THE SYSTEM PERFORMANCE OF HALF-DUPLEX RELAY NETWORK UNDER EFFECT OF INTERFERENCE NOISE

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Abstract. *In recent years, harvesting energy from radio frequency (RF) signals has drawn significant research interest as a promising solution to solve the energy problem. In this paper, we analyze the effect of the interference noise on the wireless energy harvesting performance of a decode-and-forward (DF) relaying network. In this analysis, the energy and information are transferred from the source to the relay nodes in the delay-limited transmission and Delay-tolerant transmission modes by two methods: i) time switching protocol and ii) power splitting protocol. Firstly, due to the constraint of the wireless energy harvesting at the relay node, the analytical mathematical expressions of the achievable throughput, outage probability and ergodic capacity of both schemes were proposed and demonstrated. After that, the effect of various system parameters on the system performance is rigorously studied with closed-form expressions for system throughput, outage probability, and ergodic capacity. Finally, the analytical results are also demonstrated by Monte-Carlo simulation. The results show that the analytical mathematical and simulated results agree with each other.*

1. Introduction

Nowadays, the fifth generation (5G) network technology is the best solution for the near future communication network. However, increase the energy efficiency of wireless communication networks is the critical problem, on which are strongly depended the economic and ecological aspects of 5G networks. For this target, two solutions are proposed and demonstrated. Firstly, overall energy consumption of future 5G network shall not exceed 10 percent of the current usage. Secondly, much longer battery life for mobile devices is expected [1, 5]. Significant technological steps would have to be taken shortly for this goal to become a reality. Several candidate solutions have been proposed lately to meet the goals above. Technologies based on radio frequency (RF) energy harvesting (EH) and transfer have recently been gaining momentum. With these

approaches, future wireless devices would have the capability of harvesting energy from signals emitted either by ambient or dedicated sources [1, 8]. In recent years, harvesting energy from radio frequency (RF) signals has drawn significant research interest as a promising solution to solve the energy problem. This energy collection method, referred to as RF energy harvesting, has clear advantages over other energy harvesting techniques due to its predictable, controllable and stable nature. The research in RF energy harvesting mainly falls into two broad categories: Simultaneous Wireless Information and Power Transfer (SWIPT) and Wireless Powered Communication Network (WPCN).

The working principle of SWIPT is that each information signal also carries energy, which can be harvested by energy-limited devices. However, in reality, it is not possible to simultaneously harvest energy and decode information using the same signal. In WPCN, network devices first harvest energy from the signals transmitted by RF power sources and then utilize this harvested energy for their communication needs. In last decade, there are many researchers focus on improving system performance of WPCN. The leading research studied rate-energy trade-off assuming single-input-single-output, single-input-multiple-output, and multiple-input-multiple-output setups. The application of wireless energy harvesting to orthogonal frequency division multiplexing [3, 5] and cognitive radio [6] based systems have also been proposed. Moreover, the energy beamforming through wireless energy harvesting has been analyzed for the multi-antenna wireless broadcasting system in [7, 9]. Furthermore, secure transmission in the presence of eavesdropper under wireless energy harvesting constraint has been studied in MISO beamforming systems [10, 12]. From this point of view, the system performance of RF energy harvesting communication network is necessary more and more to analyze and study.

In this paper, the effect of the interference noise on the system performance of a wireless energy harvesting. Decode-And-Forward (DF) relaying network was analyzed. In this analysis, the energy and information are transferred from the source to the relay nodes by two methods:

time switching protocol and power splitting protocol. Firstly, due to the constraint of the wireless energy harvesting at the relay node, the analytical mathematical expressions of the achievable throughput, outage probability and ergodic capacity of both schemes were presented and demonstrated. After that, the effect of various system parameters on the system performance is rigorously studied with closed-form expressions for system throughput, outage probability, and ergodic capacity. Finally, the analytical results are also demonstrated by Monte-Carlo simulation. The results show that the analytical mathematical and simulated results agree with each other. The main contributions of this paper are summarized as follows:

1) We propose the time switching and the power splitting protocols in the delay-limited and the delay-tolerant transmission modes to enable wireless energy harvesting and information processing at the energy constrained relay in wireless AF relaying networks.

2) The analytical expressions for the achievable throughput, the outage probability and the ergodic capacity for the delay-limited and the delay-tolerant transmission modes is proposed and demonstrated in connection with the various parameters of the system.

3) The influence of the interference noise on the system performance is presented and convinced in details. The rest of the paper is organized as follows. The system model is presented in detail in section II. Sections III proposes and demonstrates the analytical mathematical description of the throughput, outage probability and ergodic capacity of the time switching and power splitting protocol, respectively. Section IV presents the comparison of the simulation and analytical results from various system parameters. Finally, Section V makes some conclusion of this study.

