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RESEARCH ARTICLE

Performance Analysis of Wireless Power Transfer Enabled Dual Hop Relay System Under Generalised Fading Scenarios

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ABSTRACT Dual-hop relay communication systems have received extensive research attention due to their property of improving system reliability, spectral and power efficiency. RF wireless power transfer has also become a popular green technology for remote supply of energy to communication devices. In this paper, an RF wireless power transfer enabled dual hop relay system is analysed over generalised fading scenarios. A closed form expression is derived for the outage probability of the decode and forward as well as amplify and forward systems valid for all fading scenarios. Based on this analysis, the optimum design parameter settings for the system are also presented which serve as a reference point for measuring the outage performance of other variants of the generalised system. The numerical results obtained from derived expressions are compared with Monte-Carlo simulations and are found to be in excellent agreement with each other.

INDEX TERMS Amplify and forward, CDF approach, decode and forward, outage probability, generalized fading, wireless power transfer.

I. INTRODUCTION

Wireless communication systems are usually energy intensive as well as energy constrained. In mobile wireless applications, batteries are a primary source of energy for communicating between devices. The cost and complexity associated with frequent recharging and replacement of batteries is a major challenge in most wireless communication systems. In applications where the wireless communication system operates in remote areas, access to devices is very difficult and sometimes impossible making recharging and replacement of batteries increasingly non-feasible. In such applications, the life span of the batteries determines the performance and lifespan of the communication system. On the other hand, in the applications where devices can be easily accessed, it is the high cost and complexity of replacing and recharging batteries that makes their use very unattractive [1], [2], [3], [4].

RF wireless power transfer technology is an important technology that helps to wirelessly provide energy to communication devices at a reduced cost and complexity. RF Wireless power transfer technology uses radio frequency (RF) radiation to supply energy to devices. The devices are equipped with RF energy harvesting receivers and rechargeable batteries. Relay aided communication has emerged as a promising candidate for the implementation of wireless power transfer technology [5], [6]. Dual-hop relay aided communication implementing wireless power transfer helps to improve system reliability, capacity, spectral and power efficiency and network coverage. Therefore, it is expected

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to be an important technology for 5G systems and beyond having its applications in wireless sensor networks (WSNs) and mobile cellular communication. For this reason, dual-hop relay aided communication is currently an integral part of IEEE 802.6j wireless communication standard [7].

The integration of RF wireless power transfer technology enabled-relay aided communication systems enables the implementation of green communication systems. A lot of literature has been published on dual hop relay aided communications with RF wireless power transfer technology. The detailed surveys on wireless power transfer are presented in [1], [2], and [8] in which the opportunities, challenges and applications of wireless power transfer have been discussed. Outage analysis was conducted in [9] for a cooperative network under Rayleigh fading channels using a Markov based RF wireless energy harvesting relay in AF relaying protocol.

The outage performance of cell-edge users in MISO-NOMA systems using TAS and SWIPT-based cooperative transmissions was studied in [10]. Outage probability investigation was conducted in [11] for dual relay system with hybrid AF and DF relay protocols, in Rayleigh fading channels. Outage probability was studied in [12] for hybrid AF-based relay network using (HPTSR) protocol in Rayleigh fading channels. BER Performance of Full-Duplex Cognitive Radio Network With Nonlinear Energy Harvesting was studied in [13]. The outage probability, Symbol Error Rate (SER) and average capacity of decode-and-forward (DF) and amplify-and-forward (AF) relaying are calculated in [14] for fluctuation two-ray (FTR) fading channels. A visual integral region-based geometric analysis (GA-IR) approach is utilized in [15] for calculating the outage performance of two-way AF relaying with adjustable accuracy and a concise lower bound is derived for multiuser and multirelay scenarios. A UAV-assisted AF relaying system is analysed in [16], wherein, an integral region shape-based approximate method is applied for calculating the closed form expression of outage performance. Wireless power transfer scenario is not assumed in [16]. The outage analysis of full-duplex DF relaying over generalized $\kappa - \mu$ fading is derived in [17] in which time-switching based energy harvesting is applied only in the relay node. Nauryzbayev et al. in [18] derived the outage probability and ergodic capacity of a two-hop cooperative non-orthogonal multiple access network (NOMA) over $\alpha - \kappa - \mu$ channel. Arzykulov et al. in [19] have analysed both cognitive radio (CR) and NOMA networks with AF relay system and it was observed that CR-NOMA outperforms the traditional CR model whereas the error performance of Cooperative NOMA was analysed in [20]. The reliability and security of cooperative multi-relay system are analysed in [21] with a nonlinear energy harvesting mechanism. The residual hardware impairment and channel estimation error are included in the analysis.

A. MOTIVATION

A lot of literature has been published in the last decade on RF energy harvesting but most of these studies involve energy harvesting at the relay station only. However, RF wireless energy harvesting can also be done at either the relay or destination or both. Further, the fading process is characterized using a single fading PDF i.e. Rayleigh, Nakagami, FTR etc. in all these studies. However, these idealisations do not hold in real-world fading scenarios where the system is undergoing different types of fading due to rapidly changing environment. Therefore, it becomes incumbent to follow a unified approach for obtaining a single generalized expression for different fading channels.

A practical communication node (either relay or destination) will require a significant amount of energy to carry out the tasks of reception, decoding, and processing of data. Harvesting this energy using wireless power transfer (WPT) is very difficult due to practical restrictions on very low RF-electrical energy conversion efficiency. The challenge is further compounded by the inherent nature of RF propagation which is associated with very high transmission path losses.

On the other hand, the current system has a lot of applications in scenarios where the relay and/or destination node has the availability of a proportion of the required energy and only desire some additional energy to be transferred using WPT. Owing to the recent advancements in VLSI technology, the operation ability of ultra-low power small mobile communication nodes becomes multifold which enhances the relevance of the current system in the field.

B. CONTRIBUTION

The main contribution of this work is to analyse the performance of the proposed system under generalized fading scenarios which are not limited to only a single family of fading distribution. In order to accomplish this task, generic expressions are derived for amplify and forward as well as decode and forward schemes wherein energy harvesting are not only limited to the relay node but further extended to the destination node. As a result, the current system model has applications in a variety of scenarios wherein the relay and destination nodes have limited energy resources and require extra energy for transmission & processing of received data. The results are readily calculated using numerical methods.

