On Impact of Imperfect CSI over SWIPT Device-to-Device (D2D) MIMO Relay Systems

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***Abstract*—Simultaneous wireless information and power transfer (SWIPT) is an efficient solution for the power scarce wireless communications. In this paper, we consider a relay assisted multi-input and multi-output (MIMO) device-to-device (D2D) communications with a practical scenario of imperfect channel state information (CSI) over a generalized Nakagami-m fading channels. Further, at the relay node, energy from the received radio-frequency (RF) signals is harvested by adopting time-switch (TS) protocol for broadcasting a signal to the destination. In a resource limited environment, it is deterrent to use all the MIMO antennas due to increased system complexity with the dedicated RF chain for each active antenna. Thus, transmit antenna selection strategy (TAS) is considered in this work. Framework for the outage probability and asymptotic outage probability of TAS based MIMO D2D relay system is provided. It is observed that the diversity order of the system gets affected with small variation in imperfect CSI correlation coefficient and throughput of the system gets affected severely with increasing rates with imperfect CSI. Further, Monte-Carlo simulations are performed to validate the derived analytical expressions.**

***Index Terms*—SWIPT, D2D, MIMO, TAS, outage probability, Nakagami-m, imperfect CSI.**

I. Introduction

With an objective of green communications in an energy constraint communication, energy harvesting (EH) has received prominent research attention for the beyond 5^{th} generation (5G) communication systems. The unprecedented growth in the internet of things and online services has led to address the energy efficiency of the users by the third generation partnership project [1]. EH through the ambient resources such as radio-frequency (RF) electromagnetic signals provides a viable solution by enabling the energy constraint nodes to scavenge the energy while simultaneous wireless information and power transfer (SWIPT) [2], and wired powered communication networks [3]. Simultaneous transmission and EH does not hold in practice due to requirement for an ideal receiver [4]. Hence, EH is done by either time switching (TS) or power splitting (PS) protocol [5]. In TS protocol, the energy constraint node processes the information over specific time periods for harvesting the energy and for transmission whereas, in PS protocol, it splits the power for EH and information transmission [5].

On the other hand, device-to-device (D2D) communication plays a vital role in the next-generation cellular networks for quality-of-service (QoS) assured high data-rate multimedia services [6]. D2D communication enhances the spectrum utilization by facilitating the physical proximity of nearby active devices [7]. Further, D2D communication provides extended coverage, energy efficiency, reduced backhaul demand, and provides low latency with reduced transmission delays [8]. D2D communication finds applications in the IEEE 802.11a, wireless local area network, Infra-red, and near field communication to operate in unlicensed spectrum. However, D2D communication is limited by the proximity of the devices. Relay assisted D2D communication is a promising technology to be deployed in the future wireless communications to improve the spectrum efficiency along with coverage area [9]. Further, to enhance the system performance, multiple-input and multiple-output (MIMO) systems are a popular choice. Thus, EH over relay assisted D2D MIMO systems is a viable solution to the present-day design metrics of green communications for perpetual energy-efficient communications. However, MIMO systems require an RF chain for each of the active antennas employed which increases the system complexity [10]. Hence, it is deterrent to use multiple antennas, and thus, transmit antenna selection strategy (TAS) is employed in energy-constrained wireless communication scenarios to

Notation: Matrices (column vectors) are denoted by Bold uppercase (lowercase) letters; conjugate and complex conjugate transpose are denoted by $(\cdot)^*$ and $(\cdot)^H$, respectively; Squared Frobenius norm is denoted by $||\cdot||^2$. Nakagami-m distribution with fading severity $M_L = mN$ and variance σ^2 is denoted by $Nak(M_L, \sigma^2)$. Further, fading parameter is represented by m and receiver antennas by N; AWGN is modeled as complex Gaussian distribution with mean 0, variance σ^2 is denoted by $\mathcal{CN}(0, \sigma^2\mathbf{I}_N)$ and $\mathbf{I}$ is the identity matrix. Modified Bessel function of second kind of order ϑ is denoted by $K_\vartheta(\cdot)$. Probability density function (PDF) and cumulative distribution function (CDF) are given by $f(\cdot)$ and $F(\cdot)$, respectively. E$\{x^2\}$ denotes the expected value.

