Massive MIMO Downlink Transmission for LEO Satellite Communications

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Abstract—We investigate the downlink (DL) transmit strategy for massive multiple-input multiple-output (MIMO) low-earth-orbit (LEO) satellite communication (SATCOM) systems, in which only the slow-varying statistical channel state information (sCSI) is known at the transmitter side. First, we derive the massive MIMO LEO satellite channel model, where the uniform planar arrays are deployed at both the satellite and user terminals (UTs). Building on the rank-one property of the satellite channel matrices, we show that transmitting a single data stream to each UT is optimal in the sense that the ergodic sum rate is maximized. This result is of great importance for massive MIMO LEO SATCOM systems, since the sophisticated design of transmit covariance matrices is turned into that of precoding vectors, without loss of optimality. Furthermore, we develop an algorithm to compute the precoding vectors. Simulation results show the significant performance gains of the proposed approaches over the existing schemes.

I. INTRODUCTION

Satellites have been recognized as one of the most promising fundamental infrastructures to provide global seamless coverage \cite{zhou2021}. Recently, the low-earth-orbit (LEO) satellite communication (SATCOM) constellations have attracted great interest, due to their benefits on shorter delay, reduced pathloss, and lower manufacture costs \cite{trevor2006}. Nowadays, some LEO SATCOM systems have started to provide broadband high-throughput services, e.g., Starlink.

Multibeam satellites are the prevailing solutions in SATCOM systems, which serve the coverage areas with spot beams \cite{zhou2021}. Following the evolution of terrestrial wireless communications, the full frequency reuse (FFR) scheme, in which all spot beams use the same frequency band \cite{zhou2021}, has been adopted in SATCOM systems to further enhance spectral efficiency. To alleviate the serious inter-beam interference, the concept of precoding techniques, originated from multiuser multiple-input multiple-output (MU-MIMO) systems, is introduced in multibeam SATCOM systems, e.g., \cite{zhou2021}.

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The conventional beamforming network (BFN) at multibeam satellites is usually assumed to be fixed \cite{zhou2021}–\cite{zhou2021}. By deploying a large number of antennas at the base station (BS), massive MIMO transmission has made great success in terrestrial 5G communications, which can significantly improve the spectrum and energy efficiency \cite{zhou2021}. Indeed, the advantages of massive MIMO hinge on the multiple reconfigurable beams. Currently, the rapid development of microwave and antenna technologies has made it possible to implement a digitally reconfigurable BFN at the satellite \cite{zhou2021}. In this paper, we focus on an LEO satellite equipped with a large-scale antenna array, i.e., a massive MIMO LEO satellite, and we assume that the BFN at the satellite can be digitally reconfigurable.

Notice that the previous works on precoding in SATCOM mostly assume that the transmitter can obtain the instantaneous channel state information (iCSI) \cite{zhou2021}–\cite{zhou2021}, \cite{zhou2021}. Nevertheless, it is challenging to acquire the iCSI at the transmitter due to the satellite channel impairments, e.g., large propagation delays and Doppler effects. Compared with the iCSI, statistical CSI (sCSI) can be considered to be stable for a longer time period \cite{zhou2021}, and thus can be more easily acquired at the transmitter side. In this paper, we assume that the satellite can only exploit sCSI for the downlink (DL) transmit design.

The DL transmit design using sCSI at the transmitter (sCSIT) has been studied in massive MIMO terrestrial cellular systems, e.g., \cite{zhou2021}–\cite{zhou2021}. However, these works do not consider the massive MIMO LEO satellite channel properties, and have high implementation complexity. In \cite{zhou2021}, the authors studied the channel model, DL precoders, UL receivers, and user grouping for massive MIMO LEO SATCOM systems with single-antenna user terminals (UTs). Nevertheless, the DL precoders in \cite{zhou2021} are derived under the individual criterion of maximizing the average signal-to-leakage-plus-noise ratio (ASLNR) for each UT, thus restricting the system throughput.

