Frequency-Dependent Joint Beamforming for RIS-Aided Terahertz Systems

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I. Introduction

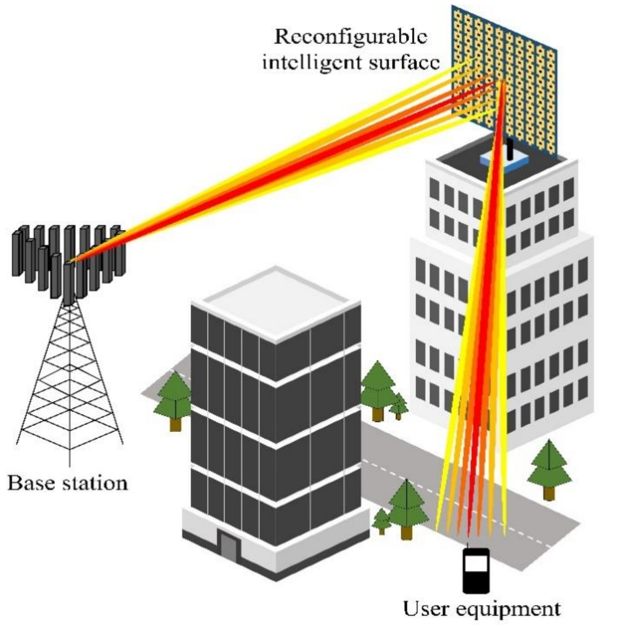
To support extremely high data rates in 6G wireless networks, reconfigurable intelligent surface (RIS)-aided terahertz (THz) massive multiple-input multiple-output (MIMO) communications have gained much attention [1] [2]. On the one hand, by exploiting the large available spectrum in the THz frequency band and controlling the phase shifts of reflecting elements, RIS-aided THz communications can support immersive mobile services such as digital twin and holographic telepresence [3]. One major challenge of the wideband THz communication is the severe array gain loss caused by the beam split effect that the path components split into different spatial directions at different subcarrier frequencies As a result, the conventional phase shift control and beamforming techniques cannot be directly applied to wideband THz systems.

Recently, various phase shift control and beamforming techniques for RIS-aided THz systems have been proposed [4-6]. In [4], a joint active and passive beamforming scheme for RIS-aided THz systems has been proposed. In [5], the holographic RISs-assisted beamforming scheme for THz systems has been proposed. Also, a hybrid beamforming technique to maximize the sum rate of the RIS-aided THz systems using the deep learning tool has been proposed in [6]. While these beamforming schemes generate directional beams for the narrowband systems, the severe array gain loss will be introduced for the wideband THz systems. Note that in the wideband THz systems, due to the beam split effect, the phase-controlled beams generated by the traditional frequency-independent phase shifters can only realize high array gain around the carrier frequency while suffering from the severe array gain loss at most subcarrier frequencies. Therefore, there will have a serious achievable data rate loss. To achieve the success of RIS-aided wideband THz systems, it is of great importance to come up with a phase shift control and beamforming method mitigating the beam split effect.

In this paper, we propose a RIS-aided frequency-dependent joint beamforming technique that maximizes the average data rate of the RIS-aided wideband THz systems. Key idea of the proposed scheme is to propose a novel active beamforming network and properly design the parameters of the network so that the average data rate of the wideband THz system is maximized. Also, we optimize the passive beamforming vector, i.e., the RIS phase shift vector, by exploiting the manifold optimization technique. Using the optimized active and passive beamforming vectors, we can achieve the maximal average data rate of the RIS-aided wideband THz systems.

II. RIS-Aided THz System Model

We consider an RIS-aided THz OFDM system where a BS equipped with N antennas serves a single-antenna UE. An RIS consisting of M passive reflecting elements is deployed to assist the downlink transmission (see Fig. 1).



We assume the analog beamforming architecture at the BS where a radio frequency (RF) chain is connected with N analog phase shifters. The number of OFDM subcarriers is S, the carrier frequency is f_c, and the bandwidth is B. Also, we assume that the direct communication link from the BS to the UE is blocked by the obstacles (e.g., walls and corners) and thus the effective channel between the BS and the UE is expressed as

$$\begin{aligned} \boldsymbol{h}_i &= \mathbf{G}_i^{\mathrm{H}} \operatorname{diag}(\boldsymbol{\psi})\boldsymbol{u}_i \\ &= \mathbf{G}_i^{\mathrm{H}} \operatorname{diag}(\boldsymbol{u}_i)\boldsymbol{\psi} \\ &= \mathbf{H}_i^{\mathrm{H}}\boldsymbol{\psi}, \end{aligned} \tag{1}$$

where $\mathbf{G}_i$ is the channel matrix from the BS to the RIS, $\boldsymbol{u}_i$ is the channel vector from the RIS to the UE, and $\mathbf{H}_i$ is the RIS reflected channel matrix at the ith subcarrier. In particular, for the channel models of the BS-RIS channel matrix $\mathbf{G}_i$ and the RIS-UE channel vector $\boldsymbol{u}_i$, we use the frequency-dependent multipath THz channel models considering the beam split effect.

In this setting, let $\boldsymbol{s}_i$ be the transmitted symbol such that $\Xi[|\boldsymbol{s}_i|^2] = 1$, then the received signal $\boldsymbol{y}_i$ of the UE at the ith subcarrier is given by

$$\begin{aligned} \boldsymbol{y}_i &= \mathbf{h}_i^{\mathrm{H}}\boldsymbol{f}_i\boldsymbol{s}_i + \boldsymbol{n}_i \\ &= \left(\mathbf{H}_i^{\mathrm{H}}\boldsymbol{\psi}\right)^{\mathrm{H}}\boldsymbol{f}_i\boldsymbol{s}_i + \boldsymbol{n}_i \\ &= \boldsymbol{\psi}^{\mathrm{H}}\mathbf{H}_i\boldsymbol{f}_i\boldsymbol{s}_i + \boldsymbol{n}_i, \end{aligned} \tag{2}$$

where $\boldsymbol{f}_i$ is the active beamforming vector at the BS, $\boldsymbol{\psi}$ is the RIS phase shift vector, and $\boldsymbol{n}_i$ is the additive Gaussian noise with the zero mean and unit variance at the ith subcarrier. The corresponding average data rate R of the UE is given by

$$R = \frac{1}{S}\sum_{i=1}^{S}\log_2\left(1 + \frac{|\boldsymbol{\psi}^{\mathrm{H}}\mathbf{H}_i\boldsymbol{f}_i|^2}{\sigma_n^2}\right). \tag{3}$$

In this work, our goal is to find out the active bea mforming vector $\boldsymbol{f}_i$ and the passive beamforming vector $\boldsymbol{\psi}$ maximizing the average data rate of the RIS-aided wideband THz systems. Note that when the active beams and RIS-reflected passive beams align with the spatial directions at the BS and the RIS, the average data rate is maximized. In wideband THz systems, due to the split effect, it is not easy to cope with this problem. In the future work, we will design the RIS-aided joint active and passive beamforming architecture and design the network parameters for the data rate maximization.

Reference

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