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LETTER

Energy Efficiency Maximization for Active RIS Switcher Assisted MISO Systems

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SUMMARY Reconfigurable intelligent surface (RIS) is treated as a promising technology for future wireless communications. In this letter, we investigate the active RIS-assisted MISO systems, which can overcome the multiplicative fading effect introduced by the passive RIS. In particular, the active sub-connection architecture of RIS is used to overcome the high power consumption of the existing fully-connected architecture, where each component independently controls its phase shift but shares the same power amplifier. In order to reduce the power loss of each component, we propose to add a switcher device in the power amplifier to select the most appropriate component. As the component is selected, the active number of components is significantly reduced along with less power consumption. Our analysis shows that the introduced switcher brings less performance loss, indicating that higher energy efficiency (EE) can be achieved. Furthermore, EE maximization problems with power constraints are considered in the active RIS assisted system for the architecture with switcher, and the corresponding joint beamforming design is derived. Simulation results show that the proposed structure and method with switcher can effectively improve EE compared with the schemes without switcher.

key words: *Active reconfigurable intelligent surface (RIS), energy efficiency (EE), sub-connected architecture, switcher.*

1. Introduction

Reconfigurable intelligent surface (RIS), also named as intelligent reflecting surface (IRS), has been emerged as a promising new paradigm for sixth-generation (6G) wireless communications [1]. RIS is a planar surface comprising a large number of passive reflecting elements, and can be massively deployed as an auxiliary device in wireless networks to enhance its spectral capacity. Since the multiplicative fading effect makes it almost impossible for passive RISs to achieve noticeable capacity gains, active RISs are proposed to overcome the fundamental physical limitation for wireless communication systems [2]. The key feature of active RISs is their added amplifications can actively reflect signals to enhance the performance and can be realized by integrating reflection-type amplifiers into their reflecting elements.

By exploiting the advantages of active RISs, new structural designs and optimization problems are considered for wireless communications in [3]. Specifically, fully-connected and sub-connected active RIS structures are investigated in [4], where the sub-connected architecture needs less power consumption is verified. Different from the fully-connected active RIS, one power amplifier is shared by the sub-connected active RIS elements. In this way, the number of required power amplifiers can be significantly reduced to save power. The research of active RIS provides good support for the basic concept of holographic multiple input single output (MISO) surfaces.

Meanwhile, energy efficiency (EE) is a key measurement of future wireless networks. The EE of an RIS-aided uplink wireless network has been optimized in [5], considering both active and nearly-passive RISs, with global reflection constraints.

Compared with the above works, this letter investigates the EE maximization problem in a MISO system assisted by a sub-connected active RIS architecture. Inspired by improved RIS architectures, we first introduce a switcher assisted architecture to further lower the cost of the sub-connected active RIS, including its signal and channel models, hardware architecture as well as practical constraints. Then, its corresponding EE optimization problem is formulated. Accordingly, a joint beamforming design is developed to solve this problem. Simulations are provided to validate its effectiveness.

Symbols: $\mathbb{C}$ and $\mathbb{R}_+$ respectively represent the set of complex and positive real numbers, $\boldsymbol{X}^*$ and $\boldsymbol{X}^{\mathrm{H}}$ respectively represent the conjugate and conjugate transpose of matrix $\boldsymbol{X}$, $\|\boldsymbol{X}\|$ represents the Frobenius norm of matrix $\boldsymbol{X}$, and diag$(\cdot)$ is the diagonal operation.

2. System Model

In this section, we firstly reconstruct the sub-connected architecture for active RIS with assisted switchers. Then, we use the general signal model to study the EE optimization problem of the switcher assisted sub-connected active RIS in MISO systems.

