RIS-ASSISTED WIRELESS COMMUNICATION FROM AN ENERGY AND A SPECTRAL EFFICIENCY PERSPECTIVE

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Due to its ability to effectively and intelligently adapt to the propagation environment, reconfigurable intelligent surface (RIS) is considered an enabling technology for future wireless networks. In this paper, within the energy efficiency (EE) and spectral efficiency (SE) context, we conduct a detailed performance analysis and a comparison of a RIS-assisted wireless communication system with two other setups, namely a decode-and-forward (DF) relaying-assisted setup and a basic single-input, single-output (SISO) setup. The simulation results along with the analytical ones reveal that both a correct power modeling and allocation and a correct choice of the number of the RIS reflective elements have a crucial role in the EE-SE trade-off.

KEY WORDS: *reconfigurable intelligent surface (RIS), performance optimization, energy efficiency (EE), spectral efficiency (SE)*

1. INTRODUCTION

Future wireless access networks, such as fifth-generation (5G) wireless networks, introduce and consolidate several technologies such as millimeter waves, pico-cells, and the massive use of antennas for spatial and temporal diversity. All of these changes bring new challenges and constraints for the wireless transmission process. Historically, the evolution of wireless communication systems has been driven entirely by the need for high data rates. Consequently, this requirement has been the primary path of technological advancement leading from 2G to today's 4G systems. Moreover, the amount of wireless data traffic has increased annually. In fact, worldwide mobile devices will rise from 8.6 billion in 2017 to 12.3 billion by 2022, of which more than 422 million will be 5G supported. The main driver of this growth is smartphones, followed by machine-to-machine (M2M) devices. Indeed, in 2022, the M2M connections accounted for 51 percent of all devices and connections (Cisco, 2019).

In contrast to previous generations, the future mobile wireless communication system must be able to provide connectivity to a massive number of users, fulfill high data transfer rates, and very have low latency times to accommodate a wide range of emerging services and applications (Jian et al., 2022). The challenge for any technology is enormous. To achieve this, focusing only on increasing the data transfer rate is not enough. Thus to meet the expectations generated by the different types of services in a 5G scenario, it is necessary to develop new technologies, both in the current field and in technology. Recently, an emerging technology called reconfigurable intelligent surfaces (RISs) is regarded as an important key technology to address such challenges (Basharat et al., 2022; Yuan et al., 2022). This technology can be mounted on wide plane surfaces (e.g., walls or roofs indoors, building fronts, or roadside billboards) so that radiofrequency energy circumvents obstacles and establishes a virtual line-of-sight (LoS) transmission link between between the source and the destination of a transmission system (Tang et al., 2021).

The RIS is presented in recent literature as a large grouping of reflecting passive elements, in which each component can be reconfigured distantly and automatically to produce a specific phase shift on the incident electromagnetic waves (Huang et al., 2019). In using appropriate phase shifts driven by all passive elements, the reflected electromagnetic waves can be combined in a constructive manner at the desired user to provide a strong received signal and destructively at the undesired users to minimize interference bias.

Because of the immense promising advantages of RIS environments, the literature has recently devoted a lot of research to various aspects, such as power/spectral optimizations (Jung et al., 2021; Li et al., 2021), channel estimation (Hu et al., 2021; Nadeem et al., 2020), deep learning-based design (Liaskos et al., 2019; Sheen et al., 2021), and RIS-assisted wireless system performance evaluation (Jung et al., 2020; Zou et al., 2020). In addition, spectral efficiency (SE) and energy efficiency (EE) are important performance metrics in research contributions related to RIS-assisted wireless communications (Taneja et al., 2022). Wu and Zhang (2019) compared the EE of the RIS to that of the conventional amplify-and-forward relaying band. They have concluded that the RIS performs better in this aspect since it improves the received power without the use of power amplifiers but only through proper phase shift design. Huang et al. (2019) have conducted more extensive benchmarking results on the EE and the sum rate where they have proposed an alternative optimization of the transmit base station (BS) beamforming and RIS phase shifts. In this respect, they have developed two low-cost computational approaches. One uses a gradient search approach, while the other exploits the sequential optimization framework. Björnson et al. (2020) investigated the application of the RIS in the context of the EE and SE, and deduced the smallest number of reflecting elements, allowing it to achieve better performance than the decode-and-forward (DF) relaying system as well as the single-input, single-output (SISO) communication system. In Di Renzo et al. (2020), the authors extended the numerical study performed in Björnson et al. (2020), where they compared the power consumption and EE of DF relays versus RIS that function as focusing lenses. Recently, Shaikh et al. (2023) derived closed-form expressions of SE and EE, as well as the outage probability for the RIS-assisted dual communication system. They showed that using distributed RISs resulted in significant performance gains in terms of SE and EE compared to the RIS-only case. The EE maximization problem was studied in Zhong et al. (2023) for an IRS-assisted dual-functional radar and communication system, where the EE is maximized by jointly optimizing the transmit beamforming and the IRS phase shift matrix for the cases of perfect channel state information (CSI) and imperfect CSI.

