Optimal Power Allocation in STAR-RIS for CoMP Transmission

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Abstract: RSimultaneous transmitting and reflecting reconfigurable intelligent surface (STAR-RIS) is a new kind of metasurface which can transmit and reflect incident signals to users located at both sides of the surface. At each element of STAR-RIS, two coefficients are used to adjust the phase shifts and amplitudes of the transmitted and reflected signals. Thus, the overall power needs to be split between transmission and reflection coefficients for the sake of energy conservation. In this letter, we focus on the STAR-RIS aided downlink coordinated multi-point (CoMP) transmission and drive a close-form expression for the optimal power allocation when maximal ratio transmission (MRT) is used. Simulation results show that although this expression is only a approximate result, using it can also achieve the same bit error rate (BER) performance as that provided by the optimal power allocation.

Keywords: CoMP, Power allocation, STAR-RIS

Classification: Wireless Communication Technologies

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1 Introduction

The rapid development of the mobile Internet and the Internet of Things (IoT) exponentially accelerates the demands for high system capacity, massive connectivity and high reliability in future wireless communications. By means of programmable electromagnetic (EM) metamaterials, reconfigurable intelligent surface (RIS) has emerged as a promising solution for satisfying these demands [1]. A RIS is composed of a large number of low-cost and programmable elements, and thus can reconfigure the propagation of incident wireless signals by adjusting the parameter of each element. Through properly configuring the phase shifts, the reflected signals can be constructively added at the intended receiver, and therefore, improving the received signal strength. It is known that the performance of the cell-edge user is a tricky issue in cellular communications. This issue can be addressed by utilizing coordinated multipoint (CoMP) transmission techniques, in which joint transmission and joint detection are the two essential techniques deployed in the downlink and uplink, respectively. To further enhance the performance of cell-edge users, RISs can be deployed to assist CoMP transmission, since they provide additional reconfigured propagation paths [2].

Conventional RISs can only act as pure reflective or transmissive metasurfaces. Hence, the served users ought to be on the same side of RIS which limits the flexibility of deploying them in CoMP. Recently, a novel concept of simultaneous transmitting and reflecting RIS (STAR-RIS) has been proposed, where incident signals can be transmitted and reflected to users located at different sides of the surface [3]. Its prototype has been developed by NTT DoCoMo which verified the practical impenetrability of STAR-RIS [4]. By using STAR-RIS, the coverage can be significantly extended which makes it easy to deploy them in any wireless communication systems [5]. Different from conventional RISs, there are two coefficients need to be configured at each element of STAR-RIS. One is used to adjust the phase shifts and amplitudes of the transmitted signal, the other is configured for reflected signal. Due to the fact of energy conservation, the sum energy of the transmitted and reflected signals has to be equal to that of the incident signals. Thus, the overall power needs to be split between transmission and reflection coefficients at each element. In this letter, we focus on the maximal ratio transmission (MRT) and drive a close-form expression for the optimal power allocation. Simulation results show that although this expression is only an approximate result, it can also achieve the same bit error rate (BER) performance as the optimal power allocation, which is obtained through solving a quartic equation.
2 System model

We consider a narrow-band downlink CoMP system operating over frequency-flat channels, where a single antenna cell-edge user communicates with two single antenna base stations (BSs). The coverage radius of each cell is $R$, and each BS is located at the center of its coverage area. In order to enhance the signal quality, a STAR-RIS consisting of $M$ elements is deployed to provide additional signal propagation paths. Assume the STAR-RIS is controlled by a certain BS, labelled by $T$, and located close to cell edge. In this case, it can not only transmit BS $T$’s signal but also reflect the signal from the neighboring cooperative BS, denoted by $R$, as illustrated in Fig. 1. Furthermore, we assume the user data can be exchanged between BS A and B through a specific interface, such as Xn in 5G, to make use of joint transmission.

The channel model is characterized by path loss and small-scale fading. Due to the long propagation distances and extensive scatters, the small-scale fading of direct channels between the BSs and the cell-edge user is assumed to follow Rayleigh fading. Thus, the channels from BS $k$, $k \in \{T, R\}$, to the user can be expressed by

$$h_{0,k} = \sqrt{\frac{\rho_0}{d_{0,k}}} v_k$$  \hspace{1cm} (1)

where $d_{0,k}$ denotes the distance between BS $k$ and the user, $\alpha_0$ represents the path loss exponent and $\rho_0$ is the path loss at a reference distance of one meter. $v_k$ is a complex Gaussian random variable with zero mean and unit variance.

