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Capacity enhancement using LEO-QZS MIMO transmission in non-terrestrial network systems

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Abstract In recent years, the demand for satellite communication has increased, and the realization of a higher capacity has become a challenge. However, the service area of each low-Earth orbital satellite changes constantly, requiring many satellites for continuous communication, which increases space debris and the risk of collision accidents. This paper proposes a multiple-input multiple-output transmission system using low-Earth orbit and quasi-zenith satellites that can expand the channel capacity while reducing the number of required satellites. Numerical simulations demonstrate a 50% increase in throughput or a quarter reduction in the number of satellites required to achieve the same performance.

Keywords: low-Earth orbit satellite, quasi-zenith satellite, multiple-input multiple-output transmission, non-terrestrial network
Classification: Satellite communications

1. Introduction

In recent years, high-capacity wireless communication applications, such as telemedicine and smart factories, have emerged. Meanwhile, it is difficult to construct terrestrial communication infrastructures in oceans and mountainous areas. In addition, if the terrestrial communication infrastructure is damaged during a disaster, communication is disrupted. In response to these problems, satellite communication has attracted attention because satellites can provide services without being affected by the state of terrestrial communication infrastructure. Recently, the use of satellite communication has been considered for remote power plants and factories [1] as a non-terrestrial network (NTN) system. To increase the satellite channel capacity required for such applications, multiple-input multiple-output (MIMO) technology using low-Earth orbit (LEO) satellites has been actively studied [2, 3, 4, 5]. These include the study of MIMO transmission using a multi-beam antenna in one LEO satellite [2, 3], multiple-satellite MIMO using multiple single beams from multiple LEO satellites [4], and distributed massive MIMO technology [5], which uses multiple LEO satellites in a cluster for cooperative transmission. To increase the capacity of LEO satellite communication, the most suitable method is multi-satellite MIMO technology, which involves the use of multiple single beams [4] because multiple channels will be different. However, in LEO satellite systems, there is a high possibility that the satellites are at a low elevation angle from the user's location, which can easily lead to non-line-of-sight (NLoS) environments and lower capacities. Naturally, many LEO satellites can maintain a high elevation angle, but the increasing number of LEO satellites has raised concerns regarding on-orbit collisions and space debris [6]. Additionally, more satellites will be launched in the future [7]. Satellite constellations are used for various purposes, such as communication and Earth observation. Therefore, improving the transmission efficiency while reducing the number of satellites can solve the problem of space debris and expand the potential of satellite use for applications other than communication. Geostationary orbit (GEO)-LEO coexistence networks, in which GEO or GEO-like satellite and LEO satellites coexist and compensate each other's weaknesses, has been studied as a solution [8, 9]. However, to the best of our knowledge, no studies have been reported on multi-satellite MIMO transmission for different altitude groups of quasi-zenith satellites (QZS) and LEO satellites.

Therefore, we propose a new LEO-QZS multi-satellite MIMO transmission system in which MIMO transmission can always be maintained at a high elevation angle in a specific region. The details of the proposed method and numerical results are shown in the following.

2. Proposed LEO-QZS MIMO transmission system

In this study, we consider a downlink LEO-QZS MIMO system in which the propagation distance between each satellite and the user differs, resulting in a received timing difference at the user side. We assume a mobile communication scenario based on the 3GPP standard [1], and therefore, orthogonal frequency-division multiplexing (OFDM) for LTE/5G is used as the communication method. If the difference exceeds the guard interval (GI) length of OFDM, the communication quality deteriorates [10]. The system configuration, transmission timing control for the propagation time difference between each satellite, and signal equalization processing at the receiver side are described as follows.