In this paper, we investigate the DL transmit strategy for massive MIMO LEO SATCOM system, where the satellite and the UTs are both equipped with uniform planar arrays (UPAs), by exploiting the long-term sCSIT only. First, we derive the massive MIMO LEO satellite channel model. The Doppler
and delay effects are compensated at each UT to support the wideband transmission. We show that transmitting a single data stream to each UT is optimal for linear transmitters to maximize the ergodic sum rate. Then, the complicated design of transmit covariance matrices is simplified into that of precoding vectors, for which an algorithm is developed within the minimization-maximization (MM) framework. Simulation results verify the effectiveness of the proposed approaches.

II. SYSTEM MODEL

A. System Setup

We consider that a massive MIMO LEO satellite at an altitude of \( H \) serves mobile UTs on ground over lower frequency bands, e.g., L/S/C bands. The satellite has a large-scale UPA with \( M_s \) and \( M_f \) elements in the x-axis and y-axis, respectively. Then, the total number of antennas at the satellite is \( M_sM_f \). Each UT’s UPA has \( N_r \) and \( N_t \) elements in the x-axis and y-axis, respectively, and \( N \triangleq N_rN_t \) is the total number of antennas at each UT.

B. Signal and Channel Models in Analog Baseband

First, the DL received signal at UT \( k \) at time instant \( t \) can be expressed as follows

\[
y_k(t) = \int_{-\infty}^{\infty} \mathbf{H}_k(t, \tau) x(t - \tau) d\tau + z_k(t),
\]

where \( \mathbf{H}_k(t, \tau) \in \mathbb{C}^{N \times M} \), \( x(t) \in \mathbb{C}^M \) and \( z_k(t) \in \mathbb{C}^{N \times 1} \) are the channel impulse response (CIR), transmit signal and additive Gaussian noise of UT \( k \), respectively. The time-varying LEO satellite CIR \( \mathbf{H}_k(t, \tau) \) can be written as

\[
\mathbf{H}_k(t, \tau) = \sum_{\ell \in \mathbb{Z}} a_{k,\ell} e^{j2\pi v_k,\ell t} \mathbf{d}_k/d_{k,\ell},
\]

where \( j \triangleq \sqrt{-1} \), \( \delta(x) \) is the Dirac delta function. In (2), \( L_k \), \( a_{k,\ell} \) \( v_k,\ell \) \( \mathbf{d}_k \) \( \mathbf{d}_{k,\ell} \in \mathbb{C}^{N \times 1} \) and \( g_k \in \mathbb{C}^{M \times 1} \) are the number of multipaths, complex channel gain, Doppler shift, propagation delay, array response vector at the UT side and array response vector at the satellite side, respectively, corresponding to path \( \ell \) of UT \( k \)'s channel. We assume that these channel parameters are unchanged within each coherence time interval. The detailed LEO satellite channel characteristics will be elaborated one by one as follows.

1) Doppler shifts:

The Doppler shifts in LEO satellite channels are more significant than those in terrestrial wireless channels, on account of the high moving velocity of the satellite. For a LEO satellite at an altitude of 1000 km operating at the 4 GHz carrier frequency, the Doppler shift can be 80 kHz [16]. The Doppler shift \( v_k,\ell \) for path \( \ell \) of UT \( k \)'s channel mainly includes two terms [17], i.e., \( v_k,\ell = v_{\text{cat}}^{k,\ell} + v_{\text{var}}^{k,\ell} \), where \( v_{\text{cat}}^{k,\ell} \) and \( v_{\text{var}}^{k,\ell} \) are the Doppler shifts due to the movement of the satellite and UT \( k \), respectively. The first term \( v_{\text{cat}}^{k,\ell} \) is almost the same for different \( \ell \)'s [17]. Hence, we have \( v_{\text{cat}}^{k,\ell} \triangleq v_{\text{cat}}^{k} \), \( \ell = 0, \ldots, L_k - 1 \). Moreover, \( v_{\text{var}}^{k,\ell} \) varies almost deterministically, and hence it can be estimated and compensated at UTs.

On the other hand, \( v_{\text{var}}^{k,\ell} \)'s of each path are different. The propagation delays for LEO satellite channels are also much larger than those in terrestrial wireless channels. For a LEO satellite at an altitude of 1000 km, the round-trip delay can be about 17.7 ms [18]. The minimal and maximal propagation delays of UT \( k \)'s channel is defined as \( \tau_{k,\text{min}} \) and \( \tau_{k,\text{max}} \), respectively.