It is to be noted that no restrictions are made on the fading channel density function in this analysis. The optimum design parameters for the system are also calculated which act as the upper limit for setting the design parameters while constructing a practical system. The numerical results obtained from derived expressions are compared with Monte Carlo simulations.

The rest of the paper is organised as follows; Section 2 provides the system model. The performance analysis of the system is conducted in Section 3. Results and discussions are provided in Section 4 and Section 5 provides the concluding remarks.

II. SYSTEM MODEL

A communication system with three nodes, source (S), relay (R) and destination (D) is assumed. Without loss of generality,

Nomenclature	
S	Source node
R	Relay node
D	Destination node
h_{SR}	instantaneous channel fading coefficients for $S-R$
h_{RD}	instantaneous channel fading coefficients for $R-D$
d_{SR}	path distances between S to R
d_{RD}	path distances between R to D
$d_{SR}^{\epsilon_1}$	path loss effect on the $S-R$
$d_{RD}^{\epsilon_2}$	path loss effect on the $R-D$
ϵ_1 and ϵ_2	path loss exponents
δ_R^2	Variance of Additive White Gaussian Noise at R
δ_D^2	Variance of Additive White Gaussian Noise at D
T	Total time frame for communication
τ	Factor for division of T into four slots
ψ	amount to energy transferred from R to D
γ_{SD}^{DF}	Instantaneous SNR of $S-D$ for DF protocol
γ_{RD}	Instantaneous SNR between $R-D$
η	Energy harvesting linear efficiency at R
P_s	Transmitted signal power from S
$C(\gamma)$	Instantaneous link capacity
C_{th}	Outage capacity threshold
$P_{OUT}^{AF}(C_{th})$	Outage probability of AF relaying
$P_{OUT}^{DF}(C_{th})$	Outage probability of DF relaying
$P/\cdot/$	Probability calculation
$F_X(\cdot)$	Cumulative Distribution Function (CDF)
$f_X(\cdot)$	Probability Density Function (PDF)
$E[\cdot]$	Expectation operator
Ω_1	average SNR per symbol for $S-R$
Ω_2	average SNR per symbol for $R-D$
$\Gamma(\cdot,\cdot)$	Incomplete Gamma function
$\Gamma(\cdot)$	Complete Gamma function

all the nodes in the system are considered to be equipped with a single antenna and the relay station operates in half-duplex (HD) mode. Further, it is assumed that channel conditions between S and D are not favourable for reliable communication. The relay node uses decode and forward relaying to transfer information from source to destination node.

The instantaneous channel fading coefficients for $S-R$ and $R-D$ channels are h_{SR} and h_{RD} respectively. The path distances between S to R and R to D are d_{SR} and d_{RD} respectively. The path loss effect on the $S-R$ and $R-D$ channels is modelled as exponents of the respective path distances and is expressed as $d_{SR}^{\epsilon_1}$ and $d_{RD}^{\epsilon_2}$, where ϵ_1 and ϵ_2 denotes the path loss exponents ($2 < \epsilon < 4$). The noise at both relay and destination nodes is assumed to be white with variances δ_R^2 and δ_D^2 respectively. The system model is illustrated in Fig. 1.

It is assumed that the relay and destination nodes do not have any fixed energy sources. Therefore, to satisfy the energy requirements, the energy harvesting technology is employed at relay and destination. Without losing generality and in order to support a more practical system, it is also assumed that a part of total power required for communication is already available with the relay and destination nodes. The source node acts as source of both energy as well as information for relay and destination nodes. It is assumed that the source has sufficient amount of energy for both relay and destination nodes and SWIPT is employed in the system using time switching relaying (TSR). The communication

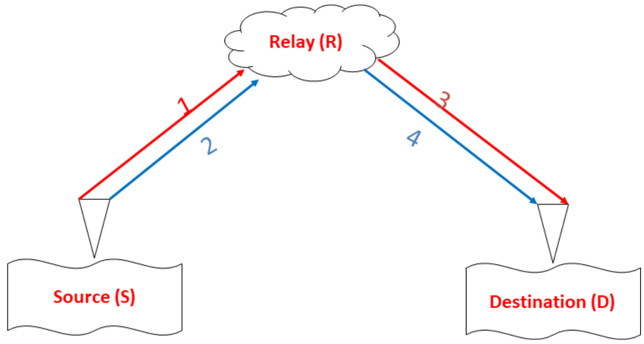

FIGURE 1. Relay aided –RF wireless energy harvesting system.

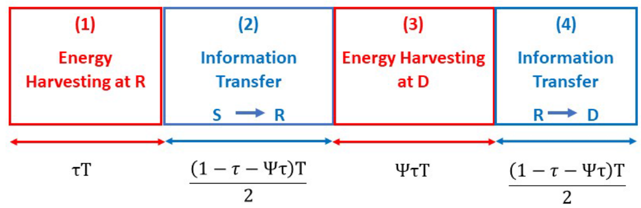

FIGURE 2. Dual-hop time switching relay protocol.

between S-R and R-D is divided into four steps. Fig. 2 shows the time slot allocation for information and energy transfer for both S-R and R-D channels.

The total time frame for communication is denoted by T in Fig. 2. This time frame is divided into four time slots using time factor $\tau (0 \leq \tau \leq 1)$. Each of these slots is used for either energy harvesting or information transfer and is explained as follows:

- In the first time slot, the relay node harvests energy for the duration τT. This energy is used for two tasks i.e. firstly to receive the information from source node and secondly to supply energy to the destination node. Let ψ be a constant representing the amount of energy transferred from relay to the destination node.
- During the second time slot, information is transferred from source to relay node for the duration $\frac{(1-\tau-\psi\tau)T}{2}$.
- This information and energy transfer process is repeated for the R-D channel during the third and fourth time slots. In the third time slot, the energy is transferred from relay node to destination for the duration $\psi\tau T$.
- Finally, the information transfer between relay and destination node takes place in duration $\frac{(1-\tau-\psi\tau)T}{2}$.

