A 3D Stochastic Channel Model for 6G Wireless Double-IRS Cooperatively Assisted MIMO Communications

Hao Jiang, *Member, IEEE*, Zaichen Zhang, *Senior Member, IEEE*, Baiping Xiong, Jian Dang, *Senior Member, IEEE*, Liang Wu, *Member, IEEE*, and Jie Zhou, *Senior Member, IEEE*

2021 13th International Conference on Wireless Communications and Signal Processing (WCSP) | 978-1-6654-0785-4/21/$31.00 ©2021 IEEE | DOI: 10.1109/WCSP52459.2021.9613605

***Abstract*—In this paper, we propose a three-dimensional (3D) stochastic channel model for double intelligent reflecting surface (IRS) cooperatively assisted multiple-input multiple-output (MIMO) communications, where two distributed IRSs are respectively deployed near a mobile transmitter (MT) and a mobile receiver (MR). The double-IRS is distributed on the surface of buildings to assist the transmitter to transmit its own signals to the receiver, and meanwhile improve the propagation by passive beamforming at the IRSs. In this channel model, some of the signals transmitted from the MT impinge on the IRS near to the transmitter or/and the IRS near to the receiver before reaching the MR. Some of the signals emitted from the MT impinge on the cluster before arriving at the MR. Furthermore, we study the double-IRS MIMO channel propagation characteristics, i.e., spatial-temporal (ST) cross-correlation functions (CCFs), for different number and layout of the unit cells in the IRSs, as well as the IRS orientation angles. Simulation results are provided to show the channel characteristics of double-IRSs cooperatively assisted MIMO channel models.**

***Index Terms*—3D stochastic channel model, double-IRS, MIMO communications, ST CCFs.**

I. Introduction

Intelligent reflecting surface (IRS), which consists of a surface of electromagnetic material containing a large number of square metallic patches, can be placed on the wall of buildings to improve the system performance [1]. In recent years, IRS has received rapidly increasing attention from both the academic and industry communities [2].

For studying the performance of wireless IRS-assisted communication systems, it is essential to propose effective channel models for describing the communication scenarios [3]. In the existing literature, the authors in [4] developed a geometry-based stochastic channel model for single-input single-output (SISO) communications in IRS-assisted scenarios, which was based on a variety of the measured data in mobile-to-mobile (M2M) channels. The aforementioned works almost focus on one distributed IRS; however, when multiple IRSs are deployed between a transmitter and a receiver, it is possible to further enhance the performance of communication systems. The authors in [5] optimized the cooperative beamforming gain in a double-IRS assisted single-user system, where a user is served by a single-antenna base station (BS) through the double-reflection link over two distributed IRSs located near the BS and user, respectively.

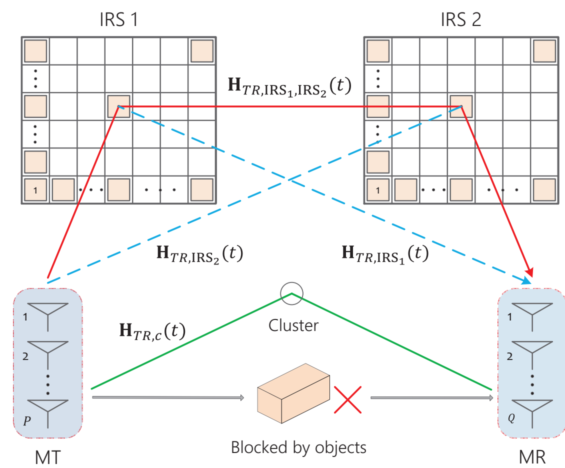

Fig. 1. Diagram of the double-IRS cooperatively assisted MIMO communication scenarios.

Recently, the integration of the double-IRS and multiple-input multiple-output (MIMO) communication systems has become a hot research topic, which key challenge is to propose effective channel models for describing the communication scenarios, which aim at efficiently designing and optimizing the performance of the double-IRS cooperatively assisted MIMO communication system. For example, the authors in [6] proposed a double-IRS cooperatively assisted MIMO communication system, where two distributed IRSs are deployed near a multi-antenna BS and a cluster of nearby users, respectively. However, in reality, there is little research achievement on channel modeling for double-IRS cooperatively assisted MIMO communications, which bring us difficulty in evaluate the communication system performance. To solve this challenge, we propose a three-dimensional (3D) stochastic channel model for describing double-IRS cooperatively assisted MIMO communication scenarios. In this paper, we consider the propagation characteristics of the double-IRS assisted channel

This work was supported by the National Natural Science Foundation of China (NSFC) (No. 61771248, 61971167, and 6210011073), the Natural Science Foundation of Jiangsu Province (BK20200820), and the Open Research Fund of National Mobile Communications Research Laboratory (No. 2020D14), Southeast University. (*Corresponding author: Zaichen Zhang*).

H. Jiang is with the College of Artificial Intelligence, Nanjing University of Information Science and Technology, 210044, P. R. China; and also with the National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, P. R. China (e-mail: jianghao@nuist.edu.cn).

