Outage Analysis for Active Reconfigurable Intelligent Surface-Enhanced Wireless Powered Communication Networks

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***Abstract*—Wireless powered communication (WPC) involves the integration of energy harvesting and data transmission. This allows devices to communicate without constant battery replacements or wired power sources. Reconfigurable intelligent surfaces (RISs) can dynamically manipulate radio signals. In this paper, we explore the use of active elements to mitigate double-fading challenges inherent in RIS-aided links. We enhance the reliability performance for an energy-constrained user by combining active RIS and WPC. The theoretical closed-form analysis, which includes transmission rate, harvested energy, and outage probability, provides valuable insights that inform parameter selection.**

***Index Terms*—Wireless powered communication (WPC), Active RIS, Outage probability.**

I. Introduction

In the realm of sixth-generation (6G) wireless networks, the deployment of reconfigurable intelligent surfaces (RIS) stands as a pivotal innovation, shaping the foundation of intelligent wireless environments, alleviating radio frequency (RF) complications, and bolstering connectivity under challenging propagation conditions [1]. By introducing controlled phase shifts to electromagnetic signals, RIS systems substantially enhance network coverage and reliability without complex signal processing or additional infrastructure [2], [3]. Wireless powered communication (WPC) represents another emerging field anticipated to play a pivotal role in 6G networks, seamlessly merging energy harvesting with data transmission. This integration empowers networked devices to communicate independently of conventional power sources, eliminating dependence on batteries or a constant power supply [4].

A. Motivation

In practical scenarios, the deployment of RIS-aided wireless communication systems may confront challenges, including the significant issue of double-fading [5], [6]. The strategic incorporation of active elements in RIS has been proposed, demonstrating considerable potential in effectively overcoming the double-fading challenge [7]. The synergistic amalgamation of active RIS with WPC emerges as a highly promising strategy, substantially enhancing both wireless reliability and energy efficiency, particularly for users facing energy limitations. This innovative integration is poised to significantly elevate network performance, energy efficiency, and connectivity, fostering a new era of advanced, sustainable, and intelligent wireless communications. The deployment of active RIS-WPC in 6G networks holds immense potential, particularly in revolutionizing sectors such as the Internet of Things (IoT), wearable technology, and autonomous vehicles [8].

B. Contribution

In our paper, we focus on RIS-WPC networks, where we employ RIS with active elements to enhance information transmission. Specifically, an energy-constrained wireless user harvests RF energy and employs it for data transmission. This approach capitalizes on RIS beamforming gain to optimize information reception and provides superior adaptability compared to conventional WPC systems without RIS. Our work presents significant contributions including a detailed statistical channel characterization that accounts for potential noise in active RIS modules, a comprehensive closed-form outage probability analysis specific to Rayleigh fading channels, and numerical results. These results not only validate our theoretical findings but also offer essential guidance for parameter selection.

II. System Model

We examine a WPC network, depicted in Fig. 1, consisting of a base station (BS), a power station (PS), and a user (U). We introduce an RIS with M elements strategically placed between the BS and U because a direct link is obstructed. Each element within the RIS module is equipped with a power amplifier to amplify the reflected signal. In this configuration, it becomes possible to mitigate the substantial path loss associated with

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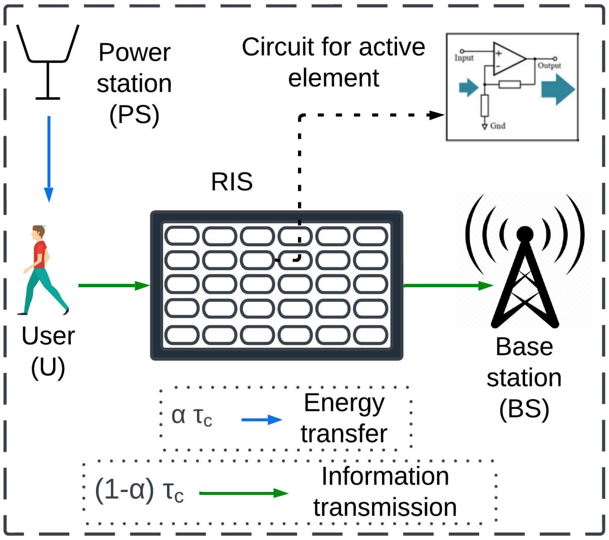

Fig. 1. Active RIS-Enhanced WPC Network.

the RIS-aided link, effectively overcoming the challenge posed by double-fading[1]. We adopt an independent and identically distributed (i.i.d.) Rayleigh fading model for all links [9]. The channel vectors are defined as follows:

- h_1 for the PS-U link,
- $\mathbf{h}_2$ for the U-RIS link,
- $\mathbf{h}_3$ for the RIS-BS link.

