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ORIGINAL PAPER

Simultaneously transmitting and reflecting reconfigurable intelligent surfaces (STAR-RIS) with energy harvesting and adaptive power

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Abstract
In this paper, we evaluate and optimize the throughput of STAR-RIS for underlay cognitive radio networks (CRN) with energy harvesting from radio frequency (RF) signals. The secondary source S_S harvests power from node A RF signal. Then, S_S adapts its power to control the interference at primary destination P_D. The broadcasted signal will be delivered to two users U_t and U_r located in the space of transmission and reflection of STAR-RIS in the secondary network. When STAR-RIS is used, the signal to interference plus noise ratio (SINR) at users U_t and U_r is maximized by a wise optimization of STAR-RIS phases. STAR-RIS offers a diversity equal to the number of its elements N. Therefore, when the number of STAR-RIS elements N is doubled, we get up to 15 dB gain.

Keywords STAR-RIS · 6G · CRN · Power adaptation

1 Introduction

STAR-RIS allows to transmit data to two users U_t and U_r [1–5]. The phases shifts of STAR-RIS are optimized to maximize the SINR at U_t and U_r [6–8]. STAR-RIS is a good candidate for 6G communications due to its large throughput and performance enhancement with an increase of number of reflectors N. STAR-RIS for **non-orthogonal multiple access (NOMA)** was studied in [1–9]. The rate of NOMA using STAR-RIS was analyzed in [1]. A comparison of orthogonal multiple access (OMA) and NOMA was presented in [2, 3]. STAR-RIS with federated learning was given in [4]. Channel estimation for STAR-RIS was investigated in [5]. Signal enhancement for STAR-RIS was studied in [6]. Weighted sum rate optimization was discussed in [7]. The security of STAR-RIS was investigated in [8]. Full-duplex communications using STAR-RIS were suggested in [9]. STAR-RIS using multiple antennas was studied in [10, 11]. Sum rate maximization and resource optimization were suggested in [12]. STAR-RIS for unmanned aerial vehicle (UAV) was studied in [13, 14]. Performance analysis of wireless communications using STAR-RIS was suggested in [15]. STAR-RIS with correlated antennas was presented in [16]. The outage probability of STAR-RIS was derived in [17, 18]. The coverage probability of STAR-RIS was derived in [19]. The performance of the network was optimized in [20]. The security of uplink NOMA was studied in [21]. The design of STAR-RIS was discussed in [24–29]. The capacity of STAR-RIS with fixed power was derived in [22, 23]. Power allocation was investigated in [24]. The design of NOMA using STAR-RIS was suggested in [25, 26]. Phase design of STAR-RIS was optimized in [27] so that the SINR is maximized at the two studied users. A network with multiple cells was studied in [28]. The security and two-way relaying were studied in [29, 30]. Device-to-device (D2D) communications using STAR-RIS were proposed in [30].

In CRN, primary and secondary users share the same channel. CRN allows larger data rates than non CRN as the throughput is equal to the sum of primary and secondary throughput. In interweave CRN, spectrum sensing is performed to detect a vacant band left unused by primary users. Therefore, secondary users transmit only when primary users are idle and the band is available. In underlay CRN, secondary users transmit over the same channel as primary users and adapt their power to minimize the interference at primary users. In this paper, we evaluate and optimize the through-

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put of underlay CRN where the secondary source harvests energy from RF signals and adapts its power to control the interference at primary destination. STAR-RIS is between the secondary source and two users U_t and U_r so that the signal to interference plus noise ratio (SINR) is maximized. STAR-RIS offers a diversity equal to the number of its elements N and allows a significant throughput enhancement. Therefore, STAR-RIS is a good candidate for 6G wireless communications.

STAR-RIS with power adaptation was not studied in [1–30]. Therefore, STAR-RIS was not yet proposed for underlay CRN where the secondary source adapts its power to minimize the interference at primary destination. In fact, the transmit power is fixed in [1–30] and cannot be used in underlay CRN. In this paper, it is assumed that S_S harvests power from the node A signal. The harvested power is used to broadcast data to two secondary users U_t and U_r. S_S controls the level of interference at P_D using power adaptation.