2.1 System configuration

In a conventional LEO-LEO MIMO transmission system [4], it is necessary to ensure effective line-of-sight (LoS) communication paths with all LEO satellites that communicate at a particular instance. That is, multiple LEO satellites

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must be located at high elevation angles that are visible to users. To achieve this goal, several LEO satellites must be deployed. Therefore, as shown in Fig. 1, we propose an LEO-QZS MIMO transmission system using QZS, which can maintain a high elevation angle in mid-to high-latitude regions, including Japan, in addition to LEO satellites. In this study, we focus on the downlink service link, where users in the cell range are covered by both LEO and QZS satellite signals, and users with two antennas are uniformly distributed in a hexagonal cell. MIMO transmission is performed by two satellites, one of which is the LEO satellite orbiting closest to the cell center, and the other is the QZS with the highest elevation angle from the cell center among the three QZSs [11]. The feeder link is assumed to operate perfectly. Figure 2 shows a system block diagram of the proposed system. It is assumed that orthogonal frequency-division multiple access (OFDMA) is adopted and that K_s subcarriers are allocated to U users with K_u $(= K_\mathrm{s}/U)$ each. Each user is assigned the same number of subcarriers K_u using the proportional fairness (PF) method [12], and the satellites transmit signals using these subcarriers in an OFDM manner. On the transmitter side, an M bit data sequence $\mathbf{b} = \{b_0, b_1, \ldots, b_{M-1}\} \in \{0, 1\}$ for the u-th user is encoded on each satellite to generate a coded sequence $\mathbf{c} = \{c_0, c_1, \ldots, c_{N-1}\} \in \{0, 1\}$ $(N > M)$. Subsequently, quadrature phase-shift keying (QPSK) modulation is performed to generate a symbol sequence $\mathbf{s} = \{s_0, s_1, \ldots, s_{K_\mathrm{u}-1}\} \in \mathbb{C}$ $(K_\mathrm{u} = N/2)$. Interleaving is performed on $\mathbf{s}$ to generate a transmission sequence $\mathbf{d} = \{d_0, d_1, \ldots, d_{K_\mathrm{u}-1}\} \in \mathbb{C}$. Each satellite transmits its signal by adjusting its timing using a timing advance (TA) mechanism [13], as described in Section 2.2. On the receiver side, OFDM demodulation is performed after extracting the signals of the subcarriers for each user, and minimum mean square error (MMSE) equalization is performed considering the residual reception timing difference, as described in Section 2.3. The obtained series $\mathbf{r} = \{r_0, r_1, \ldots, r_{K_\mathrm{u}-1}\} \in \mathbb{C}$ is then deinterleaved to obtain the series $\mathbf{p} = \{p_0, p_1, \ldots, p_{K_\mathrm{u}-1}\} \in \mathbb{C}$, and decoded.

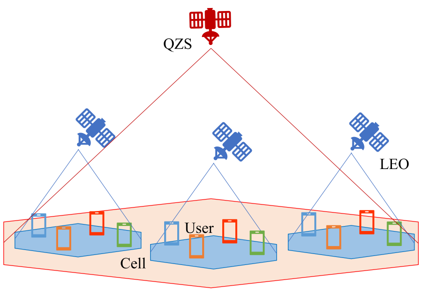

Fig. 1 System model of the proposed LEO-QZS MIMO transmission system.

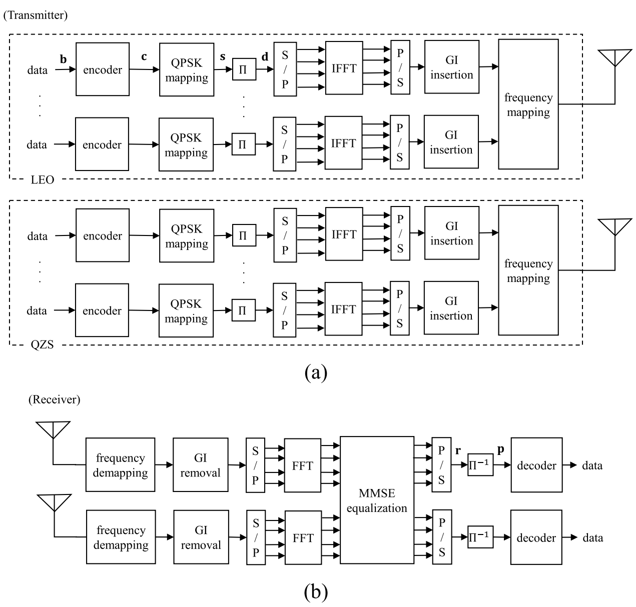

Fig. 2 System diagram of the proposed downlink LEO-QZS MIMO transmission system; (a) transmitter, (b) receiver of u-th user.