2) Propagation Delays:

The propagation delays for LEO satellite channels are also much larger than those in terrestrial wireless channels. For a LEO satellite at an altitude of 1000 km, the round-trip delay can be about 17.7 ms [18]. The minimal and maximal propagation delays of UT \( k \)'s channel is defined as \( \tau_{k,\text{min}} \) and \( \tau_{k,\text{max}} \), respectively. Then, the total number of antennas at the satellite and UT \( k \) are \( M_sM_f \). Moreover, \( \tau_{k,\text{min}} \) and \( \tau_{k,\text{max}} \) of each path are usually different.

C. Signal and Channel Models for OFDM Based Transmission

The orthogonal frequency division multiplex (OFDM) technique is used to combat frequency selective fading in LEO satellite systems. The number of subcarriers and the length of cyclic prefix (CP) are given by \( N_s \) and \( N_c \), respectively. The system sampling period is \( T_s \). Then, the time duration of CP is \( T_{c,p} = N_cT_s \). The time duration of one OFDM symbol without and with CP is given by \( T_{s,c} = N_cT_s + T_s = T_{c,p} + T_s \), respectively.

We use \( \{x_{s,r}\}_{r=0}^{N_s-1} \) to denote the \( M \times 1 \) frequency-domain transmit signal in OFDM symbol \( s \). Then, the corresponding time-domain transmit signal is given by \( x_k(t) = \sum_{n=0}^{N_s-1} x_{s,n} e^{j2\pi nt} \), \( T_{c,p} \leq t < T_{s,c} \), where \( \Delta t = 1/T_{s,c} \). Then, UT \( k \)'s time-domain receiving signal in OFDM symbol \( s \) be written as

\[
y_{k,s}(t) = \int_{-\infty}^{\infty} \mathbf{H}_k(t, \tau) x_k(t - \tau) d\tau + z_{k,s}(t),
\]

where \( z_{k,s}(t) \) is the additive Gaussian noise. By performing Doppler and delay compensation at each UT [15], the compensated time-domain receiving signal of UT \( k \) in OFDM symbol \( s \) is given by

\[
y_{k,s}^{\text{cp}}(t) = y_{k,s}(t + \tau_{k,s}^{\text{cp}}) e^{-j2\pi v_k^s(t + \tau_{k,s}^{\text{cp}})},
\]

where \( v_k^s \) and \( \tau_{k,s}^{\text{cp}} \) are estimated, and \( \tau_{k,s}^{\text{min}} \). Hence, we can choose a suitable CP duration subject to \( T_{c,p} \geq \tau_{k,s}^{\text{max}} - \tau_{k,s}^{\text{min}} \), to combat the multipath fading in LEO satellite channels.
Then, UT \( k \)'s frequency-domain receiving signal over subcarrier \( r \) in OFDM symbol \( s \) can be written as \( y_{k,s,r}(t) = \frac{1}{T_s} \sum_{t=0}^{T_s-1} d_k(t) g_{k,s,r}(t) e^{-j2\pi f r t} dt \). Let us now define the channel frequency response (CFR) of UT \( k \) after the Doppler and delay compensation as
\[
H_k(t, f) = d_k(t, f) g_{k,s}^H,
\]
where \( d_k(t, f) = \sum_{t=0}^{T_s-1} a_k e^{j2\pi fr(t-f_{\text{t}}, r_d)} d_{k, d, r} \in \mathcal{C}^{N \times 1} \). The receiving signal \( y_{k,s,r} \) can be further expressed as
\[
y_{k,s,r} = H_{k,s,r} x_{s,r} + z_{k,s,r},
\]
where \( H_{k,s,r} \) and \( z_{k,s,r} \) are the channel matrix and additive Gaussian noise of UT \( k \) over subcarrier \( r \) in OFDM symbol \( s \).

