Exact Throughput Analyses of Energy-Harvesting Cooperation Scheme with Best Relay Selections Under I/Q Imbalance

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Abstract. *In this paper, we propose an energy-harvesting cooperation scheme in which relays suffer In-phase and Quadrature-phase Imbalances (IQI) and harvest energy from a wireless transmit source. A best relay is selected based on end-to-end Signal-to-Interference-plus-Noise Ratios (SINRs) in both Amplify-and-Forward (called an EHAF protocol) and Decode-and-Forward (called an EHDF protocol) cooperation methods. We analyze and evaluate the system performance in terms of exact closed-form throughputs over Rayleigh fading channels. Simulation and analysis results discover contributions as follows. Firstly, the throughput performance of the proposed protocols EHAF and EHDF is improved when compared with that of a non-selection cooperation scheme. Secondly, the EHDF protocol is more efficient than the EHAF protocol. Finally, the theoretical analyses are validated by performing Monte Carlo simulations.*

Keywords

Amplify-and-forward, cooperative communication, decode-and-forward, energy harvesting, I/Q imbalance, opportunistic relay selection, outage probability and throughput.

1. Introduction

In recent years, widening the range and rising the diversity capacity of wireless communication are effected by cooperative relaying. The cooperative communication supports the data transmission from the wireless source nodes to the destinations. There are two main phases which are broadcast phase and cooperation phase. The source nodes broadcast their data to relays in the first phase. Then, in the next phase, the received signal is forwarded to the destinations by the relays. The data is transferred from the sources to the destinations via the relays which use the following selected cooperative techniques: Amplify-and-Forward (AF) and Decode-and-Forward (DF) [1], [2] and [3].

There are many studied cases in cooperative networks under the impact of In-phase and Quadrature-phase Im-balance (IQI) [4] and [5]. The IQI pertains to the phase and/or amplitude mismatch between the In-phase (I) and Quadrature (Q) signals at the Transmitter (TX) and Receiver (RX) sides. Most recent studies about IQI have focused on the performance analysis and baseband compensation for single hop communication systems. In [4], the authors researched a generalized performance analysis of AF dual-hop relaying, where IQI affects both the TX and RX front ends of the relay node.

In recent time, there are many studied cases about energy harvesting in cooperative networks [6], [7], [8] and [9]. The researchers in [9] presented the throughput maximization based on the assumptions of both causal and non-causal knowledge of the harvested energy in the energy harvesting two-hop AF relaying network. In [9], the authors investigated harvesting energy of relays from source signals with a best relay selection protocol in which a best relay having the highest harvested energy will forward the received signal towards the destination.

Most of the above researchers, the authors have not considered the energy-harvesting cooperation scheme with opportunistic relay selection under I/Q imbalance. In this paper, we consider a dual-hop DF and AF relaying networks with multiple wireless energy harvesting relay nodes under the impact of IQI. The main contributions of the paper are summarized as follows. Firstly, we propose an energy-harvesting cooperation scheme in which relays suffer In-phase and Quadrature-phase Imbalances (IQI). A best relay based on maximum end-to-end Signal-to-Interference-plus-Noise Ratio (SINR) is selected in both Amplify-and-Forward (called an EHAF protocol) and Decode-and-Forward (called an EHDF protocol) cooperation methods. Secondly, exact closed-form throughputs over Rayleigh fading channels are derived and are confirmed by Monte Carlo simulations. Thirdly, the proposed EHDF protocol outperforms the proposed EHAF protocol. Finally, the throughput performance of the two protocols is also improved when the number of cooperative relays increases. This paper is organized as follows: Sec. 2. describes a dual-hop DF and AF relaying networks with multiple wireless energy harvesting relay nodes under impact of IQI; Sec. 3. analyzes and calculates the exact the throughput performances of the proposed EHDF and EHAF protocols; the simulation results are presented in Sec. 4. and Sec. 5. summarizes our conclusions.

2. System Model

We consider a decode-and-forward and a amplify-and-forward relaying model with a source node defined by S, a destination node defined by D and M energy-harvesting relays denoted as R_i with i $= 1, 2, \ldots,$ M as shown in Fig. 1.