In this paper, we attempt to optimize the RIS parameters to compare the EE and to achieve a high data rate with respect to the total transmit power/RIS phase shifts and to the optimal number of reflecting elements. With these constraints, the main contributions are summarized as follows:

- We develop an analytical model for EE/SE, where the instantaneous channel gain constantly evolves with the location of the mobile stations (MSs).
- To determine the competitiveness of the RIS-assisted system, we compare its performance in terms of achievable SE, EE, and transmit power to that of a baseline transmission such as conventional SISO and DF relay systems.

- Typically, it is possible to increase the SE by using a higher transmit power. Unfortunately, this approach results in an unavoidable reduction in EE. However, under certain operating conditions, it is possible to optimize both SE and EE. For efficient optimization, we attempt to derive a closed-form solution highlighting an interesting trade-off between the SE and the EE based on key system parameters such as the number of reflecting elements and total power consumption.

- The simulation results validate our approach, showing that (1) under certain conditions, the performance of the RIS system is able to outperform its SISO and DF counterparts, and (2) the simulation results are consistent with the developed analytical conclusions.

The remainder of this paper is organized as follows. The system and channel models and their corresponding signal-to-noise ratios (SNRs) are described in Section 2. In Section 3, we compare the performance of the three considered setups in terms of the SE, the transmit power, and the EE. In Section 4, we study the trade-off between the EE and the SE. The simulation results are presented in Section 5, while Section 6 concludes the paper.

The common notations used in this work are given as follows: scalars, vectors, and matrices are denoted by italic lowercase, boldface lowercase, and boldface uppercase letters, respectively. For a vector $\boldsymbol{h}$, $\boldsymbol{h}^{\mathrm{T}}$ refers to its transpose. $\mathrm{diag}\,[\boldsymbol{h}]$ represents the diagonal matrix in which the diagonals are the elements of the input vector $\boldsymbol{h}$. $\arg(h)$ refers to the argument of a complex number h. $|h|$ denotes the absolute value of a scalar h.

2. SYSTEM MODEL

As illustrated in Fig. 1, in this work we consider two setups for a three-node transmission system, a single-antenna BS, which communicates with a single-antenna MS, where the third node consists of either a K-element RIS unit (for the first setup), or a classic DF relay (for the second setup). All the channels between different nodes are considered deterministic. If we omit the third node, in Fig. 1, we get a basic two-node SISO transmission scheme. The latter will be used as a benchmark throughout this work. The system models for both setups are detailed below. We will also derive their SNR expressions.

2.1 A RIS-Assisted Transmission

For the RIS-assisted setup, we have a K-elements RIS unit. The direct channel between the BS and the MS is denoted by $h_{\mathrm{BM}} \in \mathbb{C}$. We refer to $\boldsymbol{h}_{\mathrm{BR}} \in \mathbb{C}^K$ as the channel vector between the BS and the RIS unit, and $\boldsymbol{h}_{\mathrm{MR}} \in \mathbb{C}^K$ as the channel vector between the MS and the RIS unit. The

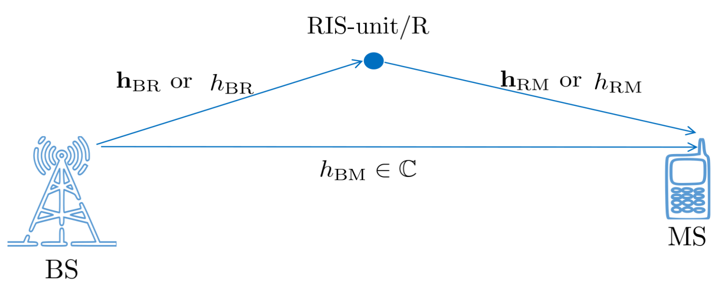

FIG. 1: RIS/relay-assisted wireless communication system

signal $s \in \mathbb{C}$ (satisfying $\mathrm{E}[|s|^2] = 1$) transmitted (with an average transmit power p) by the BS is reflected by the RIS unit toward the MS. The RIS unit produces reconfigurable phase shifts, which are regulated by the RIS controller according to the CSI, the incident signals, and the reflected signals to the MS. The received signal at the MS can be written as