2.2 Transmission timing control

In MIMO-OFDMA transmissions from multiple satellites, performance degradation occurs when the received timing difference from each satellite exceeds the GI length. Therefore, the transmission timing of each satellite is controlled to reduce the difference in the received timing. 3GPP Release 16 specifies a TA function to ensure the transmission timing synchronization performance at a base station in the NTN [13]. The TA function adjusts the transmission timing from the terminal based on the propagation time between a reference point in a cell and a satellite, assuming that the position of the terminal is known. The TA is adjusted autonomously by the terminal using the orbital information ephemeris of the satellite or sent to the terminal from the network. In this study, we assume that the TA mechanism is adopted in the downlink multi-satellite transmission and that transmission is performed by adjusting the transmission timing at each satellite using TA. Using this mechanism, the signal reception timing from multiple satellites is aligned with the reference point at the center of each cell, even with LEO and QZS. Here, the feeder link delay (between the ground base station and each satellite) and service link delay (between each satellite and the target cell) are jointly calculated by the ground base station, and the TA information is transmitted to the satellites during feeder link transmission.

2.3 Signal equalization for reception timing differences

Even if the received timing is corrected to match the reference point using the transmit timing control described above, residual received timing differences occur for users at locations different from the reference point. The phase rotation of the received signal caused by this received timing difference is corrected along with the channel coefficient during the equalization process. Here, we assume a general $M_\mathrm{s}{\times}N_\mathrm{T}$ multi-satellite MIMO-OFDM transmission and multipath reception model with M_s satellites and N_T receiving antennas at the user end. Starting from the time of signal reception by the first satellite, the transmitted signal of the m-th satellite $(1 \leq m \leq M_\mathrm{s})$ is assumed to be $x_m(t) \in \mathbb{C}$, and the residual timing difference of the received signal is t_m. Let the number of multipaths in the propagation path be L_m, the delay time of each path be $\tau_{m,l}$ $(1 \leq l \leq L_m)$, and the received noise at the receiving i-th antenna $(1 \leq i \leq N_\mathrm{T})$ be $n_i(t) \in \mathbb{C}$. The received signal $y_i(t) \in \mathbb{C}$ is then given by

$$y_i(t) = \sum_{m=1}^{M_s} \sum_{l=1}^{L_m} h_{im,l} x_m(t - t_m - \tau_{m,l}) + n_i(t), \quad (1)$$

where $h_{im,l}$ is the channel coefficient of the l-th path from satellite m to the receiving antenna i, and $\tau_{m,1} = 0$, $t_1 = 0$. Equation (1) can be transformed into the frequency domain using a fast Fourier transform (FFT), where $Y_i(f)$, $X_m(f)$, and $N_i(f)$ represent the frequency-domain signals of $y_i(t)$, $x_m(t)$, and $n_i(t)$, respectively, as follows:

$$\mathbf{Y} = \begin{pmatrix} Y_1(f) \\ \vdots \\ Y_{N_T}(f) \end{pmatrix} = \begin{pmatrix} \sum_{m=1}^{M_s} \sum_{l=1}^{L_m} h_{1m,l} e^{-j2\pi f(t_m+\tau_{m,l})} X_m(f) + N_1(f) \\ \vdots \\ \sum_{m=1}^{M_s} \sum_{l=1}^{L_m} h_{N_T m,l} e^{-j2\pi f(t_m+\tau_{m,l})} X_m(f) + N_{N_T}(f) \end{pmatrix} = \mathbf{HX} + \mathbf{N}, \quad (2)$$

where $\mathbf{H} \in \mathbb{C}^{N_T \times M_s}$ is the channel matrix in the frequency domain. As shown in (2), the phase rotation of $2\pi f t_m$ rad in $X_m(f)$ caused by the received timing difference can be jointly accommodated in the same manner as the multipath delay, and the frequency-domain equalization process yields the estimated transmitted signal $\hat{\mathbf{X}} \in \mathbb{C}^{M_s}$ as follows:

$$\hat{\mathbf{X}} = \mathbf{H}^{-1}\mathbf{Y}$$

$$\begin{pmatrix} \hat{X}_1(f) \\ \vdots \\ \hat{X}_{M_s}(f) \end{pmatrix} = \begin{pmatrix} X_1(f) + Z_1(f) \\ \vdots \\ X_{M_s}(f) + Z_{M_s}(f) \end{pmatrix}, \quad (3)$$

where $Z_m(f)$ indicates the noise and interference components from equalization. In this study, we assume that the received timing difference t_m can be calculated by the user terminal or obtained in advance by a notification from the network assisted by the synchronization process of 5G, assuming that the locations of the terminal and satellite orbit information are known.

3. Numerical results

The average user throughput characteristics for the proposed and conventional methods were calculated during LEO satellite orbit. The simulation parameters are listed in Table I. We assume ideal channel estimation; however, channel estimation for satellite links and the frame format using pilot signals can be performed using [13]. For the satellite orbits and arrangements, practical LEO satellites are assumed to have 72 circular orbits with an altitude of 550 km and an inclination of 53°, referring to the Starlink constellation planned by SpaceX [7], and QZS is assumed to have three QZSs, referring to the orbit specifications of the first QZS "MICHIBIKI" orbiting in a quasi-zenith orbit in [11].

The downlink budget calculation for the QZS transmission is presented in Table II. The LoS probability of channels between a satellite and a ground user terminal is based on the environment around the terminal and the elevation angle

Table I Simulation parameters.

	Proposed LEO-QZS MIMO	Conventional LEO-LEO MIMO
Transmission system	MIMO-OFDMA	
Modulation method	QPSK	
Channel model	8-path 1-dB decaying quasi-static Rice or Rayleigh fading	
Channel estimation	Ideal	
Environment model	Dense urban [1]	
Cell model	Regular hexagon	
Cell radius [km]	25	
TA reference point	Center of each cell	
Number of users U	8	
Number of subcarriers K_s	128	512
Frequency allocation K_u	PF method (Equal number of subcarriers for each user $K_u = K_s/U$)	
	16	64
Code length N	128	
Interleaver	Random interleaver	
Guard interval length	64	
Number of transmitting and receiving antennas	1 x 2	
Signal detection criterion	MMSE	
Error correcting code	Non-systematic convolutional code (Constraint length: 3, rate: 0.5)	
Decoding algorithm	Soft-decision Viterbi decoding	
Rice factor average [dB]	[3.59, 31.83] (S-band model [1])	
Rice factor standard deviation [dB]	[1.77, 16.34] (S-band model [1])	

Table II Downlink budget calculation for QZS transmission.

Transmitter	
EIRP [dBm]	106
Channel	
Propagation distance [m]	d
Transmission frequency [GHz]	2
Free space loss L_0 [dB]	$38.5 + 20\log_{10} d$
Rain attenuation [dB]	0
Fading loss L_f [dB]	[0.72, 15.5] (S-band model [1])
Clutter loss L_c [dB]	[16.3, 34.3] (S-band model [1])
Path loss L_{path} [dB]	$L_0 + L_f + L_c$
Receiver	
Receiver input [dB]	$76 - L_{path}$
Receiving antenna gain [dBi]	0
Receiver noise figure [dB]	1.5
G/T [dB/K]	-23.8
C/N_0 [dBHz]	$279.8 - L_{path}$
Signal bandwidth [MHz]	30
SNR [dB]	$205 - L_{path}$

of the satellite [1]. Additionally, because the user terminal on the ground is assumed to be a small mobile terminal and multisatellite MIMO transmission requires receiving signals from multiple satellites located at various angles, an omnidirectional antenna with a gain of 0 dBi is assumed on the receiver side. The downlink budget calculation of LEO satellites was performed similarly to Table II, and the equivalent isotropic radiated power (EIRP) of the LEO satellites was assumed to be 50 dBm/MHz [13]. Users are uniformly distributed in a single hexagonal cell with a radius of 25 km. In the proposed method, the QZS beam radius is 100 km and the bandwidth per beam is 30 MHz; the LEO beam radius is 25 km and the bandwidth per beam is 2 MHz ($K_s = 128$). This enables all LEO beams in the QZS cell to use different frequencies, and the QZS beam accommodates all users in the QZS cell to achieve LEO-QZS MIMO. By contrast, the conventional LEO-LEO MIMO method has a per-beam bandwidth of approximately 10 MHz in LEO ($K_s = 512$). The conventional system has a frequency reuse factor of three and uses 30 MHz of bandwidth in total,