Z. Zhang, B. Xiong, J. Dang, and L. Wu are with the National Mobile Communications Research Laboratory, Southeast University, Nanjing 210096, P. R. China; Z. Zhang is also with the Purple Mountain Laboratory, Nanjing 211111, P. R. China (e-mails: zczhang@seu.edu.cn; xiongbp@seu.edu.cn; dangjian@seu.edu.cn; wuliang@seu.edu.cn).

J. Zhou is with the College of Electronic and Information Engineering, Nanjing University of Information Science and Technology, 210044, P. R. China (e-mail: zhoujie@nuist.edu.cn).

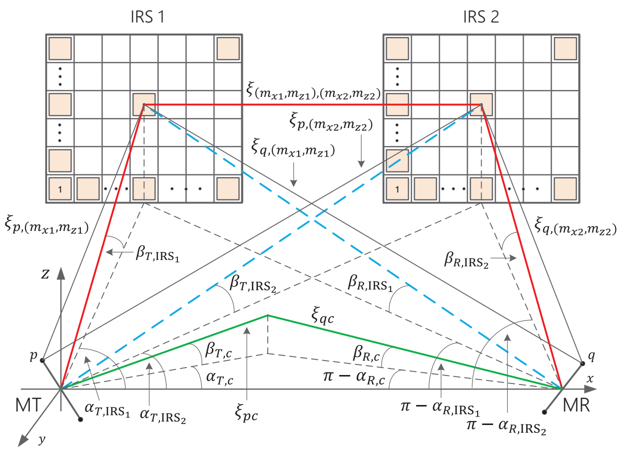

Fig. 2. Geometric relations of the proposed 3D double-IRS cooperatively assisted MIMO channel model.

model for different numbers and layouts of the unit cells in two separate IRSs around the transmitter and receiver.

The rest of this paper is organized as follows. In Section II, we describe the proposed double-IRS assisted MIMO channel model. In Section III, we discuss the propagation characteristics of the proposed channel model. In Section IV, we provide the simulation results and discussions, and our conclusions are drawn in Section V.

II. System Channel Model

This paper considers a 3D stochastic wireless channel model for double-IRS cooperatively assisted MIMO communications, as shown in Fig. 1. In such channel model, it is assumed that two distributed IRSs are deployed near a mobile transmitter (MT) and a mobile receiver (MR). The MT and MR consists of P transmit and Q receive omni-directional antennas, respectively. The IRSs around the MT and MR are IRS_1 and IRS_2, respectively. The numbers of the arranged unit cells in the horizontal and vertical directions of the IRS_1 are denoted by M_{x1} and M_{z1}, respectively. For the IRS_2, they are denoted by M_{x2} and M_{z2}, respectively. The center points of the IRS_1 and IRS_2 are denoted by $(x_{\mathrm{IRS}_1,c}, y_{\mathrm{IRS}_1,c}, z_{\mathrm{IRS}_1,c})$ and $(x_{\mathrm{IRS}_2,c}, y_{\mathrm{IRS}_2,c}, z_{\mathrm{IRS}_1,c})$, respectively. It is worth mentioning that the $x_{\mathrm{IRS}_1,c}$, $y_{\mathrm{IRS}_1,c}$, $z_{\mathrm{IRS}_1,c}$, $x_{\mathrm{IRS}_2,c}$, $y_{\mathrm{IRS}_2,c}$, and $z_{\mathrm{IRS}_2,c}$ are known in our following discussions. As shown in Fig. 2, the waves transmitted by the MT undergo different propagation mechanisms before arriving at the MR. They are: (1) the waves transmitted by MT impinge on the IRS_1 before arriving at the MR, that is, $MT \to \mathrm{IRS}_1 \to MR$; (2) the waves transmitted by MT impinge on the IRS_2 before arriving at the MR, that is, $MT \to \mathrm{IRS}_2 \to MR$; (3) the waves transmitted by MT firstly impinge on the IRS_1, and then impinge on the IRS_2 before arriving at the MR, that is, $MT \to \mathrm{IRS}_1 \to \mathrm{IRS}_2 \to MR$; (4) the waves transmitted by MT impinge on the cluster before arriving at the MR. Overall, we have [7]

$$\begin{aligned}\mathbf{H}_{TR}(t) &= \mathbf{H}_{TR,\mathrm{IRS}_1}(t) + \mathbf{H}_{TR,\mathrm{IRS}_2}(t) \\ &\quad + \mathbf{H}_{TR,\mathrm{IRS}_1,\mathrm{IRS}_2}(t) + \mathbf{H}_{TR,c}(t) \end{aligned} \tag{1}$$

where $\mathbf{H}_{TR,\mathrm{IRS}_1}(t) = [\, h_{pq,\mathrm{IRS}_1}(t) \,] \in \mathbb{C}^{Q\times P}$ characterizes the physical properties of the $MT \to \mathrm{IRS}_1 \to MR$ channel. The $h_{pq,\mathrm{IRS}_1}(t)$ represents the channel coefficient of the propagation link from the p-th ($p = 1, 2, ..., P$) transmit antenna to the q-th ($q = 1, 2, ..., Q$) receive antenna in such channel model, which can be written by