D. Statistical Properties of Channel

For simplicity, we drop the subscripts of the OFDM symbol \( s \) and the subcarrier \( r \) in \( H_{k,s,r} = H_{k,s} g_{k,s}^H \). Henceforth, we denote \( H_k = d_k g_{k,s}^H \) as the DL channel matrix of UT \( k \) over a given subcarrier. We assume that the LEO satellite channel \( H_k \) follows the Rician distribution as follows
\[
H_k = d_k g_{k,s}^H = \frac{\kappa_k \beta_k}{\kappa_k + 1} H_k + \frac{\beta_k}{\kappa_k + 1} \bar{H}_k,
\]
where \( \beta_k = \mathbb{E} \{ \| H_k \|^2 \} = \mathbb{E} \{ \| d_k \|^2 \} \) is the average channel power, \( \kappa_k \) is the Rician factor. In (7), \( H_k = d_k g_{k,s}^H \) is the line-of-sight (LoS) part, while \( \bar{H}_k = d_k g_{k,s}^H \) is the scattering component. Besides, \( d_k \) is distributed as \( d_k \sim \mathcal{CN}(0, \Sigma_k) \) with \( \text{tr}(\Sigma_k) = 1 \). These channel parameters \( H \) depend on the operating frequency bands, practical link conditions, etc.

III. DL TRANSMIT DESIGN

In this section, building on the signal and the channel models in Section II, we investigate the DL transmit strategy by only exploiting slow-varying sCSIT. First, we show that the rank of each UT's transmit covariance matrix is no greater than one for the ergodic sum rate maximization. As a result, the design of the transmit covariance matrices can be simplified into that of precoding vectors. Then, by resorting to the MM framework, an algorithm is developed to compute the precoding vectors.

A. Rank-One Property of Transmit Covariance Matrices

For convenience, we drop the subscripts of the OFDM symbol \( s \) and the subcarrier \( r \) in \( x_{k,s,r} \) and denote \( x \) as the \( M \times 1 \) transmit signal on a given subcarrier. We assume that there are \( K \) UTs simultaneously served by the satellite. Let \( \mathcal{K} = \{1, \ldots, K\} \) denote the set of UT indices. The transmit signal \( x \) can be written as \( x = \sum_{k=1}^{K} s_k \), where \( s_k \in \mathcal{C}^{M \times 1} \) is the transmit signal to UT \( k \). In this paper, \( s_k \) is assumed to be a Gaussian random vector with zero mean and covariance matrix
\[
Q_k = \mathbb{E} \{ s_k s_k^H \},
\]
which is actually the most general design of transmit signals with linear transmitters. We also assume that the transmit signals satisfy the total power constraint, i.e., \( \sum_{k=1}^{K} \text{tr}(Q_k) \leq P \). The DL received signal at UT \( k \) is given by
\[
y_k = H_k \sum_{i=1}^{K} s_i + z_k,
\]
where \( z_k \in \mathcal{C}^{N \times 1} \) is the additive Gaussian noise at UT \( k \). In addition, \( z_k \) is distributed as \( z_k \sim \mathcal{CN}(0, \sigma_k^2 I_N) \). The DL ergodic rate of UT \( k \) is given by
\[
I_k = \mathbb{E} \left\{ \log \det \left( \sigma_k^2 I_N + H_k \sum_{i=1}^{K} Q_i H_i^H \right) \right\}
\]
where (a) follows from \( H_k = d_k g_{k,s}^H \) and \( \text{det}(I + AB) = \text{det}(I + BA) \). The DL sum rate maximization problem can be formulated as
\[
\mathcal{P} : \max_{\{Q_k\}_{k=1}^{K}} \sum_{k=1}^{K} I_k \text{ s.t. } \sum_{k=1}^{K} \text{tr}(Q_k) \leq P, Q_k \succeq 0, \forall k \in \mathcal{K}.
\]
up \{ \bw_k \}_{k=1}^K$, thus improving the DL ergodic sum rate and contradicting the optimality.

### B. Precoding Vector Design

In the following, we devise an algorithm based on the MM framework in [20] to obtain a locally optimal solution of $S$. In each iteration, we replace the DL ergodic rate $R_k$ with one of its concave minorizing functions. Then, a locally optimal solution to $S$ is guaranteed to be achieved by iteratively solving a sequence of convex problems.

