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Performance Analysis for Reconfigurable Intelligent Surface-aided Communication Systems with Energy Harvesting under Imperfect Nakagami-*m* Channel Information

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Abstract

Reconfigurable intelligent surface (RIS) can serve as a passive relay to maintain communication between a transceiver in severe scenarios of no direct link between them. In addition, harvesting energy from radio frequency (RF) signals can meliorate significantly energy efficiency. In this research, we propose RIS-aided communication systems with energy harvesting (RISwEH) which combine both RIS and RF energy harvesting to improve energy efficiency as well as communication reliability. To evaluate realistically and quickly the performance of the RISwEH, we propose the explicit formulas of the system throughput and the outage probability under the realistic scenario of Nakagami-*m* fading and imperfect channel state information (CSI). Moreover, we propose an optimization algorithm relied upon a Golden section search to attain the optimum value of the time splitting factor of energy harvester to obtain the best system performance. Various results corroborate the theoretical derivations, confirm the efficacy of the proposed optimization algorithm, and illustrate the influence of innumerable system settings on the system performance. Particularly, the imperfect CSI deteriorates considerably the system performance. Nonetheless, the performance of the RISwEH can be enhanced by accreting the quantity of the elements of the RIS as well as with the lower fading severity. Furthermore, the time splitting factor also impacts dramatically the outage performance of the RISwEH and its optimal value mitigates significantly the outage probability.

Keywords: Nakagami-*m* fading, reconfigurable intelligent surface, imperfect channel state information, energy harvesting

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1. Introduction

RIS is an energy- and spectrum-efficient transmission technology that takes advantage of advances in reconfigurable and programmable metasurfaces as well as RF micro-electromechanical systems [1–3]. A RIS is made up of several passive reflecting components. Each reflecting element has the ability to reflect the incident wireless signal with a variable phase shift. Therefore, the RIS may modify the end-to-end wireless propagation medium without any sophisticated signal processing or power supply [4, 5] by leveraging the collaboration of passive reflecting devices.

The RIS has sparked extensive scientific interest because of the aforementioned enticing properties [6, 7]. Different performances in RIS-aided wireless systems were enhanced by simultaneously optimizing passive reflected beamforming and active transmit beamforming, such as maximizing energy efficiency [8], maximizing secrecy rate [9], and minimizing aggregate transmission power [10]. Lately, the performance of RIS-aided wireless networks was examined by exploiting the Generalized-K (KG) distribution and the non-central chi-square (NCCS) distribution to approximate the SNR[1] from the RIS to the destination [11–13]. The authors in [14] also discovered that as the

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[1]SNR implies signal-to-noise ratio.

quantity of passive reflecting components is minimal, the NCCS distribution is less precise than the KG distribution.

RF energy harvesting (EH) is a technology that permits the capture and conversion of ambient RF energy from various sources, such as wireless communication signals (e.g., Wi-Fi, cellular, Bluetooth), television and radio broadcasts, and other electromagnetic radiation, into electrical energy [15–17]. This scavenged energy can be utilized to power sensors, low-power electronic terminals, and wireless communication systems. RF energy harvesting is particularly useful in scenarios where it's challenging to replace or recharge batteries in remote or hard-to-reach locations. Therefore, RF EH is a promising technology for extending the operational life of battery-powered devices and reducing the environmental impact of disposable batteries. However, it has limitations, including the relatively low power levels that can be harvested from ambient RF sources and the need for efficient energy conversion and management systems to make it practical for specific applications.

CSI is crucial in the field of wireless communication and networking. It refers to the knowledge or information about characteristics of the communication channel between a transceiver in a wireless system. The communication channel is the medium through which signals or data are transmitted wirelessly, and its characteristics can alter over time owing to innumerable factors like interference, fading, and obstacles in the environment. Efforts to estimate and utilize CSI efficiently are a fundamental aspect of wireless communication system design. Techniques and algorithms for channel estimation, feedback mechanisms, and adaptive transmission are developed to make the best use of available CSI. Accurate CSI allows for the optimization of communication parameters to maximize data rates and reliability in wireless systems. However, because of a lack of radio resources at the RIS, obtaining perfect CSI is utopian. As such, imperfect CSI needs to be studied elaborately.