2. System model

In this section, DF relaying cooperative network is presented, where the information is transferred from the source (S) to the destination (D), through an energy constrained inter-

mediate relay (R). In this model, we assume that no connection between the source and the destination because of elimination transmission information. In this model, an intermediate DF relay is used for the transmission of the information from the source to the destination. In this system, the DF relay harvests energy from the signal of the source at first stage, and then the relay transfer the information to the destination by the harvested energy. For this model, the required power of the data decoding process at the relay is negligible in comparison to the signal transmission energy from the relay to the destination [10, 16]. Moreover, h and g are the $S \rightarrow R$ and $R \rightarrow D$ channel gains factor, respectively (Fig. 1.). In this paper, the energy harvesting and information processing at the relay node are proposed by the time switching and power splitting protocol at the relay.
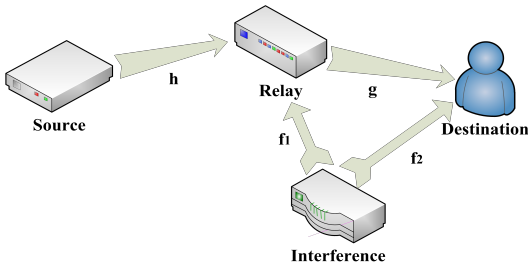

Fig. 1: System model.

For energy harvesting and information processing at the relay by the time switching protocol is presented in Fig. 2. In this scheme, T is the block time in which the source fully transmits the information data to the destination. Moreover, αT, $\alpha \in (0, 1)$ is the time in which the relay harvests energy from the source signal, and $(1-\alpha)T$, is used for information transmission in such a way that half of that, $(1-\alpha)T/2$, is used for the source to relay information transmission and the remaining half,$(1 - \alpha)T/2$, is used for the relay to destination information transmission. Furthermore, the energy harvesting and information processing at the relay by the power splitting protocol is proposed in Fig. 3. Where P is the received signal power and T is the block time (Fig. 3.). Half of the time, T/2 is used for the source to relay information transmission and the remaining half, T/2 is used for the relay

to destination information transmission. During the first half, the fraction of the received signal power, ρP is used for energy harvesting and the remaining received power, $(1 - \rho)P$ is used for transmitting source information to the relay node, where $\rho \in (0, 1)$ [17, 20]. More details of the analytical mathematical model of the achievable throughput and ergodic capacity under the effect of the interference noise (for the time switching and power splitting protocol) is presented in the following sections.
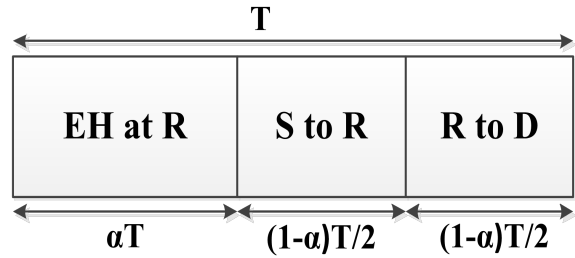

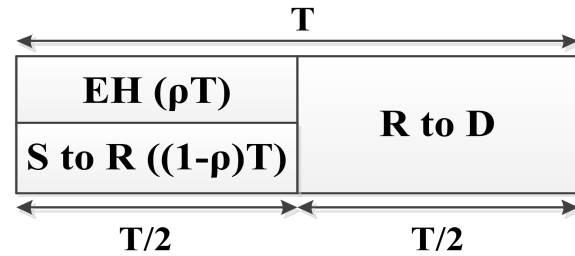**Fig. 2:** The energy harvesting and information processing by the time switching protocol.

Fig. 3: The energy harvesting and information processing by the power splitting protocol.

3. The system performance

3.1. Delay-limited transmission

Time Switching Protocol

S to R Energy Harvesting and Information Transmission The received signal at relay node:

$$y_r = \sqrt{P_s}hs(k) + \sqrt{P_I}f_1i(k) + n_r \qquad (1)$$

where $k = 1, 2, \ldots$ are the symbol index,

h is the gain factor from source to relay channel,

P_s is the transmitted power from the source,

P_I is the interference noise power,

f_1 is the interference function to the relay node.

$$E\left\{[s(k)^2]\right\} = E\left\{[i(k)^2]\right\} = 1,$$

$E\{.\}$ is the expectation operator.

The harvested energy at the relay is given by:

$$E_h = \eta\alpha T P_s |h|^2$$

In this paper, we assume that the interference power is not large enough for RF energy harvesting at the relay node. So the received power at the relay can be computed:

$$P_r = \frac{E_h}{(1-\alpha)T/2} = \frac{\eta\alpha T P_s |h|^2}{(1-\alpha)T/2}$$
$$= \frac{2\eta\alpha}{1-\alpha}P_s|h|^2 = \kappa P_s|h|^2 \qquad (2)$$

In Eq. (2) we set $\kappa = \dfrac{2\eta\alpha}{1-\alpha}$

$0 < \eta < 1$: is the energy conversion efficiency.

