LEO Satellite Communications with Massive MIMO

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***Abstract*—Low earth orbit (LEO) satellite communications are expected to be incorporated in future wireless networks to provide global wireless access with enhanced data rates. Massive multiple-input multiple-output (MIMO) techniques, though widely used in terrestrial communication systems, have not been applied to LEO satellite communication systems. In this paper, we propose a massive MIMO downlink (DL) transmission scheme with full frequency reuse (FFR) for LEO satellite communication systems by exploiting statistical channel state information (sCSI) at the transmitter. We first establish a massive MIMO channel model for LEO satellite communications and propose Doppler and time delay compensation techniques at user terminals (UTs). Then, we develop a closed-form low-complexity sCSI based DL precoder by maximizing the average signal-to-leakage-plus-noise ratio (ASLNR). Motivated by the DL ASLNR upper bound, we further propose a space angle based user grouping algorithm to schedule the served UTs into different groups, where each group of UTs use the same time and frequency resource. Numerical results demonstrate that the proposed massive MIMO transmission scheme with FFR significantly enhances the data rate of LEO satellite communication systems.**

I. Introduction

Satellite communication systems can provide seamless wireless coverage so as to complement and extend terrestrial communication networks [1], which are expected to be incorporated in future wireless networks. Low earth orbit (LEO) satellite communications, with orbits at altitudes of less than 2000 km, have recently gained broad research interests due to the less stringent requirements on, e.g., power consumption and transmission signal delays [2].

In satellite communication systems, multibeam transmission techniques have been widely adopted to increase transmission data rates [3]. As a well-know multibeam solution, a four-color frequency reuse (FR4) scheme where adjacent beams are allocated with non-overlapping frequency spectrum (or different polarizations) is adopted to mitigate the co-channel inter-beam interference. To further enhance the spectral efficiency of satellite communications, the more aggressive full frequency reuse (FFR) schemes [3]–[5], where frequency resources are reused across neighboring beams, have been considered to increase the total available bandwidth in each beam. However, using FFR might increase the inter-beam interference, which has to be properly handled via, e.g., precoding at transmitter.

In recent years, massive multiple-input multiple-output (MIMO) transmission, where a large number of antennas are equipped at a base station to serve many user terminals (UTs), has been applied in terrestrial networks, e.g., 5G [6], as an enabling technology. Massive MIMO can substantially increase available degrees of freedom, and achieve high data rates. Though widely used in terrestrial communication systems, massive MIMO has not been applied to LEO satellite communication systems. Motivated by this, we propose to exploit massive MIMO along with FFR for LEO satellite systems, where a large number of antennas are equipped at the LEO satellite side. Deploying massive MIMO on a LEO satellite would be challenging due to the practical concerns such as size, weight, cost, feeder link restrictions, etc. In this work, we focus on the physical layer transmission design for massive MIMO LEO satellite communication systems.

Albeit the existence of a large body of literature on massive MIMO in terrestrial cellular communication systems [6], so far massive MIMO has not been applied to satellite systems. The performance of massive MIMO systems relies substantially on the available channel state information (CSI) [7], [8]. However, obtaining instantaneous CSI (iCSI) at the transmitter sides of satellite communication systems is not only difficult but even infeasible due to the long propagation delay between the satellite and UTs as well as the mobility of UTs and satellites. Compared with iCSI, statistical CSI (sCSI) varies much slower and thus can be relatively easily obtained at both satellite and UTs with sufficiently high accuracy. Although there exist several works investigating sCSI based massive MIMO transmission in terrestrial systems [8], [9], it is in general not easy to extend these works to the satellite systems due to the significantly different channel propagation characteristics [10]. In this paper, we investigate massive MIMO transmission for LEO satellite communication systems using FFR based on sCSI. In particular, we focus on devising downlink (DL) precoding and user grouping utilizing sCSI.

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II. System Model

Consider a LEO satellite communication system where a satellite provides services to a number of single-antenna UTs simultaneously. The satellite is equipped with a uniform planar array (UPA) composed of $M = M_{\mathrm{x}} M_{\mathrm{y}}$ antennas where M_{x} and M_{y} are the numbers of antennas on the x- and y-axes, respectively. Assume without loss of generality that the antennas are separated by one-half wavelength in both the x- and y-axes, and both M_{x} and M_{y} are even.