It is to be noted here that by choosing appropriate values of variables τ and ψ, the process of energy harvesting and information transfer can be optimized and a variety of system configurations can be realized. For instance, by setting $\psi = 0$, the system represents a scenario in which no energy is transferred to destination i.e. sufficient energy is available with destination node. On the other hand, setting $\tau = 0$ results in a system representing a scenario in which there is no RF wireless power transfer from source thus a conventional relay system can be realised. Now, the instantaneous SNR of $S-D$

for DF protocol γ_{SD}^{DF} can be defined as [9]

$$\gamma_{SD}^{DF} = \gamma_{RD} = \frac{2\tau\eta P_s|h_{SR}|^2|h_{RD}|^2}{(\psi\tau - \tau + 1)d_{SR}^{\epsilon_1}d_{RD}^{\epsilon_2}\delta_D^2} \tag{1}$$

where, γ_{RD} is the instantaneous SNR between $R-D$, η is energy harvesting linear efficiency at the relay station ($0 < \eta < 1$) and P_s is the transmitted signal power from the source node. Similarly, the instantaneous SNR of $S-R$ node can be defined as

$$\gamma_{SR} = \frac{P_s|h_{SR}|^2}{d_{SR}^{\epsilon_1}\delta_R^2} \tag{2}$$

In order to support the generalized architecture, it is assumed that the instantaneous channel fading coefficients h_{SR} and h_{RD} in (1) and (2) can have any probability density function. No restrictions are considered hereafter in this analysis on fading scenario and the derived expressions hold for all possible fading conditions.

III. OUTAGE PERFORMANCE ANALYSIS

Considering that information transfer only takes place during the second and fourth time slots, the instantaneous link capacity can be calculated as

$$C(\gamma) = \frac{1-\tau-\psi\tau}{2}log_2(1+\gamma) \tag{3}$$

A. OUTAGE ANALYSIS OF DF RELAYING PROTOCOL

Now, the outage probability of the system in DF relaying protocol can be expressed as the probability that at least one of the link's capacity falls below the outage capacity threshold C_{th}. Mathematically, the outage probability $P_{OUT}^{DF}(C_{th})$ of DF relaying can be written as

$$P_{OUT}^{DF}(C_{th}) = 1 - P_r\{\min[C(\gamma_{SR}), C(\gamma_{RD})] \geq C_{th}\} \tag{4}$$

where $P_r\{\cdot\}$ represents the probability calculation. Further, defining $\lambda = 2^{\left(\frac{C_{th}}{1-\tau-\psi\tau}\right)}$ and using (1), (2), and (3) in (4), the outage probability can be calculated as

$$P_{OUT}^{DF}(C_{th}) = 1 - P_r\{\gamma_{SR} \geq \lambda, \gamma_{RD} \geq \lambda\} \tag{5}$$

Let $|h_{SR}|^2 = X$ and $|h_{RD}|^2 = Y$, (5) can be further simplified into

$$P_{OUT}^{DF}(C_{th}) = 1 - P_r\left\{X \geq \frac{\lambda}{\alpha}, XY \geq \frac{\lambda}{\beta}\right\} \tag{6}$$

where, $\beta = \frac{2\tau\eta P_s}{(\psi\tau-\tau+1)d_{SR}^{\epsilon_1}d_{RD}^{\epsilon_2}\delta_D^2}$ and $\alpha = \frac{P_s}{d_{SR}^{\epsilon_2}\delta_R^2}$. After some mathematical manipulations and using the definition of PDF and CDF, (6) is simplified as

$$P_{OUT}^{DF}(C_{th}) = F_X\left(\frac{\lambda}{\alpha}\right) + \int_0^{\frac{\alpha}{\beta}} F_X\left(\frac{\lambda}{Y\beta}\right) f_y(y)dy - F_X\left(\frac{\lambda}{\alpha}\right)F_Y\left(\frac{\alpha}{\beta}\right) \tag{7}$$

where $F_X(\cdot)$ and $f_X(\cdot)$ are the cumulative distribution function and probability density function respectively. Finally, defining fading co-efficient $\tilde{x} = |h_{SR}|$ and $\tilde{y} = |h_{RD}|$, the outage probability of DF relaying can be calculated from (7) as

$$P_{OUT}^{DF}(C_{th}) = F_{\tilde{x}}\left(\sqrt{\frac{\lambda}{\alpha}}\right) + \int_0^{\sqrt{\frac{\alpha}{\beta}}} F_{\tilde{x}}\left(\frac{1}{\tilde{y}}\sqrt{\frac{\lambda}{\beta}}\right) f_{\tilde{y}}(\tilde{y})d\tilde{y} - F_{\tilde{x}}\left(\sqrt{\frac{\lambda}{\alpha}}\right)F_{\tilde{y}}\left(\sqrt{\frac{\alpha}{\beta}}\right) \tag{8}$$

B. OUTAGE ANALYSIS OF AF PROTOCOL

The outage probability of the AF system is the probability that the end to end channel capacity falls below the threshold C_{th} and can be expressed mathematically as

$$P_{OUT}^{AF}(C_{th}) = P_r\{C(\gamma_{SD}^{AF}) < C_{th}\} \tag{9}$$

$$= 1 - P_r\{Y > \frac{\lambda\alpha}{\alpha\beta X - \lambda\beta}\} \tag{10}$$

$$= 1 - \int_0^\infty F_{\tilde{y}}\left(\sqrt{\frac{\lambda\alpha}{\alpha\beta x - \lambda\beta}}\right) f_X(X)dX \tag{11}$$

$$= 1 - \int_0^\infty F_{\tilde{y}}\left(\sqrt{\frac{\lambda\alpha}{\alpha\beta\tilde{x}^2 - \lambda\beta}}\right) f_{\tilde{x}}(\tilde{x})d\tilde{x} \tag{12}$$

$$= 1 - E_{\tilde{x}}\left[F_{\tilde{y}}\left(\sqrt{\frac{\lambda\alpha}{\alpha\beta\tilde{x}^2 - \lambda\beta}}\right)\right] \tag{13}$$

where $E[\cdot]$ is the expectation operator. It is to be noted that (12) can be written alternatively as

$$P_{OUT}^{AF}(C_{th}) = 1 - \int_0^\infty F_{\tilde{x}}\left(\sqrt{\frac{\lambda\alpha + \tilde{y}^2\lambda\beta}{\tilde{y}\lambda\beta}}\right) f_{\tilde{y}}(\tilde{y})d\tilde{y} \tag{14}$$

$$= 1 - E\tilde{y}\left[F_{\tilde{x}}\left(\sqrt{\frac{\lambda\alpha + \tilde{y}^2\lambda\beta}{\tilde{y}^2\lambda\beta}}\right)\right] \tag{15}$$

IV. CALCULATION OF OUTAGE PROBABILITY UNDER FADING CHANNEL

In this section, demonstrations are made on how to use (8) and (13) for the calculation of analytical expression of the outage performance of the system in various fading conditions. It is to be noted here that using (8) and (13), the outage performance can be calculated for any possible pairs of fading channels and is not restricted to these cases only.

