subsection analyze HTPR protocol enabled EH and IP in relaying transmission.

1) Energy Harvesting

The RF signal received at the relay is used for EH in the time slot $\frac{\alpha T}{2}$. The relay will scavenge energy from the source signal to assist $S-D$ information transmission. The signal received at the relay in the first EH phase is given as:

$$y_r = \frac{1}{\sqrt{d_1^{\omega}}}\sqrt{P_s}h_{sr}s + n_{ar}, \quad (1)$$

where P_s is the source transmission power, ω is the path loss parameter, s is the source signal with $\mathrm{E}\left[|s|^2\right] = 1$, $|\bullet|$ is the absolute value operator, $\mathrm{E}[\bullet]$ is the expectation operator. We assume that AWGN's energy is negligible. From Eq. (1), the harvested energy at the relay can be expressed as:

$$E_1 = \frac{\eta P_s \left|h_{sr}\right|^2}{\sqrt{d_1^{\omega}}}\frac{\alpha T}{2}, \quad (2)$$

where $0 \leq \eta \leq 1$ is the EH efficiency of the receiver [11]. The EH in the next time slot $\frac{(1-\alpha)T}{2}$ uses βP_s

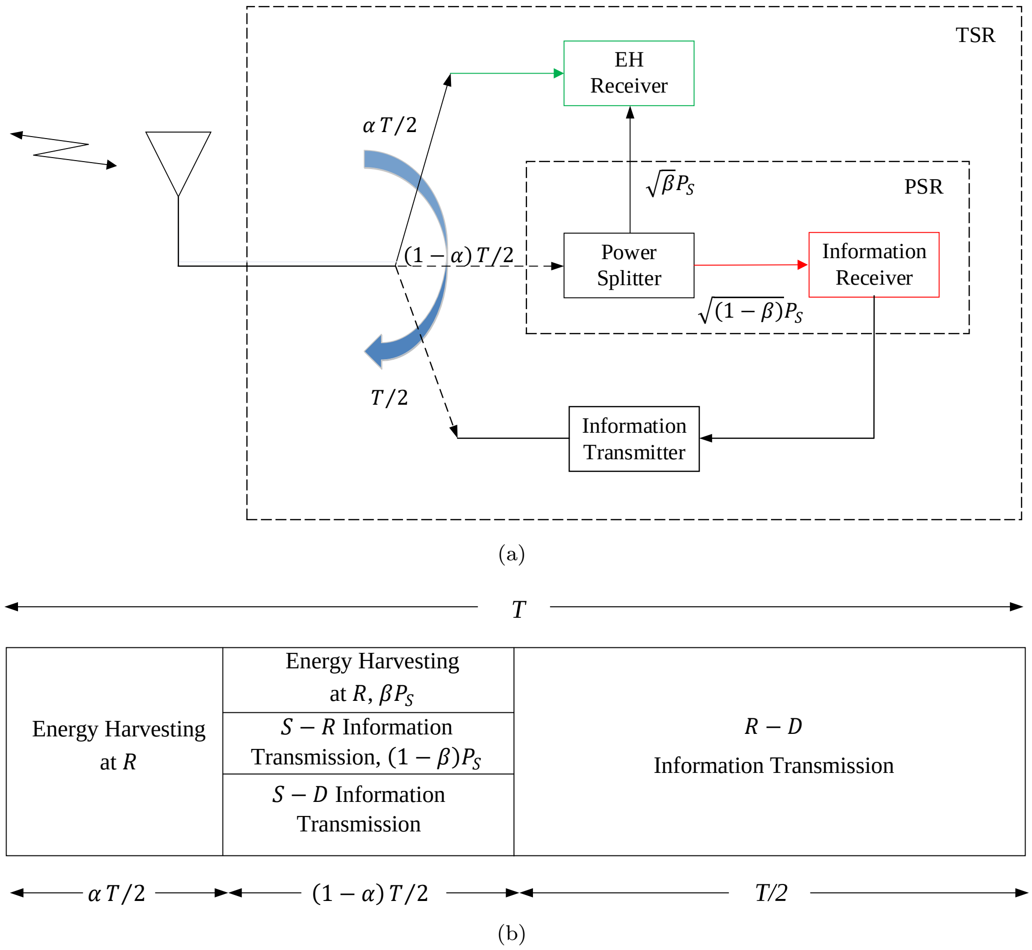

Fig. 2: HTPR protocol – (a) Relay block diagram and (b) Timing diagram.

fraction of the signal power. Accordingly, the signal received at the relay in the second EH phase is:

$$y_r = \frac{1}{\sqrt{d_1^{\omega}}}\sqrt{\beta P_s}h_{sr}s + \sqrt{\beta}n_{ar}. \tag{3}$$

Now, the energy harvested at the relay is given as:

$$E_2 = \frac{\eta\beta P_s\left|h_{sr}\right|^2}{\sqrt{d_1^{\omega}}}\frac{(1-\alpha)T}{2}. \tag{4}$$

Hence, the total energy harvested at the relay is:

$$E_r = E_1 + E_2 = \frac{\eta P_s\left|h_{sr}\right|^2 T\left(\alpha + (1-\alpha)\beta\right)}{2d_1^{\omega}}. \tag{5}$$

2) Direct Transmission

During signal transmission, the signal received at the destination via the direct link is given as:

$$y_d = \frac{1}{\sqrt{d^{\omega}}}\sqrt{P_s}h_{sd}s + n_{ad}. \tag{6}$$

The received RF signal is down-converted to a baseband signal. After down-conversion, the sampled baseband signal at the destination is given as:

$$y_d = \frac{1}{\sqrt{d^{\omega}}}\sqrt{P_s}h_{sd}s + n_{ad} + n_{cd}, \tag{7}$$

where n_{ad} is the AWGN due to the receiving antenna and n_{cd} is the AWGN due to the RF band to baseband signal conversion at the destination. From Eq. (7), the SNR at the destination is given as [30]:

$$\gamma_d^{dt} = \frac{P_s\left|h_{sd}\right|^2}{d^{\omega}\sigma_d^2}, \tag{8}$$

where $\sigma_d^2 = \sigma_{ad}^2 + \sigma_{cd}^2$.

3) Relaying Transmission

The first stage of relaying transmission is the transmission of information from source to the relay, and the signal received at the relay is given as [17]:

$$y_r = \frac{1}{\sqrt{d_1^{\omega}}}\sqrt{(1-\beta)P_s}h_{sr}s + \sqrt{(1-\beta)}n_{ar}. \tag{9}$$

The information receiver down-coverts the received RF signal to a baseband signal and processes it. The sampled baseband signal at the relay after power splitting and down-conversion is given as:

$$y_r = \frac{1}{\sqrt{d_1^\omega}}\sqrt{(1-\beta)P_s}h_{sr}s+\sqrt{(1-\beta)}n_{ar}+n_{cr}. \quad (10)$$

The relay amplifies the received signal and retransmits it to the destination. The signal transmitted from the relay is given as:

$$x = \frac{\sqrt{P_r}y_r}{\sqrt{\frac{(1-\beta)P_s|h_{sr}|^2}{d_1^\omega}+(1-\beta)\sigma_{ar}^2+\sigma_{cr}^2}}, \quad (11)$$

where the denominator term in the Eq. (11), $F = \sqrt{\frac{(1-\beta)P_s|h_{sr}|^2}{d_1^\omega}+(1-\beta)\sigma_{ar}^2+\sigma_{cr}^2}$, is the relay's power constraint factor, which guarantees that the energy consumed for information transmission by the relay is less than the energy harvested from the source [5], and P_r is the relay's transmission power that depends on the amount of energy harvested and the information transmission time, $t=\frac{T}{2}$. It is given as:

$$P_r = \frac{E_r}{T/2} = \frac{\eta P_s|h_{sr}|^2(\alpha+(1-\alpha)\beta)}{d_1^\omega}. \quad (12)$$