For the existing sub-connected architecture of active RIS in [4] [6], multiple RIS elements are served by different phase-shift circuits but the same power amplifier. Since these RIS elements can control the phase shifts independently, we propose to add a switcher for each phase-shift circuit to further reduce the power consumption, as shown in Fig. 1. The switcher is served as a selector for each RIS element, where only the most

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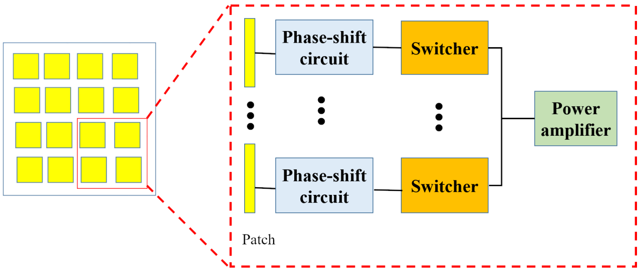

Fig. 1 Proposed architecture of switcher assisted sub-connected active RIS.

appropriate phase-shifting circuit is selected by turning on its switcher, but turn off the other phase-shifting circuits. The selection principle is determined in accordance with the practical requirement.

We consider an active RIS assisted MISO system, where the N-element active RIS assists the transmission from an M-antenna base station (BS) to K single antenna users. Specifically, based on the proposed architecture, we define $L = N/T$ as the number of power amplifiers required, where T denotes the number of elements within a sub-array. Then, the precoding matrix $\boldsymbol{\Psi} \in \mathbb{C}^{N\times N}$ at the active RIS can be written as

$$\boldsymbol{\Psi} = \mathrm{diag}(\psi) = \mathrm{diag}(\boldsymbol{\Theta}\boldsymbol{\Gamma}\boldsymbol{a})\mathrm{diag}(S_j) \tag{1}$$

where $\boldsymbol{\Theta} \in \mathbb{C}^{N\times N}$ represents the phase shift diagonal matrix, $\boldsymbol{a} \in \mathbb{R}_+^{L\times 1}$ represents the amplification factor vector, and S_j denotes the switcher condition of each reflective array. If it is turned on, $S_j = 1$; otherwise, $S_j = 0$. In addition, $\boldsymbol{\Gamma} \in \mathbb{C}^{N\times L}$ is defined as an indication matrix representing the connection relationship between the power amplifier and the phase shifting circuit. Generally, we can assume that $\boldsymbol{\Gamma} = \mathbf{I}_L \otimes \mathbf{1}_T$.

Denote $\mathbf{G}^{N\times M}$, $\boldsymbol{f_k} \in \mathbb{C}^{N\times 1}$, $\boldsymbol{h_k} \in \mathbb{C}^{M\times 1}$ as the channels of BS-to-RIS, RIS-to-user k, and BS-to-user k, respectively. Then, the signal y_k received at user k can be expressed as

$$\mathrm{y}_k = \tilde{\boldsymbol{h}}_k^{\mathrm{H}} \sum_{i=1}^{K} \boldsymbol{w}_i s_i + \boldsymbol{f}_k^{\mathrm{H}} \boldsymbol{\Psi} \boldsymbol{z} + n_k \tag{2}$$

where $\tilde{\boldsymbol{h}}_k^{\mathrm{H}} = \boldsymbol{h}_k^{\mathrm{H}} + \boldsymbol{f}_k^{\mathrm{H}}\boldsymbol{\Psi}\boldsymbol{G}$ is the $1 \times M$ equivalent channel from the BS to user k, s_i denotes the transmit signal for the k-th terminal, $\boldsymbol{w}_i \in \mathbb{C}^{M\times 1}$ represents the corresponding beamforming vector at the BS, $n_k \sim \mathcal{CN}\left(0, \sigma^2\right)$ is the additive Gaussian white noise (AWGN) with power σ^2 at user k, and $\boldsymbol{z} \sim \mathcal{CN}\left(\mathbf{0}_N, \sigma_z^2 \mathbf{I}_N\right)$ denotes the introduced dynamic noise at the active RIS. Without loss of generality, it can be assumed that $\mathbb{E}\left\{|s_i|^2\right\} = 1$ as [7]. Therefore, the received signal to interference-plus-noise ratio (SINR) at the k-th user is written as

$$SINR_k = \frac{\left|\tilde{\boldsymbol{h}}_k^{\mathrm{H}} \boldsymbol{w}_k\right|^2}{\sum_{i=1, i\neq k}^{K} \left|\tilde{\boldsymbol{h}}_k^{\mathrm{H}} \boldsymbol{w}_i\right|^2 + \left\|\boldsymbol{f}_k^{\mathrm{H}} \boldsymbol{\Psi}\right\|^2 \sigma_z^2 + \sigma^2} \tag{3}$$