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retain the MIMO gains.

Owing to the potential features of EH through SWIPT, several notable works were carried out by considering EH in relay communications in [5], [11] for a dual-hop system model. In [12], performance analysis of the dual-hop D2D relay system is carried out over Nakagami-m fading channels and derived the average symbol error rate (ASER) expressions for hexagonal quadrature amplitude modulation (HQAM), rectangular QAM (RQAM) and Cross QAM (XQAM) and further optimized the relay location. In [12], [13], authors have performed an analysis of the D2D system model without considering the SWIPT techniques. In [13], authors have obtained the outage probability, the average achievable rate for a D2D pair in an uplink cellular network. In [14], ASER analysis of HQAM and RQAM schemes is performed over Nakagami-m channels with both the integer and non-integer fading parameter for a multi-relay system model. In [10], ASER analysis of HQAM, RQAM, and XQAM is performed for a MIMO relay network over the Rayleigh fading channel.

In the above literature, the majority of the works assumes that the channel state information (CSI) is perfectly known at the receiver. However, in practice the knowledge of perfect CSI at the receiver is unknown. Since, the studies on EH based D2D MIMO relays are limited, with inspiration from the literature on green communications, in this work, we consider a dual-hop half-duplex EH based relay assisted MIMO D2D communication with a practical scenario of imperfect CSI over the Nakagami-m channel. Furthermore, at the relay amplify-and-forward (AF) relaying protocol is employed due to its low complexity and easy deployment [15]. In this work, we have obtained closed-form expressions of outage probability and the asymptotic outage probability. To best of the authors' knowledge, the derived expressions are not available in the literature. Useful insights are drawn from the obtained results, and the derived analytical expressions are validated through Monte-Carlo simulations.

Remainder of the paper is organized as follows: in Section II, system model is described. In Section III, outage probability is analyzed. In Section IV, simulation results are discussed. Finally, in Section V, conclusions are drawn.

II. System Model

We consider a SWIPT enabled three device variable gain MIMO AF D2D communication system model [12] with three multi-antenna nodes namely, source (S), relay (R), and the destination (D). Base station acts as S and the user equipments (UEs) acts as R and D, respectively. $\mathbf{H}_{AB}$ with dimensions $N_B \times N_A$ is the channel matrix from node A to node B, where N_A and N_B denotes the number of antennas at the A and B nodes, respectively. Further, $A \in \{S, R\}$, $B \in \{R, D\}$, and $A \neq B$. Without loss of generality of the MIMO system, TAS is employed to select the i^{th} transmit antenna at the node A to transmit the information through the channel vector $\mathbf{h}_{AB}^{(i)}$ to the receiver. The channel vector $(\mathbf{h}_{AB}^{(i)})$ in the channel matrix $\mathbf{H}_{AB}$ has the dimensions of $N_B \times 1$. It is assumed that the knowledge of perfect CSI is not available at the receiver and hence, minimum mean square error (MMSE) based estimator is used at the receiver. It is assumed that the direct $(S \rightarrow D)$ and the relayed links $(S \rightarrow R \rightarrow D)$ are modeled by the complex Nakagami-m frequency flat channels, $Nak(M_L, \hat{\sigma}^2_{\mathbf{H}})$. Further, it is assumed that the noise vectors are modeled by additive white Gaussian noise (AWGN) vectors with mean 0 and variance $\sigma^2_{AB}\mathbf{I}_{N_B}$. The actual channel $(\mathbf{H})$ and the estimated version $(\hat{\mathbf{H}})$ are related through channel estimation error (CEE) $(\boldsymbol{\delta}_{\mathbf{H}})$ as $\mathbf{H} = \hat{\mathbf{H}} + \boldsymbol{\delta}_{\mathbf{H}}$, where the CEE $\sim \mathcal{CN}(0, \sigma^2_{\delta} I)$. The variance of the CEE is obtained as $\sigma^2_{\delta} = (1-\rho)\sigma^2_{\mathbf{H}}$ where $\rho = \sigma^2_{\hat{\mathbf{H}}}/\sigma^2_{\mathbf{H}}$ indicates the channel correlation coefficient, where $0 < \rho < 1$ [16]. Estimated channel variance is given as $\sigma^2_{\hat{\mathbf{H}}} = \sigma^2_{\mathbf{H}} - \sigma^2_{\delta} = \rho\sigma^2_{\mathbf{H}}$. We consider the TS strategy at the relay for EH. The operation of the considered system takes place in two phases. In the first phase, R harvest the energy from the S received RF signals and then in the second phase, information transmission takes place.