We focus on investigating the DL channel between the satellite and a specific UT k, assuming that the channels between the satellite and different UTs are uncorrelated. Using a ray-tracing based channel modeling approach, the complex baseband DL space domain channel response $\mathbf{g}_k(t,f) \in \mathbb{C}^{M\times 1}$ between the LEO satellite and UT k at instant t and frequency f can be represented by [10]–[13]

$$\mathbf{g}_k(t,f) = \sum_{p=0}^{P_k-1} g_{k,p} \cdot \exp\left\{\jmath 2\pi \left[t\nu_{k,p} - f\tau_{k,p}\right]\right\} \cdot \mathbf{v}_{k,p}, \quad (1)$$

where $\jmath = \sqrt{-1}$, P_k denotes the number of channel propagation paths of UT k, and $g_{k,p}$, $\nu_{k,p}$, $\tau_{k,p}$, and $\mathbf{v}_{k,p} \in \mathbb{C}^{M\times 1}$ are the complex-valued gain, the Doppler shift, the propagation delay, and the DL array response vector associated with path p of UT k, respectively. Note that the channel model adopted in (1) is applicable over the time intervals of interest where the relative positions of the LEO satellite and UT k do not change significantly, and thus the physical channel parameters, P_k, $g_{k,p}$, $\nu_{k,p}$, $\tau_{k,p}$, and $\mathbf{v}_{k,p}$, are assumed to be invariant. When the LEO satellite and/or the UT move over large distances, the above channel parameters will vary and should be updated accordingly [11]. Hereafter, we detail some propagation characteristics of the LEO satellite channels and their impact on the modeling of the channel parameters in (1).

1) Doppler: For LEO satellite communications, assuming that the scatterers are stationary in the considered interval of interest, then the Doppler shift $\nu_{k,p}$ is mainly composed of two independent Doppler shifts, $\nu_{k,p}^{\mathrm{sat}}$ and $\nu_{k,p}^{\mathrm{ut}}$, that are caused by the motions of the LEO satellite and the UT, respectively [14]. Notice that due to the relatively high altitude of the LEO satellite, the Doppler shifts $\nu_{k,p}^{\mathrm{sat}}$ caused by the motion of the LEO satellite can be assumed to be identical for different propagation paths p of the same UT k [14], and different for different UTs. Thus, for notation simplicity, we omit the path index of the Doppler shift $\nu_{k,p}^{\mathrm{sat}}$ due to the motion of the LEO satellite and rewrite $\nu_{k,p}^{\mathrm{sat}} = \nu_k^{\mathrm{sat}}$. In addition, the Doppler shifts $\nu_{k,p}^{\mathrm{ut}}$ due to the motion of the UT are typically different for different propagation paths, contributing the Doppler spread of the LEO satellite channels [14].

2) Delay: Due to the large distance between the LEO satellite and the UTs, the propagation delay $\tau_{k,p}$ exhibits a much larger value than that in terrestrial communications. Denote by $\tau_k^{\min} = \min_p\{\tau_{k,p}\}$ and $\tau_k^{\max} = \max_p\{\tau_{k,p}\}$ the minimum and maximum values of the propagation delays of UT k, respectively. The relative delay spread of the LEO satellite channels $\tau_k^{\max} - \tau_k^{\min}$ might be much smaller than that of the terrestrial wireless channels, as observed in measurement results [15], [16]. For notational brevity, we define $\tau_{k,p}^{\mathrm{ut}} \triangleq \tau_{k,p} - \tau_k^{\min}$. Note that due to, e.g., the long propagation delays in LEO satellite communications, acquiring reliable iCSI at the transmitter sides is usually infeasible, especially when the UTs are in high mobility. Thus, it is more practical to investigate transmission design with, e.g., sCSI, in LEO satellite communications.

3) Angle: The UPA response vector $\mathbf{v}_{k,p} \in \mathbb{C}^{M\times 1}$ in (1) can be represented by [17]

$$\mathbf{v}_{k,p} \triangleq \mathbf{v}_{k,p}^{\mathrm{x}} \otimes \mathbf{v}_{k,p}^{\mathrm{y}} = \mathbf{v}_{\mathrm{x}}\left(\vartheta_{k,p}^{\mathrm{x}}\right) \otimes \mathbf{v}_{\mathrm{y}}\left(\vartheta_{k,p}^{\mathrm{y}}\right), \quad (2)$$