A. RAYLEIGH-GENERALISED GAMMA FADING

For case 1, it is assumed that the system experiences Rayleigh-Generalised Gamma fading i.e. the link between $S-R$ is facing Rayleigh fading and the $R-D$ link has fading characteristics of Generalised Gamma scenario or vice-versa. The Rayleigh CDF is given as [22]

$$F_{\tilde{x}}(\tilde{x}) = 1 - \exp\left(-\frac{\tilde{x}^2}{\Omega_1}\right) \tag{16}$$

where, Ω_1 is the average SNR per symbol for $S-R$. Generalised Gamma CDF can be written as [23]

$$F_{\tilde{y}}(\tilde{y}) = 1 - \frac{\Gamma\left(m, \left(\frac{\xi\alpha}{\tilde{y}\beta\Omega_2}\right)^{v}\right)}{\Gamma(m)} \tag{17}$$

where, $\xi = \frac{\Gamma\left(\frac{m+v+1}{v}\right)}{\Gamma(m)}$ $\Gamma(\cdot,\cdot)$ and $\Gamma(\cdot)$ is the upper incomplete Gamma function and complete Gamma function respectively; m and v are the fading parameters. Similarly, generalised Gamma PDF is given in [23] as

$$f_{\tilde{y}}(\tilde{y}) = \left(\frac{2v\tilde{y}^{2vm-1}}{\Gamma(m)(\frac{\Omega_2}{m})^m}\right)\exp\left(-\frac{m\tilde{y}^{2v}}{\Omega_2}\right) \tag{18}$$

By substituting equations (16), (17) and (18) into (8), the outage probability expression for the DF system in Rayleigh-Generalised Gamma fading becomes

$$\begin{aligned} P_{OUT}^{DF}(C_{th}) &= 1-\exp\left(\frac{-\lambda}{\alpha\Omega_1}\right)+\int_0^{\sqrt{\frac{\alpha}{\beta}}}\left(1-\exp\left(\frac{-\lambda}{\tilde{y}\beta\Omega_1}\right)\right) \\ &\times\left(\frac{2v\tilde{y}^{2vm-1}}{\Gamma(m)(\frac{\Omega_2}{m})^m}\right)\exp\left(-\frac{m\tilde{y}^{2v}}{\Omega_2}\right)d\tilde{y} \\ &-\left(1-\exp\left(-\frac{\lambda}{\alpha\Omega_1}\right)\right)\left(1-\frac{\Gamma\left(m,\left(\frac{\xi\alpha}{\beta\Omega_2}\right)^v\right)}{\Gamma(m)}\right) \end{aligned} \tag{19}$$

Similarly, by substituting (16) and (18) into (14), the outage probability expression for the system in AF relaying is:

$$P_{OUT}^{AF}(C_{th}) = 1-\int_0^{\infty}\exp\left(-\frac{\lambda\alpha+\tilde{y}^2\lambda\beta}{\tilde{y}\lambda\beta\Omega_1}\right)\left(\frac{2v\tilde{y}^{2vm-1}}{\Gamma(m)(\frac{\Omega_2}{m})^m}\right)\times\exp\left(-\frac{m\tilde{y}^{2v}}{\Omega_2}\right)d\tilde{y} \tag{20}$$

B. RAYLEIGH-WEIBULL FADING

For case 2, it is assumed that the system experiences Rayleigh-Weibull fading i.e. the link between $S-R$ is facing Rayleigh fading and the $R-D$ link has Weibull fading or vice-versa. The CDF of Weibull channel is given as [24]

$$F_{\tilde{y}}(\tilde{y}) = 1-\exp\left(-\frac{\tilde{y}^c}{\Omega_2}\right) \tag{21}$$

where c is the fading coefficient for Weibull fading. The PDF of Weibull channel is given as [24]

$$f_{\tilde{y}}(\tilde{y}) = \frac{c}{\Omega_2}\tilde{y}^{c-1}\exp\left(-\frac{\tilde{y}^c}{\Omega_2}\right) \tag{22}$$

Now, similar to Case 1, using (16), (21), (22) into (8), the outage probability for the system in DF relaying is computed as:

$$\begin{aligned} P_{OUT}^{DF}(C_{th}) &= 1-\exp\left(\frac{-\lambda}{\alpha\Omega_1}\right)+\int_0^{\sqrt{\frac{\alpha}{\beta}}}\left(1-\exp\left(\frac{-\lambda}{\tilde{y}\beta\Omega_1}\right)\right) \\ &\times\frac{c}{\Omega_2}\tilde{y}^{c-1}\exp\left(-\frac{\tilde{y}^c}{\Omega_2}\right)d\tilde{y}-\left(1-\exp\left(-\frac{\lambda}{\alpha\Omega_1}\right)\right) \\ &\times\left(1-\exp\left(-\left(\frac{\alpha}{\beta}\right)^{\frac{c}{2}}\frac{1}{\Omega_2}\right)\right) \end{aligned} \tag{23}$$

Further, for AF relaying case, using (16) and (22) into (14), the outage probability is calculated as:

$$P_{OUT}^{AF}(C_{th}) = 1-\int_0^{\infty}\exp\left(-\frac{\lambda\alpha+\tilde{y}^2\lambda\beta}{\tilde{y}\lambda\beta\Omega_1}\right)\frac{c}{\Omega_2}\tilde{y}^{c-1}\times\exp\left(-\frac{\tilde{y}^c}{\Omega_2}\right)d\tilde{y} \tag{24}$$