In the communication system, the power consumption includes the transmission power of BS and RIS, and the power consumed by all components of the system, which are respectively expressed as

$$P_{\mathrm{BS}} = \xi \sum_{k=1}^{K} \|\boldsymbol{w}_k\|^2 + W_{\mathrm{BS}} \tag{4}$$

$$P_{\mathrm{RIS}} = \zeta \left(\sum_{k=1}^{K} \|\boldsymbol{\Psi}\boldsymbol{G}\boldsymbol{w}_k\|^2 + \|\boldsymbol{\Psi}\|^2 \sigma_z^2 \right) + \sum_{j=1}^{N} S_j W_{\mathrm{PS}} + L W_{\mathrm{PA}} \tag{5}$$

where ξ and ζ are the related coefficients, W_{BS} represents the dissipated power consumed at the BS, W_{PS} and W_{PA} represent the power consumed by the phase shift circuit and power amplifier, respectively.

As a result, the energy consumption of the whole system can be denoted by

$$P_{\mathrm{total}} = P_{\mathrm{BS}} + P_{\mathrm{RIS}} + K W_{\mathrm{U}} \tag{6}$$

where W_{U} represents the dissipated power consumed at each user.

About the implementation issue, all variables related to the scheme should be determined according to the following algorithm. For example, the choices of phase shift ($\boldsymbol{\Psi}$), the switcher condition (S_j), and the power amplification factor ($\boldsymbol{a}$) need to be updated by the given solution. Generally, after central processing unit (CPU) computes and finds the optimal values of these variables, they will be sent to the related devices via bus. Thus, it is the algorithm running at the CPU to determine the choices of these variables. So no further devices are actually required. Specially, the switcher can be implemented by a multiplying operation with the switcher condition ($S_j = 0$ or $S_j = 1$), which is indicated by the proposed algorithm running at the CPU via bus. Therefore, extra device is not necessary to control the switcher in Fig. 1.

3. Joint design for EE maximization problem

According to [8], the EE problem of the system can be defined as the ratio of the total achievable rates and the total power consumption of the communication system. Therefore, the EE maximization problem can be formulated as

$$\begin{aligned} \max_{\boldsymbol{W}, \boldsymbol{\Theta}, \boldsymbol{a}, S_j} \quad & \eta = \frac{\sum_{k=1}^{K} \log_2\left(1 + SINR_k\right)}{P_{\mathrm{total}}} \\ \text{s.t.} \quad \mathrm{C}_1: \quad & P_{\mathrm{BS}} \leq P_{\mathrm{BS}}^{\max} \\ \mathrm{C}_2: \quad & P_{\mathrm{RIS}} \leq P_{\mathrm{RIS}}^{\max} \\ \mathrm{C}_3: \quad & |\theta_n| = 1, \forall n \in [N] \\ \mathrm{C}_4: \quad & a_l \geq 0, \forall l \in [L] \\ \mathrm{C}_5: \quad & S_j \in \{0, 1\}, j = 1, 2, \cdots, N \end{aligned} \tag{7}$$

where $a_1 = \cdots = a_L$ denotes the optimal amplification factor with any given T, $P_{\mathrm{BS}}^{\max}$ and $P_{\mathrm{RIS}}^{\max}$ are the maximum total power consumption at BS and active RIS, respectively. In a word, C_1 and C_2 are the power constraints, which respectively guarantee the maximum total power consumption at BS and active RIS, C_3 constrains the phase shift matrix $\boldsymbol{\Theta}$, C_4 and C_5 are the feasible sets of amplification factor vector $\boldsymbol{a}$ and switcher S_j, respectively.