Let $c_k \in \mathbb{C}^{N \times 1}$ be the linear receiver of UT $k$. Then, the recovered data symbol at UT $k$ is given by $\hat{s}_k = c_k^H y_k = c_k^H \bw_k s_k + \sum_{i \neq k} c_k^H d_k g_k^H w_i s_i + c_k^H z_k$. Define the mean-square error (MSE) of UT $k$ as $\text{MSE}_k \equiv \mathbb{E}\{ |s_k - \hat{s}_k|^2 \} = \sum_{i=1}^K |w_i^H g_k|^2 |c_k^H d_k|^2 + \sigma_k^2 |c_k^H d_k|^2 - 2R \{ g_k^H \bw_k \cdot c_k^H d_k \} + 1$. The optimal $c_k$ is given by

$$c_{\text{mmse},k} = \arg\min_{c_k} \text{MSE}_k = \frac{g_k^H \bw_k}{\sigma_k^2 + \sum_{i=1}^K |w_i^H g_k|^2 |d_i|^2}, d_k.$$  

(13)

The minimum MSE (MMSE) of UT $k$ achieved by $c_{\text{mmse},k}$ is given by

$$\text{MMSE}_k = 1 - \frac{|w_k^H g_k|^2 |d_k|^2}{\sigma_k^2 + \sum_{i=1}^K |w_i^H g_k|^2 |d_i|^2}.$$  

(14)

Then, $R_k$ can be expressed as $R_k = -\mathbb{E}\{ \log \text{MMSE}_k \}$. Hereafter, we use $(\cdot)^{(n)}$ to denote the argument in the $n$th iteration. Due to the concavity of logarithm functions, a minorizing function of $R_k$ is given by

$$R_k \geq R_k^{(n)} = \mathbb{E}\left\{ \frac{\text{MMSE}_k - \text{MMSE}_k^{(n)}}{\text{MMSE}_k} \right\}.$$  

(15)

where (a) follows from $\text{MMSE}_k \leq \text{MMSE}_k^{(n)}$ for all $c_k$. To make the inequality in (15) hold with equality at $\bw^{(n)}$, we choose the receiver $c_k$ in $\text{MMSE}_k^{(n)}$ to be $c_{\text{mmse},k}^{(n)}$. By substituting $c_{\text{mmse},k}^{(n)}$ into $R_k^{(n)}$, we have

$$R_k^{(n)} = \mathbb{E}\left\{ \frac{\text{MSE}_k - \text{MSE}_k^{(n)}}{\text{MMSE}_k^{(n)}} \right\}.$$  

(16)

where

$$a_k^{(n)} = \mathbb{E}\{ |w_k^H g_k|^2 |d_k|^2 - 2R \{ g_k^H \bw_k \cdot b_k^{(n)} \} + c_k^{(n)} \},$$

$$b_k^{(n)} = \mathbb{E}\{ d_k^H c_{\text{mmse},k}^{(n)} \text{MMSE}_k^{(n)} \},$$

$$c_k^{(n)} = \mathbb{E}\{ \sigma_k^2 |c_{\text{mmse},k}^{(n)}|^2 + 1 \}.$$  

By making use of the minorizing function $g_k^{(n)}$ in (15), the precoding vectors $\bw^{(n+1)}_{k=1}^K$ can be obtained by solving the following convex quadratic program

$$\min_{\bw_k} \sum_{k=1}^K \left\{ a_k^{(n)} |w_k^H g_k|^2 - 2R \{ g_k^H \bw_k \cdot b_k^{(n)} \} \right\}$$  

(17a)

subject to

$$\sum_{k=1}^K \| \bw_k \|^2 \leq P.$$  

(17b)