The received signal at the destination node:

$$y_d = \sqrt{P_r}gr(k) + \sqrt{P_I}f_2 i(k) + n_d \qquad (3)$$

Where g is the relay to destination channel gain,

f_2 is the interference function to the destination,

$$E\left\{[r(k)^2]\right\} = E\left\{[i(k)^2]\right\} = 1,$$

Here n_r, n_d are the zero mean additive white Gaussian noise (AWGN) with variance N_0.

The signal to noise ratio for $S \to R$ links is given by:

$$\gamma_r^{TS} = \frac{E\left\{(signal)^2\right\}}{E\left\{(noise)^2\right\}} = \frac{P_s|h|^2}{P_I|f_1|^2 + N_0} \approx \frac{P_s|h|^2}{P_I|f_1|^2} \quad (4)$$

R to D Information Transmission

Similar to S - R links:

$$\gamma_d^{TS} = \frac{P_r|g|^2}{P_I|f_2|^2 + N_0} \approx \frac{P_r|g|^2}{P_I|f_2|^2} \qquad (5)$$

Replace Eq. 2 into Eq. 5 we have:

$$\gamma_d^{TS} = \frac{P_r|g|^2}{P_I|f_2|^2} = \frac{\kappa P_s|h|^2|g|^2}{P_I|f_2|^2} \qquad (6)$$

Throughput analysis:

In this section, we need to evaluate the outage probability:

$$P_{out}^{TS} = \Pr\left[\min\left(\gamma_r^{TS}, \gamma_d^{TS}\right) < \gamma\right]$$
$$= \Pr\left[\min\left(\frac{P_s|h|^2}{P_I|f_1|^2}, \frac{\kappa P_s|h|^2|g|^2}{P_I|f_2|^2}\right) < \gamma\right] \quad (7)$$

Where $\gamma = 2^R - 1$ is the SNR threshold and R is the rate source.

$$P_{out}^{TS} = 1 + be^{b\mu}\Gamma(-1, b\mu) - be^{\lambda_h b}\Gamma(-1, \lambda_h b) \quad (8)$$

Where we set

$$b = \frac{\lambda_g P_I \gamma}{\lambda_{f_2}\kappa P_s}, \mu = \frac{\lambda_{f_1} P_s}{P_I \gamma} + \lambda_h$$

Throughput

$$\tau^{TS} = (1 - P_{out}^{TS})\frac{(1-\alpha)R}{2} \qquad (9)$$

Proof:

From Eq. 7, we have

$$P_{out}^{TS} = 1 - \Pr\left(\frac{P_s|h|^2}{P_I|f_1|^2} \ge \gamma, \frac{\kappa P_s|h|^2|g|^2}{P_I|f_2|^2} \ge \gamma\right) \quad (10)$$

$$P_{out}^{TS} = 1 - \int_0^\infty \Pr\left(\frac{P_s X}{P_I Z_1} \ge \gamma | X = x\right)$$
$$\times \Pr\left(\frac{\kappa P_s XY}{P_I Z_2} \ge \gamma | X = x\right) f_X(x)dx \quad (11)$$

Where $X = |h|^2, Y = |g|^2, Z_1 = |f_1|^2, Z_2 = |f_2|^2$

Here, S-R link and R-D link is the Rayleigh fading channel.

After that, we have the probability density function (PDF) of a random variable (RV) X,Y,Z_1,Z_2:

$f_\varphi(x) = \lambda_\varphi e^{-\lambda_\varphi x}$, which $\varphi = \{X,Y,Z_1,Z_2\}$

The cumulative density function(CDF) of RV φ

$$F_\varphi(x) = 1 - e^{-\lambda_\varphi x}$$

We denote:

$$I_1 = \Pr\left[\left(\frac{P_s X}{P_I Z_1} \geq \gamma | X = x\right)\right] = \Pr\left(\frac{P_s x}{P_I Z_1} \geq \gamma\right)$$
$$= \Pr\left(Z_1 \leq \frac{P_s x}{P_I \gamma}\right) = 1 - e^{-\frac{\lambda_{f_1} P_s x}{P_I \gamma}} \tag{12}$$

$$I_2 = \Pr\left[\left(\frac{\kappa P_s XY}{P_I Z_2} \geq \gamma | X = x\right)\right] = \Pr\left(Y \geq \frac{P_I \gamma Z_2}{\kappa P_s x}\right)$$
$$= \int_0^\infty f_{Z_2}(z_2) dz_2 \int_{\frac{P_I \gamma Z_2}{\kappa P_s x}}^\infty f_Y(y) dy \tag{13}$$

$$I_2 = \int_0^\infty \lambda_{f_2} e^{-\lambda_{f_2} Z_2} e^{-\frac{\lambda_g P_I \gamma Z_2}{\kappa P_s x}} dz_2$$
$$= \frac{\lambda_{f_2} \kappa P_s x}{\lambda_{f_2} \kappa P_s x + \lambda_g P_I \gamma} \tag{14}$$