where $\otimes$ denotes the Kronecker product, and $\mathbf{v}_{k,p}^d \in \mathbb{C}^{M_d\times 1}$ for $d \in \mathcal{D} \triangleq \{\mathrm{x},\mathrm{y}\}$ is the array response vector of the angle with respect to the x- or y-axis given by $\mathbf{v}_{k,p}^d \triangleq \mathbf{v}_d\left(\vartheta_{k,p}^d\right)$, where $\mathbf{v}_d(\vartheta) = \frac{1}{\sqrt{M_d}}\left[1 \ \exp\{-\jmath\pi\vartheta\} \ \ldots \ \exp\{-\jmath\pi(M_d-1)\vartheta\}\right]^T$ with the superscript $(\cdot)^T$ denoting the transpose operation. The parameters $\vartheta_{k,p}^{\mathrm{x}}$ and $\vartheta_{k,p}^{\mathrm{y}}$ are related to the physical angles as $\vartheta_{k,p}^{\mathrm{x}} = \sin\left(\theta_{k,p}^{\mathrm{y}}\right)\cos\left(\theta_{k,p}^{\mathrm{x}}\right)$ and $\vartheta_{k,p}^{\mathrm{y}} = \cos\left(\theta_{k,p}^{\mathrm{y}}\right)$ where $\theta_{k,p}^{\mathrm{x}}$ and $\theta_{k,p}^{\mathrm{y}}$ are the angles with respect to the x- and y-axes associated with the pth propagation path of UT k, respectively. For satellite channels, the angles of all propagation paths associated with the same UT, can be assumed to be identical due to the high altitude of the satellite compared with that of the scatterers located in the vicinity of the UTs [18], i.e., $\vartheta_{k,p}^d = \vartheta_k^d$. Note that ϑ_k^d can reflect the propagation properties of the LEO satellite channels in the space domain, and we refer to ϑ_k^d as the space angle parameters. Then, the array response vector can be rewritten as

$$\mathbf{v}_{k,p} = \mathbf{v}_k = \mathbf{v}_k^{\mathrm{x}} \otimes \mathbf{v}_k^{\mathrm{y}} = \mathbf{v}_{\mathrm{x}}\left(\vartheta_k^{\mathrm{x}}\right) \otimes \mathbf{v}_{\mathrm{y}}\left(\vartheta_k^{\mathrm{y}}\right), \quad (3)$$

which will be referred to as the DL channel direction vector of UT k that is associated with the space angles ϑ_k^{x} and ϑ_k^{y}. Note that when the number of antennas M_d for $d \in \mathcal{D}$ tends to infinity, we can know from (3) that the channel direction vectors of different UTs are asymptotically orthogonal, i.e.,

$$\lim_{M_d\to\infty} \left(\mathbf{v}_k^d\right)^H \mathbf{v}_{k'}^d = \delta\left(k-k'\right). \quad (4)$$

Based on the above modeling of the propagation properties of LEO satellite communications, we can rewrite the channel response in (1) as follows

$$\mathbf{g}_k(t,f) = \exp\left\{\jmath 2\pi \left[t\nu_k^{\mathrm{sat}} - f\tau_k^{\min}\right]\right\} \cdot g_k(t,f) \cdot \mathbf{v}_k, \quad (5)$$

where $g_k(t,f)$ is the DL channel gain of UT k given by

$$g_k(t,f) \triangleq \sum_{p=0}^{P_k-1} g_{k,p} \cdot \exp\left\{\jmath 2\pi \left[t\nu_{k,p}^{\mathrm{ut}} - f\tau_{k,p}^{\mathrm{ut}}\right]\right\}, \quad (6)$$

which will be convenient for later derivation.

4) Gain: Note that the statistical properties of the fluctuations of the channel gain $g_k(t,f)$ in LEO satellite communications mainly depend on the propagation environment in which the UT is located. In this work, we focus on the case where both the non-shadowed LOS and non-LOS paths of the LEO satellite channels exist [19]. Then, the channel gain $g_k(t,f)$ exhibits the Rician fading distribution with the Rician factor κ_k and power $\mathsf{E}\left\{|g_k(t,f)|^2\right\}=\gamma_k$.

We proceed with the DL transmission model. Consider a wideband massive MIMO LEO satellite system employing orthogonal frequency division multiplexing (OFDM) modulation [14] with the number of subcarriers, N_{us}, and the cyclic prefix (CP), N_{cp} samples. Denote by T_{s} the sampling interval. Then, the lengths of the OFDM symbol and CP are given by $T_{\mathrm{us}}=N_{\mathrm{us}}T_{\mathrm{s}}$ and $T_{\mathrm{cp}}=N_{\mathrm{cp}}T_{\mathrm{s}}$, respectively.