$$\begin{aligned} y &= \underbrace{\sqrt{p}\boldsymbol{h}_{\mathrm{BR}}^{\mathrm{T}}\boldsymbol{\Psi}\boldsymbol{h}_{\mathrm{RM}}s}_{\text{Reflected link}} + \underbrace{\sqrt{p}h_{\mathrm{BM}}s}_{\text{Direct link}} + n \qquad (1) \\ &= \sqrt{p}\left(\boldsymbol{h}_{\mathrm{BR}}^{\mathrm{T}}\boldsymbol{\Psi}\boldsymbol{h}_{\mathrm{RM}} + h_{\mathrm{BM}}\right)s + n \\ &= \sqrt{p}hs + n, \qquad (2) \end{aligned}$$

where $h = \boldsymbol{h}_{\mathrm{BR}}^{\mathrm{T}}\boldsymbol{\Psi}\boldsymbol{h}_{\mathrm{RM}} \in \mathbb{C}$ stands for the effective channel. $\boldsymbol{\Psi} \triangleq \mathrm{diag}\left[\psi_1, \psi_2, \ldots, \psi_K\right] \in \mathbb{C}^{K\times K}$ is a diagonal matrix accounting for the effective phase shifts applied by all RIS unit elements. $\psi_k = \zeta_k e^{j\theta_k}$, $\theta_k \in [0, 2\pi)$ and $\zeta_k \in [0, 1]$ denote, respectively, the phase shift and the amplitude reflection coefficient of the kth reflecting element. $n \sim \mathcal{CN}(0, \sigma^2)$ is the additive white Gaussian noise (AWGN) at the MS. By considering Eq. (1), the SNR at the MS is given as

$$\begin{aligned} \gamma_{\mathrm{RIS}} &= \frac{p\left|\boldsymbol{h}_{\mathrm{BR}}^{\mathrm{T}}\boldsymbol{\Psi}\boldsymbol{h}_{\mathrm{RM}} + h_{\mathrm{BM}}\right|^2}{\sigma^2} \qquad (3) \\ &= \frac{p\left|h_{\mathrm{BM}} + \sum\limits_{k=1}^{K}\zeta_k e^{j\theta_k}\left[\boldsymbol{h}_{\mathrm{BR}}\right]_k\left[\boldsymbol{h}_{\mathrm{RM}}\right]_k\right|^2}{\sigma^2}. \end{aligned}$$

Note that for the case of a basic SISO transmission ($K \to 0$), the received signal at the MS is given by

$$y_2 = \sqrt{p}h_{\mathrm{BM}}s + n, \qquad (4)$$

and its corresponding SNR is

$$\gamma_{\mathrm{SISO}} = \frac{p\left|h_d\right|^2}{\sigma^2}. \qquad (5)$$

2.2 A DF Relay-Assisted Transmission

For a DF relay-assisted setup, we deploy a DF relay at the same location as the RIS unit. We consider a half-duplex communication mode, which consists of two stages. During the first stage, the BS broadcasts its signal. The received signals at the relay (R) and the MS are (Björnson et al., 2020)

$$y_{1R} = h_{\mathrm{BR}}\sqrt{p_1}s + n_{1R}, \qquad (6)$$

$$y_{1\mathrm{MS}} = h_{\mathrm{BM}}\sqrt{p_1}x + n_{1\mathrm{MS}}, \qquad (7)$$

respectively, where p_1 is the transmit power at the BS, s is the signal transmitted by the BS satisfying $\mathrm{E}[|\ s\ |^2] = 1$, and $n_{1R} = n_{1\mathrm{MS}} \sim \mathcal{N}_{\mathbb{C}}\left(0, \sigma^2\right)$ are the AWGN at the relay and the BS, respectively. $h_{\mathrm{BR}} \in \mathbb{C}$ is the channel between the BS and the relay (R). At the second stage, the relay decodes y_{1R}, reencodes the resulting signal, and transmits $\sqrt{p_2}s$. The received signal at the MS is (Björnson et al., 2020)

$$y_{2\mathrm{MS}} = h_{\mathrm{RM}}\sqrt{p_2}s + n_{2\mathrm{MS}}, \qquad (8)$$