The outage probability:

$$P_{out}^{TS} = 1 - \lambda_h \int_0^\infty (I_1 \times I_2) e^{-\lambda_h x} dx$$
$$= 1 - \lambda_h \int_0^\infty \frac{\lambda_{f_2} \kappa P_s x}{\lambda_{f_2} \kappa P_s x + \lambda_g P_I \gamma} \tag{15}$$
$$\times \left(1 - e^{-\frac{\lambda_{f_1} P_s x}{P_I \gamma}}\right) e^{-\lambda_h x} dx$$

$$P_{out}^{TS} = 1 + \lambda_h \int_0^\infty \frac{\lambda_{f_2} \kappa P_s x}{\lambda_{f_2} \kappa P_s x + \lambda_g P_I \gamma} e^{-\frac{\lambda_{f_1} P_s x}{P_I \gamma}} e^{-\lambda_h x} dx$$
$$- \lambda_h \int_0^\infty \frac{\lambda_{f_2} \kappa P_s x}{\lambda_{f_2} \kappa P_s x + \lambda_g P_I \gamma} e^{-\lambda_h x} dx \tag{16}$$

$$P_{out}^{TS} = 1 + \lambda_h \int_0^\infty \frac{x}{x + \frac{\lambda_g P_I \gamma}{\lambda_{f_2} \kappa P_s}} e^{-\frac{\lambda_{f_1} P_s x}{P_I \gamma} - \lambda_h x} dx$$
$$- \lambda_h \int_0^\infty \frac{x}{x + \frac{\lambda_g P_I \gamma}{\lambda_{f_2} \kappa P_s}} e^{-\lambda_h x} dx \tag{17}$$

Where $\lambda_h, \lambda_g, \lambda_{f_1}, \lambda_{f_2}$ are the mean values of the exponential random variable $|h|^2, |g|^2, |f_1|^2, |f_2|^2$, respectively.

Using Eq [3.383,10] of Table of Integral [21], we have:

$$P_{out}^{TS} = 1 + be^{b\mu}\Gamma(-1, b\mu) - be^{\lambda_h b}\Gamma(-1, \lambda_h b) \tag{18}$$

This is the end of the proof.

Power splitting Protocol

The received signal at relay node:

$$y_r = \sqrt{(1-\rho)P_s} hs(k) + \sqrt{P_I} f_1 i(k) + n_r \tag{19}$$

Similar to time switching protocol, the received power at the relay can be computed:

$$P_r = \frac{E_h}{T/2} = \frac{\eta\rho T/2 P_s |h|^2}{T/2} = \eta\rho P_s |h|^2 \tag{20}$$

The received signal at the destination node:

$$y_d = \sqrt{P_r} gr(k) + \sqrt{P_I} f_2 i(k) + n_d \tag{21}$$

$$\gamma_r^{PS} = \frac{P_s |h|^2 (1-\rho)}{P_I |f_1|^2 + N_0} \approx \frac{P_s |h|^2 (1-\rho)}{P_I |f_1|^2} \tag{22}$$

$$\gamma_d^{PS} = \frac{P_r |g|^2}{P_I |f_2|^2 + N_0} \approx \frac{P_r |g|^2}{P_I |f_2|^2} = \frac{\eta\rho P_s |h|^2 |g|^2}{P_I |f_2|^2} \tag{23}$$

Throughput analysis:

Similar to Time Switching Protocol, we have the outage probability of system:

$$P_{out}^{PS} = \Pr\left[\min(\gamma_r^{PS}, \gamma_d^{PS}) < \gamma\right]$$
$$= \Pr\left[\min\left(\frac{P_s |h|^2 (1-\rho)}{P_I |f_1|^2}, \frac{\eta\rho P_s |h|^2 |g|^2}{P_I |f_2|^2}\right) < \gamma\right] \tag{24}$$

$$P_{out}^{PS} = 1 + ce^{c\nu}\Gamma(-1, c\nu) - ce^{\lambda_h c}\Gamma(-1, \lambda_h c) \tag{25}$$

Where $c = \frac{\lambda_g P_I \gamma}{\lambda_{f_2} \eta \rho P_s}, \nu = \frac{\lambda_{f_1} P_s (1-\rho)}{P_I \gamma} + \lambda_h$

$\Gamma(\bullet)$ is the gamma function.

Finally, we have the throughput of the system:

$$\tau^{PS} = (1 - P_{out}^{PS})\frac{R}{2} \qquad (26)$$

3.2. Delay-Tolerant transmission

Time Switching Protocol

Throughput analysis:

In this section, we need to evaluate the ergodic capacity from the source to relay C_r^{TS}, and for relay to destination link C_d^{TS}. We use the received signal SNR in (5), (6), respectively. After that C_r^{TS} and C_d^{TS} are given by the following equations:

$$C_r^{TS} = \mathrm{E}_{|h|^2, |f_1|^2}\left\{\log_2(1 + \gamma_r^{TS})\right\} \qquad (27)$$

$$C_d^{TS} = \mathrm{E}_{|h|^2, |f_1|^2, |f_2|^2}\left\{\log_2(1 + \gamma_d^{TS})\right\} \qquad (28)$$

$$C_r^{TS} = \frac{\ln(\xi)}{\ln 2(\xi - 1)} = \frac{\log_2(\xi)}{\xi - 1} \qquad (29)$$