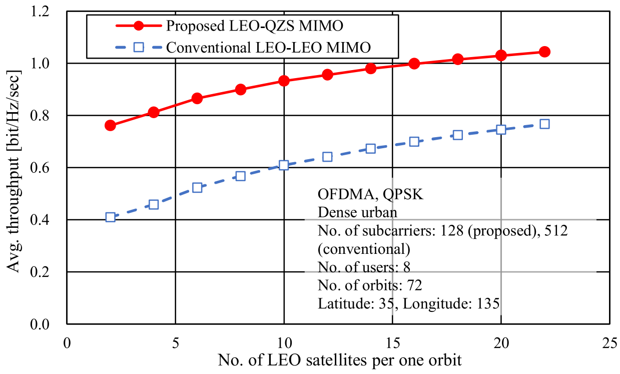

Fig. 3 Average user throughput versus number of LEO satellites.

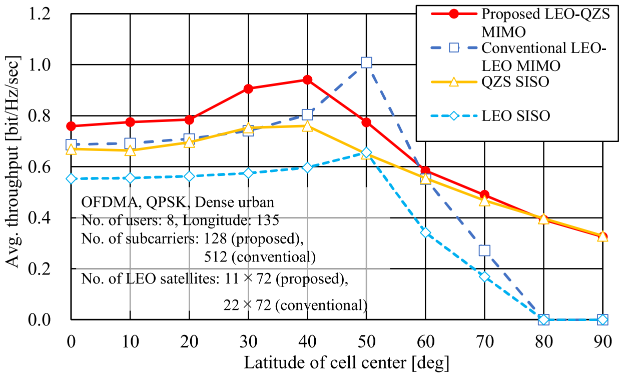

Fig. 4 Average user throughput at different latitudes.

making the system bandwidth fair within a 100 km radius. In addition, for a fair comparison of the channel-coding effect, the proposed system uses four time slots for a single codeword to achieve the same code length as the conventional method. The simulation was performed assuming that the same fading was applied to all four time slots.

Figure 3 shows the average user throughput characteristics in Japan at 35° north latitude and 135° east longitude. The number of LEO orbits in each system is 72, and the horizontal axis represents the number of LEOs per orbit. The legend "Conventional LEO-LEO MIMO" (conventional method) shows MIMO transmission from two LEO satellites, and "Proposed LEO-QZS MIMO" (proposed method) is a MIMO transmission from one LEO satellite and one QZS. The figure shows that the throughput of the proposed method is approximately 50% higher than that of the conventional method for the same number of satellites. Conversely, the number of satellites can be reduced to approximately one-fourth for the same throughput. This is because the QZS is always at a higher elevation, and the LoS channel is better maintained compared to the LEO-LEO environment. Therefore, in the next simulation, we reduced the number of satellites in the proposed system by half, and compared the throughput characteristics with respect to latitude.

Figure 4 presents the results when the longitude is 135° east and the horizontal axis is the latitude at the cell center. Note that "LEO single-input single-output (SISO)" and "QZS SISO" in the legend refer to SISO transmission from LEO satellites and QZS, respectively. The figure shows that MIMO transmission can expand the capacity compared to SISO transmission. It can also be confirmed that the proposed method is effective at latitudes below 40° and above 60° (LEO satellites are dense at approximately 50° in the orbit [7]), and that it improves the throughput characteristics while reducing the number of satellites.

4. Conclusions

The LEO-QZS MIMO transmission method was proposed to enhance the channel capacity while reducing the number of satellites required in NTN satellite communication by utilizing QZS. Numerical results demonstrated a 50% increase in throughput or a quarter reduction in the number of satellites required to achieve the same performance in certain regions.

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