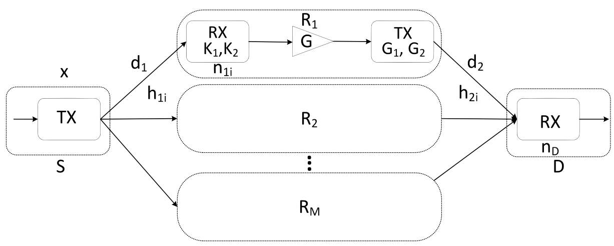

Fig. 1: A dual-hop decode-and-forward and amplify-and-forward relaying model with M energy-harvesting relays under I/Q imbalance.

In Fig. 1, each node is installed with a single antenna, and transmittance is forced in half-duplex mode where transmitting and receiving works can not happen concurrently. Assuming that there is no connection between the source and destination, the transmission signal from S to D is just via relays R_i because of deep shadowing. In addition, the relays R_i suffer In-phase and Quadrature-phase Imbalances (IQI).

Operation principle of the proposed scheme is performed in two stages to transfer a single data. In the first stage, the data is transferred from the source S to the relays R_i, after that the relays harvest energy from the RF signals of the source S. Then the signal is moved to the destination in the second stage. The relays R_i apply two methods to process the received signals: magnify and transmit to the destination D (called the EHAF protocol), and decode and transmit to the destination D (called the EHDF protocol). In this paper, we select a best relay based on end-to-end Signal-to-Interference-plus-Noise Ratios (SINRs).

The mathematical expressions and throughput analyses of the two protocols EHDF and EHAF will be discussed in the next section.

3. Throughput Performance Analyses

In this section, let h_{1i} and h_{2i} define the Rayleigh channel factors of the $S - R_i$ link and the $R_i - D$ link, respectively. Moreover, let $n_{1i} \sim CN(0, N_1)$ and $n_D \sim CN(0, N_2)$ as the complicated Gaussian noises at the relays R_i and D.

Throughputs of the proposed protocols EHDF and EHAF are obtained based on [10] as follows:

$$\tau_{\mathrm{X}} = (1 - \mathrm{P}_{out}^{X})(1{-}\alpha)R/2, \tag{1}$$

where: P_{out}^{X} are outage probabilities of the protocols X, X $\in \{\mathrm{EHAF}, \mathrm{EHDF}\}$; α is a time-switching coefficient, $0 < \alpha < 1$; and R is a target data rate and is related to a threshold SINR γ_0 as $R = \log_2(1 + \gamma_0)$. In the first stage, the signal is transmitted from the source S to the relays R_i. Then, the received baseband signals at the relays R_i of the proposed protocols EHAF and EHDF after down shift and under effects of RX I/Q mismatch can be given as

$$y_{X\_SR_i} = K_1(h_{1i}x + n_{1i}) + K_2(h_{1i}x + n_D)^*, \tag{2}$$

where x is the transmit signal of the source node S with average transfer energy E|x|2=P (Ez is an expectation expression of z), and

$$K_1 \triangleq (1 + g_T^{e^{j\varphi_T}})/2, \tag{3}$$

$$K_2 \triangleq (1 - g_T^{e^{j\varphi_T}})/2. \tag{4}$$

In Eq. (3) and Eq. (4), g_T and φ_T create the TX magnitude and phase mismatch.

The mirror datum introduced by the IQI is often assigned as $(h_{1i}x + n_{1i})^*$ terms in Eq. (2). From Eq. (2) and [10], the power is gotten from the collected energy in over the time $(1-\alpha)T/2$ for forwarding the processed signal to the destination D as

$$P_{R_i} = \frac{\left(|K_1|^2 + |K_2|^2\right) 2\alpha\eta P|h_{1i}|^2}{(1-\alpha)}. \quad (5)$$

In the second stage, the signal after is amplified (the EHAF protocol) or decoded (the EHDF protocol), it is transmitted from the relays R_i to the destination D.