Where we set

$$\xi = \frac{\lambda_h P_I}{\lambda_{f_1} P_s}$$

The throughput:

$$C_d^{TS} = \frac{1}{\ln 2}\int_0^\infty \frac{1}{1+\gamma}\sum_{n=0}^\infty \frac{(-1)^n (\lambda_{f_2})^{n+1}}{n!} 4^{n+1} \qquad (30)$$
$$\times \psi^{-2-2n}\Gamma(2+n)\Gamma(1+n)d\gamma$$

Where

$$\psi = \sqrt{\frac{4\lambda_h \lambda_g \gamma P_I}{\kappa P_s}}$$

Here we set: $C^{TS} = \min(C_r^{TS}, C_d^{TS})$

Proof:

$$C_r^{TS} = \frac{1}{\ln 2}\int_0^\infty \frac{1 - F_{\gamma_r^{TS}}(\gamma)}{1+\gamma}d\gamma \qquad (31)$$

$$F_{\gamma_r^{TS}}(\gamma) = \Pr(\gamma_r^{TS} < \gamma) = \Pr\left(\frac{P_s |h|^2}{P_I |f_1|^2} < \gamma\right)$$
$$= \Pr\left(\frac{P_s X}{P_I Y} < \gamma\right) = \Pr\left(X < \frac{\gamma P_I Y}{P_s}\right) \qquad (32)$$

We set $X = |h|^2, Y = |f_1|^2$

$$F_{\gamma_r^{TS}}(\gamma) = \int_0^\infty f_Y \, dY \int_0^{\frac{\gamma P_I Y}{P_s}} f_X \, dX$$
$$= \int_0^\infty f_y \, dy \left[1 - \exp\left(-\frac{\lambda_h \gamma P_I Y}{P_s}\right)\right] \qquad (33)$$
$$= 1 - \int_0^\infty \lambda_{f_1}\exp(-\lambda_{f_1}Y)$$
$$\times \exp\left(-\frac{\lambda_h \gamma P_I Y}{P_s}\right)dY$$

$$F_{\gamma_r^{TS}}(\gamma) = 1 - \frac{1}{1 + \xi\gamma} \qquad (34)$$

Replace into equation (30), we have:

$$C_r^{TS} = \frac{1}{\ln 2}\int_0^\infty \frac{1}{(1+\xi\gamma)(1+\gamma)}d\gamma = \frac{\log_2(\xi)}{\ln 2(\xi - 1)} \qquad (35)$$

$$C_d^{TS} = \frac{1}{\ln 2}\int_0^\infty \frac{1 - F_{\gamma_d^{TS}}(\gamma)}{1+\gamma}d\gamma \qquad (36)$$

We denote $\vartheta = |h|^2 |g|^2, Z = |f_2|^2$

$$F_{\gamma_d^{TS}}(\gamma) = \Pr(\gamma_d^{TS} < \gamma) = \Pr\left(\frac{\kappa P_s |h|^2 |g|^2}{P_I |f_2|^2} < \gamma\right)$$
$$= \Pr\left(\frac{\kappa P_s \vartheta}{P_I Z} < \gamma\right) = \Pr\left(\vartheta < \frac{\gamma P_I Z}{\kappa P_s}\right) \qquad (37)$$

$$F_{\gamma_d^{TS}}(\gamma) = \int_0^\infty f_Z \Pr\left(\vartheta < \frac{\gamma P_I Z}{\kappa P_s}\right)dZ$$
$$= \int_0^\infty f_Z \, dZ \qquad (38)$$
$$\cdot \left[1 - \int_0^\infty \lambda_g \exp(-\lambda_g y)\exp\left(-\frac{\lambda_h \gamma P_I Z}{\kappa P_s y}\right)dy\right]$$

Using the equation (3.324,1) in [21], we have:

$$F_{\gamma_d^{TS}}(\gamma) = 1 - \int_0^\infty \lambda_{f_2}e^{-\lambda_{f_2}Z}\sqrt{\frac{4\lambda_h \lambda_g \gamma P_I Z}{\kappa P_s}}$$
$$K_1\left(\sqrt{\frac{4\lambda_h \lambda_g \gamma P_I Z}{\kappa P_s}}\right)dZ \qquad (39)$$

We set $t = \sqrt{Z}$

$$F_{\gamma_d^{TS}}(\gamma) = 1 - 2 \int_0^\infty \frac{\lambda_{f_2} t^2 e^{-\lambda_{f_2} t^2} \sqrt{\frac{4\lambda_h \lambda_g \gamma P_I}{\kappa P_s}}}{K_1 \left(t\sqrt{\frac{4\lambda_h \lambda_g \gamma P_I}{\kappa P_s}} \right)} \, dt$$