A. TS relaying protocol

TS protocol at the R node is employed for EH in the analysis. Entire communication takes place between S and D over the time period (T) in two phases as shown in Fig. 1. In the first phase for αT time, EH takes place at R and in the second phase, for the remaining $(1-\alpha)T$ time, information transmission takes place, where $0 < \alpha < 1$ is the fraction of time. The $(1-\alpha)T$ phase is further divided into two equal phases of $\frac{(1-\alpha)T}{2}$. In the first $\frac{(1-\alpha)T}{2}$ fraction of time, the S transmits information to both R and D, simultaneously. In the second $\frac{(1-\alpha)T}{2}$ fraction of time, R forwards the S information to the D. The energy harvested in EH phase is completely used by R in forwarding the information to D. The amount of energy harvested depends on the factor α and affects the achievable throughput. Thus, there is a trade-off between the energy harvested and the throughput attained. The received signal at the relay and the destination is given as

$$\mathbf{y}_{SR} = \sqrt{P_s}(\mathbf{h}^i_{SR} + \delta_{\mathbf{h}^i_{SR}})x + \mathbf{n}_{SR}, \quad (1)$$

$$\mathbf{y}_{SD} = \sqrt{P_s}(\mathbf{h}^i_{SD} + \delta_{\mathbf{h}^i_{SD}})x + \mathbf{n}_{SD}, \quad (2)$$

respectively, where P_s is the transmit power at the S, $\mathbf{n}_{SR}$, and $\mathbf{n}_{SD}$ are the AWGNs in the SR and SD links, respectively. It is assumed that $\mathrm{E}\{x^2\} = 1$ [17]. During EH phase, the energy harvested at the relay is given

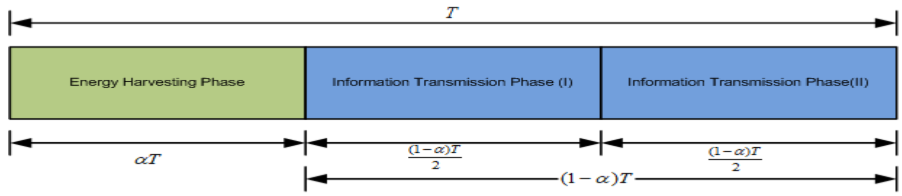

Fig. 1 TS protocol for SWIPT.

as $E_h = \eta\alpha T P_S||\mathbf{h}_{SR}^i||^2$ [5], where $0 < \eta < 1$, is the energy conversion efficiency and it depends on the rectification process and the energy harvesting circuitry [5]. The received signal at R is amplified with gain $G \leq \sqrt{P_R/(P_S||\mathbf{h}_{SR}^i||^4 + \sigma_N^2)} \approx \sqrt{P_R/(P_S||\mathbf{h}_{SR}^i||^4)}$ [10], [18], and transmitted to D through the k^{th} transmit antenna at R as

$$\mathbf{y}_{RD} = \sqrt{P_r} G(\mathbf{h}_{RD}^j + \delta_{\mathbf{h}_{RD}^j})(\mathbf{h}_{SR}^i)^H \mathbf{y}_{SR} + \mathbf{n}_{RD}, \quad (3)$$

where P_r is transmit power at the R and is obtained from the EH phase and is given as $P_r = \frac{2E_h}{(1-\alpha)T} = \frac{2\eta\alpha P_S||\mathbf{h}_{SR}^i||^2}{(1-\alpha)}$ [5] and $\mathbf{n}_{RD}$ is the AWGN of the RD link. Finally, at D, the received signals in two time slots are combined using maximum ratio combiner with an MMSE filter [10]. Thus, the end-to-end (e2e) SNR at D is given as