Since the STAR-RIS is usually deployed close to the user, the channel between STAR-RIS and user is thus dominated by line-of-sight (LOS) path

Fig. 1. An illustration of STAR-RIS aided downlink CoMP.
and obeys Rician fading distribution. In this case, the channel can be written by

\[
G = \sqrt{\frac{\rho_0}{d_1^{\alpha_1}}} \left( \sqrt{\frac{K}{K+1}} g^{\text{LOS}} + \sqrt{\frac{1}{K+1}} g^{\text{NLOS}} \right)
\]

(2)

where \(d_1\) denotes the propagation distance between the STAR-RIS and the user, \(\alpha_1\) represents the path loss exponent and \(K\) denotes the Rician factor. \(g^{\text{LOS}}\) and \(g^{\text{NLOS}}\) are both \(M\) by one vectors with their elements denoting the deterministic LOS components and the random non-line-of-sight (NLOS) components, respectively, of the channels from each element in STAR-RIS to user. Moreover, each entry in \(g^{\text{NLOS}}\) is modelled as an independent and identically distributed (i.i.d.) Gaussian random variable with zero mean and unit variance. On the other hand, since the STAR-RIS is located far from BSs, the channel between the STAR-RIS and BS \(k\) can be expressed by

\[
F_k = \sqrt{\frac{\rho_0}{d_{2,k}^{\alpha_2}}} f_k^{\text{NLOS}}
\]

(3)

where \(d_{2,k}\) and \(\alpha_2\) denote the distance and path loss exponent between the STAR-RIS and BS \(k\). Similarly, \(f_k^{\text{NLOS}}\) is an \(M\) by one vector with each entry following Rayleigh distribution.

Finally, the integrated propagation channels for BS \(T\) and \(R\) can be expressed by

\[
h_T = h_{0,T} + h_{1,T} = h_{0,T} + G^H \Theta_T F_T
\]

(4)

and

\[
h_R = h_{0,R} + h_{1,R} = h_{0,R} + G^H \Theta_R F_R,
\]

(5)

where \(\Theta_T = \sqrt{\beta_t} \text{diag} \left( e^{j\theta_{t0}}, e^{j\theta_{t1}}, \ldots, e^{j\theta_{tM-1}} \right)\) and \(\Theta_R = \sqrt{\beta_r} \text{diag} \left( e^{j\theta_{r0}}, e^{j\theta_{r1}}, \ldots, e^{j\theta_{rM-1}} \right)\) denote the transmission and reflection coefficient matrices, respectively. Here, \(\sqrt{\beta_t}, \sqrt{\beta_r} \in [0, 1]\) and \(\theta_{t0}, \theta_{r0} \in [0, 2\pi)\) characterize the amplitude and phase shift adjustments imposed on the incident signals facilitated by the \(m\)-th element during transmission and reflection, respectively. It should be noted that to reduce the signaling overhead between the STAR-RIS and its controlling BS, all elements are assumed to have the same adjusting amplitude coefficients and \(\beta_t + \beta_r = 1\) for the sake of energy conservation.

Assuming the real channel parameters are available, we can calculate the phase of each individual cascade channel, for BS \(k\), as

\[
\varphi_k^m = \arg \left( F_k (m) \cdot G (m) \right), \quad m = 0, 1, \ldots, M - 1
\]

(6)

where \(F_k (m)\) and \(G (m)\) denote the \(m\)-th entry of vector \(F_k\) and \(G\), respectively. In order to enhance the signal quality, the phase shifts for transmission and reflection coefficient of the \(m\)-th element are usually set to \(\theta_{t0} = \arg (h_{0,T}) - \varphi_{t0}\) and \(\theta_{r0} = \arg (h_{0,R}) - \varphi_{r0}\), respectively. In this case, when maximal ratio transmission (MRT) is used, the received baseband equivalent discrete-time signal at user can be written as
\[ y(n) = \left([|h_{0,T}| + \sqrt{\beta_t} |h_{1,T}|]^2 + 
(|h_{0,R}| + \sqrt{\beta_r} |h_{1,R}|)^2\right) x(n) + w(n) \] (7)

where \( x(n) \) denotes the data symbol transmitted to the cell-edge user, at the \( n \)-th time instant, which belongs to a finite-alphabet complex constellation with power of \( P \). \( w(n) \) is the additive white complex Gaussian noise (AWGN) with zero mean and variance of \( \sigma_w^2 \). Splitting energy between transmission and reflection coefficients will lead to different signal power at receiver. Therefore, the optimal value is left to find.