(40)

Apply Taylor series of

$$e^{-\lambda_{f_2} t^2} = \sum_{n=0}^\infty \frac{(-\lambda_{f_2} t^2)^n}{n!} = \sum_{n=0}^\infty \frac{(-\lambda_{f_2})^n}{n!} t^{2n}$$

We have:

$$F_{\gamma_d^{TS}}(\gamma) = 1 - 2\psi \sum_{n=0}^\infty \frac{(-1)^n (\lambda_{f_2})^{n+1}}{n!} \int_0^\infty t^{2+2n} K_1(\psi t) \, dt$$

(41)

We apply eq[6.561,16] of Table of Integral [21], we have:

$$F_{\gamma_d^{TS}}(\gamma) = 1 - \sum_{n=0}^\infty \frac{(-1)^n (\lambda_{f_2})^{n+1}}{n!} 4^{n+1} \times \psi^{-2-2n} \Gamma(2+n)\Gamma(1+n)$$

(42)

$\Gamma(\bullet)$ is the gamma function.

It is the end of the proof.

The throughput of the system:

$$\tau^{TS} = \frac{(1-\alpha)C^{TS}}{2}$$

(43)

Power splitting Protocol

$$C_r^{PS} = \frac{\log_2(\chi)}{\ln 2(\chi - 1)}$$

(44)

$$\chi = \frac{\lambda_h P_I}{\lambda_{f_1} P_s (1 - \rho)}$$

(45)

$$C_d^{PS} = \frac{1}{\ln 2} \int_0^\infty \frac{1}{1+\gamma} \sum_{n=0}^\infty \frac{(-1)^n (\lambda_{f_2})^{n+1}}{n!} 4^{n+1} \times \theta^{-2-2n} \Gamma(2+n)\Gamma(1+n) d\gamma$$

(46)

Where $\theta = \sqrt{\frac{4\lambda_h \lambda_g \gamma P_I}{\eta \rho P_s}}$

$$C^{PS} = \min(C_r^{PS}, C_d^{PS})$$

(47)

The throughput of the system:

$$\tau^{PS} = \frac{C^{PS}}{2}$$

(48)

We do not need proof for second protocol because of similar proof as the first protocol.

4. Results and Discussion

In this segment, the throughput performance and the ergodic capacity of an energy harvesting DF relaying network under the effect of the interference noise are analyzed in details. The system performance is analyzed in connection with the η, λ, ρ, P_s and P_I under the interference noise effect. We consider a network with one source, one relay, and one destination, where source-relay and relay-destination distances are both normalized to unit value. Other simulation parameters are listed in Tab. 1.

Tab. 1: Simulation parameters.

Symbol	Name	Values
η	Energy harvesting efficiency	0.6
λ_h	Mean of $|h|^2$	0.5
λ_g	Mean of $|g|^2$	0.5
λ_{f_1}	Mean of $|f_1|^2$	1
λ_{f_2}	Mean of $|f_2|^2$	1
Ps	The transmit power at source	$0 - 30dB$

Fig. 4. presents the analytical mathematical and simulation results of throughput in the varied value of η with the delay-limited transmission (a) and the delay-tolerant transmission (b). In this simulation, the power P_s and P_I are set at 30 dB and 10 dB, respectively. From the Fig. 4, the achievable throughput of the delay-limited and the delay-tolerant transmission modes are increased significantly when the η varied from 0 to 1. Furthermore, the analytical mathematical and simulation results of throughput, concerning α and ρ, for the time switching and the power splitting protocols in the delay-limited transmission mode is demonstrated in Fig. 5(a).

and in the delay-tolerant transmission mode in Fig. 5(b), respectively. In the time switching protocol, the achievable throughput had an optimal value with the value α around 0.2, and in the power splitting protocol with the value ρ around 0.6. In both schemes, the throughput increased while α and ρ increased to the optimal values, and then decreased.
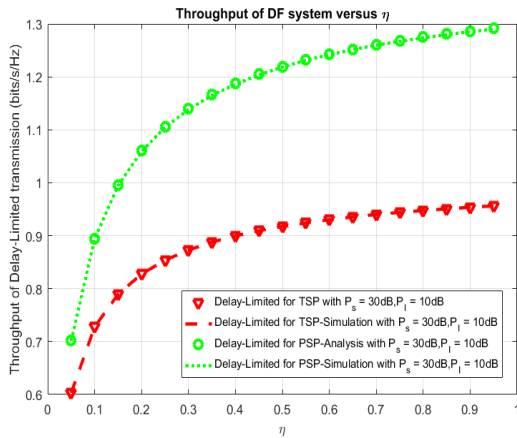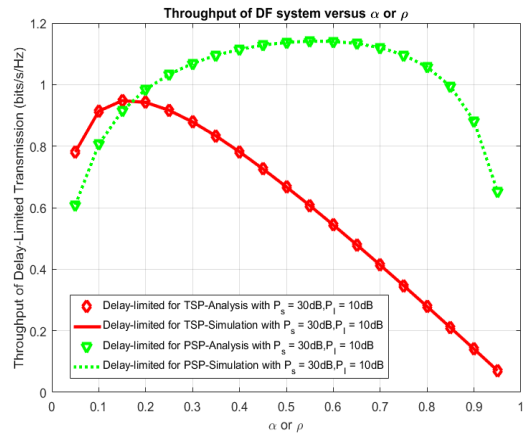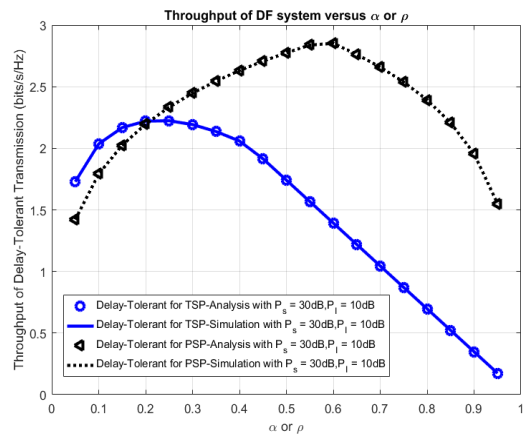