#### Algorithm 1: Precoder design algorithm for solving $S$

**Input:** Initialize $\bw_k^{(0)} = \bw_{\text{init},k}$, $k \in K$, iteration index $n = 0$.

**Output:** Precoding vectors $\bw_k^{(n)}$, $k = 1, \ldots, K$.

1: while $1$ do
2: Calculate $a_k^{(n)}$ and $b_k^{(n)}$ for all $k \in K$.
3: Update $\bw_k^{(n+1)}$, $k \in K$, with (18).
4: if $n \geq N_{\text{iter}} - 1$ or $\sum_{k=1}^K R_k^{(n+1)} - \sum_{k=1}^K R_k^{(n)} < \epsilon$ then
5: else
6: Set $n := n + 1$.
7: end if
8: end while

The optimal solution to (17) can be obtained as

$$\bw_k^{(n+1)} = \left( \sum_{i=1}^K a_i^{(n)} g_i^H \right) + \mu^{(n)} b_k^{(n)}.$$  

(18)

where $\mu^{(n)} \geq 0$ is chosen such that $\sum_{k=1}^K \| \bw_k^{(n+1)} \|^2 = P$.

The precoding vector optimization algorithm is presented in Algorithm 1, which guarantees convergence to a locally optimal solution of $S$.

### IV. Simulation Results

In this section, we show the simulation results to demonstrate the proposed DL transmit designs in a massive MIMO LEO SATCOM system. The simulation parameters are listed in TABLE I. The paired space angles $\{ \phi_k \}_{k=1}^K$ are generated by following the uniform distribution in the circle region \{$(x, y)$ : $x^2 + y^2 \leq \sin^2 \theta_{\text{max}}$\}. The elevation angle seen at UT $k$ is given by $\alpha_k = \cos^{-1}\left( \frac{R_e}{R_k} \sin \phi_k \right)$ [19], where $R_e$ is the earth radius, $R_k$ is the orbit radius. The distance between the satellite and UT $k$ is given by $D_k = \sqrt{R_e^2 \sin^2 \alpha_k + H^2 + 2HR_k - R_k \sin \alpha_k}$ [1]. Define the per-antenna gains of the UPAs at the satellite and each UT as $G_{\text{sat}}$ and $G_k$, respectively. The random vector $d_k$ in (7) is generated on the basis of $d_k(t, f)$ in (4), where the first path is for the LoS part $d_k, 0 = d(\varphi_k, 0)$, and the remaining $L_k - 1$ paths are for the scattering part $d_k$. Each UT’s UPA is assumed to be placed horizontally, and thus $\varphi_k, 0$ satisfies $\sin \varphi_k', \sin \varphi_k'' = \sin \alpha_k$, e.g., $\varphi_k', 0 = 90^\circ$ and $\varphi_k'' = \alpha_k$. In $\bw_k$, the path gains $\{ a_k, k \}_{k=1}^{L_k-1}$ are generated by using the exponential power delay profile model, and the paired AoAs $\{ \varphi_k, k \}_{k=1}^{L_k-1}$ are generated by using the wrapped Gaussian power angle spectrum [1, Section 6]. In addition, the pathloss, shadow fading and Rician factors are also generated based on the channel models in [1, Section 6]. The noise variance is given by $\sigma_k^2 = k_B T_n B$ where $k_B = 1.38 \times 10^{-21}$ J·K$^{-1}$ is the Boltzmann constant, $T_n$ is the noise temperature and $B$ is the system bandwidth.

In Fig. 1, the convergence performance of Algorithm 1 is shown. It is observed that Algorithm 1 will converge to a locally optimum within a small number of iterations. In Fig. 2, the sum rate performance of Algorithm 1 and ASLNR precoding vectors $\bw_k^{\text{fin}, k}$ [15] is shown. The ASLNR precoding

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**TABLE I.** The paired space angles $\{ \phi_k \}_{k=1}^K$.
we demonstrated the performance gains of the proposed DL transmit design with the simulation results.

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V. CONCLUSION

In this paper, we studied the DL transmit strategy with sCSIT in massive MIMO LEO SATCOM systems. First, we established the massive MIMO LEO satellite channel model, where the satellite and the UTs are both equipped with UPAs. Then, we showed that it is sufficient to transmit a single data stream to each UT for the ergodic sum rate maximization. Hence, the design of transmit covariance matrices is degenerated into that of precoding vectors without loss of optimality. Afterwards, we derived an algorithm to compute the precoding vectors. Finally,