C. RAYLEIGH-$\eta-\lambda-\mu$ FADING

In another scenario, we assume that the link between $S-R$ is facing Rayleigh fading and the $R-D$ link has $\eta-\lambda-\mu$ fading or vice-versa. The CDF of $\eta-\lambda-\mu$ channel is given as [25]

$$\begin{aligned} F_{\tilde{y}}(\tilde{y}) &= \left(\frac{2\hat{b}\sqrt{\eta_1(1-\lambda_1^2)}}{\Omega_2}\right)^{2\mu_1}\frac{\sqrt{\pi}}{\Gamma[\mu_1]\hat{c}^{2\mu_1}\hat{d}^{\mu-\frac{1}{2}}} \\ &\times\sum_{j=0}^{\infty}\frac{1}{j!\Gamma[0.5+\mu_1+j]}\left(\frac{\hat{d}}{2\hat{c}}\right)^{2j} \\ &\times\left(\Gamma[2(\mu_1+j)]-\Gamma\left[2(\mu_1+j),\frac{\hat{c}\tilde{y}^2}{\Omega_2}\right]\right) \end{aligned} \tag{25}$$

where η_1, λ_1, and μ_1 are the fading parameters and $\hat{d} = \frac{2\mu_1(1+\eta_1)\sqrt{(\eta_1-1)^2+4\eta_1\lambda_1}}{4\eta_1(1-\lambda_1^2)}$; $\hat{c} = \frac{2\mu_1(1+\eta_1)^2}{4\eta_1(1-\lambda_1^2)}$; $\hat{b} = \frac{2\mu_1(1+\eta_1)}{4\eta_1(1-\lambda_1^2)}$ are variables defined for simplification. Further, the PDF of $\eta-\lambda-\mu$ channel is [25]

$$f_{\tilde{y}}(\tilde{y}) = \left(\frac{2\hat{b}\sqrt{\eta_1(1-\lambda_1^2)}}{2^{\frac{2\mu_1-3}{2}}\Omega_2^{\mu_1+\frac{1}{2}}}\right)^{2\mu_1}\frac{\tilde{y}^{2\mu_1}\sqrt{\pi}}{\Gamma[\mu_1]\hat{d}^{\mu_1-\frac{1}{2}}}\exp\left(-\frac{\hat{c}\tilde{y}^2}{\Omega_2}\right)\times I_{\mu_1-\frac{1}{2}}\left[\frac{\tilde{y}^2\hat{d}}{\Omega_2}\right] \tag{26}$$

Now, using (16), (25) and (26) in (8), the outage probability for the system in DF relaying can be calculated as:

$$\begin{aligned} P_{OUT}^{DF}(C_{th}) &= 1-\exp\left(\frac{-\lambda}{\alpha\Omega_1}\right)+\int_0^{\sqrt{\frac{\alpha}{\beta}}}\left(1-\exp\left(\frac{-\lambda}{\tilde{y}\beta\Omega_1}\right)\right) \\ &\times\left(\frac{2\hat{b}\sqrt{\eta_1(1-\lambda_1^2)}}{2^{\frac{2\mu_1-3}{2}}\Omega_2^{\mu_1+\frac{1}{2}}}\right)^{2\mu_1}\frac{\tilde{y}^{2\mu_1}\sqrt{\pi}}{\Gamma[\mu_1]\hat{d}^{\mu_1-\frac{1}{2}}}\exp\left(-\frac{\hat{c}\tilde{y}^2}{\Omega_2}\right) \\ &\times I_{\mu_1-\frac{1}{2}}\left[\frac{\tilde{y}^2\hat{d}}{\Omega_2}\right]d\tilde{y}-\left(1-\exp\left(-\frac{\lambda}{\alpha\Omega_1}\right)\right) \\ &\times\left(\frac{2\hat{b}\sqrt{\eta_1(1-\lambda_1^2)}}{\Omega_2}\right)^{2\mu_1}\frac{\sqrt{\pi}}{\Gamma[\mu_1]\hat{c}^{2\mu_1}\hat{d}^{\mu_1-\frac{1}{2}}} \end{aligned}$$

$$\times\left(\sum_{j=0}^{\infty}\frac{1}{j!\Gamma[0.5+\mu_1+j]}\left(\frac{\hat{d}}{2\hat{c}}\right)^{2j}\right.$$
$$\left.\times\left(\Gamma[2(\mu_1+j)]-\Gamma[2(\mu_1+j),\frac{\hat{c}\alpha}{\beta\Omega_2}]\right)\right) \quad (27)$$

Further, for the case of AF relaying, the outage probability can be derived using (16) and (26) into (14) as:

$$P_{OUT}^{AF}(C_{th})$$
$$=1-\int_0^{\infty}\exp\left(-\frac{\lambda\alpha+\tilde{y}^2\lambda\beta}{\tilde{y}\lambda\beta\Omega_1}\right)\frac{\tilde{y}^{2\mu_1}\sqrt{\pi}}{\Gamma[\mu_1]\hat{d}^{\mu_1-\frac{1}{2}}}$$
$$\times\left(\frac{2\hat{b}\sqrt{\eta_1(1-\lambda_1^2)}}{2^{\frac{2\mu_1-3}{2}}\Omega_2^{\mu_1+\frac{1}{2}}}\right)^{2\mu_1}\exp\left(\frac{-\hat{c}\tilde{y}^2}{\Omega_2}\right)I_{\mu_1-\frac{1}{2}}\left[\frac{\tilde{y}^2\hat{d}}{\Omega_2}\right]d\tilde{y} \quad (28)$$

The method illustrated in Case 1, 2 and 3 can be utilized to compute the outage performance of all fading scenarios irrespective of the PDF and CDF complexity.

V. RESULTS AND DISCUSSIONS

The performance study of the system is conducted using three approaches, (i) varying the amount of energy received at the relay station, (ii) varying the amount of energy transferred to the destination station, and (iii) varied source to destination distance. In each approach, the system is subject to some selected fading conditions expected in 5G scenarios and beyond. Owing to the fact that 5G scenarios are ubiquitous in nature, the system is finally subjected to several other miscellaneous fading conditions for outage performance study. For simulation purpose, the following set of parameters have been utilized: $P_s = 20$ W, $d_1 = d_2 = 1$ m, $\delta_D^2 = 1$, $\epsilon = 2.5$, $C = 0.1$, $\sigma^2 = 1$, $C_{th} = 0.1$ $bit/s/Hz$, number of samples $= 10^7$, number of iterations $= 10^3$. Numerical integration in MATLAB is utilized for solving the integration involved in expressions.