$$\begin{aligned} h_{pq,\mathrm{IRS}_1}(t) &= \sqrt{\frac{K\eta_{\mathrm{IRS}_1}}{K+1}} \sum_{m_{x1}=1-M_{x1}/2}^{M_{x1}/2} \sum_{m_{z1}=1-M_{z1}/2}^{M_{z1}/2} \\ &\quad \times e^{-j2\pi f_c \left(\xi_{p,(m_{x1},m_{z1})}+\xi_{q,(m_{x1},m_{z1})}\right)/c} \\ &\quad \times e^{j\frac{2\pi}{\lambda} v_T t \cos\left(\alpha_{T,\mathrm{IRS}_1}-\eta_T\right)\cos\beta_{T,\mathrm{IRS}_1}} \\ &\quad \times e^{j\frac{2\pi}{\lambda} v_R t \cos\left(\alpha_{R,\mathrm{IRS}_1}-\eta_R\right)\cos\beta_{R,\mathrm{IRS}_1}} \end{aligned} \tag{2}$$

where η_{IRS_1} denotes the energy-related parameter of the $MT \to \mathrm{IRS}_1 \to MR$ channel model. The $\alpha_{T,\mathrm{IRS}_1}$ and β_{T,IRS_1} are, respectively, the azimuth angle of departure (AAoD) and elevation angle of departure (EAoD) of the waves that impinge on the IRS_1; whereas $\alpha_{R,\mathrm{IRS}_1}$ and β_{R,IRS_1} are, respectively, the azimuth angle of arrival (AAoA) and elevation angle of arrival (EAoA) of the waves scattered from the IRS_1. Here, K is Rician factor, λ is the wavelength, c is the speed of light, and t is the moving time of the transceivers. Parameters v_T and v_R are the moving velocities of the MT and MR, respectively. The η_T and η_R are the moving directions of the MT and MR, respectively. Furthermore, $\xi_{p,(m_{x1},m_{z1})}$ is the distance from the p-th antenna to the (m_{x1}, m_{z1})-th IRS_1 unit, where $m_{x1} \in [1-M_{x1}/2, M_{x1}/2]$ and $m_{z1} \in [1-M_{z1}/2, M_{z1}/2]$, assuming that the M_{x1} and M_{z1} are even numbers in our discussions. This can be derived by taking the magnitude of the $\mathbf{d}_{p,(m_{x1},m_{z1})}$, i.e.,

$$\begin{aligned} \mathbf{d}_{p,(m_{x1},m_{z1})} &= \begin{bmatrix} x_{\mathrm{IRS}_1,c} - (\frac{M_{x1}}{2} - m_{x1} + \frac{1}{2}) d_{x1}\cos\theta_{\mathrm{IRS}_1} \\ y_{\mathrm{IRS}_1,c} - (\frac{M_{x1}}{2} - m_{x1} + \frac{1}{2}) d_{x1}\sin\theta_{\mathrm{IRS}_1} \\ z_{\mathrm{IRS}_1,c} - m_{z1}d_{z1} + d_{z1}/2 \end{bmatrix} \\ &\quad - \begin{bmatrix} \frac{P-2p+1}{2}\delta_T \cos\psi_T \\ \frac{P-2p+1}{2}\delta_T \sin\psi_T \\ 0 \end{bmatrix} \end{aligned} \tag{3}$$

where θ_{IRS_1} denotes the rotation angle of the IRS_1 relative to the positive direction of the x-axis. Parameters δ_T and δ_R are the spaces between the two adjacent antennas at the MT and MR, respectively. The ψ_T and ψ_R are the orientations of the transmit and receive antenna arrays, respectively. The d_{x1} and d_{z1} are the sizes of each unit in the IRS_1 along the horizontal and vertical directions, respectively. Furthermore, in (2), $\xi_{q,(m_{x1},m_{z1})}$ is the distance from the q-th receive antenna to the (m_{x1}, m_{z1})-th unit of the IRS_1, which is derived by taking the magnitude of the $\mathbf{d}_{q,(m_{x1},m_{z1})}$, i.e.,

$$\mathbf{d}_{q,(m_{x1},m_{z1})} = \begin{bmatrix} x_{\mathrm{IRS}_1,c} - (\frac{M_{x1}}{2} - m_{x1} + \frac{1}{2})d_{x1}\cos\theta_{\mathrm{IRS}_1} \\ y_{\mathrm{IRS}_1,c} - (\frac{M_{x1}}{2} - m_{x1} + \frac{1}{2})d_{x1}\sin\theta_{\mathrm{IRS}_1} \\ z_{\mathrm{IRS}_1,c} - m_{z1}d_{z1} + d_{z1}/2 \end{bmatrix} - \begin{bmatrix} D_0 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} \frac{Q-2q+1}{2}\delta_R\cos\psi_R \\ \frac{Q-2q+1}{2}\delta_R\sin\psi_R \\ 0 \end{bmatrix} \quad (4)$$

where D_0 denotes the distance between the centers of the transmit and receive antenna arrays. In (1), $\mathbf{H}_{TR,\mathrm{IRS}_2}(t) = [h_{pq,\mathrm{IRS}_2}(t)] \in \mathbb{C}^{Q\times P}$ characterizes the physical properties of the $MT \to \mathrm{IRS}_2 \to MR$ channel. The $h_{pq,\mathrm{IRS}_2}(t)$ represents the channel coefficient of the propagation link from the p-th transmit antenna to the q-th receive antenna in such channel model, which can be written by