Nakagami-m fading is a statistical model used to describe the variation in signal strength that occurs in wireless communication channels [18, 19]. It is often used to model the effects of multipath propagation in wireless channels, where signals take multiple paths to reach the receiver, leading to variations in signal amplitude. Also, it is useful in modeling various wireless channel environments, including both non-line-of-sight and line-of-sight cases. The value of m can be adjusted to model numerous fading scenarios; for example, Rayleigh fading ($m = 1$) is a particular case.

The above discussions infer that a RIS-aided communication system with energy harvesting (RISwEH), which combine two modern technologies (RIS and RF EH), is a promising candidate for meeting the critical requirements of high energy efficiency and reliable information transmission for future wireless networks. Notwithstanding, the performance of the RISwEH needs to be evaluated in practical and generalized conditions, including the Nakagami-m fading and the imperfect CSI. Moreover, system parameters like the time splitting factor of the energy harvester needs to be optimized to reach the peak system performance. This research is working towards to such a performance optimization and evaluation.

The authors in [20] analyzed the outage probability of the RIS-aided non-orthogonal multiple access (NOMA) downlink with EH. Nonetheless, [20] derived only the worst- and best-case of explicit outage probability formulas under the Rayleigh fading without considering the imperfect CSI and optimizing the system parameters. In [21], RIS-aided communication systems are secure by optimizing the system parameters under consideration of the imperfect CSI. Nonetheless, [21] did not investigate the EH for energy efficiency improvement nor conduct the performance analysis. Moreover, [21] considered less-generalized fading models (Rayleigh, Rician) than the Nakagami-m fading model. Also, [22] conducted the optimization of the system parameters for RIS-aid communication systems under the investigation of the imperfect CSI. However, [22] did not consider the EH nor execute the performance analysis. In addition, [22] studied the Rician fading which is less-generalized than the Nakagami-m fading. Additionally, [23] analyzed the error performance of the RIS-aided NOMA downlink under the imperfect CSI. Notwithstanding, [23] did not study the EH nor the optimization of the system parameters. Additionally, [23] investigated the Rayleigh fading that is less-generalized than the Nakagami-m fading. Also, [25] analyzed the outage probability of RIS-aided communication networks by applying saddlepoint approximations and Chernoff bounds. However, similar to [23], the work in [25] did not investigate the EH nor the optimization of the system parameters nor the imperfect CSI. In addition, [25] investigated only the Rayleigh fading that is less-generalized than the Nakagami-m fading. In [26], the analyses on the channel capacity, the outage probability, and the average symbol error probability of RIS-aided communication networks were conducted over the Nakagami-m fading links. Also, [26] carried out the optimization of the quantity of the reflectors of the RIS. However, [26] did not investigate the EH nor the imperfect CSI. In [27], the authors analyzed the throughput performance of the RISwEH over Nakagami-m fading links. Additionally, [27] carried out the optimization of the time splitting factor of the energy harvester by the exhaustive search. However, the exhaustive search in [27] takes a long time to reach the optimal value of the time splitting factor. Further, [27] did not consider the imperfect CSI in their problems of the performance analysis and optimization.

In summary, the above literature review exposes that the analyses on the system throughput (TH) and the outage probability (OP) of the RISwEH, and the optimization of the time splitting factor for this system under the relatively-generalized fading (Nakagami-m fading) and the practical operation condition (imperfect CSI) have been still open. Motivated by this, we develop the explicit formulas of the OP and the TH, and find the best solution of the time splitting factor that optimizes the system performance for the RISwEH with the proposed optimization algorithm relied upon the Golden section search [28] under the investigation of the Nakagami-m fading and the imperfect CSI. Various results corroborate the theoretical derivations, prove the efficacy of the suggested optimization algorithm as compared to the exhaustive search in [27], and illustrate the influence of innumerable system settings on the system performance. Particularly, the imperfect CSI deteriorates considerably the system performance. Nonetheless, the performance of the RISwEH can be enhanced by accreting the quantity of the elements of the RIS as well as with the lower fading severity. Furthermore, the time splitting factor also impacts dramatically the outage performance of the RISwEH and its optimal value mitigates significantly the outage probability.