- We evaluate the throughput of STAR-RIS when S_S harvests power from node A signal. We also consider that S_S use power adaptation to control the level of interference at P_D.
- There are two main contributions in this paper. First, we study STAR-RIS for underlay CRN where the secondary source has an adaptive transmit power while the power is fixed in [1–30]. Second, the secondary source does not have a battery that should be recharged as assumed in [1–30]. The secondary source harvests energy from node A RF signal to be able to transmit data to U_t and U_r using STAR-RIS.
- We optimize the throughput by adjusting the harvesting duration.

Next section describes the harvested power. Section 3 computes the throughput of STAR-RIS. Section 4 describes the theoretical and simulation results. Section 5 concludes the article.

2 Energy harvesting

The harvested energy is [30]

$$E = P_A \alpha F \varepsilon \mu_0 |h|^2, \tag{1}$$

where F and $0 < \alpha F < F$ are frame and harvesting durations, P_A is the power of node A, $0 < \varepsilon < 1$ is the efficiency of the energy conversion, and $\sqrt{\mu_0} h$ is channel from A to S_S.

The available transmit symbol energy is

$$E_{s,\text{available}} = \frac{E}{(1-\alpha)\frac{F}{T_s}} = \beta |h|^2, \tag{2}$$

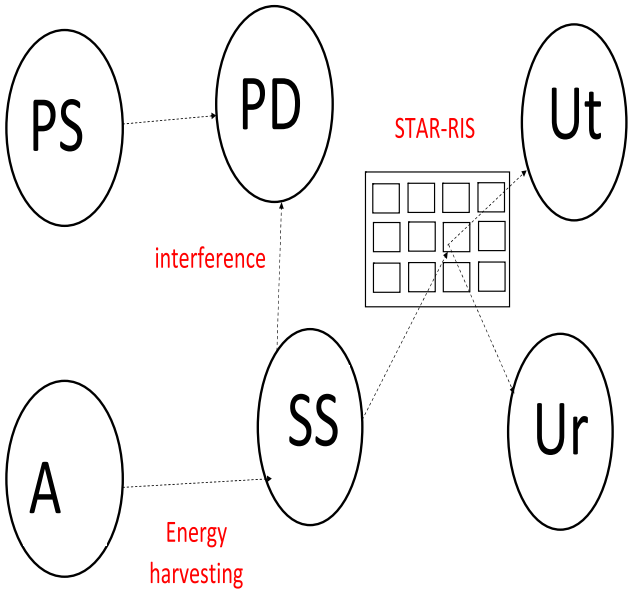

Fig. 1 STAR-RIS for CRN

where T_s is the symbol period,

$$\beta = \frac{\mu_0 E_A \varepsilon \alpha}{1-\alpha} \tag{3}$$

where $E_A = P_A T_s$

We deduce the symbol energy as

$$E_s = \min\left(\frac{T}{|h_{S_S P_D}|^2}, E_{s,\text{available}}\right) \tag{4}$$

where h_{XY} is the channel from X to Y and T is the interference threshold. The generated interference at P_D is less than T: $E_s |h_{S_S P_D}|^2 \leq T$. E_s and T are in Joules, F and T_s are in seconds, and all other parameters do not have units.

The cumulative distribution function (CDF) of E_s is

$$F_{E_s}(x) = 1 - P\left(\min\left(\frac{T}{|h_{S_S P_D}|^2}, E_{s,\text{available}}\right) > x\right) \tag{5}$$

We deduce

$$\begin{aligned} F_{E_s}(x) &= 1 - P\left(\frac{T}{|h_{S_S P_D}|^2} > x\right) P(E_{s,\text{available}} > x) \\ &= 1 - \left[1 - e^{\frac{-T}{x \rho_{S_S P_D}}}\right] e^{-\frac{x}{\beta}} \end{aligned} \tag{6}$$

where $\rho_{S_S P_D} = E(|h_{S_S P_D}|^2)$.