Let $\{\mathbf{x}_{\ell,n}\}_{n=0}^{N_{\mathrm{us}}-1}$ be the DL transmit symbols during symbol ℓ. Then, the transmitted signal $\mathbf{x}_\ell(t)$ can be written as [20]

$$\mathbf{x}_\ell(t)=\sum_{n=0}^{N_{\mathrm{us}}-1}\mathbf{x}_{\ell,n}\cdot\exp\left\{\bar{\jmath}2\pi\frac{n}{T_{\mathrm{us}}}t\right\}\in\mathbb{C}^{M\times1}, \quad (7)$$

where $-T_{\mathrm{cp}}\le t-\ell(T_{\mathrm{cp}}+T_{\mathrm{us}})<T_{\mathrm{us}}$ and the corresponding received signal at UT k is given by (where the noise is omitted for brevity)

$$y_{k,\ell}(t)=\int_{-\infty}^{\infty}\mathbf{g}_k^T(t,\tau)\cdot\mathbf{x}_\ell(t-\tau)\,\mathrm{d}\tau, \quad (8)$$

where $\mathbf{g}_k(t,\tau)$ is the inverse Fourier transform of $\mathbf{g}_k(t,f)$ in (5) in terms of τ.

Utilizing the Doppler and delay properties of the LEO satellite propagation channels addressed previously, we proceed to perform time and frequency synchronizations. In particular, with delay compensation $\tau_k^{\mathrm{syn}}=\tau_k^{\min}$ and Doppler compensation $\nu_k^{\mathrm{syn}}=\nu_{k,p}^{\mathrm{sat}}$ applied to the received signal at UT k, the resultant signal can be represented by

$$y_{k,\ell}^{\mathrm{syn}}(t)=y_{k,\ell}(t+\tau_k^{\mathrm{syn}})\cdot\exp\left\{-\bar{\jmath}2\pi(t+\tau_k^{\mathrm{syn}})\nu_k^{\mathrm{syn}}\right\}. \quad (9)$$

Then, the corresponding signal dispersion in the delay and Doppler domains can be significantly reduced, and it is not difficult to select proper OFDM parameters to mitigate the intersymbol and intercarrier interference [20]. Consequently, the demodulated DL received signal at UT k over subcarrier n of OFDM symbol ℓ can be represented by

$$y_{k,\ell,n}=\mathbf{g}_{k,\ell,n}^T\mathbf{x}_{\ell,n}, \quad (10)$$

where $\mathbf{g}_{k,\ell,n}$ is the DL channel of UT k over symbol ℓ and subcarrier n given by [20]

$$\mathbf{g}_{k,\ell,n}=\mathbf{v}_k\cdot g_{k,\ell,n}\in\mathbb{C}^{M\times1}, \quad (11)$$

where $g_{k,\ell,n}=g_k(\ell(T_{\mathrm{us}}+T_{\mathrm{cp}}),n/T_{\mathrm{us}})$.

III. Statistical CSI based DL Transmission

In this section, we investigate DL precoder design for LEO satellite communications based on the channel and signal models established in the above section. Note that the conventional designs of DL precoding vectors in MIMO transmission usually require knowledge of iCSI. However, it is in general infeasible to obtain precise iCSI at the satellite sides for DL of LEO satellite communications. In addition, frequent update of the DL precoding vectors using iCSI will be challenging for implementation on payload of practical satellite communications. Hereafter, we focus on the design of DL precoder utilizing slowly-varying sCSI for satellite communications.

A. DL Precoder

We first consider DL transmission where K single antenna UTs are simultaneously served in the same time-frequency blocks, and the served UT set is denoted by $\mathcal{K}=\{0,1,\ldots,K-1\}$. For DL linear precoding performed at the satellite, the signal received by UT $k\in\mathcal{K}$ in (10) can be rewritten as

$$y_k=\mathbf{g}_k^T\sum_{i\in\mathcal{K}}\sqrt{q_i}\mathbf{b}_is_i+z_k, \quad (12)$$

where the subcarrier and symbol indices are omitted for brevity, q_k is the transmit power allocated to UT k, $\mathbf{b}_k\in\mathbb{C}^{M\times1}$ is the normalized transmit precoding vector satisfying the $\|\mathbf{b}_k\|=\sqrt{\mathbf{b}_k^H\mathbf{b}_k}=1$, s_k is the signal for UT k with mean 0 and variance 1, and z_k is the additive circular symmetric complex-valued Gaussian noise with mean 0 and variance σ_k, i.e., $z_k\sim\mathcal{CN}(0,\sigma_k)$.