The paper keeps going with Section 2 that clearly describes the system model. Subsequently, the analyses on the TH and the OP are given in Section 3. Next, the optimization problem of the time splitting factor of the energy harvester is formulated and solved with the Golden section search in Section 4. Section 5 provides the numerical and simulation results together with in-depth discussions. Eventually, Section 6 summarizes the research's contributions.

2. System model

We consider the RISwEH, as depicted in Figure 1, where a signal x is sent by a source (S) to a destination (D) through the aid of a RIS which has a signal reflection function. The RIS is made up of N reflectors. A communication process lasting T seconds consists of two phases. In the EH phase lasting αT seconds wherein $0 < \alpha < 1$ is the time splitting factor, a power beacon (PB) sends wireless energy to the S. One supposes a direct channel between the S and the D to be obstructed by barriers like trees and buildings, which is more frequent when wireless communication systems operate at high frequencies. Then, the S utilizes the harvested energy to broadcast x which is reflected by the RIS to the D in the transmission phase lasting $(1-\alpha)T$ seconds.

The amount of energy the S gathers from the RF signal sent by the PB is expressed to be

$$E = \eta \alpha T P_{PB} |h|^2, \tag{1}$$

wherein $\eta \in (0,1)$ denotes the efficiency of EH, h is the channel gain between the S and the PB, and P_{PB} is the transmission power of the PB.

We assume the channel between the PB and the S to follow the Nakagami-m fading with the parameter pair (m_h, Ω_h) wherein $\mu_h = \frac{m_h}{\Omega_h}$ with m_h being fading severity and $\Omega_h = \mathbb{E}\left\{|h|^2\right\}$ being fading power, and $\mathbb{E}\{X\}$ is the mean of X. Therefore, the random variable (RV) $|h|^2$ has the cumulative distribution function (CDF) and the probability density function (PDF), respectively, as [29]

$$F_{|h|^2}(x) = 1 - e^{-\mu_h x} \sum_{s=0}^{m_h - 1} \frac{(\mu_h x)^s}{s!}, \tag{2a}$$

$$f_{|h|^2}(x) = \frac{\mu_h^{m_h} x^{m_h - 1} e^{-\mu_h x}}{\Gamma(m_h)}. \tag{2b}$$

As in several prior works, we also assume that all the scavenged energy is consumed in the transmission phase. Thence, the S sends signals with the power:

$$P_S = \frac{E}{(1-\alpha)T} = \frac{\eta \alpha P_{PB}}{1-\alpha} |h|^2. \tag{3}$$

Since the S uses the gathered energy to transmit x to the D with the RIS's assistance in the transmission phase, the D receives the signal to be [23]

$$\begin{aligned} y &= \left(\mathbf{g}_1^H \mathbf{\Phi} \mathbf{g}_2 + e_D\right)\sqrt{P_S} x + \omega \\ &= \mathbf{g}_1^H \mathbf{\Phi} \mathbf{g}_2 \sqrt{P_S} x + e_D \sqrt{P_S} x + \omega \end{aligned} \tag{4}$$