3 STAR-RIS system model

In Fig. 1, the source S_S harvests power from node A RF signal to broadcast data to two users U_t and U_r. A STAR-RISS

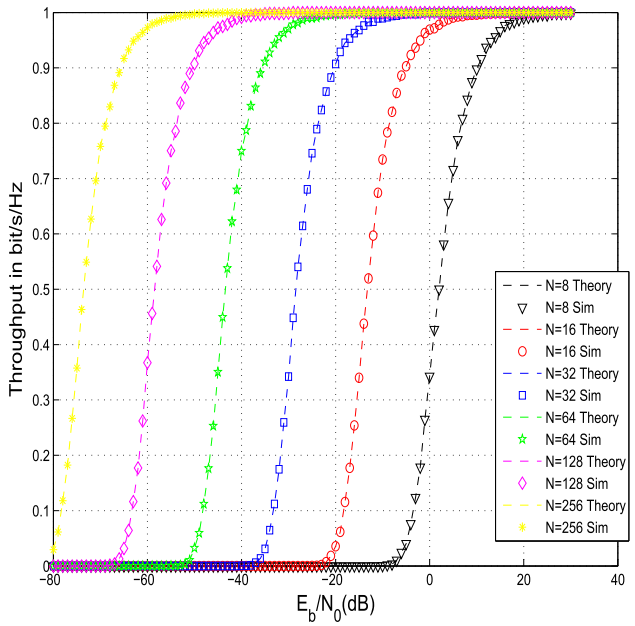

Fig. 2 Throughput for interference threshold $T = 1$ and number of STAR-RIS elements $N = 8, 16, 32, 64, 128, 256$

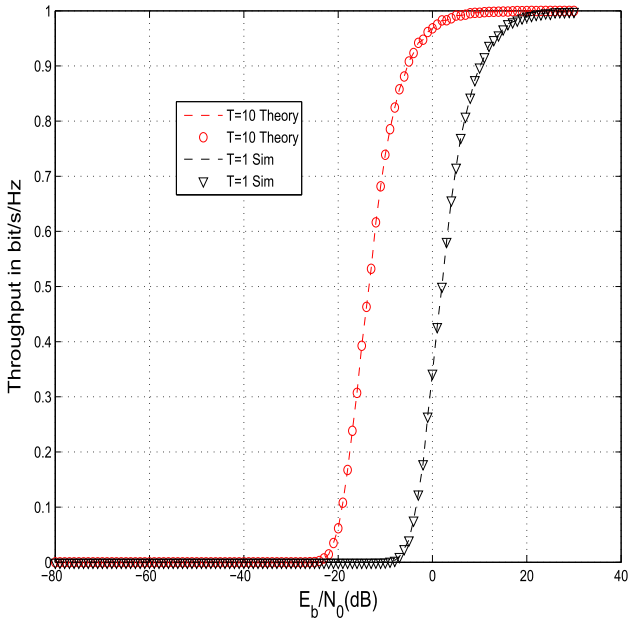

Fig. 3 Throughput for interference threshold $T = 1, 10$ and number of STAR-RIS elements $N = 8$

with N elements is between the source S_S and U_t, U_r. We assume a line-of-sight (LOS) propagation between the secondary source and STAR-RIS and from STAR-RIS to U_t and U_r as considered in [1–30]. The transmission and reflection coefficients are $\eta_n^t e^{j\theta_n^t}$ and $\eta_n^r e^{j\theta_n^r}$ where $0 < \theta_n^r, \theta_n^t < 1$ and $0 < \eta_n^r < 1, 0 < \eta_n^t < 1$ such that $(\eta_n^r)^2 + (\eta_n^t)^2 = 1$. U_r and U_t are located, respectively, in the space of reflection and transmission of STAR-RIS. The channel between the source S_S and STAR-RIS is denoted by $h_n = |h_n|e^{j\phi_{h_n}}$ while the channel between nth element of STAR-RIS and user U_q for $q = t, r$ is $g_n^q = |g_n^q|e^{j\phi_{g_n^q}}$.

The signal at U_q $q = r, t$ is

$$y_q = \sqrt{E_s \zeta_q} \sum_{n=1}^{N} g_n^q \eta_n^q e^{j\theta_n^q} h_n x_q + \sqrt{E_s \zeta_{q'}} \sum_{n=1}^{N} g_n^q \eta_n^q e^{j\theta_n^q} h_n x_{q'} + n_q; \quad (7)$$

where $q' = r$ when $q = t$ and $q' = t$ when $q = r$, ζ_q and $\zeta_{q'}$ are power allocation coefficient for U_q and $U_{q'}$ where $\zeta_q + \zeta_{q'} = 1$. x_q (resp. $x_{q'}$) is the symbol of U_q (resp. $U_{q'}$). The broadcasted signal by S_S is equal to $\sqrt{E_s}[\sqrt{\zeta_r} x_r + \sqrt{\zeta_t} x_t]$. n_q is Gaussian, zero mean with variance N_0.