$$\gamma_{e2e}^{(i,j)} = \hat{\gamma}_{SD}^{(i)} + \hat{\gamma}_{SRD}^{(i,j)}, \quad (4)$$

where $\hat{\gamma}_{SD}^{(i)} = \gamma_{SD}^{(i)}/\Omega_{SD}$, $\Omega_{SD} = (1 + \hat{\sigma}_{\delta SD}^2)$, $\hat{\sigma}_{\delta SD}^2 = \gamma_0 \sigma_{\delta SD}^2$, $\gamma_0 = P/\sigma_N^2$ with P transmit power and noise variance (σ_N^2). $\hat{\gamma}_{SRD}^{(i,k)}$ is approximated as [16]

$$\hat{\gamma}_{SRD}^{(i,j)} \approx \frac{\gamma_{SR}^{(i)}}{\Omega_{SR}} \frac{\gamma_{RD}^{(j)}}{\Omega_{RD}} \Big/ \Big(\frac{\gamma_{SR}^{(i)}}{\Omega_{SR}} + \frac{\gamma_{RD}^{(j)}}{\Omega_{RD}}\Big), \quad (5)$$

where $\Omega_{SR} = (1+\hat{\sigma}_{\delta SR}^2)$, $\Omega_{RD} = (\frac{1}{P_s} + \hat{\sigma}_{\delta RD}^2)$, $\hat{\sigma}_{\delta SR}^2 = \gamma_0 \sigma_{\delta SR}^2$, $\hat{\sigma}_{\delta RD}^2 = \frac{K_1}{\sigma_N^2}\sigma_{\delta RD}^2$, $\gamma_{SD}^{(i)} = \overline{\gamma}_{SD}||\mathbf{h}_{SD}^i||^2$, $\gamma_{SR}^{(i)} = \overline{\gamma}_{SR}||\mathbf{h}_{SR}^i||^2$, $\gamma_{RD}^{(j)} = \frac{K_1}{\sigma_N^2}||\mathbf{h}_{RD}^j||^2$, and $K_1 = \frac{2\eta\alpha}{(1-\alpha)}$. Furthermore, $\gamma_{SD}^{(i)}$, $\gamma_{SR}^{(i)}$, and $\gamma_{RD}^{(i)}$ are the instantaneous SNRs of SD, SR and RD links, respectively and $\overline{\gamma}_{SD}$, $\overline{\gamma}_{SR}$ are the average SNRs of the SD and SR links, respectively.

III. Outage Probability

Outage probability (OP) is an important system performance metric. OP is defined as the probability where the e2e SNR of the system falls below a fixed threshold. The threshold depends on the rate of transmission. The closed-form UB expression of the OP for a rate, $R_{th} = \frac{1-\alpha}{2}\log_2(1+\gamma_{e2e})$ bits/sec/Hz, is given as

$$\begin{aligned} P_{out}^{(UB)}(\gamma_{th}) &= P\Big(\max_{1\leq j\leq N_s}\{\hat{\gamma}_{SD}^{(i)} + \hat{\gamma}_{SRD}^{(i,j)}\} \leq \gamma_{th}\Big) \\ &\leq P\Big(\max_{1\leq j\leq N_s}\hat{\gamma}_{SD}^{(i)} \leq \gamma_{th}\Big) P\Big(\max_{1\leq j\leq N_s}\hat{\gamma}_{SRD}^{(i,j)} \leq \gamma_{th}\Big), \\ &= F_{\hat{\gamma}_{SD}^{(i)}}(\gamma_{th}) F_{\hat{\gamma}_{SRD}^{(i,j)}}(\gamma_{th}), \end{aligned} \quad (6)$$