Note that signal-to-leakage-plus-noise ratio (SLNR) is a convenient and efficient design metric widely adopted in DL multiuser MIMO transmission, and we first review the SLNR maximization criterion based precoding approach. In particular, the SLNR of UT k in the DL is given by [21]

$$\mathsf{SLNR}_k=\frac{\left|\mathbf{g}_k^T\mathbf{b}_k\right|^2}{\sum_{i\ne k}\left|\mathbf{g}_i^T\mathbf{b}_k\right|^2+\frac{1}{\rho_k}}, \quad (13)$$

where $\rho_k\triangleq q_k/\sigma_k$ is the DL signal-to-noise ratio (SNR) of UT k. Then the precoder of UT k that maximizes SLNR_k in (13) can be obtained as

$$\mathbf{b}_k^{\mathrm{slnr}}=\frac{1}{\eta_k^{\mathrm{slnr}}}\left[\left(\sum_i\mathbf{g}_i\mathbf{g}_i^H+\frac{1}{\rho_k}\mathbf{I}_M\right)^{-1}\mathbf{g}_k\right]^*, \quad (14)$$

where $(\cdot)^H$ and $(\cdot)^*$ denote the conjugate-transpose and conjugate operations, respectively, η_k^{slnr} is the power normalization coefficient that is set to satisfy $\left\|\mathbf{b}_k^{\mathrm{slnr}}\right\|=1$. We mention that the SLNR maximization DL precoder in (14) requires knowledge of iCSI $\mathbf{g}_k$ for all k. However, it is in general difficult to obtain precise DL iCSI for transmitter at the satellite side.

In the following, we investigate DL precoding for satellite communications using long-term sCSI at the transmitter, including the channel direction vector $\mathbf{v}_k$ and the statistics of the channel gain $g_{k,\ell,n}$. We consider the ASLNR performance metric as follows [22]

$$\mathsf{ASLNR}_k\triangleq\frac{\gamma_k\left|(\mathbf{v}_k)^T\mathbf{b}_k\right|^2}{\sum_{i\ne k}\gamma_i\left|(\mathbf{v}_i)^T\mathbf{b}_k\right|^2+\frac{1}{\rho_k^{\mathrm{dl}}}}, \quad (15)$$

where the numerator and the denominator account for the average power of the signal and leakage plus noise, respectively.

The sCSI based precoder that maximizes ASLNR_k is presented in the following proposition.

Proposition 1: The precoding vector that maximizes ASLNR_k in (15) is given by

$$\mathbf{b}_k^{\mathrm{aslnr}} = \frac{1}{\eta_k^{\mathrm{aslnr}}} \left(\mathbf{A}_k^{-1}\mathbf{v}_k\right)^*, \tag{16}$$

where $\mathbf{A}_k = \sum_i \gamma_i \mathbf{v}_i \mathbf{v}_i^H + \frac{1}{\rho_k}\mathbf{I}_M$, η_k^{aslnr} is the power normalization coefficient that is set to satisfy $\left\|\mathbf{b}_k^{\mathrm{aslnr}}\right\| = 1$, and the corresponding maximum ASLNR value is given by

$$\mathsf{ASLNR}_k^{\max} = \frac{1}{1-\gamma_k \mathbf{v}_k^H \mathbf{A}_k^{-1}\mathbf{v}_k} - 1. \tag{17}$$

Note that Proposition 1 provides a sCSI based DL precoder that maximizes the ASLNR in closed-form. As the proposed sCSI based DL precoding design is independent of subcarriers and OFDM symbols in transmission interval where the channels statistics do not change significantly and thus is convenient for practical implementation of the satellite payloads. Then, the computational overhead for DL precoding design can be reduced compared with the iCSI based approach.

B. Upper Bound of ASLNR

In this subsection, we investigate the condition under which the DL ASLNR metric considered above can be upper bounded.

Proposition 2: The maximum DL ASLNR value $\mathsf{ASLNR}_k^{\max}$ in (17) is upper bounded by

$$\mathsf{ASLNR}_k^{\max} \le \rho_k^{\mathrm{dl}}\gamma_k, \tag{18}$$

and the upper bound can be achieved under the condition that

$$\left(\mathbf{v}_k^{\mathrm{x}}\right)^H \mathbf{v}_i^{\mathrm{x}} = 0 \text{ or } \left(\mathbf{v}_k^{\mathrm{y}}\right)^H \mathbf{v}_i^{\mathrm{y}} = 0,\ \forall k \ne i. \tag{19}$$

Proposition 2 shows that the DL ASLNRs of all served UTs with the proposed sCSI based precoder can reach their upper bounds provided that the corresponding channel direction vectors of different UTs are mutually orthogonal. The result in Proposition 2 is physically intuitive as the DL channel leakage power can be eliminated provided that the condition in (19) is satisfied.