3.1. The EHAF Protocol

In the EHAF protocol, the received signals at the relay R_i are typically magnified at the baseband level with a magnification coefficient G, then converted up the Radio Frequency level (RF), and after that are transferred to the destination D. Under TX IQI at the relay R_i, the received baseband signal at the destination D is expressed as

$$\begin{aligned} y_{EHAF\_R_iD} = h_{2i}(G_1(G\, y_{EHAF\_SR_i}) \\ +G_2^*(G\, y_{EHAF\_SR_i})^*) + n_D, \end{aligned} \quad (6)$$

where

$$G_1 \triangleq (1 + g_R^{e^{j\varphi_R}})/2, \quad (7)$$

$$G_2 \triangleq (1 - g_R^{e^{j\varphi_R}})/2, \quad (8)$$

$$G = \sqrt{\frac{P_{R_i}}{F(|h_{1i}|^2 P + N_i)}}. \quad (9)$$

In Eq. (7) and Eq. (8), g_R and φ_R denote the RX magnitude and phase mismatch.

Substituting Eq. (2), Eq. (9) into Eq. (6), and after applying some manipulations, the end-to-end SINR is obtained as

$$\gamma_{EHAF\_R_iD} = \frac{aPP_{R_i}|h_{1i}|^2|h_{2i}|^2}{\begin{aligned}(bPP_{R_i}|h_{1i}|^2|h_{2i}|^2) + aN_1P_{R_i}|h_{2i}|^2 + \\ bN_1P_{R_i}|h_{2i}|^2 + N_2P|h_{1i}|^2 + N_1N_2)\end{aligned}} \quad (10)$$

where $a = {A^2}/{F}$, $b = {B^2}/{F}$, $c = a + b$,

$$A \triangleq K_1G_1 + K_2^*G_2^*; B \triangleq K_1G_2 + K_2^*G_1^*,$$

$$F \triangleq (|K_1|^2 + |K_2|^2)(|G_1|^2 + |G_2|^2).$$

Substituting the P_{R_i} in Eq. (5) into Eq. (10), we obtain the following result:

$$\gamma_{EHAF\_R_iD} = \frac{2a\alpha\eta P^2(|K_1|^2 + |K_2|^2)|h_{1i}|^4|h_{2i}|^2}{\begin{aligned}(2b\alpha\eta P|h_{1i}|^4|h_{2i}|^2) + \\ 2a\alpha\eta N_1P|h_{1i}|^2|h_{2i}|^2 + \\ 2b\alpha\eta N_1P|h_{1i}|^2|h_{2i}|^2 + \\ N_2P|h_{1i}|^2(1-\alpha) + \\ N_1N_2(1-\alpha).\end{aligned}} \quad (11)$$

In the proposed EHAF protocol, the best relay R_{b_1} is selected so that the end-to-end SINR $\gamma_{EHAF\_R_{b_1}D}$ is maximize. A selection criterion is expressed as

$$R_{b_1} = \arg \max_{i\in\{1,2,\ldots,M\}} \gamma_{EHAF\_R_iD}. \quad (12)$$

The outage probability of the EHAF protocol is obtained by a math expression as follows

$$\begin{aligned} P_{out}^{EHAF} &= \Pr\left[\gamma_{EHAF\_R_{b_1}D} < \gamma_0\right] \\ &= \Pr\left[\max_{i=1,2,\ldots,M}(\gamma_{EHAF\_R_iD}) < \gamma_0\right] \\ &= \prod_{i=1}^{M} \Pr\left[\gamma_{EHAF\_R_iD} < \gamma_0\right] \\ &= \prod_{i=1}^{M} \Pr\left[w_{2i} < \frac{\omega w_{1i} + \psi}{uw_{1i}^2 - vw_{1i}}\right]. \end{aligned} \quad (13)$$

Applied the proposition in [10], the expression P_{out}^{EHAF} is given as:

$$P_{out}^{EHAF} = \left[1 - \lambda_1 \int_{v/u}^{\infty} e^{-\left(\lambda_1 x + \lambda_2 \frac{\omega x + \psi}{(ux^2 - vx)}\right)} \mathrm{d}x\right]^M \quad (14)$$

$$\approx \left[1 - e^{-\frac{\lambda_1 v}{u}} \mu K_1(\mu)\right]^M, \text{ (SINR approximation)}$$

where

$$\begin{aligned} \omega &= \gamma_0 N_2 P(1-\alpha), \\ \psi &= \gamma_0 N_1 N_2 (1-\alpha), \\ u &= 2a\alpha\eta P^2 \left(|K_1|^2 + |K_2|^2\right) - 2b\alpha\eta\gamma_0 P^2, \\ v &= 2a\alpha\eta P - 2b\alpha\eta\gamma_0 P. \end{aligned}$$