The relay makes full use of the harvested energy for information transmission to the destination. Using P_r, the sampled baseband signal received at the destination via the $S-R-D$ link is given as:

$$y_d = \frac{1}{\sqrt{d_2^\omega}}h_{rd}x+n_{ad}+n_{cd}. \quad (13)$$

Substituting Eq. (11) into Eq. (13), we have:

$$y_d = n_{ad}+n_{cd}+ \\ +\frac{h_{rd}\sqrt{P_r d_1^\omega}y_r}{\sqrt{d_2^\omega}\sqrt{(1-\beta)P_s|h_{sr}|^2+d_1^\omega((1-\beta)\sigma_{ar}^2+\sigma_{cr}^2)}}. \quad (14)$$

Finally, substituting y_r from Eq. (10), y_d is given as:

$$y_d = \frac{\sqrt{(1-\beta)P_sP_r}h_{sr}h_{rd}s}{\sqrt{d_2^\omega}\sqrt{(1-\beta)P_s|h_{sr}|^2+d_1^\omega\sigma_r^2}}+ \\ +\frac{\sqrt{P_r d_1^\omega}h_{rd}n_r}{\sqrt{d_2^\omega}\sqrt{(1-\beta)P_s|h_{sr}|^2+d_1^\omega\sigma_r^2}}+n_d, \quad (15)$$

where $n_r=\sqrt{(1-\beta)}n_{ar}+n_{cr}$ and $n_d=n_{ad}+n_{cd}$ are the overall AWGNs at the relay and destination with $\sigma_r^2=\sqrt{(1-\beta)}\sigma_{ar}^2+\sigma_{cr}^2$ and $\sigma_d^2=\sigma_{ad}^2+\sigma_{cd}^2$, respectively. By substituting Eq. (12) into Eq. (15), the signal received at the destination in terms of P_s, η, α, β, d_1 and d_2 is given as:

$$y_d = \underbrace{\frac{\sqrt{\eta|h_{sr}|^2(1-\beta)(\alpha+(1-\alpha)\beta)P_s}h_{sr}h_{rd}s}{\sqrt{d_1^\omega d_2^\omega}\sqrt{P_s|h_{sr}|^2(1-\beta)+d_1^\omega\sigma_r^2}}}_{\text{Signal}}+ \\ +\underbrace{\frac{\sqrt{\eta P_s|h_{sr}|^2(\alpha+(1-\alpha)\beta)}h_{rd}n_r}{\sqrt{d_2^\omega}\sqrt{P_s|h_{sr}|^2(1-\beta)+d_1^\omega\sigma_r^2}}}_{\text{Noise}}+n_d. \quad (16)$$

Thus, the SNR at the destination in relaying transmission employing HTPR protocol is given as shown in Eq. (17).

3. Outage Probability and Throughput Analysis

In this section, closed-form expressions for outage probability and throughput for the different transmission schemes employed in the network are derived. The probability that instantaneous output SNR falls below a pre-defined threshold γ_0 is defined as outage probability P_{out}. The threshold SNR at the destination for a fixed source transmission rate of R_s bits·s^{-1} is given as $\gamma_0 = 2^{\frac{2}{2-\alpha}R_s}-1$. Thus, P_{out} is given as:

$$P_{out} = P(\gamma_d<\gamma_0). \quad (18)$$

Destination processing has a vital role to play in keeping the achievable throughput of the system. So, to improve the overall system performance, it is necessary to combine the signals coming through different paths constructively. Here, we consider MRC at the destination and the outage probability of HTPR protocol in different information transmission phases can be obtained as follows.

1) HTPR Protocol – Direct Transmission

The $S-D$ information transmission in HTPR protocol happens in the time slot $\frac{(1-\alpha)T}{2}$ and it is denoted as HTPR – DT. The channel gain of $S-D$ link $|h_{sd}|^2$ is Exponentially Distributed (ED) with $\mathrm{E}\left[|h_{sd}|^2\right]=1$. Therefore, the SNR γ_d^{dt} in Eq. (8) is also ED with parameter $\lambda_{dt}=\frac{d^\omega\sigma_d^2}{P_s}$. The outage probability of direct link to the specified SNR threshold γ_0 is given as:

$$P_{out}^{dt} = P\left(\gamma_d^{dt}<\gamma_0\right) = P\left(\frac{P_s|h_{sd}|^2}{d^\omega\sigma_d^2}<\gamma_0\right) = \\ = P\left(|h_{sd}|^2<\frac{\gamma_0 d^\omega\sigma_d^2}{P_s}\right). \quad (19)$$

$$\gamma_d^{dt} = \frac{\mathrm{E}\left\{|\text{Signal part in Eq. (16)}|^2\right\}}{\mathrm{E}\left\{|\text{Noise part in Eq. (16)}|^2\right\}} = \frac{\frac{\eta P_s^2 |h_{sr}|^4 |h_{rd}|^2 (1-\beta)(\alpha+(1-\alpha)\beta)}{d_1^\omega d_2^\omega \left(P_s |h_{sr}|^2 (1-\beta) + d_1^\omega \sigma_r^2\right)}}{\frac{\eta P_s^2 |h_{sr}|^2 |h_{rd}|^2 \sigma_r^2 (\alpha+(1-\alpha)\beta)}{d_2^\omega \left(P_s |h_{sr}|^2 (1-\beta) + d_1^\omega \sigma_r^2\right)} + \sigma_d^2} = \tag{17}$$
$$= \frac{\eta P_s^2 |h_{sr}|^4 |h_{rd}|^2 (1-\beta)(\alpha+(1-\alpha)\beta)}{\eta P_s |h_{sr}|^2 |h_{rd}|^2 d_1^\omega \sigma_\gamma^2 (\alpha+(1-\alpha)\beta) + P_s |h_{sr}|^2 d_1^\omega d_2^\omega \sigma_d^2 (1-\beta) + d_1^{2\omega} d_2^\omega \sigma_r^2 \sigma_d^2}.$$

From the Cumulative Distribution Function (CDF) of exponential distribution, outage probability in Eq. (19) can be simplified as:

$$P_{out}^{dt} = 1 - \exp\left(-\frac{\gamma_0 d^\omega \sigma_d^2}{P_s}\right). \tag{20}$$

2) HTPR Protocol – Relaying Transmission

The relaying transmission consists of $S-R$ and $R-D$ information transmission and it is denoted as HTPR – RT. The SNR at the destination for the relaying transmission is given in Eq. (17). Thus, the outage probability can be expressed as:

$$P_{out}^{rt} = P\left(\gamma_d^{rt} < \gamma_0\right) = $$
$$= 1 - \frac{1}{\lambda_{h_{sr}}} \int\limits_{z=\frac{d}{c}}^{\infty} e^{-\frac{z}{\lambda_{h_{sr}}} + \frac{az+b}{(cz^2-dz)\lambda_{h_{rd}}}}. \tag{21}$$

At high SNR approximation:

$$P_{out}^{rt} \approx 1 - e^{-\frac{d}{c\lambda_{h_{sr}}}} u K_1(u), \tag{22}$$

where $u = \sqrt{\frac{4a}{c\lambda_{h_{sr}}\lambda_{h_{rd}}}}$, $a = P_s d_1^\omega d_2^\omega \sigma_d^2 \gamma_0 (1-\beta)$, $b = d_1^{2\omega} d_2^\omega \sigma_r^2 \sigma_d^2 \gamma_0$, $c = \eta P_s^2 (1-\beta)(\alpha+(1-\alpha)\beta)$ and $d = \eta P_s d_1^\omega \sigma_r^2 \gamma_0 (\alpha+(1-\alpha)\beta)$. $K_1(\bullet)$ is the first order modified Bessel function of the second kind [40], and the terms $\lambda_{h_{sr}}$ and $\lambda_{h_{rd}}$ are the mean values of ED random variables $|h_{sr}|^2$ and $|h_{rd}|^2$, respectively. The proof of the Eq. (22) refers to Appendix A in [5].