From (4), we can observe that the optimal conditions obtained in Proposition 2 can be asymptotically satisfied when the number of antennas M tends to infinity. This corroborates the rationality and potential of exploiting massive MIMO in enhancing the transmission performance of satellite communications.

Remark 1: Note that for the case with a sufficiently large number of antennas at the satellite side, the precoder in (16) will asymptotically tend to the discrete Fourier transform (DFT) based fixed precoder as follows

$$\mathbf{b}_k = \left[\mathbf{v}_{\mathrm{x}}\left(\overline{\vartheta}_k^{\mathrm{x}}\right) \otimes \mathbf{v}_{\mathrm{y}}\left(\overline{\vartheta}_k^{\mathrm{y}}\right)\right]^*, \tag{20}$$

where $\overline{\vartheta}_k^d$ is the nearest point of ϑ_k^d in the DFT grid satisfying $\overline{\vartheta}_k^d = -1 + 2n_k^d/M_d$ with $n_k^d \in [0, M_d-1]$ being integers and $\left|\overline{\vartheta}_k^d - \vartheta_k^d\right| < 2/M_d$ for $d \in \mathcal{D}$. In this case, the precoding vectors for the simultaneously served UTs in the same user group are orthogonal, and can be efficiently implemented with fast Fourier transform (FFT).

IV. Space Angle based User Grouping

From the results in the above section, we can observe that the performance of the proposed sCSI based precoder in massive MIMO LEO satellite communications will largely depend on the channel statistics of the simultaneously served UTs. As the number of the UTs to be served is usually much larger than that of antennas equipped at the satellites, user grouping is of practical importance. Compared with the terrestrial counterpart, user grouping is of greater interest as the satellite service provider generally aims at serving all UTs in satellite communications. In this section, we investigate user grouping for massive MIMO LEO satellite communications.

Although the presented condition in Proposition 2 are desirable for optimizing the performance of DL ASLNRs in satellite communications, it is in general difficult to schedule the UTs that rigorously satisfy this condition, and the optimal user grouping pattern can be found through exhaustive search. However, due to the large number of existing UTs in satellite communications, it is usually infeasible to perform an exhaustive search in practical systems.

The optimal user grouping condition presented in Proposition 2 indicates that the channel direction vectors of UTs in the same group should be as orthogonal as possible. From the definition in (3), the channel direction vectors are directly related to the channel propagation properties in the space domain, i.e., the channel space angles. Then, the condition for achieving the upper bound of ASLNR presented in (19) can be reduced to that the channel space angles should satisfy

$$\vartheta_k^{\mathrm{x}} - \vartheta_i^{\mathrm{x}} = \frac{2}{M_{\mathrm{x}}} n_{k,i}^{\mathrm{x}} \text{ or } \vartheta_k^{\mathrm{y}} - \vartheta_i^{\mathrm{y}} = \frac{2}{M_{\mathrm{y}}} n_{k,i}^{\mathrm{y}},\ \forall k \ne i, \tag{21}$$

where both $n_{k,i}^{\mathrm{x}}$ and $n_{k,i}^{\mathrm{y}}$ are non-zero integers. Motivated by the condition in (21), we propose a space angle based user grouping (SAUG) approach as follows. Specifically, we uniformly divide the space angle range $[-1, 1)$ into $M_{\mathrm{x}}G_{\mathrm{x}}$ and $M_{\mathrm{y}}G_{\mathrm{y}}$ equal sectors in the x- and y-axes, respectively, where G_{x} and G_{y} are both integers and their physical meaning will be clear later. Then, the space angle intervals after division can be represented by

$$\mathcal{A}_{(g,r)}^{(m,n)} = \left\{ (\phi_{\mathrm{x}}, \phi_{\mathrm{y}}) \middle| \phi_{\mathrm{x}} \in \left[\phi_{g,m}^{\mathrm{x}} - \frac{\Delta_{\mathrm{x}}}{2}, \phi_{g,m}^{\mathrm{x}} + \frac{\Delta_{\mathrm{x}}}{2}\right) \right.$$
$$\left. \phi_{\mathrm{y}} \in \left[\phi_{r,n}^{\mathrm{y}} - \frac{\Delta_{\mathrm{y}}}{2}, \phi_{r,n}^{\mathrm{y}} + \frac{\Delta_{\mathrm{y}}}{2}\right) \right\}, \tag{22}$$