A. OUTAGE PERFORMANCE OF THE SYSTEM AT VARIED AMOUNTS OF ENERGY RECEIVED AT RELAY STATION

This study is conducted by varying the energy harvesting efficiency η at the relay station, setting it to four different values; 0.25, 0.5, 0.75 and 1. Using Rayleigh-Generalised Gamma fading model and setting $v = 1$, $m = 1$ and $\psi = 1$, the outage performance of the system is shown in Fig 3 (a).

The outage performance study of the system using Rayleigh-Weibull fading model, setting $c = 1$, $\psi = 0.25$, is shown in Fig 3 (b). The outage performance study of the system using Rayleigh-$\eta-\lambda-\mu$ fading model, setting $\eta_1 = 0.5$, $\lambda_1 = 0.5$, $\mu_1 = 2$ and $\psi = 0.25$, is shown in Fig 3 (c). The inset figure in (a) which is denoted by **B** is for Amplify and Forward system with same system parameters so that a comparison can be made between the two systems.

It is observed from Fig. 3 that the outage performance of the system improves as the value of η increases, hence the optimum performance of the system is when η is equal to 1. It is observed that the spacing of the graph curves gets narrower when the value of η increases. Conversely, it is observed that the spacing of the graphs gets wider with decreasing value of η. Similar results are presented for Amplify and Forward Relaying system in Fig 6 wherein the effect of varied amount of energy received at R can be analysed.

B. OUTAGE PERFORMANCE OF THE SYSTEM AT VARIED AMOUNTS OF ENERGY TRANSFERRED TO DESTINATION STATION

The study is conducted by varying the time switching factor ψ at the relay station, setting it to four different values 0.25, 0.5, 0.75, and 1. Setting the system parameters as $P_s = 20$ W, $d_1 = d_2 = 1$ m, $\delta_D^2 = 1$, $\eta = 0.75$, $\epsilon = 2.5$ and the fading parameters as $v = 1$, $m = 1$, the outage performance study of the system under Rayleigh-Generalised Gamma fading model is shown in Fig. 4 (a). Setting $c = 1$ and $\eta = 0.75$, the outage performance study of the system under Rayleigh-Weibull fading model is shown in Fig. 4 (b). Setting $\eta_1 = 0.5$, $\lambda_1 = 0.5$, and $\mu_1 = 2$, the outage performance study of the system under Rayleigh-$\eta-\lambda-\mu$ fading model is shown in Fig. 4 (c).

It is observed in Fig. 4 that the outage performance improves when the value of ψ decreases, indicating that the optimum performance for the system is obtained when $\psi = 0$. It is observed that the spacing between graphs becomes narrower as the value of ψ decreases. Further, for Amplify and Forward relaying system, the outage performance analysis at varying amounts of energy transferred to D are shown in Fig. 7.

C. PERFORMANCE OF THE SYSTEM AT VARIED SOURCE-DESTINATION DISTANCE SCENARIO

The study is conducted with the following system parameter settings: $P_s = 20$ W, $\delta_D^2 = 1$, $\eta = 0.75$, $\psi = 0.25$, and $\epsilon = 2.5$. Varying the distance (d) to 0.5 m, 1 m, 1.5 m and 2 m, the outage performance of the system, using Rayleigh-Generalised Gamma fading model with fading parameters set as follows: $v = 1$, $m = 1$, is shown in Fig. 4 (a). Setting $C = 1$, the outage performance of the system in Rayleigh-Weibull fading is shown in Fig. 4 (b). Setting $\eta_1 = 0.5$, $\lambda_1 = 0.5$, $\mu_1 = 2$, the outage performance of the system in Rayleigh-$\eta-\lambda-\mu$ fading is shown in Fig 4 (c).

It is observed in Fig. 4 that the outage performance improves as the value of d decreases hence the optimum performance of the system is at $d = 0$ m. It is observed that the spacing between curves decreases rapidly as the value of d decreases, or conversely, the spacing between curves expands rapidly as the value of d increases. In order to study the effect of P_s and d on outage performance of system, two different cases are taken under consideration i.e. $P_s = 1000$ W and $P_s = 20$ W by keeping other system parameters constant. A considerable improvement in the outage can be visualized by increasing the transmission power. But, it is also to be

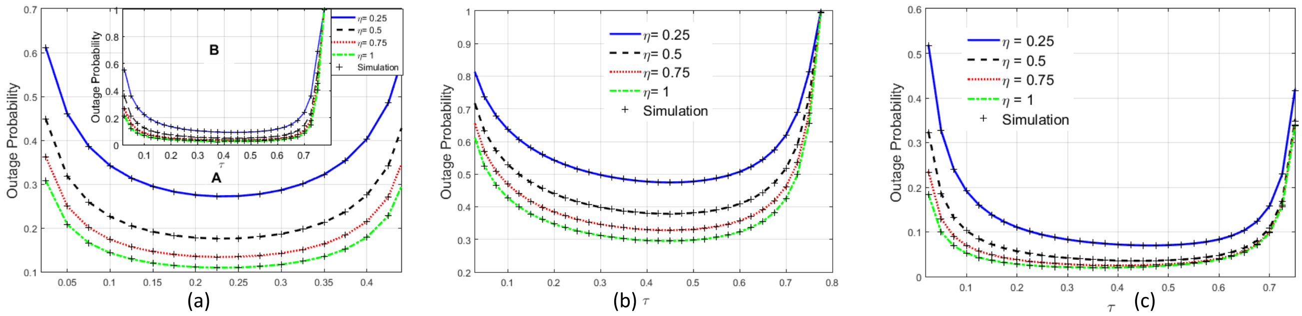

FIGURE 3. **Outage probability v/s time factor (τ) for various η values for decode and forward system for varied amounts of energy received at *R* under (a) Rayleigh-Generalized gamma (b) Rayleigh-Weibull and (c) Rayleigh-$\eta-\lambda-\mu$ fading. Inset figure in (a) is for amplify and forward system.**