The closed-form expressions of $F_{\hat{\gamma}_{SD}^{(i)}}(\gamma_{th})$ and $F_{\hat{\gamma}_{SRD}^{(i,j)}}(\gamma_{th})$ are given in (7) are derived by following the procedure as in [10]. In (7), $\Delta_1 = \frac{p}{\lambda_{SR}}(\frac{\Omega_{SR}}{\Omega_{RD}}) + \frac{t+1}{\lambda_{RD}}$, $\Delta_2 = \frac{\Omega_{SR}p(t+1)}{\Omega_{RD}\lambda_{SR}\lambda_{RD}}$, $\Delta = q + n + M_{RD}$, $\vartheta = z - q + 1$, $M_{SD} = m_{SD}N_D$, $M_{SR} = m_{SR}N_R$, and $M_{RD} = m_{RD}N_D$. Further, $\lambda_{SD} = \frac{\overline{\gamma}_{SD}}{m_{SD}}$, $\lambda_{SR} = \frac{\overline{\gamma}_{SR}}{m_{SR}}$, and $\lambda_{RD} = \frac{K_1}{\sigma_N^2}\mathrm{E}||\mathbf{h}_{RD}^j||^2/m_{RD}$. $\phi_{a,b,c}$ is the coefficient of the multinomial theorem [12].

A. Asymptotic Analysis

In high SNR regime, the system design parameters such as diversity and coding gain are obtained which are crucial in determining the system performance. The closed-form asymptotic OP expression is derived at $\overline{\gamma} \to \infty$ by taking the high SNR approximation of e^x and $K_\vartheta(z)$ as given in [19, eq. (1.211.1), eq. (8.446)] as

$$P_{out}^{\infty}(\gamma_{th}) = \begin{cases} f_1 f_2 \Big(\frac{\gamma_{th}}{\overline{\gamma}}\Big)^{d_1}, m_{SR}N_S < m_{RD}N_D \\ f_1 f_3 \Big(\frac{\gamma_{th}}{\overline{\gamma}}\Big)^{d_2}, m_{SR}N_S > m_{RD}N_D \\ f_1(f_2+f_3)\Big(\frac{\gamma_{th}}{\overline{\gamma}}\Big)^{d_3}, m_{SR}N_S = m_{RD}N_D \end{cases}$$

$$f_i = \Big((\frac{\sigma_{PQ}m_{SD}}{k_{PQ}})^{M_{PQ}}/(M_{PQ})!\Big)^{N_P}, \quad (8)$$

Further, when $i = 1, PQ = SD$, when $i = 2, PQ = SD$, and when $i = 3, PQ = RD$. Furthermore, $d_1 = M_{SD}N_S + M_{SR}N_R$, $d_2 = M_{SD}N_S + M_{RD}N_R$, $d_3 = M_{SD}N_S + MN_R$, $M = m_{SR}N_S = m_{RD}N_D$ and $k_{AB} = \frac{\overline{\gamma}_{AB}}{\overline{\gamma}}$.

Throughput Analysis

In delay-limited transmission mode, throughput can be calculated at a fixed transmission rate from the outage probability as [5]

$$\tau = \frac{(1 - P_{out})R_{th}(1-\alpha)}{2}, \quad (9)$$

$$F_{\hat{\gamma}_{SD}^{(i)}}(\gamma_{th}) = \sum_{m=0}^{N_S}\sum_{n=0}^{m(M_{SD}-1)} \binom{N_S}{m}(-1)^m \left(\frac{\Omega_{SD}}{\lambda_{SD}}\right)^n \psi_{n,m,M_{SD}} \gamma_{th}^n e^{\frac{-m\Omega_{SD}\gamma_{th}}{\lambda_{SD}}},$$

$$F_{\hat{\gamma}_{SRD}^{(i,k)}}(\gamma_{th}) = 1 + \sum_{p=1}^{N_S}\sum_{q=0}^{p(M_{SR}-1)}\sum_{t=0}^{(N_R-1)}\sum_{s=0}^{t(M_{RD}-1)}\sum_{z=0}^{\Delta-1} \frac{(-1)^{p+t}2N_R\psi_{q,p,M_{SR}}\psi_{s,t,M_{RD}}}{\Gamma(M_{RD})\lambda_{RD}^{\frac{2M_{RD}+2s+q-z-1}{2}}} \frac{1}{(\Omega_{RD}\lambda_{SR})^{\frac{z+q+1}{2}}}\left(\frac{p}{t+1}\right)^{\frac{z-q+1}{2}}$$
$$\times \Omega_{SR}^{(\frac{2\Delta+z+q+1}{2})}\binom{N_S}{p}\binom{N_R-1}{t}\binom{\Delta}{z}\gamma_{th}^{\Delta+1}e^{-\Omega_{SR}\Delta_1\gamma_{th}}K_{\vartheta}(2\Omega_{SR}\sqrt{\Delta_2}\gamma_{th}). \quad (7)$$