We consider h_1 and each entry in $\mathbf{h}_2$ and $\mathbf{h}_3$ to be an independent complex Gaussian distribution with a zero mean and a unit variance [10]. Within each channel coherence interval (τ_c), communication unfolds in two distinct phases: energy transfer and information transmission. During the $\alpha\tau_c$ duration, the PS facilitates the transfer of RF energy to U.

The energy harvested by U can be expressed as follows:

$$E = \eta\alpha\tau_c P_{ps}|h_1|^2\zeta_1 \tag{1}$$

where

- $0 < \alpha < 1$ is time switching factor between energy transfer and information transmission.
- η denotes the energy conversion efficiency,
- P_{ps} denotes the transmission power of PS,
- and ζ_1 denotes the path loss from PS to U.

Following this, U transmits its information to BS via RIS during $(1-\alpha)\tau_c$ using the energy harvested during $\alpha\tau_c$. The transmission power of U can be calculated as,

$$P_u = \frac{E}{(1-\alpha)\tau_c} = \frac{\eta\alpha P_{ps}|h_1|^2\zeta_1}{(1-\alpha)} = P_e|h_1|^2\zeta_1, \tag{2}$$

where $P_e = \frac{\eta\alpha P_{ps}}{(1-\alpha)}$

At BS, the signal-to-noise ratio (SNR) can be written as,

$$z_u = \frac{P_e\zeta_1\zeta_2|h_1|^2|\mathbf{h}_3^T\boldsymbol{\Theta}\mathbf{h}_2|^2}{\sigma_T^2} = p_e\zeta_1\zeta_2|h_1|^2|\mathbf{h}_3^T\boldsymbol{\Theta}\mathbf{h}_2|^2 \tag{3}$$

where

- $\boldsymbol{\Theta} = \rho\,\mathrm{diag}(e^{j\theta_1}, ..., e^{j\theta_M})$ is $M \times M$ diagonal response matrix of RIS,
- ρ is the amplification gain of each RIS element[2],
- $p_e = \frac{P_e}{\sigma_T^2}$, $\sigma_T^2 = \sigma_b^2 + \rho^2\sigma_R^2$ is sum of powers of AWGN noises at the BS and RIS,
- and ζ_2 is the path loss from U to BS via RIS.

All channels are assumed to be known [11]. This implies that the phase shifts at the RIS can be intelligently controlled, i.e., $\theta_m = -\arg(\mathbf{h}_{2,m}\mathbf{h}_{3,m})$, to maximize the reception quality of BS [12]. In this case, the SNR in Eq. (3) can be rewritten as,

$$z_u = p_e\zeta_1\zeta_2|h_1|^2\left(\rho\sum_{m=1}^{M}|\mathbf{h}_{2,m}||\mathbf{h}_{3,m}|\right)^2 \tag{4}$$

III. Outage Probability Analysis

The outage probability is the probability of an event occurring when channel capacity drops below the codeword rate of the transmission signal (r), and is mathematically expressed as:

$$P_{Out} = \Pr\left[(1-\alpha)\log_2(1+z_u) < r\right] \tag{5}$$

By substituting the SNR from Eq. (4), Eq. 5 can be accurately expressed as:

$$\begin{aligned} P_{Out} =& \\ &\Pr\left[(1-\alpha)\log_2\left(p_e\zeta_1\zeta_2|h_1|^2\left(\rho\sum_{m=1}^{M}|\mathbf{h}_{2,m}||\mathbf{h}_{3,m}|\right)^2\right) < r\right] \\ =&\Pr\left[\left(|h_1|\sum_{m=1}^{M}|\mathbf{h}_{2,m}||\mathbf{h}_{3,m}|\right)^2 < \frac{\Delta}{p_e\zeta_1\zeta_2\rho^2}\right] \end{aligned} \tag{6}$$

Using the statistical characteristics of Rayleigh channels and employing algebraic manipulations, Eq. (6) can be elegantly simplified as follows,

[1]Double-fading can be mitigated by increasing passive RIS elements. However, this may result in an increased physical size of the RIS module.