The SNR at U_q is expressed as

$$\gamma_q = \frac{E_s \zeta_q |\sum_{n=1}^{N} |g_n^q||h_n|\eta_n^q exp(j[\theta_n^q + \phi_{h_n} + \phi_{g_n^q}])|^2}{N_0 + E_s \zeta_{q'} |\sum_{n=1}^{N} |g_n^q||h_n|\eta_n^q exp(j[\theta_n^q + \phi_{h_n} + \phi_{g_n^q}])|^2} \quad (8)$$

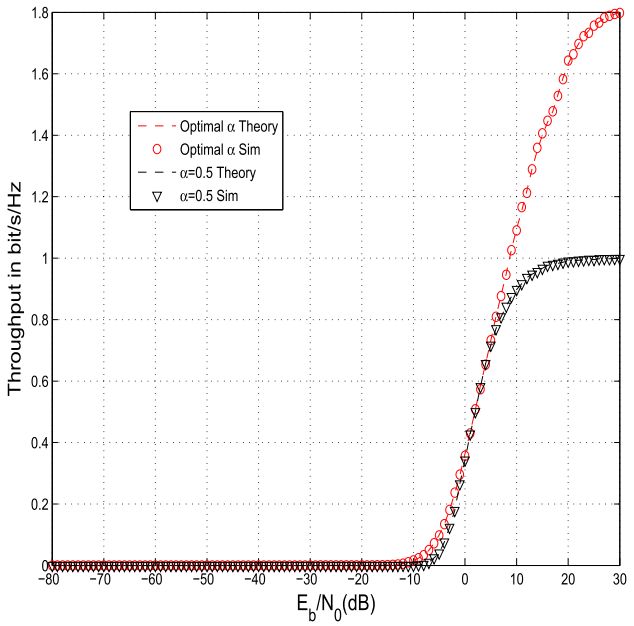

Fig. 4 Throughput for number of STAR-RIS elements $N = 8$, interference threshold $T = 1$, optimal harvesting duration α and $\alpha = 0.5$

The optimal STAR-RIS phase shifts are chosen so that all reflections have a zero phase $\theta_n^q + \phi_{h_n} + \phi_{g_n^q} = 0$ [1]. Therefore, we have

$$\theta_n^q = -\phi_{h_n} - \phi_{g_n^q}. \quad (9)$$

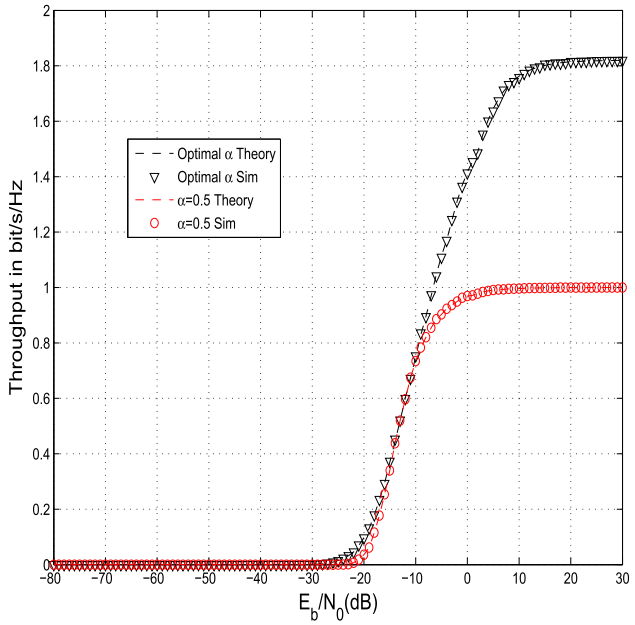

Fig. 5 Throughput for number of STAR-RIS elements $N = 16$, interference threshold $T = 1$, optimal harvesting duration α and $\alpha = 0.5$