3) HTPR Protocol – MRC

The MRC method in HTPR protocol is denoted as HTPR – MRC. In MRC, the direct and relaying transmission signals are combined together at the destination to obtain a better-quality signal. This minimizes the outage probability and maximizes the system throughput. We linearly combine the received signals in our network model to maximize the destination SNR. Thus, output SNR can be expressed in terms of the individual links SNR and is given as:

$$\gamma_d^{mrc} = \gamma_d^{dt} + \gamma_d^{rt}. \tag{23}$$

Thus, outage probability of the MRC can be written as:

$$P_{out}^{mrc} = P\left(\gamma_d^{mrc} < \gamma_0\right) = P\left(\gamma_d^{dt} + \gamma_d^{rt} < \gamma_0\right). \tag{24}$$

It can be simplified as shown in Eq. (25). Thus, from the above analysis, outage probability can be generally written as shown in Eq. (26).

4) Throughput Analysis

The number of bits that are successfully decoded at the destination per unit time per unit bandwidth is defined as throughput. Since we employ DLT, the throughput is determined by estimating the outage probability P_{out} at a fixed source transmission rate of R_s bits·s^{-1}. The expression for throughput is given as:

$$\tau = (1 - P_{out}) R_s \frac{t}{T}, \tag{27}$$

where t represents the $S-D$ effective communication time in the block time of T seconds. In HTPR protocol, $t = (1-\alpha)\frac{T}{2} + \frac{T}{2}$ and outage probability at the destination in different transmission schemes can be obtained from Eq. (26). Thus, the destination throughput is given as:

$$\tau = \frac{(1 - P_{out}) R_s (2 - \alpha)}{2}. \tag{28}$$

4. Optimization Formulation for Throughput Maximization

This section provides joint optimization of EH ratios in the HTPR protocol such that system throughput is maximized. The problem of maximizing end-to-end throughput can be formulated as:

$$\mathcal{P}_0 : \max \tau. \tag{29}$$

The corresponding optimization can be written as follows:

$$\mathcal{P}_0 : \max \frac{(1 - P_{out}) R_s (2 - \alpha)}{2}, \tag{30}$$

subject to the constraints:

$$\mathcal{C}_1 : E_r^{\min} \le E_r \le E_r^{\max}, \tag{31}$$

$$\begin{aligned} P_{out}^{mrc} &= \int_0^{\gamma_0}\int_0^{\gamma_0-X} f_Y(y) f_X(x) dy dx = 1 - e^{-\lambda_{rt}\gamma_0} u K_1(u) - e^{-\lambda_{dt}\gamma_0} \int_0^{\gamma_0} e^{\lambda_{dt} X} f_X(x) dx = \\ &= \int_0^{\gamma_0} \left[\left(1 - e^{\lambda_{dt} y}\right) \Big|_0^{\gamma_0 - X} \right] f_X(x) dx = \\ &= 1 - e^{-\lambda_{rt}\gamma_0} u K_1(u) - e^{-\lambda_{dt}\gamma_0} \cdot \left(1 - e^{(\lambda_{dt}-\lambda_{rt})\gamma_0} u K_1(u) + \lambda_{dt} e^{-\lambda_{rt}\gamma_0} \int_0^{\gamma_0} e^{\lambda_{dt} x} u K_1(u) dx\right) = \\ &= 1 - e^{-\lambda_{dt}\gamma_0} - \lambda_{dt} e^{-(\lambda_{dt}+\lambda_{rt})\gamma_0} \int_0^{\gamma_0} e^{\lambda_{dt} x} u K_1(u) dx. \end{aligned} \tag{25}$$

$$P_{out} = \begin{cases} 1 - \exp\left(-\dfrac{\gamma_0 d^\omega \sigma_d^2}{P_s}\right) & ; \text{DT} \\ 1 - e^{-\dfrac{d}{c\lambda_{h_{sr}}}} u K_1(u) & ; \text{RT} \\ 1 - e^{-\lambda_{dt}\gamma_0} - \lambda_{dt} e^{-(\lambda_{dt}+\lambda_{rt})\gamma_0} \int_0^{\gamma_0} e^{\lambda_{dt} x} u K_1(u) dx & ; \text{MRC} \end{cases}. \tag{26}$$

$$\mathcal{C}_2 : P_r^{\min} \leq P_r \leq P_r^{\max}, \tag{32}$$

$$\mathcal{C}_3 : \gamma_d^{\min} \leq \gamma_d \leq \gamma_d^{\max}, \tag{33}$$

$$\mathcal{C}_4 : 0 \leq \alpha \leq 1, \tag{34}$$

$$\mathcal{C}_5 : 0 \leq \beta \leq 1. \tag{35}$$

$\mathcal{C}_1$ is the EH constraint at the relay, which reflects the energy causality. It indicates that the energy harvested by the relay E_r is upper-bounded by maximum harvested energy $E_r^{\max}$ and lower-bounded by minimum harvested energy $E_r^{\min}$. $\mathcal{C}_2$ is the relay's transmission power constraint which ensures that the power radiated by the relay is non-negative. It is upper-bounded by maximum transmission power of the relay $P_r^{\max}$ and lower-bounded by minimum transmission power of the relay $P_r^{\min}$. $\mathcal{C}_3$ is the destination SNR constraint, which is upper and lower-bounded by maximum SNR $\gamma_d^{\max}$ and minimum SNR $\gamma_d^{\min}$, respectively, such that $\gamma_d \geq \gamma_0$. $\mathcal{C}_4$ and $\mathcal{C}_5$ describe the constant upper and lower bounds of the EH ratios. Observing this optimization problem, it can be found that all conditions are linear and $\mathcal{P}_0$ is a convex optimization problem, so it is possible to use the Lagrange multiplier approach and KKT conditions to find the optimal solution. The Lagrange function is:

$$\begin{aligned} L = &\frac{(1-P_{out}) R_s (2-\alpha)}{2} + \\ &+\kappa_1 \left(E_r - E_r^{\min}\right) + \kappa_2 \left(E_r + E_r^{\max}\right) + \\ &+\kappa_3 \left(P_r - P_r^{\min}\right) + \kappa_4 \left(P_r + P_r^{\max}\right) + \\ &+\kappa_5 \left(\gamma_d - \gamma_d^{\min}\right) + \kappa_6 \left(\gamma_d + \gamma_d^{\max}\right), \end{aligned} \tag{36}$$

with conditions $0 \leq \alpha \leq 1$ and $0 \leq \beta \leq 1$. $\kappa_1, \kappa_2, \ldots, \kappa_6$ are the non-negative Lagrange multipliers for the restrictive conditions. The optimal solution is obtained when the partial derivative of the Lagrangian is equal to zero and we can obtain:

$$\frac{\partial L}{\partial \alpha} = 0 \text{ and } \frac{\partial L}{\partial \beta} = 0. \tag{37}$$

The remaining KKT conditions are $\kappa_1 \left(E_r - E_r^{\min}\right) = 0$, $\kappa_2 \left(E_r + E_r^{\max}\right) = 0$, $\kappa_3 \left(P_r - P_r^{\min}\right) = 0$, $\kappa_4 \left(P_r + P_r^{\max}\right) = 0$, $\kappa_5 \left(\gamma_d - \gamma_d^{\min}\right) = 0$ and $\kappa_6 \left(\gamma_d + \gamma_d^{\max}\right) = 0$. Now, the optimization problem is reduced to a system of equations with linear constraints, and the optimal solution for $\mathcal{P}_0$ can be easily found by using existing numerical methods.