3 Proposed method

Let us focus on the overall channel in Eq. (7) and denote it by

\[ z = \left([|h_{0,T}| + \sqrt{\beta_t} |h_{1,T}|]^2 + (|h_{0,R}| + \sqrt{\beta_r} |h_{1,R}|)^2\right). \] (8)

Since \( \beta_t + \beta_r = 1 \), Eq. (8) can also be written as

\[ z = \left([|h_{0,T}| + \sqrt{\beta_t} |h_{1,T}|]^2 + (|h_{0,R}| + \sqrt{1-\beta_t} |h_{1,R}|)^2\right). \] (9)

By setting the first derivative of Eq. (9) with respect to \( \beta_t \) equal to zero, we obtain

\[
\frac{|h_{0,T}| |h_{1,T}| + \sqrt{\beta_t} |h_{1,T}|^2}{\sqrt{\beta_t}|h_{0,R}| |h_{1,R}| + \sqrt{1-\beta_t} |h_{1,R}|^2} = 0.
\] (10)

Unfortunately, the closed-form expressions of its roots are not easily to find. Notice that as \( 0 \leq \beta_t \leq 1 \), \( \sqrt{\beta_t} \) and \( \sqrt{1-\beta_t} \) can be approximated by \( \beta_t \) and \((1-\beta_t)\). In this case, we obtain

\[
\frac{|h_{0,T}| |h_{1,T}| + \beta_t |h_{1,T}|^2}{|h_{0,R}| |h_{1,R}| + (1-\beta_t) |h_{1,R}|^2} = 0
\] (11)

which is a quadratic equation and has two roots. Both of the roots can be expressed by closed-form formulas and the single positive one is found to be close to the meaningful root of Eq. (10) which can be expressed by

\[
\beta_t^{\text{opt}} \approx \frac{|h_{1,T}|^2 - |h_{1,R}|^2 - |h_{0,T}| |h_{3,T}| - |h_{0,R}| |h_{1,R}| + \sqrt{\eta_1 + \eta_2}}{2(|h_{1,T}|^2 - |h_{1,R}|^2)}
\] (12)

where

\[
\eta_1 = |h_{0,T}|^2 |h_{1,T}|^2 + 2 |h_{0,T}| |h_{1,T}| |h_{0,R}| |h_{1,R}| 
+ 2 |h_{0,T}| |h_{1,T}|^3 - 2 |h_{0,R}| |h_{1,R}|^2
\] (13)

and

\[
\eta_2 = |h_{0,R}|^2 |h_{1,R}|^2 - 2 |h_{0,R}| |h_{1,R}| |h_{1,T}|^2 + 2 |h_{0,R}| |h_{1,R}|^3 
+ |h_{1,T}|^4 - 2 |h_{1,T}|^2 |h_{1,R}|^2 + |h_{1,R}|^4.
\] (14)
It should be noted that when a channel falls into deep fading, no power needs to be allocated to its corresponding coefficient. However, this situation is nearly impossible to happen, since there are additional propagation paths provided by the STAR-RIS.

4 Simulation and results

Several computer simulations are carried out in this section to evaluate the performance of the proposed method with QPSK modulation. The channel is assumed to be a quasi-static fading channel, i.e., the channel remains constant within the block duration time, and changes to new independent realizations for the next block duration time. In simulation, we set $\rho_0 = -30\text{dB}$, $d_{0,T} = d_{0,R} = R = 100\text{m}$, $\alpha_0 = \alpha_1 = \alpha_2 = 2.2$, $d_1 = 20\text{m}$, $d_{2,R} = 110\text{m}$, $d_{2,T} = 90\text{m}$, $P = 30\text{dBm}$ and $K = 10$. Moreover, ideal channel estimation is assumed and no channel coding is considered.

Fig. 2 shows an example of $z$ under a realization of channel for the case of $\sigma_n^2 = -110\text{dBm}$. As can be seen from Fig. 2, $z$ varies with the change of $\beta_t$ and has a maximal value at 0.457 through solving Eq. (10). When using the closed-form expression in Eq. (12), we obtain 0.476 which is close to the accurate value and the loss in $z$ can almost be neglected. In Fig. 3, the BER performance of the STAR-RIS aided CoMP is given as a function of noise variance. For comparison, the conventional CoMP, where no STAR-RIS is deployed, is also simulated. From Fig. 3, we find that with the aid of STAR-RIS, the MRT performance can be further improved and the optimal power allocation can also be achieved by using the derived closed-form expression.

5 Conclusion

In this letter, we investigated the STAR-RIS aided downlink CoMP transmission and derived a approximate close-form expression for the optimal power splitting, when MRT is used. Simulation results show that this approximate solution can also achieve the same BER performance as the optimal power allocation which is obtained through solving a quartic equation. Moreover, with the aid of the STAR-RIS, additional propagation paths have been introduced which improves the MRT performance largely.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (No. 2020YFB1806603) and the Research and Development Center China, Sony (China) Ltd.
Fig. 2. An example of power allocation.

Fig. 3. BER comparison.