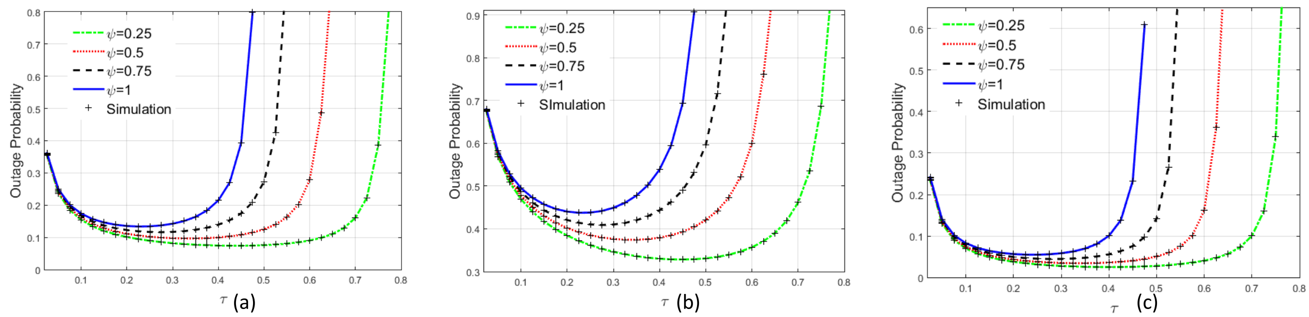

FIGURE 4. **Outage probability v/s time factor (τ) for various ψ values for decode and forward system for varied amounts of energy transferred to *D* under (a) Rayleigh-Generalized Gamma (b) Rayleigh-Weibull and (c) Rayleigh-$\eta-\lambda-\mu$ fading.**

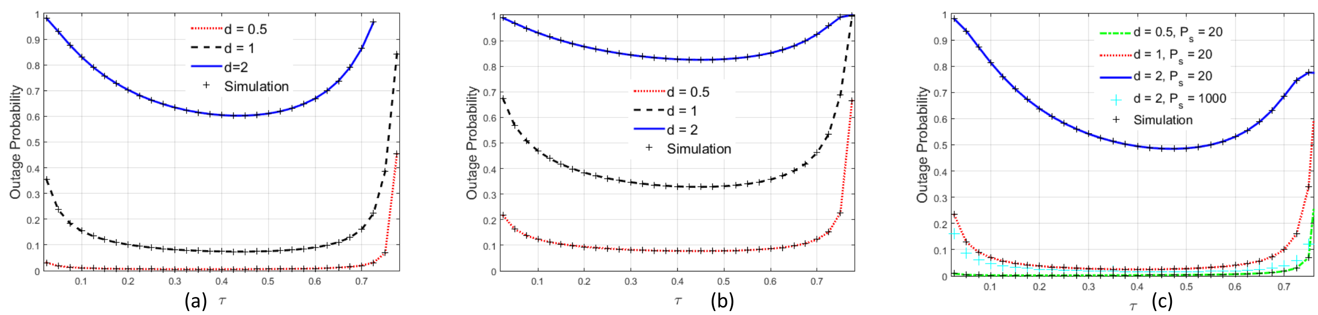

FIGURE 5. **Outage probability v/s time Factor (τ) for various *d* values for decode and forward system at varied source-destination distance under (a) Rayleigh-Generalized gamma (b) Rayleigh-Weibull and (c) Rayleigh-$\eta-\lambda-\mu$ fading.**

noted here that increasing P_s to 1000 W, at $d = 2$ m, fails to match the outage performance of the system at $d = 0.5$ m with $P_s = 20$ W. The outage performance of Amplify and Forward relaying system under variable $S-D$ distance is presented in Fig. 8.

D. GENERAL OBSERVATION

Figs. 3, 4 and 5 provide the opportunity to study the outage performance of the system in various fading conditions. In using the Rayleigh-Generalised Gamma fading model and setting $m = 1$, $v = 1$, the system was actually subjected to Rayleigh-Rayleigh fading condition in Fig. 3 (a), 4 (a) and 5(a). In using the Rayleigh-Weibull fading model and setting $C = 1$, the system in 3 (b), 4 (b) and 5(b) was subject to Rayleigh fading in one hop and multipath fading worse than Rayleigh fading in another hop. In using the Rayleigh-$\eta-\lambda-\mu$ fading model, and setting the fading parameters as follows; $\eta_1 = 0.5$, $\lambda_1 = 0.5$, $\mu_1 = 2$, the system performance is shown in Figs 3 (c), 4 (c) and 5(c). subjected to Rayleigh fading in one hop and multipath fading better than Rayleigh fading in the other hop.

Comparing Fig. 3 (a) to Fig. 3 (b), Figs. 4 (a) to Fig. 4 (b), and Fig. 5 (a) to Fig. 5 (b), it is observed that, as expected, the outage performance has deteriorated in Fig. 3 (b), 4 (b) and 5 (b). It is also observed that the spacing of the graph curves is wider in Figs. 3 (b), 4 (b) and 5 (b). Comparing Fig. 3 (a) to Fig. 3 (c), Figs. 4 (a) to Fig. 4 (c), and Fig. 5 (a) to Fig. 5 (c), it is observed that, as expected, the outage