wherein $(.)^H$ denotes the Hermitian transpose and x has the unit energy (i.e., $\mathbb{E}\left\{|x|^2\right\} = 1$). Additionally, $N \times 1$ vectors, $\mathbf{g}_1$ and $\mathbf{g}_2$, notate the S-RIS and RIS-D links, correspondingly. Moreover, the $N \times N$ matrix, $\mathbf{\Phi} = \mathrm{diag}\{\theta\}$, notates the phase shift matrix of the RIS, wherein $\theta = \left[\beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, \ldots, \beta_N e^{j\theta_N}\right]$ with β_n and $\theta_n \in [0, 2\pi)$, being the amplitude and the phase shift of the nth reflection coefficient of the RIS, correspondingly; $1 \le n \le N$. For simplicity, we suppose $\beta_n = 1$. Further, we consider the imperfect channel estimation that results in the channel estimation error (CEE) represented by e_D. It is well-known that e_D can be modeled to be a complex Gaussian RV (CGRV), i.e., $e_D \sim \mathcal{CN}\left(0, \sigma_D^2\right)$. Here, $\mathcal{CN}(0, \sigma)$ notates a CGRV with variance σ and zero mean. Also, it is apparent that σ_D^2 represents the relative amount of CSI uncertainties. The smaller σ_D^2, the lower the uncertainties. According to [24], σ_D^2 is represented through $\delta^2 \simeq \frac{\sigma_D^2}{\mathbb{E}\left\{\left|\mathbf{g}_1^H \mathbf{\Phi} \mathbf{g}_2\right|^2\right\}}$ that

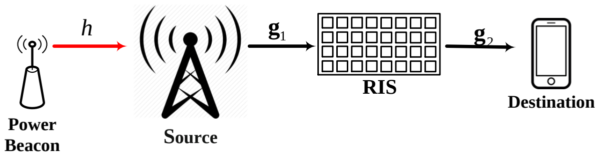

Figure 1. RIS-aided communication system with energy harvesting.

means the relative CEE. Finally, ω represents the noise with variance N_0.

As per [25] and (4), the received SNR at the D, $\gamma = \frac{|\mathbf{g}_1^H \mathbf{\Phi} \mathbf{g}_2|^2 P_S}{\sigma_D^2 P_S + N_0}$, can approach its peak when $\theta_n = -\arg(g_{1,n}) - \arg(g_{2,n})$ wherein $g_{1,n}$ and $g_{2,n}$ are the nth entries of $\mathbf{g_1}$ and $\mathbf{g_2}$, respectively. Then, we have

$$\left|\mathbf{g}_1^H \mathbf{\Phi} \mathbf{g}_2\right|^2 = \left(\sum_{n=1}^N |g_{1,n}| |g_{2,n}|\right)^2. \tag{5}$$

and the peak SNR of the RISwEH is attained to be

$$\gamma^p = \frac{\left(\sum\limits_{n=1}^N |g_{1,n}| |g_{2,n}|\right)^2 P_S}{\sigma_D^2 P_S + N_0}. \tag{6}$$

By substituting (3) into (6), one can express γ^p as

$$\gamma^p = \frac{\xi |A|^2 |h|^2}{1 + \sigma_D^2 \xi |h|^2}, \tag{7}$$

wherein $\xi = \eta\alpha\rho/(1-\alpha)$, $A = \sum_{n=1}^N |g_{1,n}| |g_{2,n}|$, and $\rho = \frac{P_{PB}}{N_0}$ represents the transmit SNR.

We assume the S-RIS and the RIS-D channels to follow the Nakagami-m fading with the parameter pairs, (m_1, Ω_1) and (m_2, Ω_2), where $\mu_i = \frac{m_i}{\Omega_i}$ with m_i being the fading severity and $\Omega_i = \mathbb{E}\left\{|g_{i,n}|^2\right\}$ being the fading power; $i = \{1, 2\}$ and $1 \le n \le N$. Then, the PDF and the CDF of $|A|^2$, $f_{|A|^2}(x)$ and $F_{|A|^2}(x)$, are respectively formulated by [26]

$$f_{|A|^2}(x) \simeq \frac{x^{\frac{a}{2}} e^{-\frac{\sqrt{x}}{b}}}{2b^{a+1}\Gamma(a+1)\sqrt{x}}, \tag{8}$$