5. Numerical Results and Discussions

This section numerically analyzes the throughput of an AF network employing HTPR protocol for SWIPT. We compare the performance difference of HTPR protocol with TSR, PSR and hybrid protocols [5] and [7] in different transmission schemes at the destination and also with traditional $S - D$ Direct Transmission (DT) having total information transmission time $t = T$. For simplicity, the variances of AWGNs at the relay and destination are taken as $\sigma_{ar}^2 = \sigma_{ad}^2 = \sigma_{na}^2$ and $\sigma_{cr}^2 = \sigma_{cd}^2 = \sigma_{nc}^2$. The network parameters for numerical analysis are given in Tab. 1.

Tab. 1: Network parameters.

Parameter	Value
d_1	1 m
d	0.3 m
d_2	0.8 m
ω	2.7
η	1
P_s	1 W
R_s	3 bits·s^{-1}
σ_{na}^2	0.01 W
σ_{nc}^2	0.01 W

The effect of EH ratios on the throughput is shown in Fig. 3(a). The throughputs of TSR and PSR protocols are dependent on α and β, respectively, whereas the throughputs of hybrid protocols are dependent on both α and β. First, uniform EH ratio $\alpha = \beta$ is considered at the relay for hybrid protocols. It is clear from the figure that the proposed HTPR protocol shows better throughput even for the unoptimized case, $\alpha = \beta$. This is because EH and information transmission are well balanced in HTPR protocol as compared to other protocols, so relay can harvest sufficient energy for information transmission without sacrificing the information transmission time. Thus, HTPR protocol can achieve higher throughput than other protocols. In the figure, other than the DT, irrespective of the transmission scheme adopted, the throughput shows a concave nature. First, it increases and then it decreases. It is justifiable as follows. The values of α and β, for which the maximum throughput is obtained, are denoted as α_{opt} and β_{opt}, respectively. For any values of $\alpha < \alpha_{opt}$ and $\beta < \beta_{opt}$, less time and power will be expended for EH at the relay. Consequently, less energy is harvested and the relay has limited power for information transmission, which deteriorates the SNR as well as throughput at the destination.

Conversely, α and β exceeding α_{opt} and β_{opt} is also not beneficial to the system because EH is performed rather than information transmission, i.e., when $\alpha > \alpha_{opt}$ and $\beta > \beta_{opt}$, less time and power will be dedicated for information transmission at the relay, which results in poor SNR and throughput decrease. The throughput of DT remains constant showing that it is independent of EH ratios, and it is better than any other schemes when the EH ratio is small or large enough. This is due to the fact that in HTPR protocol, when we employ uniform EH ratios $\alpha = \beta$, the worse performance happens when $\alpha = \beta = 0$ and $\alpha = \beta = 1$. This is justifiable as follows. When $\alpha \to 0$, the EH ratio β also tends to zero $\beta \to 0$, so no communication is possible between $S-R$ as well as $R-D$ since no energy is harvested at the relay, i.e. $E_r \to 0$, $P_r \to 0$, $\gamma_d^{rt} \to 0$ and $\tau \to 0$. When MRC is employed at the destination, there will be $S-D$ information transmission via the direct link (HTPR – DT) in the timeslot $t \approx \frac{T}{2}$. In contrast, when only DT is employed between source and destination, the total information transmission time is $t = T$. The resulting throughput obtained at the destination for the information transmission time $t = T$ will be greater than for $t = \frac{T}{2}$. Thus, DT outperforms HTPR – MRC and HTPR – RT when $\alpha/\beta \to 0$.

On the contrary, when $\alpha \to 1$, EH dominates in the timeslot $\frac{\alpha T}{2}$ and no information transmission is possible between $S-R$ as well as $R-D$ in HTPR protocol since the time slot $\frac{(1-\alpha)T}{2}$, i.e., $\gamma_d^{dt} \to 0$, $\gamma_d^{rt} \to 0$ and $\gamma_d^{mrc} \to 0$. Consequently, $P_{out}^{dt} \to 1$, $P_{out}^{rt} \to 1$ and $P_{out}^{mrc} \to 1$, which results in low throughput at the destination, $\tau \to 0$. Similar to the above mentioned case, the throughput obtained when only DT is employed between source and destination for the time $t = T$ will be greater while employing HTPR – MRC and HTPR – RT at the destination when $\alpha/\beta \to 1$. Thus, unlike conventional relay networks, DT outperforms MRC and relaying transmission in HTPR protocol. The same happens in rest of the SWIPT protocols and our results are in line with the results given in [31]. Therefore, the direct link in cooperative networks should be considered. In the case of HTPR protocol with uniform EH ratios, the throughput is almost stable for a wide range of SNR. The performance improvement of SWIPT protocols and transmission schemes

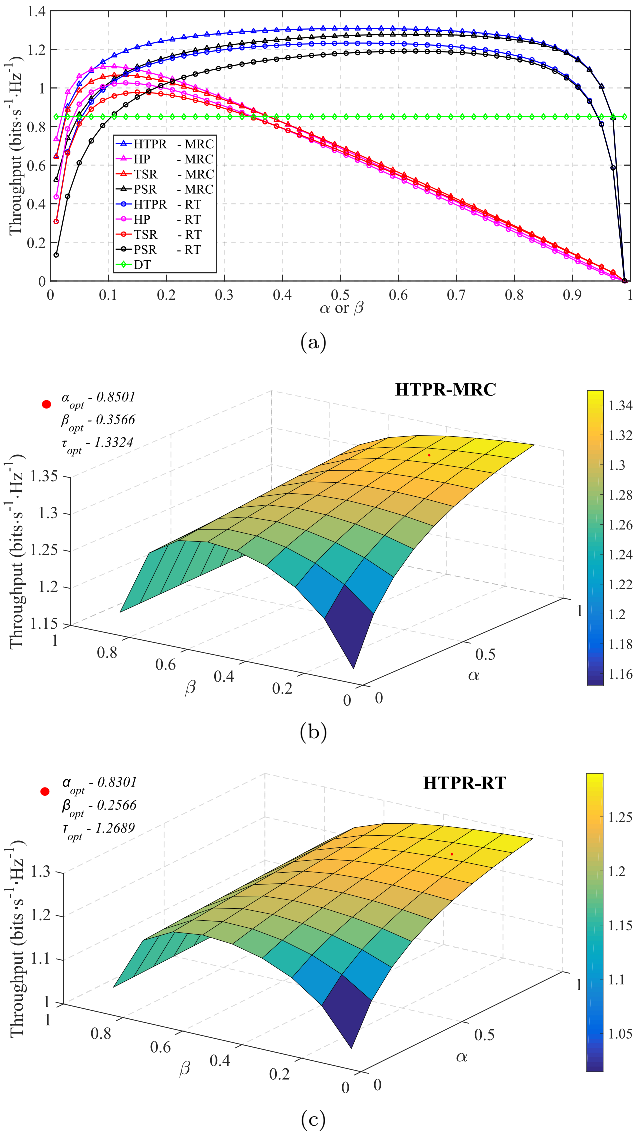

Fig. 3: Throughput vs. EH ratios.