3.2. The EHDF Protocol

From Eq. (2), the SINR at the relays R_i to decode the information signal x is obtained as follows

$$y_{EHDF\_SR_i} = \frac{|K_1|^2 P|h_{1i}|^2}{|K_2|^2 P|h_{1i}|^2 + \left(|K_1|^2 + |K_2|^2\right) N_1}. \quad (15)$$

After successful decoding, the relays R_i will forward the decoded signal x to the destination D. The received signal at the destination D with the TX IQI at the relays R_i is expressed as

$$y_{EHDF\_R_iD} = G_1(h_{2i}x + n_D) + G_2(h_{2i}x + n_D)^*. \quad (16)$$

Then, the SINR $\gamma_{EHDF\_R_iD}$ at the destination D is obtained as

$$\begin{aligned} \gamma_{EHDF\_R_iD} &= \frac{|G_1|^2 P_{R_i}|h_{2i}|^2}{|G_2|^2 P_{R_i}|h_{2i}|^2 + \left(|G_1|^2 + |G_2|^2\right) N_2} \\ &= \frac{2\alpha\eta P|G_1|^2|h_{1i}|^2|h_{2i}|^2}{\begin{aligned}2\alpha\eta P|G_2|^2|h_{1i}|^2|h_{2i}|^2 + \\ \left(|G_1|^2 + |G_2|^2\right) N_2 (1-\alpha)\end{aligned}}. \end{aligned} \quad (17)$$

Similar to the EHDF, the best relay R_{b_2} is selected according a criterion as follows

$$R_{b_2} = \arg \max_{i\in\{1,2,\ldots,M\}} \min\left(\gamma_{EHDF\_SR_i},\ \gamma_{EHDF\_R_iD}\right). \tag{18}$$

The outage probability of the EHDF protocol is obtained as

$$\begin{aligned} P_{out}^{EHDF} &= \Pr\left[\max_{i\in\{1,2,\ldots,M\}} \min\left(\begin{array}{c}\gamma_{EHDF\_SR_i},\\ \gamma_{EHDF\_R_iD}\end{array}\right) < \gamma_0\right] \\ &= \prod_{i=1}^{M} \Pr\left[\min\left(\begin{array}{c}\gamma_{EHDF\_SR_i},\\ \gamma_{EHDF\_R_iD}\end{array}\right) < \gamma_0\right] \\ &= \prod_{i=1}^{M}\left[1 - \Pr\left[\begin{array}{c}\min(\gamma_{EHDF\_SR_i},\\ \gamma_{EHDF\_R_iD}) > \gamma_0\end{array}\right]\right] \\ &= \prod_{i=1}^{M} \Pr\left[1 - \underbrace{\Pr\left[\begin{array}{c}(\gamma_{EHDF\_SR_i} > \gamma_0,\\ \gamma_{EHDF\_R_iD}) > \gamma_0\end{array}\right]}_{\Phi}\right]. \end{aligned} \tag{19}$$

The Φ term is calculated as

$$\begin{aligned} \Phi &= \Pr\left(w_{1i} > m, w_{2i} > \frac{o}{(p-q)w_{1i}}\right) \\ &= \begin{cases} \Pr\left[w_{1i} > m, w_{2i} > \frac{o}{(p-q)w_{1i}}\right], & p > q \\ \Pr\left[w_{1i} > m\right], & p \le q \end{cases} \\ &= \begin{cases} \lambda_1 \int_m^{\infty} e^{-\left(\lambda_1 x + \lambda_2 \frac{t}{x}\right)} dx, & p > q \\ e^{-\lambda_1 m}, & p \le q \end{cases} \end{aligned} \tag{20}$$

where $m = \frac{\left(|K_1|^2 + |K_2|^2\right)N_1\gamma_0}{\left(|K_1|^2 - |K_2|^2\gamma_0\right)P}$;
$w_{1i} = |h_{1i}|^2$;
$o = \left(|G_1|^2 + |G_2|^2\right) N_1(1-\alpha)\gamma_0$
$p = |G_1|^2 2\alpha\eta P$;
$q = |G_2|^2 2\alpha\eta P\gamma_0$.