and

$$F_{|A|^2}(x) = \frac{1}{\Gamma(a+1)} \gamma\left(a+1, \frac{1}{b}\sqrt{x}\right), \tag{9}$$

where $b = \frac{m_1 m_2 \Gamma(m_1)^2 \Gamma(m_2)^2 - \Gamma(m_1+0.5)^2 \Gamma(m_2+0.5)^2}{\sqrt{\Omega_1^{-1} m_1} \Gamma(m_1) \Gamma(m_1+0.5) \sqrt{\Omega_2^{-1} m_2} \Gamma(m_2) \Gamma(m_2+0.5)}$, $a = \frac{m_1 m_2 N \Gamma(m_1)^2 \Gamma(m_2)^2}{m_1 m_2 \Gamma(m_1)^2 \Gamma(m_2)^2 - \Gamma(m_1+0.5)^2 \Gamma(m_2+0.5)^2} - N - 1$, $\gamma(.,.)$ is the lower incomplete Gamma function [32, Eq. (8.350.2)], and $\Gamma(.)$ is the Gamma function [32, Eq. (8.310)].

3. Performance Analyes

This part aims to analyze the key system performance metrics of the RISwEH like the OP and the TH in order to evaluate the system performance quickly and attain helpful insights into system design.

3.1. Outage probability

The OP is referred to the likelihood that the attainable SNR γ^p subceeds a predefined SNR γ_{th}, which is tightly related to the target quality of service. Then, the formula for the OP of the RISwEH is

$$\Psi = \Pr\left([1-\alpha]\log_2(1+\gamma^p) < R\right) = \Pr\left(\gamma^p < \gamma_{th}\right), \tag{10}$$

where $\gamma_{th} = 2^{\frac{R}{1-\alpha}} - 1$ owing to the duration of the transmission phase of $(1-\alpha)T$. Here, R is the target data rate of the RISwEH.

Substituting (7) into (10), one attains the OP as

$$\begin{aligned}\Psi &= \Pr\left(|A|^2 < \frac{\gamma_{th}}{\xi |h|^2} + \sigma_D^2 \gamma_{th}\right) \\ &= \int_0^\infty f_{|h|^2}(x) F_{|A|^2}\left(\frac{\gamma_{th}}{\xi x} + \sigma_D^2 \gamma_{th}\right) dx.\end{aligned} \tag{11}$$

By inserting (2b) and (9) into (11), one rewrites the Ψ as

$$\Psi = \frac{\mu_h^{m_h}}{\Gamma(m_h)\Gamma(a+1)} \int_0^\infty x^{m_h-1} e^{-\mu_h x} \gamma\left(a+1, \frac{1}{b}\sqrt{\frac{\gamma_{th}}{\xi x} + \sigma_D^2 \gamma_{th}}\right) dx. \tag{12}$$

Performing the variable transform $q = \mu_h x$ and applying the Gauss-Laguerre integration [33, Eq. (25.4.45)], the OP is represented in closed-form as

$$\begin{aligned}\Psi &= \frac{1}{\Gamma(m_h)\Gamma(a+1)} \int_0^\infty q^{m_h-1} e^{-q} \gamma\left(a+1, \frac{1}{b}\sqrt{\frac{\mu_h \gamma_{th}}{\xi q} + \sigma_D^2 \gamma_{th}}\right) dq \\ &\approx \frac{1}{\Gamma(m_h)\Gamma(a+1)} \sum_{u=1}^U H_u q_u^{m_h-1} \gamma\left(a+1, \frac{1}{b}\sqrt{\frac{\mu_h \gamma_{th}}{\xi q_u} + \sigma_D^2 \gamma_{th}}\right),\end{aligned} \tag{13}$$

where U is the Gauss-Laguerre parameter, q_u is the u-th zero of Laguerre polynomial $\mathcal{L}_U(q_u)$, and $\mathcal{H}_u = \frac{(U!)^2 q_u}{[\mathcal{L}_{U+1}(q_u)]^2}$ is the weight of the Gauss-Laguerre integration.