where $\gamma_{th} = 2^{\frac{2R_{th}}{1-\alpha}} - 1$ is the threshold SNR for a fixed rate R_{th}.

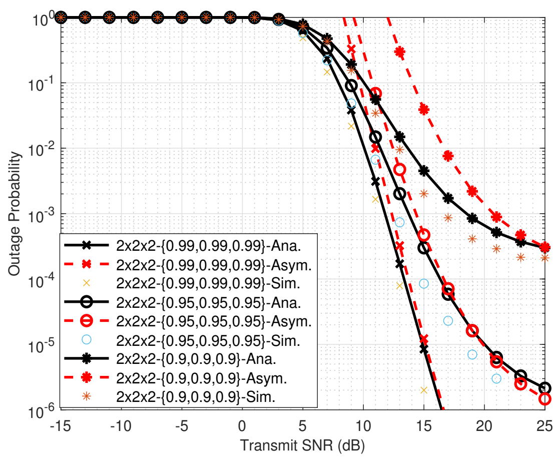

Fig. 2 Outage probability analysis of $2 \times 2 \times 2$ MIMO antenna configurations under different CEE conditions with $\alpha = 0.2$.

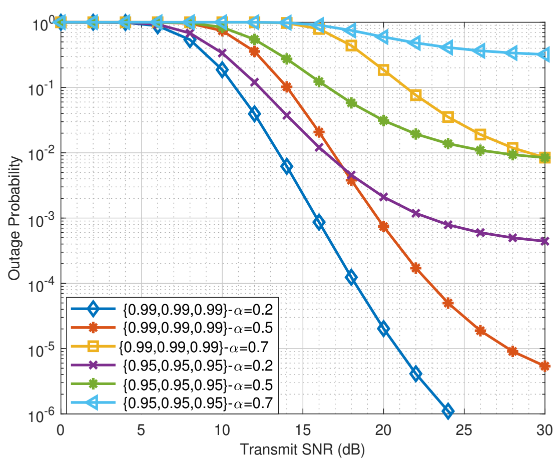

Fig. 3 Outage probability analysis of $2 \times 1 \times 2$ MIMO antenna configurations for perfect and imperfect CSI for different α values.

IV. Numerical and Simulation Results

In this section, the derived analytical expressions of OP and asymptotic OP are verified through the Monte-Carlo simulations. We consider the antenna config-

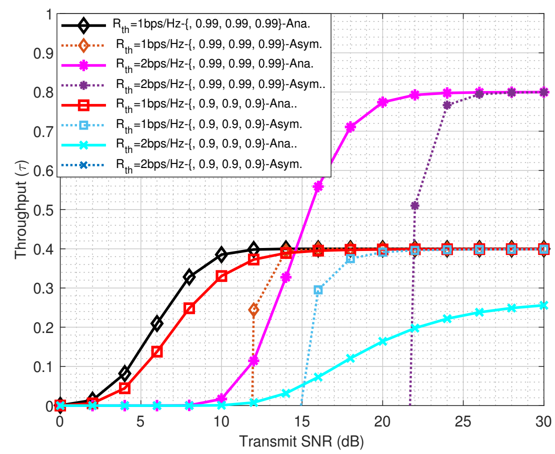

Fig. 4 Throughput analysis of $2 \times 2 \times 1$ MIMO antenna configurations for different threshold rates under different imperfect CSI conditions.