The probability Φ in Eq. (20) contains the complex integrals, and solving of these integrals is not practical. However, we use numerical methods to find values of Φ.

4. Simulation Results

In this section, the systems performance of the proposed protocols EHAF and EHDF is analyzed and evaluated using the exact theoretical analyses and the Monte Carlo simulations of the throughput. In the two dimensional plane, the coordinates of S, D, and R_i are S(0, 0), D(1, 0) and R_i(x, y), respectively, satisfying $0 < x < 1$. Therefore, d1$=\sqrt{x^2+y^2}$ and d2 $=\sqrt{(1-x)^2+y^2}$. The IQI parameters are set to $20\log 10(g_T) = 20\log 10(g_R) = 1.58$ dB. In addition, the SINR on the x-axis is defined as $\gamma = \frac{P}{N_i}$, $\{i \in 1, 2\}$.

Figure 2 presents the throughputs of the proposed protocols EHDF and EHAF versus α when the symmetric network model is considered with d1 = d2 = 1, SINR = 5 dB, $\eta = 0.9$ and $0 < \alpha < 1$. It can be seen that the throughputs at the destination in both protocols EHDF and EHAF increase by time-switching coefficient α and then throughputs decreases when α increases. In addition, these throughputs are largest when values α become to an optimal value. For example, in the EHDF protocol, the optimal values are approximately to 0.27 and 0.17 when the number of relays, M, is set to 1 and 3, respectively.

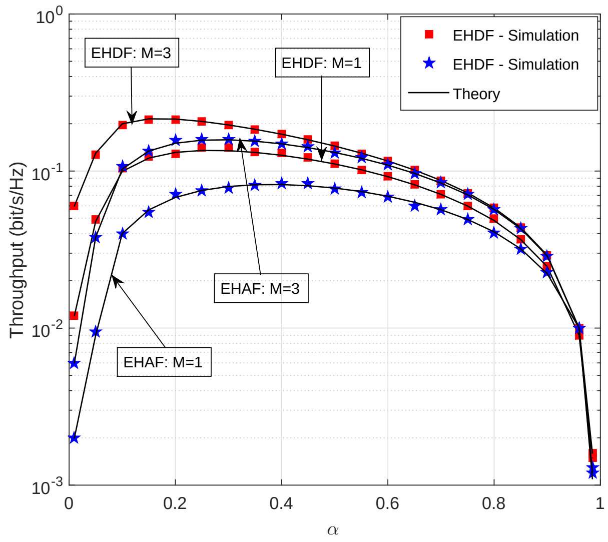

Fig. 2: The throughput at the destination in the protocols EHDF and EHAF versus when the IQI parameters: $20\log 10(g_T) = 20\log 10(g_R) = 1.58$ dB and $\varphi_T = \varphi_R = 10^0$, $\eta = 0.9$.

In EHAF protocol, the optimal value $\alpha = 0.39$ when M = 1 and $\alpha = 0.29$ when M = 3. These optimal values can be obtained by the Golden Section Search (GSS) method in [11] with a minimal interval 10^{-3}. The results show that the throughputs ascend by α and achieve the optimal limitation at the ideal value α. Furthermore, because of the effects of IQI noise on the system, the throughput will descend by α. From Fig. 2, the throughput performance of the EHDF protocol is greater than that of the EHAF protocol. In addition, due to the optimal relay selection approach, we have figured out that, the system model with 3 relays achieves the better throughput than the system model with 1 relay in both protocols.

Figure 3 presents the throughput performances of the proposed protocols EHDF and EHAF versus SINR (dB) in which α is set to the optimal values α_{opt_AF} and α_{opt_DF} at each value of the SINR (dB), respectively. We have figured that the throughputs go up when the SINRs increase, and the throughput performance of the proposed EHDF protocol outperforms the EHAF protocol.