where $\phi_{a,b}^d$ for $d \in \mathcal{D}$ is the center space angle of the interval in the x-/y-axis given by

$$\phi_{a,b}^d = -1 + \frac{\Delta_d}{2} + (a + bG_d)\Delta_d, \tag{23}$$

where $0 \le a \le G_d - 1$, $0 \le b \le M_d - 1$ and $\Delta_d = 2/\left(M_d G_d\right)$ is the length of the space angle interval in the x-/y-axis.

With the above definition of the space angle interval division, the UTs can be grouped as follows. A given UT k is scheduled into the (g,r)th group if there exist $0 \le m \le M_{\mathrm{x}}-1$ and $0 \le n \le M_{\mathrm{y}}-1$ such that the corresponding channel space angles satisfy

$$(\vartheta_k^{\mathrm{x}}, \vartheta_k^{\mathrm{y}}) \in \mathcal{A}_{(g,r)}^{(m,n)}. \tag{24}$$

Denote by $\mathcal{K}_{(g,r)}^{(m,n)} = \left\{ k : (\vartheta_k^{\mathrm{x}}, \vartheta_k^{\mathrm{y}}) \in \mathcal{A}_{(g,r)}^{(m,n)} \right\}$ the set of UTs whose space angles lie in the interval $\mathcal{A}_{(g,r)}^{(m,n)}$. In the proposed SAUG approach, we always require $\left| \mathcal{K}_{(g,r)}^{(m,n)} \right| \le 1$ to avoid intra-beam interference. Note that other UTs located in the same space angle interval can be scheduled over different time-frequency resources in a round-robin manner to preserve fairness. Based on the above user grouping procedure, the UTs are scheduled into at most $G_{\mathrm{x}}G_{\mathrm{y}}$ groups, where the (g,r)th UT group is defined as

$$\mathcal{K}_{(g,r)} \triangleq \bigcup_{0 \le m \le M_{\mathrm{x}}-1,\ 0 \le n \le M_{\mathrm{y}}-1} \mathcal{K}_{(g,r)}^{(m,n)}. \tag{25}$$

Note that the UTs scheduled in the same group will perform transmission over the same time-frequency resources, while UTs in different groups will be allocated with different time-frequency transmission resources.

V. Simulation Results

In this section, we provide simulation results to evaluate the performance of the proposed massive MIMO transmission approach for LEO satellite communications. The major simulation setup parameters are listed as follows. The numbers of antennas equipped at the satellite side are set to be $M_{\mathrm{x}} = M_{\mathrm{y}} = 16$ with half-wavelength antenna spacing in both the x- and y-axes. The channel Rician factor is set to be $\kappa_k = \kappa = 10$ dB, and the channel power is normalized as $\gamma_k = M_{\mathrm{x}}M_{\mathrm{y}}$ for all UT k. In addition, the channel space angles $\vartheta_{k,p}^{\mathrm{x}}$ and $\vartheta_{k,p}^{\mathrm{y}}$ are independently and uniformly distributed in the interval $[-1,1)$ for all UTs. The numbers of UT groups in the proposed SAUG approach are set to be equal for both x- and y-axes, i.e., $G_{\mathrm{x}} = G_{\mathrm{y}} = G$. The number of UTs to be grouped is set as G^2M.

Note that massive MIMO has not been applied to LEO satellite communications. We consider and compare the following DL precoding approaches in the simulations:

- **IntF:** An ideal interference-free (IntF) case where the interference from other scheduled UTs over the same time and frequency resource is "genie-aided" eliminated will be considered as the performance upper bound.
- **iCSI:** Relying on the iCSI, the SLNR maximization DL precoder in (14) is adopted, with the assumption that the iCSI can be "genie-aided" obtained.
- **sCSI:** The proposed sCSI based ASLNR maximization DL precoder in (16) is adopted.
- **Fixed:** DFT based fixed DL precoding vectors in (20) are adopted.