$$h_{pq,\mathrm{IRS}_2}(t) = \sqrt{\frac{K\eta_{\mathrm{IRS}_2}}{K+1}} \sum_{m_{x2},m_{z2}=1}^{M_{x2},M_{x2}} \times e^{-j2\pi f_c\left(\xi_{p,(m_{x2},m_{z2})}+\xi_{q,(m_{x2},m_{z2})}\right)/c} \times e^{j\frac{2\pi}{\lambda}v_T t\cos\left(\alpha_{T,\mathrm{IRS}_2}-\eta_T\right)\cos\beta_{T,\mathrm{IRS}_2}} \times e^{j\frac{2\pi}{\lambda}v_R t\cos\left(\alpha_{R,\mathrm{IRS}_2}-\eta_R\right)\cos\beta_{R,\mathrm{IRS}_2}} \quad (5)$$

where η_{IRS_2} denotes the energy-related parameter of the $MT \to \mathrm{IRS}_2 \to MR$ channel model. The $\alpha_{T,\mathrm{IRS}_2}$ and β_{T,IRS_2} are, respectively, the AAoD and EAoD of the waves that impinge on the IRS_2; whereas $\alpha_{R,\mathrm{IRS}_1}$ and β_{R,IRS_1} are, respectively, the AAoA and EAoA of the waves scattered from the IRS_2. The $\xi_{p,(m_{x2},m_{z2})}$ is the distance from the p-th antenna to the (m_{x2},m_{z2})-th IRS_2 unit, which is derived by taking the magnitude of the distance vector $\mathbf{d}_{p,(m_{x2},m_{z2})}$, i.e.,

$$\mathbf{d}_{p,(m_{x2},m_{z2})} = \begin{bmatrix} x_{\mathrm{IRS}_2,c} - (\frac{M_{x2}}{2} - m_{x2} + \frac{1}{2})d_{x2}\cos\theta_{\mathrm{IRS}_2} \\ y_{\mathrm{IRS}_2,c} - (\frac{M_{x2}}{2} - m_{x2} + \frac{1}{2})d_{x2}\sin\theta_{\mathrm{IRS}_2} \\ x_{\mathrm{IRS}_2,c} - m_{z2}d_{z2} + d_{z2}/2 \end{bmatrix} - \begin{bmatrix} \frac{P-2p+1}{2}\delta_T\cos\psi_T \\ \frac{P-2p+1}{2}\delta_T\sin\psi_T \\ 0 \end{bmatrix} \quad (6)$$

where θ_{IRS_2} denotes the rotation angle of the IRS_2 relative to the positive direction of the x-axis. The d_{x2} and d_{z2} are the sizes of each unit in the IRS_2 along the horizontal and vertical directions, respectively. The $\xi_{q,(m_{x1},m_{z1})}$ is the distance from the q-th antenna to the (m_{x2},m_{z2})-th IRS_2 unit, which is calculated by taking the magnitude of the vector $\mathbf{d}_{q,(m_{x2},m_{z2})}$, i.e.,

$$\mathbf{d}_{q,(m_{x2},m_{z2})} = \begin{bmatrix} x_{\mathrm{IRS}_2,c} - (\frac{M_{x2}}{2} - m_{x2} + \frac{1}{2})d_{x2}\cos\theta_{\mathrm{IRS}_2} \\ y_{\mathrm{IRS}_2,c} - (\frac{M_{x2}}{2} - m_{x2} + \frac{1}{2})d_{x2}\sin\theta_{\mathrm{IRS}_2} \\ x_{\mathrm{IRS}_2,c} - m_{z2}d_{z2} + d_{z2}/2 \end{bmatrix} - \begin{bmatrix} D_0 \\ 0 \\ 0 \end{bmatrix} - \begin{bmatrix} \frac{Q-2q+1}{2}\delta_R\cos\psi_R \\ \frac{Q-2q+1}{2}\delta_R\sin\psi_R \\ 0 \end{bmatrix} \quad (7)$$

Furthermore, in (1), $\mathbf{H}_{TR,\mathrm{IRS}_1,\mathrm{IRS}_2}(t) = [h_{pq,\mathrm{IRS}_1,\mathrm{IRS}_2}(t)] \in \mathbb{C}^{Q\times P}$ characterizes the physical properties of the $MT \to \mathrm{IRS}_1 \to \mathrm{IRS}_2 \to MR$ channel. The $h_{pq,\mathrm{IRS}_1,\mathrm{IRS}_2}(t)$ represents the channel coefficient of the link from the p-th antenna propagates to the q-th antenna in such channel model, which is written by

$$h_{pq,\mathrm{IRS}_1,\mathrm{IRS}_2}(t) = \sum_{m_{x1},m_{z1},m_{x2},m_{z2}=1}^{M_{x1},M_{z1},M_{x2},M_{z2}} \times \sqrt{\frac{K\eta_{\mathrm{IRS}_1,\mathrm{IRS}_2}}{K+1}} e^{-j2\pi f_c \xi_{(m_{x1},m_{z1}),(m_{x2},m_{z2})}/c} \times e^{-j2\pi f_c\left(\xi_{p,(m_{x1},m_{z1})}+\xi_{q,(m_{x2},m_{z2})}\right)/c} \times e^{j\frac{2\pi}{\lambda}v_T t\cos\left(\alpha_{T,\mathrm{IRS}_1}-\eta_T\right)\cos\beta_{T,\mathrm{IRS}_1}} \times e^{j\frac{2\pi}{\lambda}v_R t\cos\left(\alpha_{R,\mathrm{IRS}_2}-\eta_R\right)\cos\beta_{R,\mathrm{IRS}_2}} \quad (8)$$