are as follows:

$$\tau = \begin{cases} \text{HTPR} > \text{PSR} > \text{HP} > \text{TSR} & ;\text{ high SNR} \\ \text{MRC} > \text{RT} > \text{DT} & \\ \text{TSR} > \text{HP} > \text{HTPR} > \text{PSR} & ;\text{ low SNR} \\ \text{DT} > \text{MRC} > \text{RT} & \end{cases} . \quad (38)$$

The HTPR protocol outperforms other protocols at high values of EH ratios (high SNR region) and TSR protocol outperforms others at low values of EH ratios (low SNR region) in terms of throughput from outage probability. The following are the respective explanations. The value of throughput is dependent on the SNR of the two hops and the information transmission time. At the low SNR region, the main factor affecting the throughput is the SNR of the two hops, the value of which would increase rapidly with optimal TS ratio α_{opt} during the first phase of the TSR protocol [41]. Thus, TSR protocol shows superiority over other protocols at low SNR. At high SNR region, the HTPR protocol strictly performs better in terms of effective throughput than the other protocols. This is due to the hybrid nature, and effective communication rate of HTPR protocol is more than TSR protocol at this time [42]. In addition, even though PS degrade the signal quality at the relay at low SNR region, it seems that at high SNR region, PS scheme of the HTPR protocol with optimal PS ratio would not degrade the received SNR considerably so that information could still be correctly received at the relays, thereby increasing the throughput.

Tab. 2: Comparison of throughput between HTPR_{U} and HTPR_{opt}.

Transmission schemes	**HTPR_{U}**	**HTPR_{opt}**
MRC	1.4094	1.4335
RT	1.3235	1.3601

The throughput obtained when we jointly optimized the EH ratios of HTPR protocol in MRC and relaying transmission at the destination are shown in Fig. 3(b) and Fig. 3(c), respectively. In HTPR protocol, the relay is able to choose a fair time fraction and power fraction for SWIPT by the optimization of EH ratios. Therefore, optimized EH ratios can lead to high throughput in a network compared to a network employing uniform EH ratios. The optimal values of EH ratios with the corresponding throughput in HTPR_{U} and HTPR_{opt} are tabulated in Tab. 2.

The effect of EH efficiency on the throughput is shown in Fig. 4(a). For a given η, the value of EH ratios that results in maximum throughput at the destination is chosen in each case. EH efficiency accounts for the receiver's effectiveness in converting the harvested energy into electrical energy. For higher η, more energy is harvested and the transmit power in

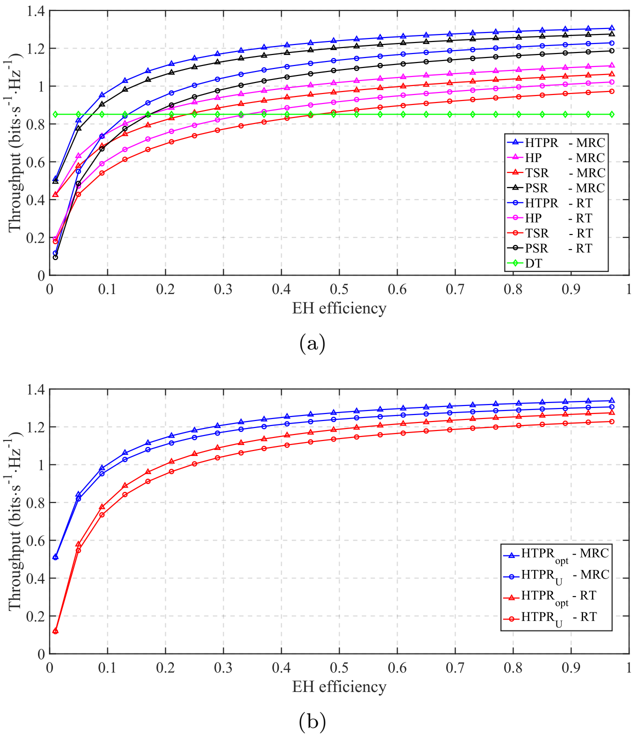

Fig. 4: Throughput vs. EH efficiency.

the data transmission phase is higher. Therefore, as η increases, the throughput also increases. The throughput of DT remains constant with respect to η, showing that $S-D$ link is independent of η. The DT outperforms other schemes for low values of η, but as the value of η increases, EH-based schemes outperform DT. HTPR protocol has high throughput in all transmission schemes compared to other protocols at high values of η. The performance improvement of different transmission schemes and protocols is the same as mentioned before. The throughput of HTPR_{U} and HTPR_{opt} versus EH efficiency is shown in Fig. 4(b). For example, when $\eta = 0.53$, HTPR_{opt} has achieved 2.86 % and 4.34 % increase in throughput in MRC and RT when compared to HTPR_{U}, respectively.

The impact of source transmission power on throughput is shown in Fig. 5(a). Source transmission power is the only energy source that can be used by the relay for information transmission to the destination. The throughput of all protocols increases as the source transmission power increases. TSR protocol performs better at low transmission power and HTPR protocol shows superiority over other SWIPT protocols at high transmission power. For DT, as source transmission power increases, the SNR γ_d^{dt} in Eq. (8) increases, thus, the achievable throughput at the destination increases. For the relay-assisted transmission via $S-R-D$ link, as source transmission power increases, the harvested energy at the relay increases. This will reduce the chances of outage owing to fading and path

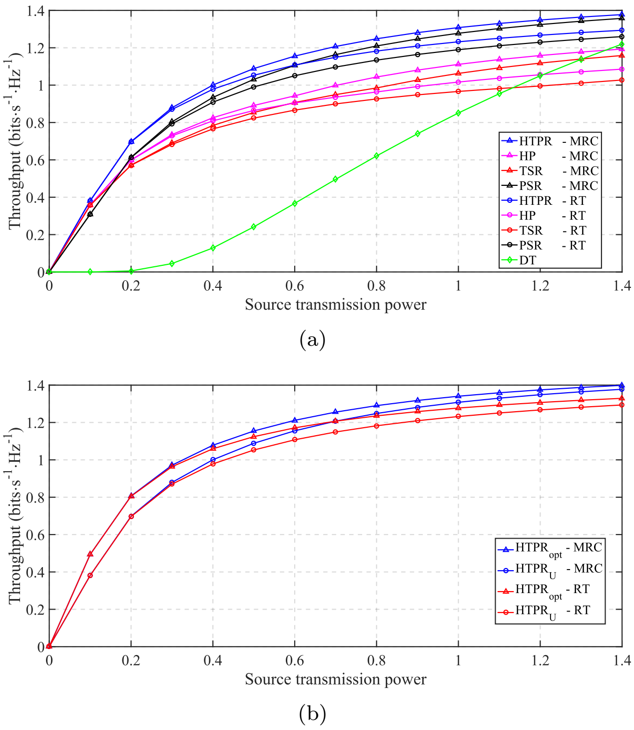

Fig. 5: Throughput vs. source transmission power.