urations (ACs) as $N_S \times N_R \times N_D$, and the fading parameters (FPs) of the Nakagami-m channels as $\{m_{SR}, m_{RD}, m_{SD}\}$. The channel correlation coefficients are taken as $\{\rho_{SD}, \rho_{SR}, \rho_{RD}\}$ In the analysis we have considered the CSI parameters $\rho = 0.99$ as perfect case and $\rho = 0.95, 0.9$ as imperfect cases. Further, in the analysis, the efficiency factor (η) for EH is taken as unity and different values of α are considered. In figures, 'Ana.' denotes the 'analytical results', 'Asym.' denotes the 'asymptotic results' and 'Sim.' denotes the 'simulation results'. In the analysis analytical results are obtained by Mathematica and the simulation results are obtained through Matlab.

In Fig. 2, OP analysis of $2 \times 2 \times 2$ AC with FP $\{1,1,1\}$ is performed by considering harvesting time constant $\alpha = 0.2$ for the cases $\{0.99, 0.99, 0.99\}$, $\{0.95, 0.95, 0.95\}$, and $\{0.9, 0.9, 0.9\}$. It is observed that the derived analytical results of OP and asymptotic OP are in well agreement at medium-to-high SNR regime and is validated through simulation results. System performs better even after the EH phase at the relay over a time fraction of $\alpha = 0.2$. Further, it is also observed due to SNR independent CEE variance, diversity order of the system gets effected with a small change in CEE values and maintains a constant error floor at high SNR regime.

In Fig. 3, impact of EH time constant α over the OP analysis is analyzed for $2 \times 1 \times 2$ AC with $\{1, 2, 1\}$ FPs under different symmetric CEE conditions. In Fig. 3, analytical results of OP are presented. The curves illustrates the negative impact of α over the OP analysis. It is observed that the error floors increase with the EH time and its impact is severe under imperfect CSI conditions. We observe as the α increases, the EH time increases leading to a lower information processing time. Lower information processing time leads to higher outage probability for the whole time duration. For an OP of 10^{-3} with $\alpha = 0.2$, system with perfect CSI has a SNR gain of 6 dB over $\{0.95, 0.95, 0.95\}$ case. It further increases to 10 dB SNR gain for an OP of 10^{-2} with $\alpha = 0.5$. It further escalates to ∞ gain for $\alpha = 0.7$ over $\{0.95, 0.95, 0.95\}$ case and the system maintains a constant error floor for$\{0.95, 0.95, 0.95\}$ case.

In Fig. 4, throughput of the $2 \times 2 \times 1$-$\{1, 1, 2\}$ AC is analyzed over SNR for different rates with different CEE values. It is observed that for when $R_{th} = 1$ bps/Hz, the system gets into saturation with $\tau \sim 0.4$ at 12 dB and 15 dB for $\{0.99, 0.99, 0.99\}$ and $\{0.9, 0.9, 0.9\}$ cases, respectively. However, when $R_{th} = 2$ bps/Hz, the system gets into saturation with $\tau \sim 0.7$ at 22.5 dB approximately for perfect CSI whereas for imperfect CSI case of $\{0.9, 0.9, 0.9\}$, system gets into saturation with $\tau < 0.3$ at 30dB approximately. It illustrates the negative impact of both high data rate and also imperfect CSI over the system performance.

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V. Conclusion

In this paper, energy harvesting based relay assisted MIMO D2D system is considered for deriving the closed form expressions of the outage probability and asymptotic outage probability with imperfect CSI. The impact of multiple antennas and the severity of fading parameters with imperfect CSI is analyzed along with the SWIPT. It is observed that the system performance gets effected by the energy harvesting time constant. For smaller values of α, system performs better in both perfect and imperfect CSI scenarios. It is also observed that the system performance gets severely effect at high rates with imperfect CSI conditions. It is also observed that with slight increase in CEE, system performance degrades and the diversity order is lost due to variance of imperfect CSI is SNR independent. Further, accuracy of derived exact and asymptotic analytical results are in well agreement at medium to high SNR regime and is validated through the simulation results.

VI. Acknowledgement

The authors would like to thank IIT Indore, University Grants Commission of India and MeitY's Visvesvarya PhD scheme for all the support.

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