In this section, we provide a solution for problem in (7). To tackle the nonlinear fractional objective function in EE optimization problems [8], Dinkelbach method [9] can be applied. Moreover, for the jointly non-convex optimization problem, an alternating based algorithm can be used [10]. Specifically, we decouple problem (7) into beamforming design problem, phase shift optimization subproblem and switcher-selection subproblem alternatively.

By using Dinkelbach method, the fractional objective function is converted into a subtractive form of numerator and denominator, the maximum achievable EE η^{opt} can be obtained through

$$\max_{\boldsymbol{W},\boldsymbol{\Theta},\boldsymbol{a},S_j} \left(R-\eta^{\mathrm{opt}}\ P\right)=0 \tag{8}$$

where $R=\sum_{k=1}^{K}\log_2\left(1+SINR_k\right)$. Hence, the optimal η^{opt} can be solved by the following problem

$$\begin{aligned} &\max_{\boldsymbol{W},\boldsymbol{\Theta},\boldsymbol{a},S_j} f(\boldsymbol{W},\boldsymbol{\Theta},\boldsymbol{a},S_j)=R-\eta P \\ &\quad \text{s.t.}\ \ \mathrm{C}_1,\mathrm{C}_2,\mathrm{C}_3,\mathrm{C}_4,\mathrm{C}_5 \end{aligned} \tag{9}$$

Compared with the equation (7) in [4], we observed that (9) has an additional variable S_j and its related constraint C_5. According to the alternating optimization algorithm, the variables are alternately optimized with the other variables fixed. In other words, with fixed S_j, (9) is equivalent to (7) in [4].

Similarly, since the objective function in (9) is still nonconvex, auxiliary variables $\boldsymbol{\mu}\in\mathbb{C}^{K\times 1}$ and $\boldsymbol{\nu}\in\mathbb{C}^{K\times 1}$ are introduced, the problem is reformulated as

$$\begin{aligned} &\max_{\boldsymbol{W},\boldsymbol{\Theta},\boldsymbol{a},S_j,\boldsymbol{\mu},\boldsymbol{\nu}} g(\boldsymbol{W},\boldsymbol{\Theta},\boldsymbol{a},S_j,\boldsymbol{\mu},\boldsymbol{\nu}) \\ &\quad \text{s.t.}\ \ \mathrm{C}_1,\mathrm{C}_2,\mathrm{C}_3,\mathrm{C}_4,\mathrm{C}_5 \end{aligned} \tag{10}$$

where

$$\begin{aligned} &g(\boldsymbol{W},\boldsymbol{\Theta},\boldsymbol{a},S_j,\boldsymbol{\mu},\boldsymbol{\nu}) \\ &=\sum_{k=1}^{K}\Bigg[\ln\left(1+\mu_k\right)-\mu_k+2\sqrt{1+\mu_k}\,\mathrm{Re}\left\{\nu_k^{*}\tilde{\boldsymbol{h}}_k^{\mathrm{H}}\boldsymbol{w}_k\right\} \\ &\quad -\left|\nu_k\right|^2\left(\sum_{i=1}^{K}\left|\tilde{\boldsymbol{h}}_k^{\mathrm{H}}\boldsymbol{w}_i\right|^2+\left\|\boldsymbol{f}_k^{\mathrm{H}}\boldsymbol{\Psi}\right\|^2\sigma_z^2+\sigma^2\right)\Bigg]-\eta P \end{aligned}$$

For clarity, we first fix the variable $\{S_j\}$, and solve (10) by using Algorithm 1 in [4]. And then, with the above optimal solution, (10) is reduced to a function of $\{S_j\}$ which is related to the optimal reflective array switcher. For $\{S_j\}$, we can formulate the problem (7) as

$$\begin{aligned} &\max_{S_j}\quad \eta=\frac{\sum_{k-1}^{K}\log_2\left(1+\mathrm{SINR}_k\right)}{P_{\mathrm{toal}}} \\ &\text{s.t.}\ \ \mathrm{C}_1:\quad P_{\mathrm{RIS}}\le P_{\mathrm{RIS}}^{\max} \\ &\qquad \mathrm{C}_2:\quad S_j\in\{0,1\},j=1,2,\cdots,N \end{aligned} \tag{11}$$

For the above problem with one variable, exhaustive search method can be used to test each switcher one by one, and then find the optimal one.