3.2. System throughput

Based on the explicit formula of Ψ, we further evaluate the TH in delay-constrained communication mode as

$$\kappa = (1 - \Psi) R. \tag{14}$$

4. Performance Optimization

We can see from (13) that the OP correlates the time splitting factor α, which is directly proportional to the EH period. Therefore, a short EH period (i.e., small α) results in the little amount of gathered energy, leading to the less reliable transmission. In the contrary, if the EH period is long (i.e., large α), there isn't sufficient time for information transmission in the transmission phase lasting $(1-\alpha)T$ seconds, also leading to the reduced throughput. As a result, one needs to optimize α for attaining the best system performance. Then, the optimization problem to attain the best solution of α is formulated as

$$\begin{aligned} \alpha^* &= \arg\min_{\alpha} \Psi(\alpha) \\ &\text{subject to } \; 0 < \alpha < 1 \end{aligned} \tag{15}$$

where α^* denotes the optimal solution of α for minimizing the outage probability of the RISwEH.

We know from (10) that R is a fixed number and that there is a correlation between Ψ (α) and γ_{th}. Also, the convexity of Ψ (α) is established for α in the interval (0, 1), indicating the uniqueness of the solution for the problem in (15). This unique solution can be efficiently determined through a linear search algorithm such as the Golden section method. Consequently, we employ the Golden section method to solve the optimization problem, and the step-by-step procedure is outlined in Algorithm 1. It is also important to note that the accuracy and complexity of Algorithm 1 is chiefly influenced by the specified step search parameter Δ.

Algorithm 1: Golden section search-based optimization algorithm for finding α^*

Input : Initialize $\psi_{\max} = 1$, $\psi_{\min} = 0$, a stopping threshold $\Delta = 10^{-3}$ and a Golden section search $\varpi = \frac{\sqrt{5}-1}{2}$

Output: The optimum solution of α^* which minimizes the outage probability $\Psi(\alpha^*)$

```
begin
    Set β2 = ψmin + (ψmax − ψmin) ϖ and
      β1 = ψmax − (ψmax − ψmin) ϖ
    while |ψmax − ψmin| ≤ Δ do
        Update: Ψtemp1 = Ψ (β1) and
          Ψtemp2 = Ψ (β2)
        if Ψtemp1 < Ψtemp2 then
            Update: ψmax ← β2
        else
            Update: ψmin ← β1
        end
        Update: β1 ← ψmax − (ψmax − ψmin) ϖ and
          β2 ← ψmin + (ψmax − ψmin) ϖ
    end
    return The optimum solution of
      α* = (ψmax + ψmin)/2
end
```

Table 1. Key parameters

System Parameters	Values
Number of channel realizations	10^7
Target data rate	$R = 2$ BPCU
Energy conversion efficiency	$\eta = 1$
Fading severity parameter	$m = 2$
Time splitting factor	$\alpha = 0.5$
Number of reflecting elements	$N = 16$
Imperfect CSI impacting factor	$\delta^2 = 0.05$
Fading power	$\Omega_h = \Omega_1 = \Omega_2 = 1$

5. Illustrative Results

This part presents both simulation and analytical results wherein the simulation results are generated by Monte-Carlo simulations to compare with the analytical ones to affirm the performance analyses in the previous parts. The fading severity parameters are set as $m = m_h = m_1 = m_2$. Also, key parameters referenced from [30]-[31] are tabulated in Table 1 wherein BPCU means bit per channel. Moreover, the simulation and the computation were conducted using the MATLAB software. Further, the Gauss-Laguerre parameter is set as $U = 100$ to attain a high accuracy of approximation.