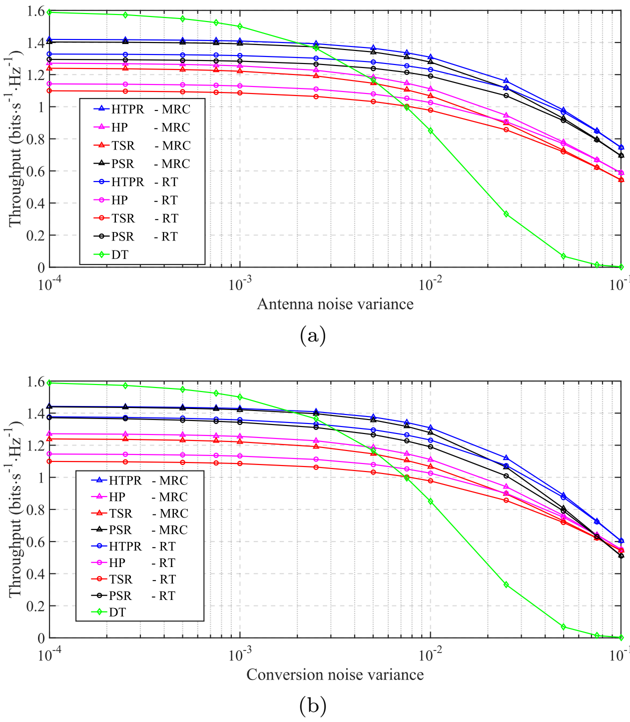

Fig. 6: Throughput vs. (a) Antenna noise variance and (b) Conversion noise variance.

loss since the effect of higher transmission power depends on an exponential function (Eq. (26)). Hence, it results in high network throughput. The throughput of HTPR_{opt} with respect to source transmission power is shown in Fig. 5(b). As expected, the joint optimization of EH ratios in HTPR_{opt} has increased the system throughput when compared to HTPR_{U} with uniform EH ratios.

The throughput versus antenna noise variance $\left(\sigma_{na}^2\right)$ and conversion noise variance $\left(\sigma_{nc}^2\right)$ is shown in Fig. 6. Increase in noise variance can degrade the SNR at the destination, resulting in a decrease in the throughput. The DT outperforms all the other methods at low noise levels. As noise power increases, relaying transmission $(S-R-D)$ and relay assisted transmission $(S-D$ and $S-R-D)$ is better. The HTPR protocol achieves larger throughput than other SWIPT protocols at low noise variance values of σ_{na}^2 and σ_{nc}^2. At high noise variances, the TSR protocol outperforms other protocols. Hence, the TSR protocol is more suitable for data transmission at high noise power [10].

The throughput of the network for different source transmission rates is shown in Fig. 7(a). The throughput increases as R_s increases to a certain value, and then tends to decrease for large values of R_s. For the given specifications, the threshold value of R_s is different in each case. For DT, the threshold value of R_s is 2.1 bits·s^{-1}, and in all the other schemes, the threshold lies between $2.5 \leq R_s \leq 3.5$ bits·s^{-1}. At low transmission rates, DT has high throughput than any other

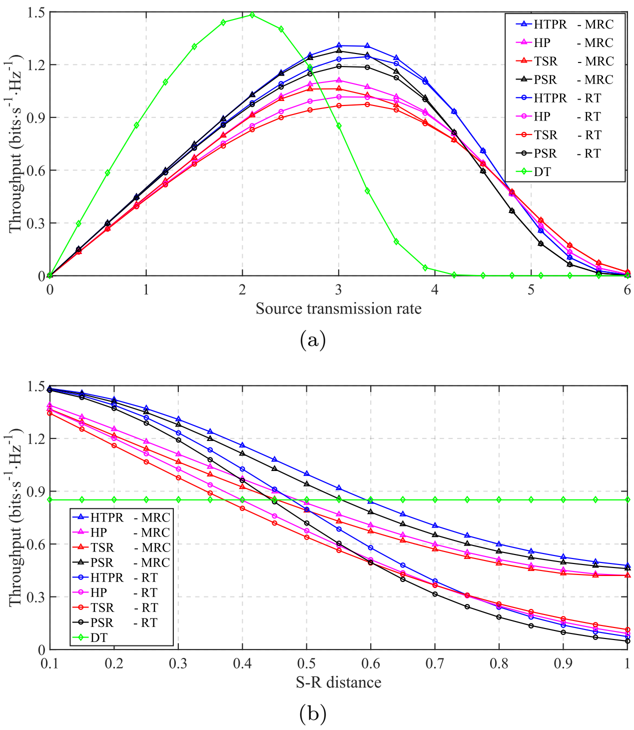

Fig. 7: Throughput vs. (a) source transmission rate and (b) $S-R$ distance.

schemes, and the EH schemes outperform DT when $R_s \geq 2.6$ bits·s^{-1}. The throughput is directly proportional to R_s, so low throughput is detected at the destination at low transmission rates. On the contrary, the receiver fails to accurately decode large amounts of information in a limited time at high transmission rates. Hence, the outage probability will increase and destination throughput decreases. HTPR and TSR protocols have better throughput at the destination at high and low transmission rates, respectively.

The throughput as a function of $S-R$ distance is shown in Fig. 7(b). The throughput of the DL remains constant since it is independent of d_1. In all the other schemes, as the distance increases, the throughput decreases as expected. This is because by increasing d_1, both the harvested energy and received signal strength at the relay decreases due to large path loss d_1^{ω}. Correspondingly, the destination SNR as well as throughput decrease. Comparing the EH protocols with the transmission schemes employed, our proposed HTPR protocol with MRC is achieving better throughput at the destination.

6. Conclusion

A hybrid protocol for SWIPT in an amplify-and-forward network is proposed in this paper, which is named as HTPR protocol. Using HTPR protocol, the relay harvests energy from the source signal and then exploits the harvested energy for information transmission to the destination. There is also a source-destination direct link and MRC method is applied at the destination focusing on a point-to-point communication with a single relay. For constant data rate, HTPR protocol with uniform and optimal EH ratios are employed for throughput maximization. The convex optimization method, Lagrange method and KKT conditions are used for solving the optimization problem. Under DLT, analytical expressions for outage probability and throughput are derived at the destination in direct, relaying and MRC transmission schemes. The performance of HTPR protocol is compared with both conventional and hybrid SWIPT protocols. The numerical results described in this paper offers insight into the impact of different parameters on overall system performance. It also portrays the performance differences in EH protocols by validating our theoretical analysis. The results showed that HTPR protocol outperforms other protocols at high SNR, and TSR protocol outperforms others at low SNR. Furthermore, different fading scenarios, modulation techniques, protocols adaptive to different information transmission rates, and non-coherent type sub-optimal/optimal EH protocols can be other interesting research directions for future green wireless networks.

Author Contributions

Sethu Lakshmi P. and Jibukumar M. G. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript.

References

[1] LANEMAN, J. N., D. N. C. TSE and G. W. WORNELL. Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory*. 2004, vol. 50, iss. 12, pp. 3062–3080. ISSN 1557-9654. DOI: 10.1109/TIT.2004.838089.

[2] VARSHNEY, L. R. Transporting information and energy simultaneously. In: *2008 IEEE International Symposium on Information Theory*. Toronto: IEEE, 2008, pp. 1612–1616. ISBN 978-1-4244-2256-2. DOI: 10.1109/ISIT.2008.4595260.

[3] HUYNH, T. P., P. N. SON and M. VOZNAK. Exact Throughput Analyses of Energy-Harvesting Cooperation Scheme with Best Relay Selections Under I/Q Imbalance. *Advances in Electrical and Electronic Engineering*. 2017, vol. 15, iss. 4, pp. 585–590. ISSN 1804-3119. DOI: 10.15598/aeee.v15i4.2302.