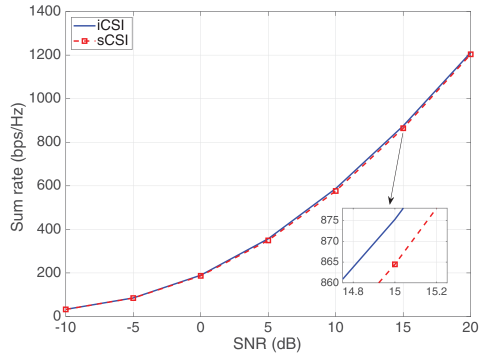

Fig. 1. Sum rate performance comparison between the proposed sCSI and iCSI based precoding approaches.

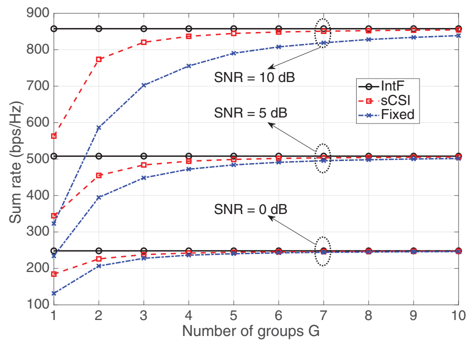

Fig. 2. Sum rate performance of SAUG with different transmission approaches versus the number of scheduled UT groups when FFR is adopted.

In Fig. 1, we evaluate the performance of the proposed sCSI based precoding approaches, and compare them with the iCSI based approaches where UTs are grouped using the proposed SAUG with $G = 1$. We can observe that, the proposed sCSI based precoder exhibits almost identical performance as the iCSI based one, while having significantly reduced computational overhead.

In Fig. 2, we evaluate the performance of the proposed SAUG approach with different precoding approaches versus the number of scheduled groups G when FFR is adopted across neighboring beams. We can observe that the performance of the proposed sCSI based precoder can approach that of the interference-free scenario, especially in the case with a large number of scheduled groups, which demonstrates the asymptotic optimality of the proposed transmission approach. In addition, the performance gap between the approach with fixed precoding vectors and the proposed sCSI based ones becomes smaller as the number of scheduled groups increases, especially in the low SNR regime, which indicates the near-optimality of the approach with fixed precoding vectors in the case where interference is not dominated.

In Fig. 3, the performance between the proposed transmission approach with FFR and the conventional FR4 is compared. Similarly as FFR, only one UT is scheduled per

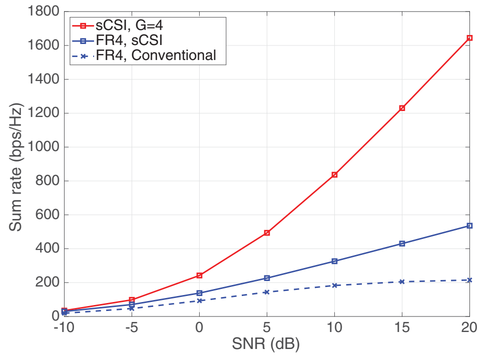

Fig. 3. Sum rate performance comparison between the proposed approach with FFR and the conventional FR4 one.

beam over the same time and frequency resource in FR4. Note that in FR4, the UTs with the same color are a group of UTs performing transmission over the same time and frequency resource. For FR4, we consider two transmission approaches where "FR4, Conventional" denotes the fixed precoder in (20) and "FR4, sCSI" denotes the proposed sCSI based precoder in (16) applied to the group of UTs over the same time and frequency resource for interference mitigation, respectively. We can observe that the proposed sCSI based precoder applied to FR4 shows sum rate performance gains over the conventional FR4 approach. Moreover, with FFR across neighboring beams, the proposed sCSI based precoder combined with SAUG can provide significant rate performance gains over the conventional FR4 approach, especially in the high SNR regime. Notably, at an SNR of 20 dB, the proposed transmission approach with $G = 4$ can provide about eight-folded rate performance gain over the conventional FR4 approach.

VI. Conclusion

In this paper, we have investigated massive MIMO transmission for LEO satellite communications exploiting sCSI with FFR. We first established the massive MIMO channel model for LEO satellite communications by taking into account the LEO satellite signal propagation properties and simplified the DL transmission designs via performing Doppler and delay compensations at UTs. Then, we developed the sCSI based DL precoder in closed-form, under the criterion of maximizing the ASLNR. We further showed that the DL ASLNRs can reach their upper bounds provided that the channel direction vectors of the simultaneously served UTs are orthogonal, and proposed a space angle based user grouping (SAUG) approach motivated by this condition. Simulation results showed that the proposed massive MIMO transmission scheme with FFR significantly enhances the data rate of LEO satellite communication systems. Notably, the proposed sCSI based precoder achieved the similar performance with the iCSI based one that is often infeasible in practice.

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