4. Simulation Results

In this section, simulations are provided to evaluate the performance of the proposed scheme. We consider that the active RIS has 256 elements for transmission with $M=6, K=4$. The hardware static power of the power amplifier and the phase shift circuit are set to $W_{\mathrm{PS}}=10$ dBm and $W_{\mathrm{PA}}=10$ dBm, respectively, the dissipated powers are set to $W_{\mathrm{U}}=10$ dBm and $W_{\mathrm{BS}}=6$ dBm. In the following simulations, the BS position serves as the original point, and the user position ranges from 0m to 100m. The fully-connected architecture and sub-connected architecture provided in [4] are considered for performance comparison.

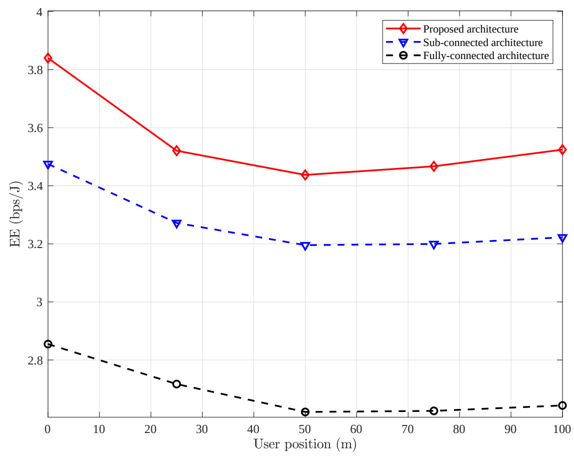

Fig. 2 EE comparison versus user position.

Fig. 2 illustrates the EE performance of the proposed algorithm and architecture versus the user's position. We find that the switcher assisted architecture can enhance the system performance, while the EE is increased by about 10% compared with the original sub-connected architecture.

In Fig. 3, we fixed the user's location at (100m, 0m), and then evaluated the EE performance of the proposed solution under the different power constraints of $P_{\mathrm{BS}}^{\max}$. It is shown that the EE of the proposed solution is increased by 11% compared with the original sub-connected algorithm.

Moreover, the proposed switcher assisted structure

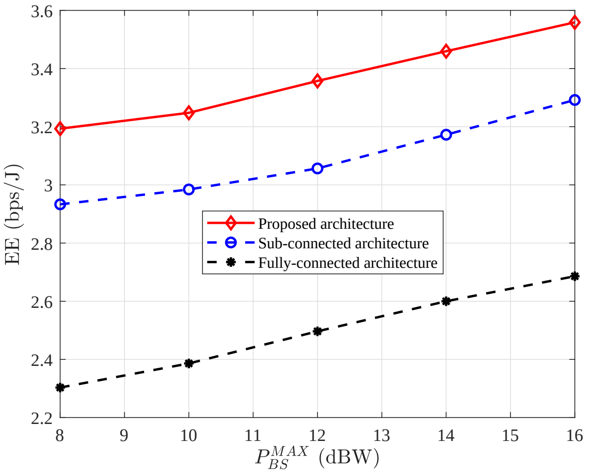

Fig. 3 Comparison of EE under different $P_{\mathrm{BS}}^{\max}$ constraints.

can be applied to the fully connected architecture. Both figures show that it still outperforms the one without switcher.

5. Conclusion

In this letter, we proposed a switcher assisted architecture for sub-connected active RIS. Specifically, a switcher device is added as an on-off controller for each component in RIS. With switchers, only the suitable phase shift is selected to save power. We investigated the EE optimization problem with some power constraints of the proposed architecture in MISO systems. The existing sub-connected active RIS systems are considered as a benchmark. In order to obtain a feasible solution to the problem, alternative optimization approach is adopted combined with an exhaustive search algorithm. The simulation results show that the EE of the proposed architecture is 11% higher than the original one without switcher, which verifies the proposed architecture as an energy-efficient implementation of active RIS.

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