where $\eta_{\mathrm{IRS}_1,\mathrm{IRS}_2}$ denotes the energy-related parameter of the $MT \to \mathrm{IRS}_1 \to \mathrm{IRS}_2 \to MR$ channel model. In the proposed Rician channel model, the η_{IRS_1}, η_{IRS_2}, and $\eta_{\mathrm{IRS}_1,\mathrm{IRS}_2}$ can be normalized to satisfy $\eta_{\mathrm{IRS}_1} + \eta_{\mathrm{IRS}_2} + \eta_{\mathrm{IRS}_1,\mathrm{IRS}_2} = 1$ for brevity. The $\xi_{(m_{x1},m_{z1}),(m_{x2},m_{z2})}$ denotes the distance from the (m_{x1},m_{z1})-th IRS_1 unit to the (m_{x2},m_{z2})-th IRS_2 unit, which can be calculated by taking the magnitude of the vector $\mathbf{d}_{(m_{x1},m_{z1}),(m_{x2},m_{z2})}$, i.e.,

$$\mathbf{d}_{(m_{x1},m_{z1}),(m_{x2},m_{z2})} = \begin{bmatrix} x_{\mathrm{IRS}_1,c} \\ y_{\mathrm{IRS}_1,c} \\ z_{\mathrm{IRS}_1,c} \end{bmatrix} - \begin{bmatrix} x_{\mathrm{IRS}_2,c} \\ y_{\mathrm{IRS}_2,c} \\ z_{\mathrm{IRS}_2,c} \end{bmatrix} - \begin{bmatrix} (\frac{M_{x1}}{2} - m_{x1} + \frac{1}{2})d_{x1}\cos\theta_{\mathrm{IRS}_1} \\ (\frac{M_{x1}}{2} - m_{x1} + \frac{1}{2})d_{x1}\sin\theta_{\mathrm{IRS}_1} \\ m_{z1}d_{z1} - d_{z1}/2 \end{bmatrix} + \begin{bmatrix} (\frac{M_{x2}}{2} - m_{x1} + \frac{1}{2})d_{x2}\cos\theta_{\mathrm{IRS}_2} \\ (\frac{M_{x2}}{2} - m_{x2} + \frac{1}{2})d_{x2}\sin\theta_{\mathrm{IRS}_2} \\ m_{z2}d_{z2} - d_{z2}/2 \end{bmatrix} \quad (9)$$

Moreover, in (1), $\mathbf{H}_{TR,c}(t) = [h_{pq,c}(t)] \in \mathbb{C}^{Q\times P}$ characterizes the physical properties of the propagation link from the MT that impinge on the cluster before arriving at the MR. The $h_{pq,c}(t)$ represents the channel coefficient of the propagation links from the p-th transmit antenna to the q-th receive antenna, which is written by

$$h_{pq,c}(t) = \sqrt{\frac{1}{K+1}} \sum_{n=1}^{N} \sqrt{\frac{1}{N}} e^{j\varphi_0 - j2\pi f_c\left(\xi_{pn}+\xi_{qn}\right)/c} \times e^{j\frac{2\pi}{\lambda}v_T t\cos\left(\alpha_{T,n}-\eta_T\right)\cos\beta_{T,n}} \times e^{j\frac{2\pi}{\lambda}v_R t\cos\left(\alpha_{R,n}-\eta_R\right)\cos\beta_{R,n}} \quad (10)$$

where $\alpha_{T,n}$ and $\beta_{T,n}$ denote the AAoD and EAoD of the waves that impinge on the n-th scatterer of cluster, whereas $\alpha_{R,n}$ and $\beta_{R,n}$ are the AAoA and EAoA of the waves scattered from the n-th scatterer of cluster. The ξ_{pn} and ξ_{qn} are the distances from the p-th transmit antenna and q-th receive antenna to the n-th scatterer of cluster, respectively. In the following, we suppose that every scatterer within a cluster is approximately at the same angle and same distance from the center of the corresponding array [8], e.g., $\alpha_{T,n} \approx \alpha_{T,c}$, $\beta_{T,n} \approx \alpha_{T,c}$, $\alpha_{R,n} \approx \alpha_{R,c}$, $\beta_{R,n} \approx \alpha_{R,c}$, $\xi_{pn} \approx \xi_{pc}$, $\xi_{qn} \approx \xi_{qc}$. The φ_0, which is random, denotes the initial phase for the NLoS rays. This characterizes the statistical properties of the proposed channel model [9]. In the following, we define $(x_{cluster}, y_{cluster}, z_{cluster})$ as the center point of the cluster. Then, the distances ξ_{pc} and ξ_{qc} can be respectively calculated by taking the magnitude of the $\mathbf{d}_{pc}$ and $\mathbf{d}_{qc}$ as follows:

$$\mathbf{d}_{pc} = \begin{bmatrix} x_{cluster} - \frac{P-2p+1}{2}\delta_T \cos\psi_T \\ y_{cluster} - \frac{P-2p+1}{2}\delta_T \sin\psi_T \\ z_{cluster} \end{bmatrix} \tag{11}$$

$$\mathbf{d}_{qc} = \begin{bmatrix} x_{cluster} - D_0 - \frac{Q-2q+1}{2}\delta_R \cos\psi_R \\ y_{cluster} - \frac{Q-2q+1}{2}\delta_R \sin\psi_R \\ z_{cluster} \end{bmatrix} \tag{12}$$