Figure 2 unveils the OP against the transmit SNR ρ for various values of $N = 4, 8, 16$. We see that the simulation results match the analytical results, validating the preciseness of the derived expressions in the previous parts. Also, increasing ρ ameliorates significantly the system performance, as predicted. In addition, the OP is significantly mitigated with increasing the quantity of the reflecting elements of the RIS. For instance, when N increases from 4 to 16, the transmit SNR required for obtaining the OP of 10^{-4} reduces from 36 dB to 23 dB for the scenario of perfect CSI, i.e., the SNR gain is 13 dB for the increase of 12 reflecting elements of the RIS. Also, the imperfect CSI degrades considerably the system performance. Further, it also causes the performance saturation which is not present in the scenario of perfect CSI.

Figure 3 examines the effect of the fading severity parameter m on the outage performance. It is evident that m significantly influences the system performance.

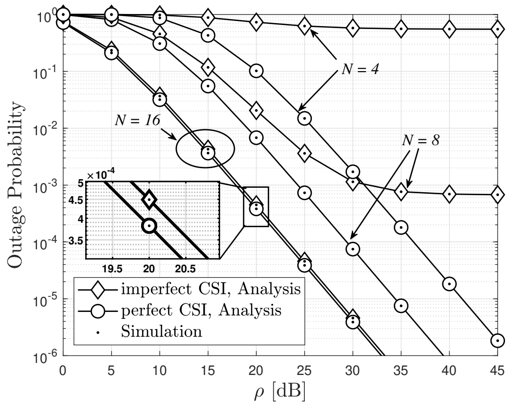

Figure 2. Impact of N on the OP versus ρ.

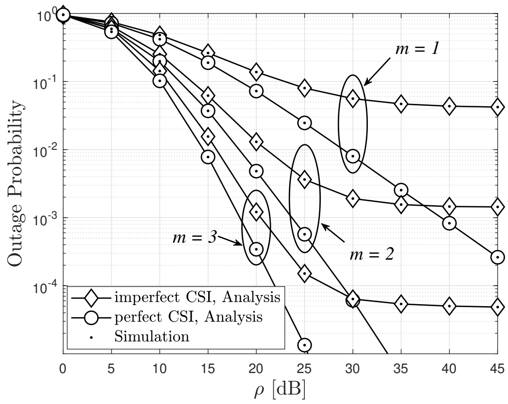

Figure 3. OP against ρ for various m.

Particularly, the increase in m drastically mitigates the outage probability. This makes senses as the higher m results in the better fading channel quality, leading to the better performance.

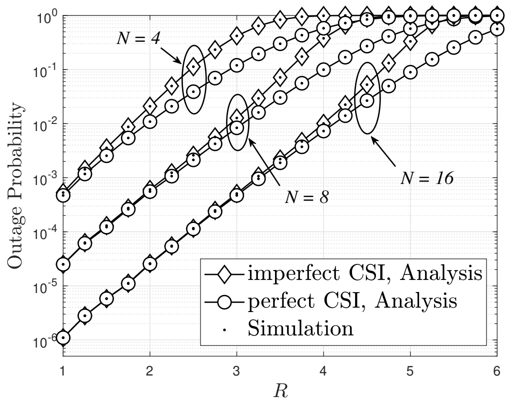

Figure 4. OP versus R with $\delta^2 = 0.1$ and $\rho = 15$ dB.

Figure 4 depicts the OP versus the target data rate R with $\delta^2 = 0.1$ and $\rho = 15$ dB. Again, one sees that the increase in the quantity of the reflectors N improves dramatically the system performance. Also, the imperfect CSI deteriorates considerably the outage performance, as anticipated. Further, increasing in R mitigates significantly the outage performance and the RISwEH experiences the complete outage for large R; for instance, $\Psi = 1$ as $R = 4$ BPCU.