Figure 4 illustrates the throughput performances of the proposed protocols EHDF and EHAF in the asym-

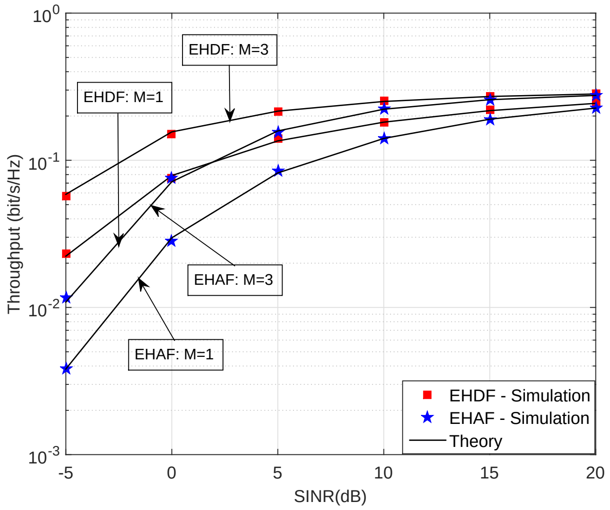

Fig. 3: The throughput at the destination in the protocols EHDF and EHAF versus when the IQI parameters: $20\log 10(g_T) = 20\log 10(g_R) = 1.58$ dB and $\varphi_T = \varphi_R = 10^0$, $\eta = 0.9$.

metric network scheme as a function of the IQI parameters $g_T = g_R$ (dB) when $\varphi_T = \varphi_R = 10^0$, $\eta = 0.9$, the IQI parameters values are set to 0 dB and 30 dB, respectively. The parameters α are set to the optimal values α_{opt_AF} and α_{opt_DF} at each value of the g_T. It can be seen that when the IQI parameters values increase, the throughput performances of both protocols EHDF and EHAF decrease.

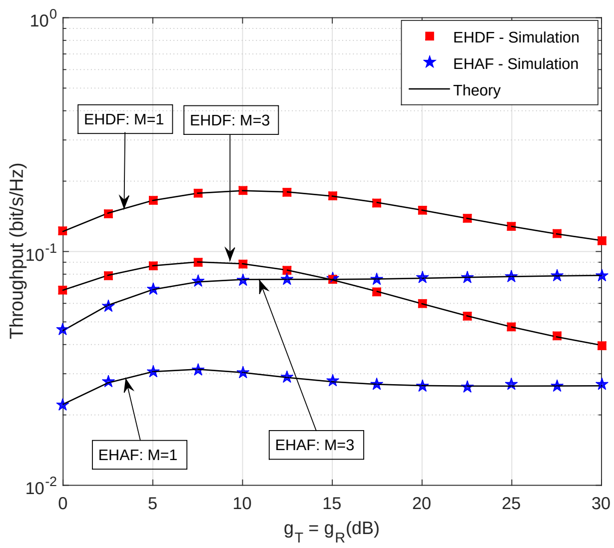

Fig. 4: The throughputs in the protocols EHDF and EHAF versus the IQI parameters $g_T = g_R$ (dB) and $\varphi_T = \varphi_R = 10^0$, $\eta = 0.9$.

Lastly, we can see that the simulation results fit well to the theoretical results. Hence, we can conclude that the derived formulas during analyzing are accurate.

5. Conclusion

In this paper, we propose an energy-harvesting cooperation scheme in which relays suffer In-phase and Quadrature-phase Imbalances (IQI) and harvest energy from a wireless transmit source. One best relay is selected based on end-to-end SINRs in both Amplify-and-Forward (called an EHAF protocol) and Decode-and-Forward (called an EHDF protocol) cooperation methods. We have analyzed and evaluated the system performance in terms of exact closed-form throughputs over Rayleigh fading channels. Simulation and analysis results discover that the proposed EHDF protocol achieves higher throughput performance when comparing with the proposed EHAF protocol. In addition, the throughput performance of the two protocols also improved when the number of relays increase.

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