III. Double-IRS Assisted MIMO Channel Characteristics

In general, the spatial-temporal (ST) cross-correlation functions (CCFs) of the the double-IRS assisted channel model can be defined as the correlations between two different channel coefficients $h_{pq}(t)$ and $h_{p'q'}(t)$, where $p' = 1, 2, ..., P$ and $q' = 1, 2, ..., Q$. Therefore, we can obtain

$$\rho_{h_{pq}h_{p'q'}}(\Delta t) = \mathbb{E}\Big[\, h_{pq}(t)\, h^*_{p'q'}(t + \Delta t) \Big] \tag{13}$$

where $(\cdot)^*$ stands for the complex conjugate operation and $\mathbb{E}[\cdot]$ is the expectation operation. The Δt is the time difference. It deserves to mention that the propagation components through different mechanisms are assumed to be independent to each other, we therefore have

$$\begin{aligned} \rho_{h_{p,q}h_{p',q'}}(\Delta t) &= \rho_{h_{pq,\mathrm{IRS}_1}h_{p'q',\mathrm{IRS}_1}}(\Delta t) \\ &+ \rho_{h_{pq,\mathrm{IRS}_2}h_{p'q',\mathrm{IRS}_2}}(\Delta t) \\ &+ \rho_{h_{pq,\mathrm{IRS}_1,\mathrm{IRS}_2}h_{p'q',\mathrm{IRS}_1,\mathrm{IRS}_2}}(\Delta t) \\ &+ \rho_{h_{pq,c}h_{p'q',c}}(\Delta t) \end{aligned} \tag{14}$$

where $\rho_{h_{pq,\mathrm{IRS}_1}h_{p'q',\mathrm{IRS}_1}}(\Delta t)$ denotes the ST CCF of two different propagation links through the IRS_1. In substituting (3) into (13), we can obtain

$$\begin{aligned} \rho_{h_{pq,\mathrm{IRS}_1}h_{p'q',\mathrm{IRS}_1}}(\Delta t) = &\sum_{m_{x1},m_{z1}=1}^{M_{x1},M_{z1}} \\ &\times e^{-j2\pi f_c\left(\xi_{p,(m_{x1},m_{z1})}+\xi_{q,(m_{x1},m_{z1})}\right)/c} \\ &\times e^{j2\pi f_c\left(\xi_{p',(m_{x1},m_{z1})}+\xi_{q',(m_{x1},m_{z1})}\right)/c} \\ &\times e^{j\frac{2\pi}{\lambda}v_T\Delta t\cos\left(\alpha_{T,\mathrm{IRS}_1}-\eta_T\right)\cos\beta_{T,\mathrm{IRS}_1}} \\ &\times e^{j\frac{2\pi}{\lambda}v_R\Delta t\cos\left(\alpha_{R,\mathrm{IRS}_1}-\eta_R\right)\cos\beta_{R,\mathrm{IRS}_1}} \end{aligned} \tag{15}$$

In (14), $\rho_{h_{pq,\mathrm{IRS}_2}h_{p'q',\mathrm{IRS}_2}}(\Delta t)$ is the ST CCF of two different propagation links through the IRS_2. In substituting (5) into (13), we can obtain

$$\begin{aligned} \rho_{h_{pq,\mathrm{IRS}_2}h_{p'q',\mathrm{IRS}_2}}(\Delta t) = &\sum_{m_{x2},m_{z2}=1}^{M_{x2},M_{x2}} \\ &\times e^{-j2\pi f_c\left(\xi_{p,(m_{x2},m_{z2})}+\xi_{q,(m_{x2},m_{z2})}\right)/c} \\ &\times e^{j2\pi f_c\left(\xi_{p',(m_{x2},m_{z2})}+\xi_{q',(m_{x2},m_{z2})}\right)/c} \\ &\times e^{j\frac{2\pi}{\lambda}v_T\Delta t\cos\left(\alpha_{T,\mathrm{IRS}_2}-\eta_T\right)\cos\beta_{T,\mathrm{IRS}_2}} \\ &\times e^{j\frac{2\pi}{\lambda}v_R\Delta t\cos\left(\alpha_{R,\mathrm{IRS}_2}-\eta_R\right)\cos\beta_{R,\mathrm{IRS}_2}} \end{aligned} \tag{16}$$