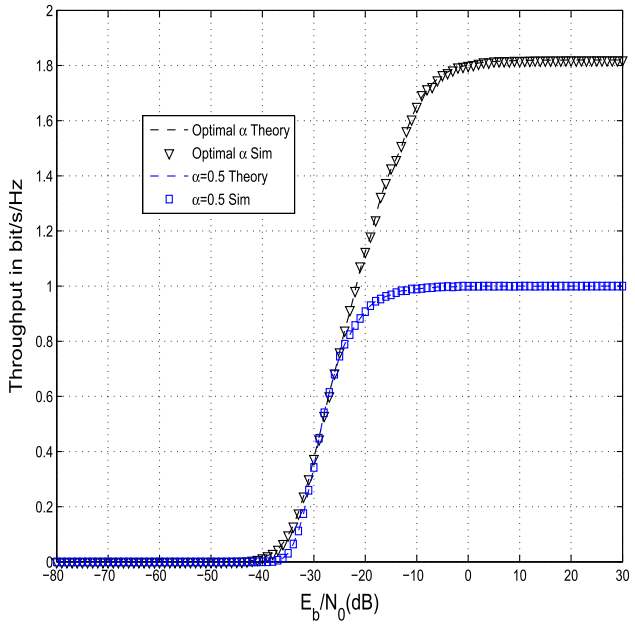

Fig. 6 Throughput for number of STAR-RIS elements $N = 32$, interference threshold $T = 1$, optimal harvesting duration α and $\alpha = 0.5$

Using (9), the optimal SINR at U_q is equal to

$$\gamma_q = \frac{E_s \zeta_q A_q^2}{E_s \zeta_{q'} A_q^2 + N_0} \tag{10}$$

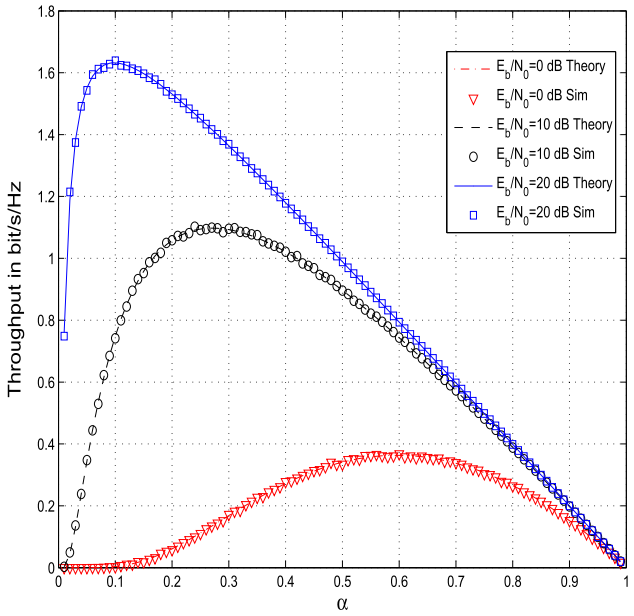

Fig. 7 Throughput versus harvesting duration α for number of STAR-RIS elements $N = 8$ and interference threshold $T = 1$

where

$$A_q = \sum_{n=1}^{N} |g_n^q||h_n|\eta_n^q \tag{11}$$

A_q is Gaussian with mean

$$m_{A^q} = \sum_{n=1}^{N} \eta_n^q \frac{\pi}{4} \frac{1}{d_{\text{STAR-RIS},U_q}^{\text{ple}/2} d_{S_S,\text{STAR-RIS}}^{\text{ple}/2}} \tag{12}$$

and variance

$$\sigma_{A_q}^2 = \sum_{n=1}^{N} (\eta_n^q)^2 \left[1 - \frac{\pi^2}{16}\right] \frac{1}{d_{\text{STAR-RIS},U_q}^{\text{ple}} d_{S_S,\text{STAR-RIS}}^{\text{ple}}} \tag{13}$$

where ple is the path loss exponent and d_{XY} is the distance from X to Y.

Let $X_q = A_q^2$ and $Y_q = E_s A_q^2 = E_s X_q$, the CDF of SINR γ_q is deduced from that of Y_q as

$$F_{\gamma_q}(x) = F_{Y_q}\left(\frac{N_0 x}{\zeta_q - \zeta_{q'} x}\right). \tag{14}$$

where $F_{Y_q}(x)$ is provided in (18).

