Doppler Analysis and Compensation for Distributed LEO-MIMO Satellite Communications

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***Abstract*—In this paper, we propose a Doppler compensation method in LEO-MIMO communication, where two LEO satellites are used as amplify-and-forward (AF) relays, and line-of-sight (LOS) propagation dominates the communication channel. We first analyze Doppler effects in uplink and downlink, and propose a dual-hop AF relay channel model including Doppler effects. Also we show that Doppler effects in our scenario can be easily compensated at the LEO satellites, without the need of inter-satellite link (ISL) communication.**

***Index Terms*—Low earth orbit (LEO), Satellite, Doppler effect**

I. Introduction

Recently, there have been increasing interests in satellite communication, which provides seamless connectivity. Especially, LEO satellites have gained attention for they have low round trip delay, compared to geostationary satellites, and thus able to provide reliable and low latency communication. Therefore, thousands of low earth orbit (LEO) satellites are already being launched over the earth (e.g., Starlink, OneWeb, Kuiper) and various techniques have been studied to increase the capacity of LEO communications [1], [2].

On the other hand, several studies have been proposed to handle Doppler effects in LEO satellite communication, which is called Doppler compensation [3]–[5]. For relative motion of the LEO satellite with respect to the ground station results in severe Doppler shifts [6], compensating the Doppler is an important issue in LEO satellite communication. The authors of [3] have proposed linear decreasing frequency sweep Doppler compensation function which requires the information on S-shaped Doppler-time curve [7]. In [4], analog Doppler compensation technique is suggested to mitigate the Doppler-effect without the need of Doppler-time curve information. The authors of [5] proposed Doppler compensation methods that LEO satellite compensates the Doppler for the static ground cell first and the mobile user in the static ground cell compensates the residual Doppler. However, existing studies on Doppler compensation only considered Doppler compensation for single LEO satellite, where only one LEO is utilized in the uplink or downlink channel.

In this paper, we study the Doppler effects in LEO-MIMO communication where multiple LEO satellites are used as AF relays and propose a novel Doppler compensation method. We show that simple compensation scheme can effectively handle Doppler effects in LEO satellites constellation networks.

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II. System Model

In this paper, we consider LEO satellite communication system where M LEO satellites with single antenna are used as an AF relay. Ground terminal (GT) has an uniform-linear array (ULA) antenna that have N antenna elements whose separation distance is s^u, and user terminal (UT) also has an ULA antenna with N antenna elements that are separated by separation distance s^d. The distance between mth transmit antenna element of GT and nth LEO is $d^u_{n,m}$ and distance between mth LEO and nth receive antenna element of UT is $d^d_{n,m}$. For LEO satellites are located in high altitude with few scatters in the propagation path, we can assume LOS channel between GT and LEO, and UT and LEO. Our system model is depicted in Fig 1.

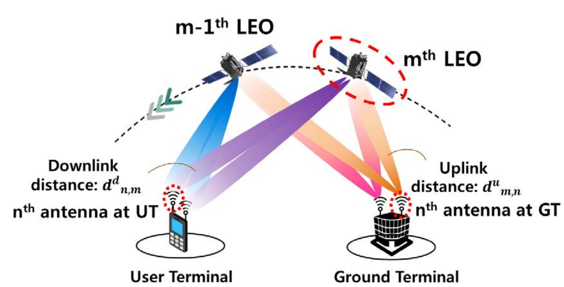

Fig. 1. System model for LEO satellite communication

A. Dual-hop Satellite channel

In the dual-hop satellite channel, the signal between transmitter and receiver can be expressed as

$$\mathbf{y} = \mathbf{H}_d\mathbf{F}\mathbf{H}_u\mathbf{x} + \mathbf{H}_d\mathbf{F}\mathbf{w}_u + \mathbf{w}_d, \tag{1}$$

where $\mathbf{x} \in \mathbb{C}^{N\times 1}$ and $\mathbf{y} \in \mathbb{C}^{N\times 1}$ represents transmitted signal and received signal, and $\mathbf{H}_u \in \mathbb{C}^{N\times M}$ and $\mathbf{H}_d \in \mathbb{C}^{M\times N}$ represents communication channel of uplink and downlink, and $\mathbf{w}_u \in \mathbb{C}^{M\times 1}$ and $\mathbf{w}_d \in \mathbb{C}^{N\times 1}$ are zero-mean complex additive white Gaussian noise vectors in uplink and downlink, and $\mathbf{F} \in \mathbb{C}^{M\times M}$ denotes a relaying matrix at LEO satellites.[1]

III. Doppler analysis and compensation in multi LEO satellite communication

We now analyze the Doppler effects in the LEO communication system. Let us denote the relative speed of mth LEO satellites at nth antenna component of GT and UT as $v^u_{m,n}$ and $v^d_{n,m}$, respectively. Considering the height of Starlink LEO satellites are usually 550km and ULA antenna separation is for about few meters, antenna separation distance s^u and s^d are much smaller than $d^u_{m,n}$ and $d^d_{n,m}$. Therefore the relative speeds of LEO satellites at the UT and GT antenna elements are almost same. Furthermore, speed of UT is much smaller than speed of LEO satellites and we can model relatively speed as $v^u_{m,n} \simeq v^u_m$ and $v^d_{n,m} \simeq v^d_m$, which implies that Doppler effects are decided by the relative speed of LEO satellites.