[2]The amplification gain for each reflection-type amplifier is set to ρ, reducing configuration overhead and enabling variable beamforming design.

$$P_{Out} = 1 - \frac{\pi^2}{4K}\sum_{k=1}^{K}\sqrt{1-\omega_k^2}\sec^2\mu_k\frac{(\tan\mu_k)^{v-1}}{\Gamma(v)\delta^v} \times \exp\left(-\frac{\Delta}{p_e\zeta_1\zeta_2\rho^2 tan^2\mu_k} - \frac{tan\mu_k}{\delta}\right) \quad (7)$$

where

- $\mu_k = \frac{\pi(\omega_k+1)}{4}$,
- $\omega_k = \cos\left(\frac{2k-1}{K}\pi\right)$,
- K is the accuracy versus complexity parameter,
- $\Delta = 2^{\frac{r}{1-\alpha}} - 1$,
- $v = M\frac{\frac{\pi}{4}}{\frac{4}{\pi}-\frac{\pi}{4}}$,
- $\delta = \frac{4}{\pi} - \frac{\pi}{4}$,
- and $\Gamma(.)$ denotes the Gamma function.

IV. Numerical Results

Numerical results validate the theoretical expressions and provide valuable insights. Monte Carlo simulations with 10^4 independent trials are used. Unless otherwise specified, the simulation parameters are as follows: $\alpha = 0.5$, $\tau_c = 1$, $\eta = 0.90$, $r = 1.4$ bps/Hz, $P_{ps} = 10$ dBm, $M = \{0, 100\}$, $\sigma_b^2 = 0$ dBm, and $\sigma_R^2 = -80$ dBm, and $\rho = \{2, 4\}$.

Fig. 2 shows the outage probability vs. number of active elements (M), and amlification factor for active elements (ρ). The results validate the analytical analysis and imply that an increase in M, and ρ (which demonstrates the amplification impact due to the active RIS) positively impacts outage performance, subsequently increasing transmission reliability. As an example, deploying an active RIS rather than a passive RIS allows for a decrease in the transmit power as well as the number of elements required to achieve a certain outage probability.

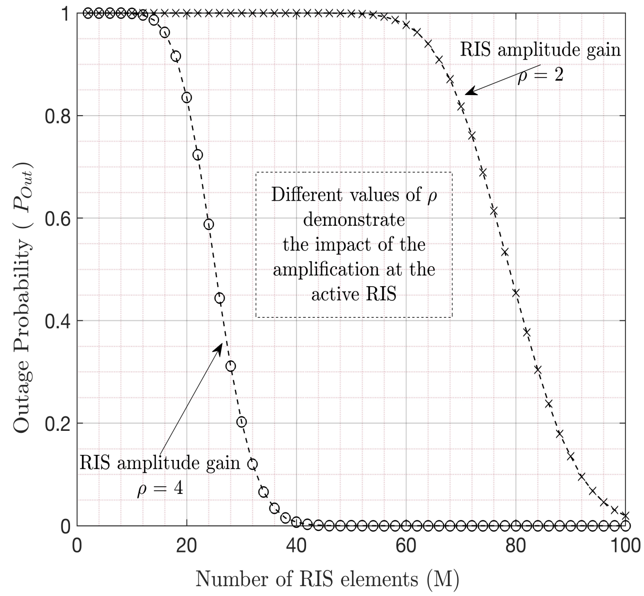

Fig. 2. Outage probability vs. M and ρ

V. Conclusion

The integration of active RIS and WPC significantly enhances the reliability and energy efficiency of users with limited energy resources. This paper demonstrates how a user can harvest RF energy from a PS and utilize it for data transmission to a BS via RIS, optimizing the use of available energy and ensuring reliable communication. The theoretical analysis and numerical results provide crucial insights and practical guidelines for parameter selection, contributing to the advancement of energy-efficient and reliable wireless communication, particularly as we transition into the 6G era.

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