[4] NGUYEN, H.-N., H.-P. DANG, S.-P. LE, T.-D. LE, D.-T. DO, M. VOZNAK, and J. ZDRALEK. Enabling D2D Transmission Mode with Energy Harvesting and Information Transfer in Heterogeneous Networks. *Advances in Electrical and Electronics Engineering*. 2018, vol. 16, iss. 2, pp. 178–184. ISSN 1804-3119 DOI: 10.15598/aeee.v16i2.2393.

[5] NASIR, A. A., X. ZHOU, S. DURRANI and R. A. KENNEDY. Relaying Protocols for Wireless Energy Harvesting and Information Processing. *IEEE Transactions on Wireless Communications*. 2013, vol. 12, iss. 7, pp. 3622–3636. ISSN 1558-2248. DOI: 10.1109/TWC.2013.062413.122042.

[6] DO, D.-T. Time Power Switching Based Relaying Protocol in Energy Harvesting Mobile Node: Optimal Throughput Analysis. *Mobile Information Systems*. 2015, vol. 2015, iss. 1, pp. 1–8. ISSN 1875-905X. DOI: 10.1155/2015/769286.

[7] DO, D.-T. Optimal Throughput Under Time Power Switching Based Relaying Protocol in Energy Harvesting Cooperative Networks. *Wireless Personal Communications*. 2016, vol. 87, iss. 2, pp. 551–564. ISSN 1572-834X. DOI: 10.1007/s11277-015-3120-9.

[8] SHAH, S. T., K. W. CHOI, S. F. HASAN and M. Y. CHUNG. Throughput analysis of two-way relay networks with wireless energy harvesting capabilities. *Ad Hoc Networks*. 2016, vol. 53, iss. 1, pp. 123–131. ISSN 1570-8705. DOI: 10.1016/J.ADHOC.2016.09.024.

[9] XIAO, R., Y. LIU, H. YANG, J. SHEN and C. YAN. Performance Analysis of Hybrid Protocol Based Two-Way Decode-and-Forward Relay Networks. In: *2018 IEEE 4th International Conference on Computer and Communications (ICCC)*. Chengdu: IEEE, 2018, pp. 146–151. ISBN 978-1-5386-8339-2. DOI: 10.1109/CompComm.2018.8781001

[10] NGUYEN, H.-S., D.-T. DO, T.-S. NGUYEN and M. VOZNAK. Exploiting hybrid time switching-based and power splitting-based relaying protocol in wireless powered communication networks with outdated channel state information. *Automatika*. 2017, vol. 58, iss. 1, pp. 111–118. ISSN 1848-3380. DOI: 10.1080/00051144.2017.1372124.

[11] OJO, F. K. and M. F. M. SALLEH. Throughput Analysis of a Hybridized Power-Time Splitting Based Relaying Protocol for Wireless Information and Power Transfer in Cooperative Networks. *IEEE Access*. 2018, vol. 6, iss. 1, pp. 24137–24147. ISSN 2169-3536. DOI: 10.1109/ACCESS.2018.2828121.

[12] DO, D.-T., H.-S. NGUYEN, M. VOZNAK and T.-S. NGUYEN. Wireless Powered Relaying Networks Under Imperfect Channel State Information: System Performance and Optimal Policy for Instantaneous Rate. *Radioengineering*. 2017, vol. 26, iss. 3, pp. 869–877. ISSN 1805-9600. DOI: 10.13164/re.2017.0869.

[13] OJO, F. K. and M. F. M. SALLEH. Optimal Power Allocation with Time Power Switching Relaying Protocol in Cooperative Networks. In: *10th International Conference on Robotics, Vision, Signal Processing and Power Applications*. Penang: Springer, 2018, pp. 387–394. ISSN 1876-1100. ISBN 978-981-13-6446-4. DOI: 10.1007/978-981-13-6447-1_49.

[14] ATAPATTU, S. and J. EVANS. Optimal Energy Harvesting Protocols for Wireless Relay Networks. *IEEE Transactions on Wireless Communications*. 2016, vol. 15, iss. 8, pp. 5789–5803. ISSN 1558-2248. DOI: 10.1109/TWC.2016.2569097.

[15] SHEN, J., Y. LIU, H. YANG and C. YAN. Joint Time Allocation and Power Splitting Schemes for Amplify-and-forward Relaying Network over Log-normal Fading Channel. In: *2018 10th International Conference on Wireless Communications and Signal Processing (WCSP)*. Hangzhou: IEEE, 2018, pp. 1–5. ISBN 978-1-5386-6119-2. DOI: 10.1109/WCSP.2018.8555892.

[16] LIU, Y., R. XIAO, J. SHEN, H. YANG and C. YAN. Hybrid protocol for wireless energy harvesting network over log-normal fading channel. *The Journal of Engineering*. 2018, vol. 2018, iss. 6, pp. 339–341. ISSN 2051-3305. DOI: 10.1049/joe.2017.0892.

[17] TAO, R., A. SALEM and K. A. HAMDI. Adaptive Relaying Protocol for Wireless Power Transfer and Information Processing. *IEEE Communications Letters*. 2016, vol. 20, iss. 10, pp. 2027–2030. ISSN 1558-2558. DOI: 10.1109/LCOMM.2016.2593877.

[18] NGUYEN, T. L. and D.-T. DO. Exploiting Optimal Throughput of Adaptive Relaying Based Wireless Powered Systems under Impacts of Co-channel Interference. *KSII Transactions on Internet and Information Systems*. 2018, vol. 12, iss. 5, pp. 2009–2028. ISSN 1976-7277. DOI: 10.3837/tiis.2018.05.006.

[19] NGUYEN, T. N., T. HOANG, Q. MINH, P. T. TRAN and M. VOZNAK. Adaptive Energy Harvesting Relaying Protocol for Two-Way Half-Duplex System Network over Rician Fading Channels. *Wireless Communications and Mobile Computing*. 2018, vol. 2018, iss. 1, pp. 1–10. ISSN 1530-8677. DOI: 10.1155/2018/7693016.

[20] MALEKI, M., A. M. D. HOSEINI and M. MASJEDI. Performance Analysis of SWIPT Relay Systems Over Nakagami-m Fading Channels with Non-linear Energy Harvester and Hybrid Protocol. In: *Iranian Conference on Electrical Engineering (ICEE)*. Mashhad: IEEE, 2018, pp. 610–615. ISBN 978-1-5386-4916-9. DOI: 10.1109/ICEE.2018.8472559.

[21] YE, Y., Y. LI, L. SHI, R. Q. HU and H. ZHANG. Improved Hybrid Relaying Protocol for DF Relaying in the Presence of a Direct Link. *IEEE Wireless Communications Letters*. 2019, vol. 8, iss. 1, pp. 173–176. ISSN 2162-2345. DOI: 10.1109/LWC.2018.2865476.

[22] LIU, Z., P. WU, D. B. DA COSTA and M. XIA. Cooperative Relaying with Energy Harvesting: Performance Analysis Using Extreme Value Theory. In: *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)*. Kuala Lumpur: IEEE, 2019, pp. 1–6. ISBN 978-1-7281-1217-6. DOI: 10.1109/VTCSpring.2019.8746624.

[23] SUBHASH, A. and S. KALYANI. Cooperative relaying with energy harvesting relays : Asymptotic analysis using extreme value theory for non-identically distributed RVs. 2020. Available at: `https://arxiv.org/pdf/2004.05300v1.pdf`.

[24] SHENG, X., G. LU, L. SHI and Y. YE. Performance Analysis of Hybrid Protocol Based AF EH Relaying over Asymmetric Fading Channels. *Information*. 2019, vol. 10, iss. 2, pp. 1–12. ISSN 2078-2489. DOI: 10.3390/info10020050.