(a)
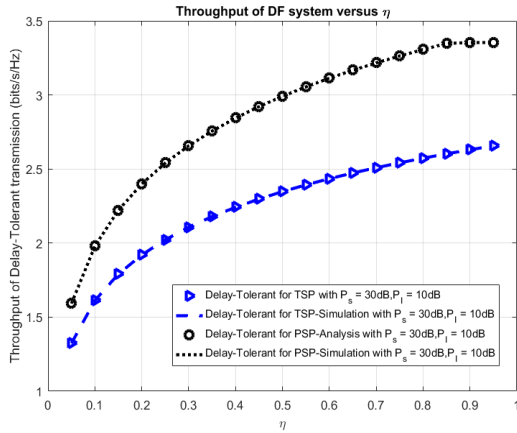
(b)

Fig. 4: Simulation and analytical throughput versus η at the destination node.

For more detail analysis, Fig. 6(a)plots the dependent of the throughput on the interference power P_I in the delay-limited transmission mode and for the delay-tolerant transmission mode in the Fig. 6(b) for the time switching and the power splitting protocols, respectively.


(a)

(b)

Fig. 5: Simulation and analytical throughput at the destination concerning α for the time switching and ρ for power splitting protocols.

Both Figs show that the achievable throughput decreased while the P_I increased from -10 dB to 10 dB. In the same way, the Fig. 7 indicates the influence of the source power on the throughput and the outage probability in the delay-limited transmission mode. Then, the influence of the source power on the throughput and the ergodic capacity in the delay-tolerant transmission mode is presented in the Fig. 8. All these results are considered in the time switching and the power splitting protocols. Furthermore, the comparison between the throughput in the delay-limited and the delay-tolerant transmission modes for the time switching and the power

splitting protocols is proposed in Fig. 9. In this analysis, the analytical mathematical throughput results are calculated by the analytical expressions of throughput and the simulation results based on the equations (in the second section). The research results indicated that the analytical mathematical result and the simulation result based on Monter Carlo analysis are totally matched each other.
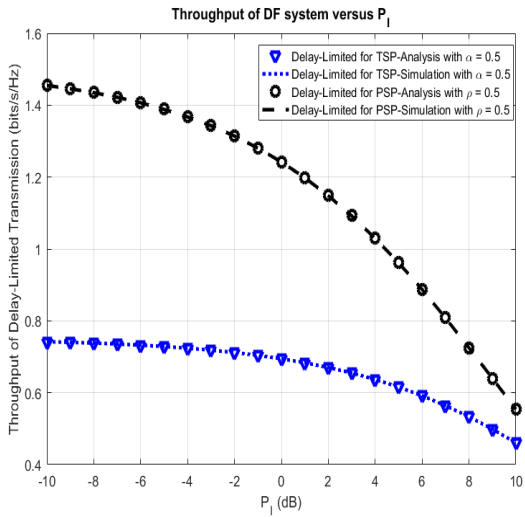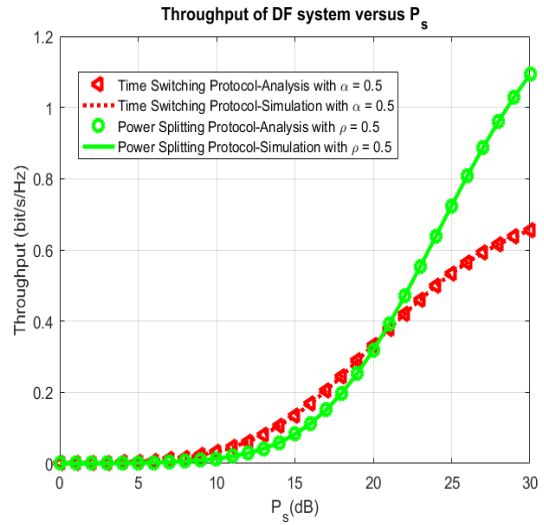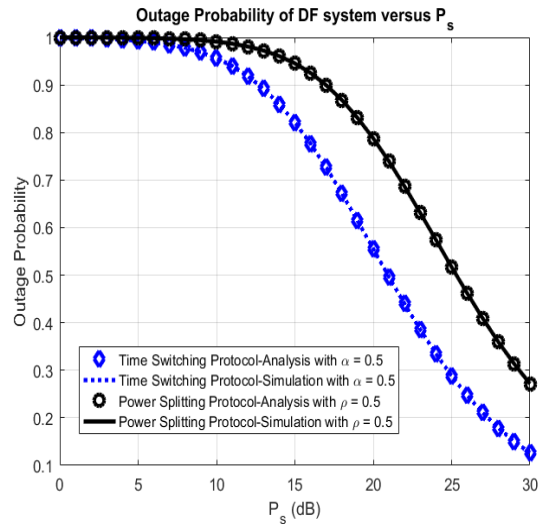