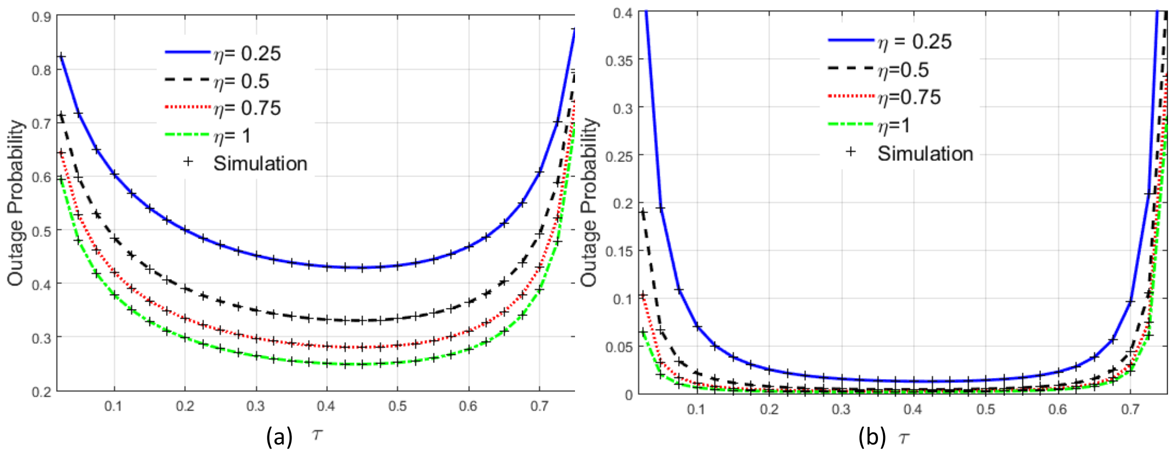

FIGURE 6. Outage probability v/s time factor (τ) for various η values for amplify and forward system for varied amounts of energy received at *R* under (a) Rayleigh-Generalized gamma (b) Rayleigh-Weibull and (c) Rayleigh-$\eta - \lambda - \mu$ fading.

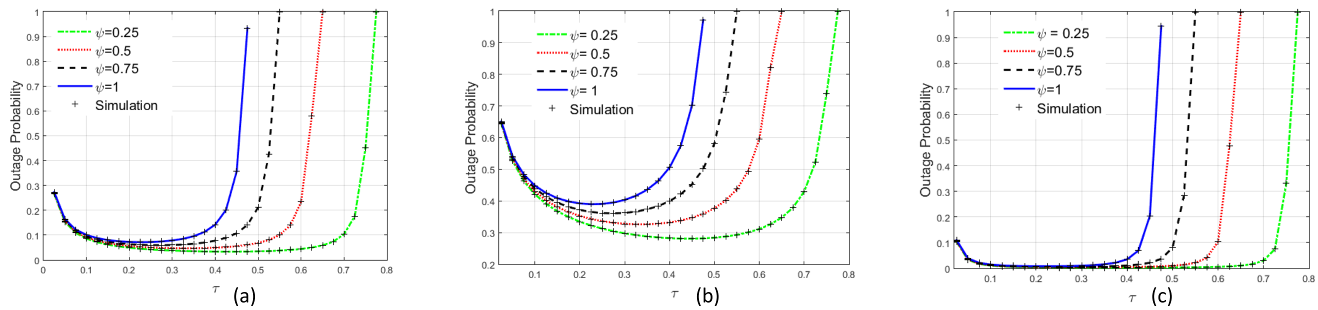

FIGURE 7. Outage probability v/s time factor (τ) for various ψ values for amplify and forward system for varied amounts of energy transferred to *D* under (a) Rayleigh-Generalized gamma (b) Rayleigh-Weibull and (c) Rayleigh-$\eta - \lambda - \mu$ fading.

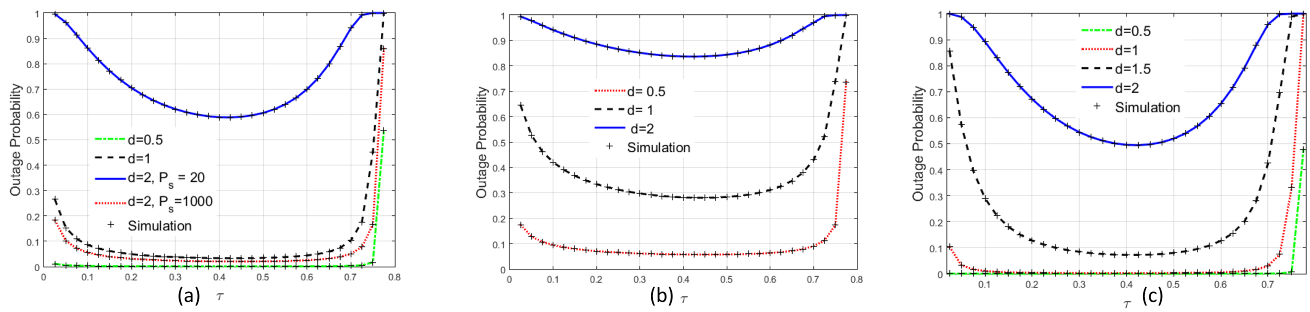

FIGURE 8. Outage probability v/s time factor (τ) for various *d* values for amplify and forward system at varied source-destination distance under (a) Rayleigh-Generalized gamma (b) Rayleigh-Weibull and (c) Rayleigh-$\eta - \lambda - \mu$ fading.

performance has improved in Fig. 3 (c), 4 (c) and 5 (c). It is also observed that the spacing of the graph curves is narrower in the aforementioned results.

It is observed in all the figures that the outage probability is the lowest around the midpoint range of the time factor τ, of which the range of τ is given by the expression $1/(1+\psi)$. Comparing the spacing of the curves in Fig. 5 to the spacing of the curves in Fig. 3 and Fig. 4, it is observed that the spacing of the curves is wider in Fig. 5 which shows that the system outage performance is more sensitive to changes in distance than to changes in η and ψ. Comparing Fig. 3 (a) to Fig. 4 (a), Fig. 3 (b) to Fig. 4 (b) and Fig. 3 (c) to Fig. 4 (c), it is observed that the spacing of the curves at midpoints of the range of τ is narrower in Fig. 4 which may suggest that the system outage performance is more sensitive to changes in the amount of energy harvested at the relay station η than to changes of energy amounts transferred to the destination ψ.

VI. CONCLUSION

An RF powered dual hop relay system has been analysed in this paper considering DF and AF schemes under generalized fading scenarios. The expressions derived in this work are generic in nature and independent of the fading channel distribution. The system parameters are designed in such a way that a very wide range of system settings can be realized from the presented system model. Further, the application of derived outage probability expressions is explored by taking three scenarios suited for real-life applications of communication systems. Monte-Carlo simulations are utilized to verify the results of derived expressions. It has been observed from the obtained results that good outage performance for this system is obtained when large amount of energy is harvested at the relay and later used for signal transmission to the destination (η approaches 1), however achieving high energy amounts harvested at the relay is difficult due to practical restrictions on very low RF-electrical energy conversion efficiencies ($\eta \leq 0.5$). The challenge is compounded by the inherent nature of RF propagation that is associated with very high transmission path losses (d^{ϵ}).

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