[25] RAZA, W., H. NASIR and N. JAVAID. Unification of RF energy harvesting schemes under mixed Rayleigh-Rician fading channels. *AEU - International Journal of Electronics and Communications*. 2020, vol. 123, iss. 1, pp. 1–16. ISSN 1434-8411. DOI: 10.1016/j.aeue.2020.153244.

[26] SINGH, V. and H. OCHIAI. An Efficient Time Switching Protocol with Adaptive Power Splitting for Wireless Energy Harvesting Relay Networks. In: *2017 IEEE 85th Vehicular Technology Conference (VTC Spring)*. Sydney: IEEE, 2017, pp. 1–5. ISBN 978-1-5090-5932-4. DOI: 10.1109/VTC-Spring.2017.8108268.

[27] HA, D.-H., D.-B. HA, J. ZDRALEK and M. VOZNAK. Performance Analysis of Hybrid Energy Harvesting AF Relaying Networks over Nakagami-m Fading Channels. In: *2018 International Conference on Advanced Technologies for Communications (ATC)*. Ho Chi Minh City: IEEE, 2018, pp. 157–162. ISBN 978-1-5386-6542-8. DOI: 10.1109/ATC.2018.8587424.

[28] HA, D.-H., D.-B. HA, J. ZDRALEK and M. VOZNAK. A New Protocol based on Optimal Capacity for Energy Harvesting Amplify-and-Forward Relaying Networks. In: *2018 5th NAFOSTED Conference on Information and Computer Science (NICS)*. Ho Chi Minh City: IEEE, 2018, pp. 11–16. ISBN 978-1-5386-7983-8. DOI: 10.1109/NICS.2018.8606829.

[29] HA, D.-H., D.-B. HA, V.-A. VO and M. VOZNAK. Performance Analysis on Wireless Power Transfer Wireless Sensor Network with Best AF Relay Selection over Nakagami-m Fading. In: *International Conference on Industrial Networks and Intelligent Systems*. Ho Chi Minh City: Springer, 2019, pp. 193–204. ISBN 978-3-030-30148-4. DOI: 10.1007/978-3-030-30149-1_16.

[30] MAHAMA, S., D. K. P. ASIEDU and K.-J. LEE. Simultaneous Wireless Information and Power Transfer for Cooperative Relay Networks With Battery. *IEEE Access*. 2017, vol. 5, iss. 1, pp. 13171–13178. ISSN 2169-3536. DOI: 10.1109/ACCESS.2017.2724638.

[31] ZHAO, N., F. HU, Z. LI and Y. GAO. Simultaneous Wireless Information and Power Transfer Strategies in Relaying Network With Direct Link to Maximize Throughput. *IEEE Transactions on Vehicular Technology*. 2018, vol. 67, iss. 9, pp. 8514–8524. ISSN 1939-9359. DOI: 10.1109/TVT.2018.2850747.

[32] GESBERT, D., M. SHAFI, D.-S. SHIU, P. J. SMITH and A. NAGUIB. From theory to practice: an overview of MIMO space-time coded wireless systems. *IEEE Journal on Selected Areas in Communications*. 2003, vol. 21, iss. 3, pp. 281–302. ISSN 1558-0008. DOI: 10.1109/JSAC.2003.809458.

[33] MOLISCH, A. F., M. Z. WIN, Y.-S. CHOI and J. H. WINTERS. Capacity of MIMO systems with antenna selection. *IEEE Transactions on Wireless Communications*. 2005, vol. 4, iss. 4, pp. 1759–1772. ISSN 1558-2248. DOI: 10.1109/TWC.2005.850307.

[34] ALBAAJ, A., S. V. A. MAKKI, Q. AL-ABKHAT and A. ZAHEDI. Simultaneous energy harvesting and information processing in wireless multiple relays with multiple antennas. *International Journal of Electronics*. 2017, vol. 104, iss. 7, pp. 1214–1227. ISSN 1362-3060. DOI: 10.1080/00207217.2017.1292557.

[35] ZAHEDI, A., M. LARI, A. ALBAAJ and Q. AL-ABKHAT. Simultaneous energy harvesting and information processing considering multi-relay multi-antenna using maximum ratio transmission and antenna selection strategies. *Transactions on Emerging Telecommunications Technologies*. 2017, vol. 28, iss. 11, pp. 1–13. ISSN 2161-3915. DOI: 10.1002/ett.3182.

[36] SUDEVALAYAM, S. and P. KULKARNI. Energy Harvesting Sensor Nodes: Survey and Implications. *IEEE Communications Surveys & Tutorials*. 2011, vol. 13, iss. 3, pp. 443–461. ISSN 1553-877X. DOI: 10.1109/SURV.2011.060710.00094.

[37] ZHOU, X., R. ZHANG and C. K. HO. Wireless Information and Power Transfer: Architecture Design and Rate-Energy Tradeoff. *IEEE Transactions on Communications*. 2013, vol. 61, iss. 11, pp. 4754–4767. ISSN 1558-0857. DOI: 10.1109/TCOMM.2013.13.120855.

[38] AL-HABOB, A. A., A. M. SALHAB and S. A. ZUMMO. An efficient time-switching relaying protocol for multiuser cognitive radio relay networks with SWIPT. *Physical Communication*. 2018, vol. 30, iss. 1, pp. 86–96. ISSN 1876-3219. DOI: 10.1016/j.phycom.2018.07.017.

[39] SETHU LAKSHMI, P. and M. G. JIBUKUMAR. SWIPT in multi-hop amplify-and-forward wireless sensor networks. *International Journal of Electronics*. 2020, vol. 107, iss. 4, pp. 630–643. ISSN 1362-3060. DOI: 10.1080/00207217.2019.1672804.

[40] GRADSHTEYN, I. S. and I. M. RYZHIK. *Table of Integrals, Series, and Products*. 7th ed. San Diego: Academic Press, 2007. ISBN 978-0-080-47111-2.

[41] HU, G., Y. CAI, L. AO and X. WANG. Joint design of beamforming and time switching/power splitting for wireless-powered multi-antenna dual-relay network. *EURASIP Journal on Wireless Communications and Networking*. 2019, vol. 2019, iss. 1, pp. 1–16. ISSN 1687-1499. DOI: 10.1186/s13638-019-1580-4.

[42] CHEN, D., W. YANG, J. HU, W. MOU and Y. CAI. Security–reliability tradeoff analysis of untrusted energy harvesting relay networks. *International Journal of Distributed Sensor Networks*. 2018, vol. 14, iss. 1, pp. 1–11. ISSN 1550-1477. DOI: 10.1177/1550147718754729.

About Authors

Pradeep SETHU LAKSHMI received her B.Tech. in Electronics and Communication Engineering from the Cochin University, Kerala, India in 2012 and M.Tech. in Wireless Technology from the Cochin University in 2014. Currently, she is a Research Scholar at Division of Electronics, School of Engineering, Cochin University of Science and Technology. Her research interest includes wireless sensor networks, cooperative communication, energy harvesting and storage.

Mangalathu Gopalakrishnan JIBUKUMAR received his B.Tech. in Electronics and Communication Engineering from the Mahatma Gandhi University, Kerala, India in 1994. He received his M.Tech. in Optoelectronics and Laser Technology from the Cochin University, India in 1997, and Ph.D. in Electronics and Electrical Communication Engineering from the Indian Institute of Technology Kharagpur, India in 2010. From 1999, he is working as a faculty member of Cochin University. His research interest includes wireless communication, 5G, physical layer security, MIMO, cooperative communication and network protocols.