(a)
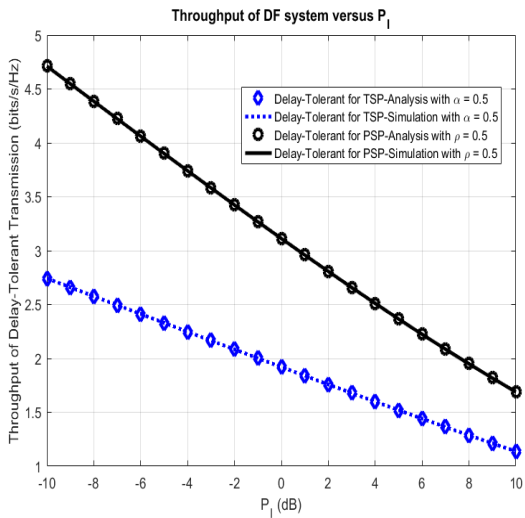
(b)

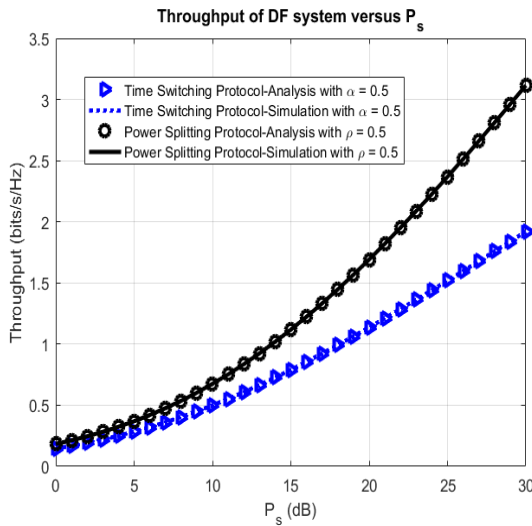**Fig. 6:** Throughput of DF system versus P_I

(a) Throughput versus P_s

(b) Outage Probability versus P_s

Fig. 7: Delay-limited transmission.

5. Conclusions

In this paper, the system performance of the DF relaying network in the delay-limited and the delay-tolerant transmission modes have been proposed and analyzed. In this model, both the time switching and the power splitting protocols are fully considered. From that system model, the throughput, outage probability and the ergodic capacity of a DF relaying network

are demonstrated by analytical mathematical algorithm and the Monte Carlo simulation. The research results show that the simulation and the analytical system performance are agreed with each other. The numerical analysis in this paper has provided practical approach into the effect of the interference noise on the system performance of wireless energy harvesting and information processing with DF relay nodes

Throughput of DF system versus P_s

(a) Throughput versus P_s

Ergodic Capacity of DF system versus P_s
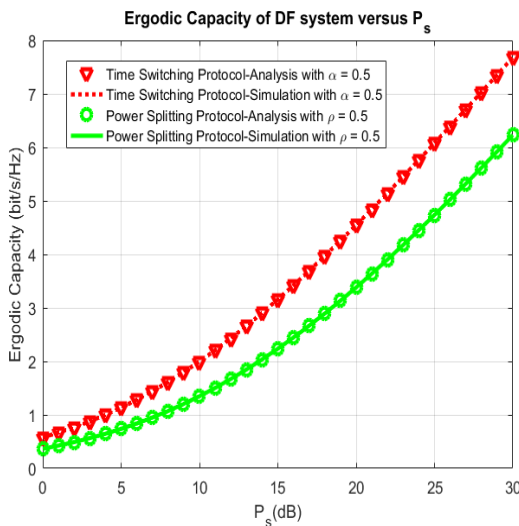
(b) Ergodic Capacity versus P_s

Fig. 8: Delay-Tolerant transmission.

Throughput of DF system versus P_s

Fig. 9: Throughput of DF system versus P_s.

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