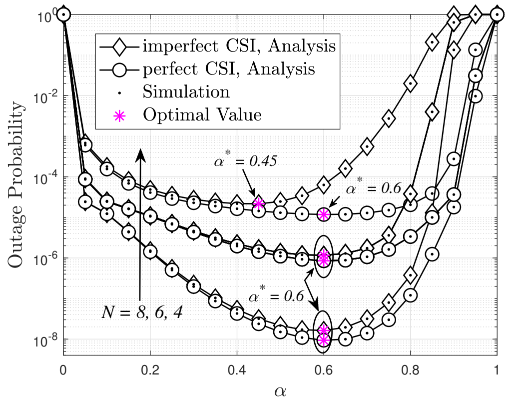

Figure 5. OP versus α with $R = 0.6$ BPCU, $\delta^2 = 0.5$ and $\rho = 10$ dB.

Figure 5 depicts the OP versus the time splitting factor α. Also, this figure denotes α^* as the optimum α using the suggested optimization algorithm in Part 4. It is seen that the optimum α through the suggested optimization algorithm coincides that through the exhaustive search. However, the time for searching α^* in the suggested optimization algorithm is significantly faster than that in the exhaustive search, showing the efficacy of the proposed optimization algorithm. Moreover, α^* is different for different quantity of the reflectors of the RIS. Further, the system performance is significantly ameliorated with increasing N and the lower CSI imperfection level.

Figure 6 shows the system throughput versus R with $m = 4$, $\alpha = 0.2$, $\delta^2 = 0.1$, $\rho = 15$ dB, and $N = 4, 8, 16$. One observes that the TH dramatically accretes with increasing N and the lower CSI imperfection level. Also, the system throughput is optimized by selecting the target data rate R appropriately. This is reasonable since (14) shows the tight relation between the system throughput κ and the target data rate R. Particularly, increasing R accretes the outage probability Ψ and thence, the product of $(1 - \Psi)R$ in (14) only increases to a certain value and then, it will reduce. This product is the system throughput, i.e., κ reaches the peak at a certain value of R.

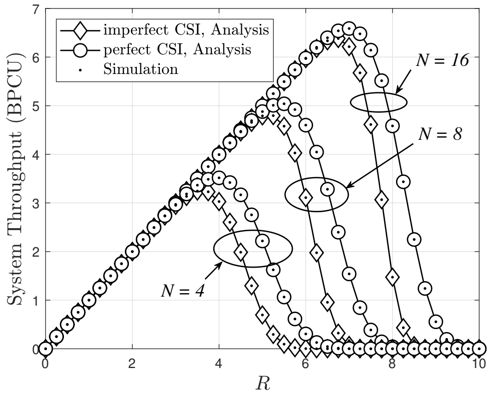

Figure 6. TH in delay-constrained communication mode against R with $m = 4$, $\alpha = 0.2$, $\delta^2 = 0.1$ and $\rho = 15$ dB.

6. Conclusion

In this research, we derived the explicit formulas of the OP and the TH for the RIS-aided communication system with energy harvesting over the Nakagami-m fading channels under the realistic scenario of the imperfect CSI. Additionally, we proposed the optimization algorithm based on the Golden section search to attain the optimum value of the time splitting factor at the best performance. Innumerable results validated the theoretical derivations, proved the efficacy of the suggested optimization algorithm, and demonstrated the affect of various system configurations on the system performance. Particularly, the imperfect CSI degrades significantly the system performance. However, the performance of the RISwEH can be improved by accreting the quantity of the reflectors of the RIS as well as with the better fading conditions. Further, the time splitting factor has a considerable influence on the outage performance of the RISwEH and its optimal value reduces drastically the outage probability.

In future works, we will develop the RISwEH equipped with an active RIS which can control its phases and amplitudes actively in order to support multiple destinations. In this extended system model, multi-user detection techniques at destinations and optimization algorithms of phases and amplitudes for the RIS will be also developed for efficient signal detection. Moreover, more generalized fading channels (e.g., $\kappa - \mu$ shadowed fading channels [34]) should be investigated to make the system model suitable to real-world deployment.

Data Availability

The data used to support the findings of this study are included in the paper.

Conflicts of Interest

The authors declare there is no conflict of interest in this manuscript.

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