Furthermore, in (14), the $\rho_{h_{pq,\mathrm{IRS}_1,\mathrm{IRS}_2}h_{p'q',\mathrm{IRS}_1,\mathrm{IRS}_2}}(\Delta t)$ is the ST CCF of two different propagation links through the IRS_1 and IRS_2. In substituting (8) into (13), we can obtain

$$\begin{aligned} \rho_{h_{pq,\mathrm{IRS}_1}h_{p'q',\mathrm{IRS}_2}}(\Delta t) = &\sum_{m_{x1},m_{z1},m_{x2},m_{z2}=1}^{M_{x1},M_{z1},M_{x2},M_{z2}} \\ &\times e^{-j2\pi f_c\left(\xi_{p,(m_{x1},m_{z1})}+\xi_{q,(m_{x2},m_{z2})}\right)/c} \\ &\times e^{j2\pi f_c\left(\xi_{p',(m_{x1},m_{z1})}+\xi_{q',(m_{x2},m_{z2})}\right)/c} \\ &\times e^{j\frac{2\pi}{\lambda}v_T\Delta t\cos\left(\alpha_{T,\mathrm{IRS}_1}-\eta_T\right)\cos\beta_{T,\mathrm{IRS}_1}} \\ &\times e^{j\frac{2\pi}{\lambda}v_R\Delta t\cos\left(\alpha_{R,\mathrm{IRS}_2}-\eta_R\right)\cos\beta_{R,\mathrm{IRS}_2}} \end{aligned} \tag{17}$$

Moreover, the $\rho_{h_{pq,c}h_{p'q',c}}(\Delta t)$ is the ST CCF of the propagation links through the cluster. In substituting (10) into (13), and then averaging over the random phases φ_0, we can obtain

$$\begin{aligned} \rho_{h_{pq,c}h_{p'q',c}}(\Delta t) = &\, e^{-j2\pi f_c\left(\xi_{pc}+\xi_{qc}-\xi_{p'c}-\xi_{q'c}\right)/c} \\ &\times e^{j\frac{2\pi}{\lambda}v_T\Delta t\cos\left(\alpha_{T,c}-\eta_T\right)\cos\beta_{T,c}} \\ &\times e^{j\frac{2\pi}{\lambda}v_R\Delta t\cos\left(\alpha_{R,c}-\eta_R\right)\cos\beta_{R,c}} \end{aligned} \tag{18}$$

It is obviously noted that the ST CCFs are related to the physical properties of the distributed IRSs, such as the number and layout of the unit cells in the IRS_1 and IRS_2, as well as the orientation angles. Furthermore, by imposing $\Delta t = 0$, we are able to derive the ST CCF of the IRS-assisted MIMO channel model; and by setting $p = p'$ and $q = q'$, we are able to obtain the temporal auto-correlation function of the channel model.

IV. Numerical Results and Discussions

In the following, we investigate the ST CCFs of the IRS-assisted MIMO channel model. The basic model parameters without specific statements are set as $f_c = 5.9$ GHz, $D_0 = 100$ m, $x_{\mathrm{IRS}_1,c} = 30$ m, $y_{\mathrm{IRS}_1,c} = 30$ m, $z_{\mathrm{IRS}_1,c} = 15$ m, $x_{\mathrm{IRS}_2,c} = 70$ m, $y_{\mathrm{IRS}_2,c} = 30$ m, $z_{\mathrm{IRS}_2,c} = 15$ m, $\theta_{\mathrm{IRS}_1} = \pi/6$, $\theta_{\mathrm{IRS}_2} = \pi/18$, and $d_{x1} = d_{z1} = d_{x2} = d_{z2} = \pi/4$. For the transmit and receive antenna arrays, we set $P = 4$, $Q = 6$, $\psi_T = \pi/3$, and $\psi_R = \pi/4$. Furthermore, we set the moving velocities/directions of the transceivers as $v_T = 1$ m/s, $\eta_T = 0$, $v_R = 2$ m/s, and $\eta_R = 0$.

By using (17), Fig. 3 plots the ST CCFs of the propagation links through the IRS_1 and IRS_1 for different antenna spacings at the MR. It is obviously observed that the ST correlations gradually drop as the receive antenna spacing rises from 0 to

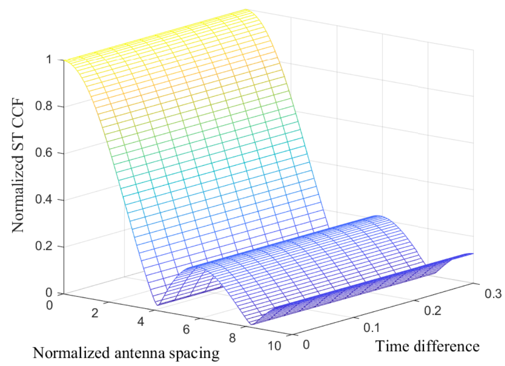

Fig. 3. ST CCFs of the double-IRS cooperatively assisted MIMO channel model with respect to the receive antenna spacings and time difference when $M_{x1} = M_{z1} = M_{x2} = M_{z2} = 300$.