We have

$$Y_q = E_s X_q \tag{15}$$

where

$$X_q = A_q^2, \tag{16}$$

The CDF of X_q is

$$F_{X_q}(x) = P\left(-\sqrt{x} \le A_q \le \sqrt{x}\right) \simeq 0.5erfc\left(\frac{-\sqrt{x} - m_{A_q}}{\sqrt{2}\sigma_{A_q}}\right) - 0.5erfc\left(\frac{\sqrt{x} - m_{A_q}}{\sqrt{2}\sigma_{A_q}}\right) \quad (17)$$

By derivation, the probability density function (PDF) of X_q is

$$p_{X_q}(x) \simeq \sqrt{\frac{1}{8\pi\sigma_{A_q}^2 x}} e^{-\frac{\left[\sqrt{x}+m_{A_q}\right]^2}{2\sigma_{A_q}^2}} + \sqrt{\frac{1}{8\pi\sigma_{A_q}^2 x}} e^{-\frac{\left[\sqrt{x}-m_{A_q}\right]^2}{2\sigma_{A_q}^2}}. \quad (18)$$

The CDF of Y_q is evaluated as

$$F_{Y_q}(y) = \int_0^{+\infty} F_{E_s}\left(\frac{y}{x}\right) p_{X_q}(x)\mathrm{d}x, \quad (19)$$

The packet error probability (PEP) is deduced from the CDF of the SINR γ_q, $F_{\gamma_q}(x)$, using the waterfall threshold w_0: [31]

$$\mathrm{PEP}_q < F_{\gamma_q}(w_0), \quad (20)$$

In this paper, we use the upper bound (20) to evaluate the PEP_q at U_q. w_0 is defined as [31]

$$w_0 = \int_0^{+\infty} [1 - \mathrm{SEP}(z)]^{PL}\mathrm{d}z, \quad (21)$$

SEP is the symbol error probability [32]

$$\mathrm{SEP}(z) = 2\left(1 - \frac{1}{\sqrt{Q}}\right) erfc\left(\sqrt{\frac{3z}{Q-1}}\right) \quad (22)$$

PL and Q are packet and constellation size.

The throughput is

$$\mathrm{Thr}_q(\alpha) = (1-\alpha)[1 - \mathrm{PEP}_q(\alpha)], \quad (23)$$

In Eq. (23), $0 < \alpha < 1$ gives the harvesting duration αF where F is the frame duration in seconds. The throughput is maximized as

$$Thr_q^{\max} = \max_{0<\alpha<1} Thr_q(\alpha). \quad (24)$$

4 Results

We plotted the throughput for $\varepsilon = 0.5$, $d_{S_S,\text{STAR-RIS}} = 1$, $d_{\text{STAR-RIS},U_t} = 1$, $d_{\text{STAR-RIS},U_r} = 1.5$, PL = 500, ple = 3. The other parameters are $\zeta_q = 0.8 = 1 - \zeta_{q'}$ $\eta_n^t = \eta_n^r = \frac{1}{\sqrt{2}}$.

Figure 2 shows the throughput for CRN with adaptive power for $T = 1$, $\alpha = 0.5$, $T = 1$ and $N = 8, 16, 32, 64, 128, 256$. When STAR-RIS is used, the SINR at users U_t and U_r is maximized by a wise optimization of STAR-RIS phases. STAR-RIS offers a diversity equal to the number of its elements N. Therefore, when the number of STAR-RIS elements N is doubled, we get 15 dB diversity gain.

Figure 3 depicts the throughput for $T = 10, 1$, $N = 8$, and $\alpha = 0.5$. We observe the throughput improves for $T = 10$ as S_S can increase its power. The numerical results are close to the simulation results and confirms that our derivations are correct.

Figures 4, 5, and 6 depict the throughput for $N = 8, 16, 32$, $T = 1$. The obtained throughput for optimal α is better than $\alpha = 0.5$ since harvesting duration optimization offers an important increase in throughput.

Figure 7 depicts the throughput versus α for $N = 8$ and $T = 1$. Throughput is concave and can be maximized.

5 Conclusion

In this article, we proposed the use of STAR-RIS for underlay cognitive radio networks. We studied the throughput of STAR-RIS with energy harvesting. Power adaptation is used by the secondary source to control the level of interference at P_D. The secondary source transmits data to two users U_t and U_r. We obtained 15 dB gain when the number of reflectors is doubled. The obtained results can be applied for underlay cognitive radio networks. As a perspective, we can study STAR-RIS with multipath propagation.

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Data availability Material and data are not available.

Code Availability Custom code and software application are not available.

Declarations

Conflict of interest There is no conflict of interest for this article.

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