A. Doppler effects in uplink channel

In uplink communication, GT sends precoded signal $\mathbf{x}$ to LEO satellites along with two antennas, therefore the uplink channel including the Doppler effects can be modeled as

$$\begin{aligned}\mathbf{H}_u &= \begin{bmatrix} h^u_{1,1}\times\delta^u_{1,1} & h^u_{1,2}\times\delta^u_{1,2} \\ h^u_{2,1}\times\delta^u_{2,1} & h^u_{2,2}\times\delta^u_{2,2}\end{bmatrix} \\ &\simeq \begin{bmatrix} h^u_{1,1}\times\delta^u_{1} & h^u_{1,2}\times\delta^u_{1} \\ h^u_{2,1}\times\delta^u_{2} & h^u_{2,2}\times\delta^u_{2}\end{bmatrix} \\ &= \begin{bmatrix} \delta^u_1 & 0 \\ 0 & \delta^u_2 \end{bmatrix} \times \begin{bmatrix} h^u_{1,1} & h^u_{1,2} \\ h^u_{2,1} & h^u_{2,2}\end{bmatrix} \\ &= \mathbf{D}_u\tilde{\mathbf{H}}_u, \end{aligned} \quad (2)$$

where $h^u_{m,n}$ represents the channel coefficient without Doppler and $\delta^u_{m,n}$ represents the Doppler effect, that the signal from the nth GT antenna to the mth LEO satellite experiences. As we can see in (2), the uplink channel matrix $\mathbf{H}_u$ can be decomposed into multiplication of Doppler matrix $\mathbf{D}_u$ and channel matrix without Doppler $\tilde{\mathbf{H}}_u$.

B. Doppler effects in downlink channel

Doppler effects in downlink channel can be modeled in similar way with uplink channel.

$$\begin{aligned}\mathbf{H}_d &\simeq \begin{bmatrix} h^d_{1,1}\times\delta^d_{1} & h^d_{1,2}\times\delta^d_{2} \\ h^d_{2,1}\times\delta^d_{1} & h^d_{2,2}\times\delta^d_{2}\end{bmatrix} \\ &= \begin{bmatrix} h^d_{1,1} & h^d_{1,2} \\ h^d_{2,1} & h^d_{2,2}\end{bmatrix} \times \begin{bmatrix} \delta^d_1 & 0 \\ 0 & \delta^d_2 \end{bmatrix} \\ &= \tilde{\mathbf{H}}_d\mathbf{D}_d, \end{aligned} \quad (3)$$

where $h^d_{n,m}$ represents the channel coefficient and $\delta^d_{n,m}$ represents the Doppler effect, that the signal from the mth LEO satellite to the nth UT antenna experiences. As we can see in (3), the downlink channel matrix $\mathbf{H}_d$ also can be expressed as multiplication of Doppler matrix $\mathbf{D}_d$ and channel matrix without Doppler $\tilde{\mathbf{H}}_d$. One interesting feature is that Doppler matrix in downlink is multiplied after $\tilde{\mathbf{H}}_d$, while Doppler matrix in uplink is multiplied before $\tilde{\mathbf{H}}_u$. This is because the Doppler effect is mainly decided by the movement of LEO satellites. Thus the overall channel can be modeled as

$$\mathbf{y} = \tilde{\mathbf{H}}_d\mathbf{D}_d\mathbf{F}\mathbf{D}_u\tilde{\mathbf{H}}_u\mathbf{x} + \mathbf{H}_d\mathbf{F}\mathbf{w}_u + \mathbf{w}_d. \quad (4)$$

C. Doppler compensation at LEO satellites

Doppler effects can be compensated by setting

$$\begin{aligned}\mathbf{F} &= (\mathbf{D}_u\mathbf{D}_d)^{-1} \quad (5) \\ &= \begin{bmatrix} \frac{1}{\delta^d_1} & 0 \\ 0 & \frac{1}{\delta^d_2}\end{bmatrix} \times \begin{bmatrix} \frac{1}{\delta^u_1} & 0 \\ 0 & \frac{1}{\delta^u_2}\end{bmatrix} \\ &= \begin{bmatrix} \frac{1}{\delta^u_1\delta^d_1} & 0 \\ 0 & \frac{1}{\delta^u_2\delta^d_2}\end{bmatrix}. \end{aligned}$$

It should be noted that Doppler matrix $\mathbf{D}_d$ and $\mathbf{D}_u$ are diagonal, thus $\mathbf{F} = \mathbf{D}_d^{-1}\mathbf{D}_u^{-1}$ are also diagonal. Therefore, the Doppler effects in LEO satellites can be compensated by using diagonal relaying matrix, which implies each LEO can individually compensate Doppler effects without any co-operation between satellites, not requiring ISL communication. Considering the large distance between LEO satellites, overhead of inter-satellite communication is tremendous thus the advantage of compensation scheme without the need of ISL communication is obvious.

IV. Conclusion

In this paper, we have analyzed the Doppler effects in distributed LEO MIMO communication system, where two LEO satellites are used as AF relays, and each LEO satellite has one antenna. We have modeled the uplink and downlink channel including Doppler effects, and have showed that the Doppler effects can be compensated at the LEO satellite, not requiring any ISL communication.

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[1] In this paper, we analyze Doppler in setting $M = N = 2$ for simplicity, but our scheme can be extended to general cases, which will be discussed in our future work.