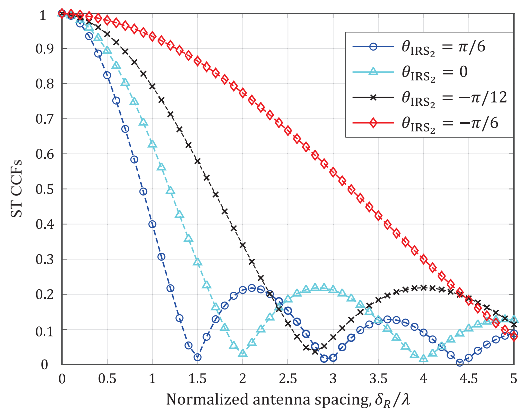

Fig. 4. Proposed ST CCFs of the propagation links through the IRS_1 and IRS_1 with respect to the receive antenna spacings when $M_{x1} = M_{z1} = M_{x2} = M_{z2} = 500$.

10, which are in consistent with the observations in [9]. On the other hand, when the time difference Δt is set as different values, the ST correlations are not the same.

By using (16), Fig. 4 illustrates the ST CCFs of the propagation links through the IRS_2 for different orientation angles of the distributed IRSs. It is obvious that the ST correlations vary as we set different values of the orientation angle θ_{IRS_1}. Specifically, we notice that when the θ_{IRS_1} drops from $\pi/6$ to $-\pi/6$, the ST correlations rise gradually.

Fig. 5 illustrates the ST CCFs of the propagation links through different propagation mechanisms. It can be seen that when the waves transmitted by MT experience different mechanisms before arriving at the MR, the differences of the ST correlations are significant. Specifically, when the waves impinge on the IRS_1 before arriving at the MR, the ST correlations drop rapidly as the M_{x1} and M_{z1} rise from 100 to 500. A similar conclusion can be achieved as the waves transmitted by transmitter impinge on the IRS_2 before arriving at the receiver.

V. Conclusions

In this article, we have provided a 3D stochastic wireless channel model for double-IRS cooperatively assisted MIMO

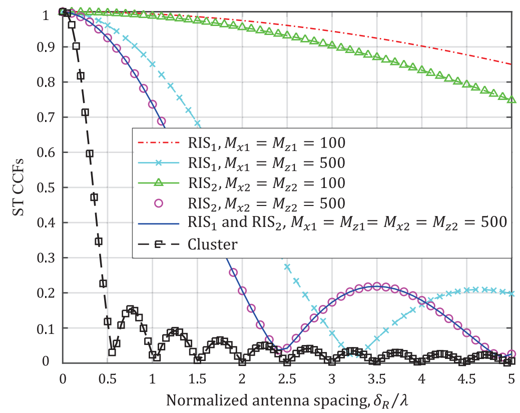

Fig. 5. Proposed ST CCFs of the propagation links through the IRS_2 with respect to the layout of the unit cells in the IRS_1 and IRS_2.

communications. It has been demonstrated that the proposed double-IRS cooperatively assisted MIMO channel characteristics depend on the number and layout of the unit cells as well as the orientations in the distributed IRSs. Specifically, it has been demonstrated that the proposed ST correlations drop slowly as the receive antenna spacing rises. It has also shown that the ST correlations drop as the numbers of the elements in the distributed IRSs increase. As future works, we can extend the proposed channel model to non-stationary channel models, and then study the double-IRS cooperatively assisted MIMO channel characteristics in the spatial/time/frequency domain.

References

[1] D. Chang *et al.*, "Capacity optimization using augmented lagrange method in intelligent reflecting surface-based MIMO communication systems," *China Commun.*, vol. 17, no. 12, pp. 123-138, Dec. 2020.

[2] M. Najafi, V. Jamali, R. Schober, and H. V. Poor, "Physics-based modeling and scalable optimization of large intelligent reflecting surfaces," *IEEE Trans. Commun.*, vol. 69, no. 4, pp. 2673-2691, Apr. 2021.

[3] Q.-U.-A. Nadeem *et al.*, "Intelligent reflecting surface assisted wireless communication: modeling and channel estimation," *arXiv preprint arXiv:1906.02360*, 2019.

[4] Steven W. Ellingson, "Path loss in reconfigurable intelligent surface-enabled channels," *arXiv preprint arXiv:1912.06759*, 2019.

[5] Y. Han *et al.*, "Cooperative double-IRS aided communication: Beamforming design and power scaling," *IEEE Wireless Commun. Lett.*, vol. 9, no. 8, pp. 1206-1210, Aug. 2020.

[6] B. Zheng, C. You, and R. Zhang, "Double-IRS assisted multi-user MIMO: cooperative passive beamforming design," *IEEE Trans. Wireless Commun.*, vol. 20, no. 7, pp. 4513-4526, July 2021.

[7] H. Jiang *et al.*, "A general wideband non-stationary stochastic channel model for intelligent reflecting surface-assisted MIMO communications," *IEEE Trans. Wireless Commun.*, vol. 20, no. 8, pp. 5314-5328, Aug. 2021.

[8] C. F. Lopez and C. Wang, "Novel 3-D non-stationary wideband models for massive MIMO channels," *IEEE Trans. Wireless Commun.*, vol. 17, no. 5, pp. 2893-2905, May 2018.

[9] H. Jiang *et al.*, "A novel 3D UAV channel model for A2G communication environments using AoD and AoA estimation algorithms," *IEEE Trans. Commun.*, vol. 68, no. 11, pp. 7232-7246, Nov. 2020.