

Performance Analysis of DSSS-PDMA with SIC in GEO Satellite-Terrestrial Uplink Networks

Yosuke Higasa*, Kazutoshi Yoshii*, Megumi Saito*, Jiang Liu*, Shigeru Shimamoto*,
Takuya Okura**, Naoko Yoshimura**, Amane Miura**, Hiroyuki Tsuji**, Morio Toyoshima**

**Department of Communications and Computer Engineering, School of Fundamental Science and Engineering Waseda University, 8-01A, R. J. Shillman hall, 3-4-1 Ohkubo, Shinjuku-ku, Tokyo, Japan.*

***National Institute of Information and Communications Technology, 4-2-1, Nukui-Kitamachi, Koganei, Tokyo, Japan.*

{gmpdf.7704@ruri., kazutoshi@suou, megumi.saito@ruri., zhenni.pan@aoni, jiang@, shima@}waseda.jp,
{okura,naoko,amane,tsuji,morio}@nict.go.jp

Abstract—There is a growing trend to utilize satellite networks for the construction of 5G and Beyond 5G high-capacity systems. The power division scheme used in non-orthogonal multiple access (NOMA), which is a key technology for terrestrial networks, can contribute to improving the system capacity of satellite networks. In this paper, we propose a direct sequence spread spectrum-power level division multiple access (DSSS-PDMA) scheme that combines non-orthogonal PDMA with DSSS technology to mitigate the depletion of communication resources and interference to terrestrial terminals. Finally, simulation results with ETS-9 as the high throughput satellite (HTS) and active electronically scanned array (AESA) antenna as the earth station validate the effectiveness and superiority of the proposed schemes as compared with several existing schemes.

Keywords— Power level division multiple access, Direct sequence spread spectrum, Successive interference cancellation, Satellite-terrestrial communication, Active electronically scanned array

I. INTRODUCTION

Satellite networks are attracting attention as a solution to realize the next generation of high-capacity communications by linking the terrestrial networks and the non-terrestrial networks. Among them, HTS can provide a wider bandwidth and higher capacity than conventional geostationary orbit (GEO) satellites by using the Ka band and reusing frequency resources through multi-beams. HTS have been launched in many countries to date, and are generally divided into two main generations. The first generation, including IPStar and Wildblue-1, and the second generation, including KA-SAT and Jupyter, can achieve throughputs of several Gbit/s and hundreds of Gbit/s, respectively. The throughput of HTS has been increasing with time. For instance, ViaSat-2 which was launched on 2017 is capable of providing total throughput of over 300 Gbit/s for commercial communications [1][2].

In Japan, an engineering test satellite named ETS-9, which is scheduled to be launched in 2023, is being developed to establish the next-generation HTS technologies. ETS-9 will be used to perform communication missions for wideband digital channelizer/multi-beam feeder technology, wideband digital beamforming technology, and 10 Gbit/s class optical feeder link technology [3]. They are also developing a low-profile and

scalable AESA antenna system. Based on [4], we assume that AESA will be installed on top of vehicles in this paper.

In the era of 5G and Beyond 5G, new communication satellites will be launched and linkage with aerial networks will be put into practical use, which will lead to the sharing of circuits between services with different quality of service (QoS) requirements. In this paper, we propose a method that combines PDMA and successive interference cancellation (SIC) technology in order to achieve compatibility with QoS control [5]. SIC not only reduces retransmissions, but also enables QoS control by adjusting the power level allocated to each service, which results in a difference in noise immunity.

The PDMA technology proposed in [5] corresponds to the orthogonal multiple access (OMA) technology represented by frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). However, OMA has the problem of channel limitation, so NOMA technologies were proposed for 5G systems. In NOMA, each user transmits signal in the same band and at the same time. At the receiver, received signals can be separated and decoded by using SIC technology. The NOMA scheme is being studied not only for terrestrial cellular networks, but also for many applications in next generation satellite communications [6].

In the QoS control scheme based on PDMA proposed in this paper, the power is divided into multiple levels according to the priority, but there is a concern that the amount of permissible interference to surrounding terminals may be exceeded due to allocating higher power levels. Thus, we propose a DSSS-PDMA scheme that divides the power with reduced peak power in the same frequency band using direct spreading technology, which is currently used in satellite communications and is easy to implement. In the DSSS-PDMA scheme, the signals of each user can be transmitted to GEO satellite with less power by multiplying the spreading codes such as M-sequence and Gold-sequence. After the spreading process, the signal is divided by power difference for each priority, and AESA transmits the signal to the GEO satellite. The receiver performs despreading and signal cancellation to demodulate the signals of all users by applying DSSS-SIC scheme described in Section II. The user

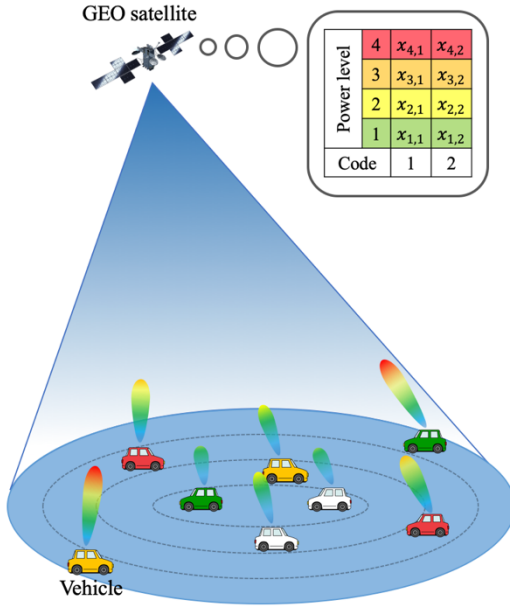


Figure 1. System model of GEO satellite-terrestrial uplink networks based on DSSS-PDMA scheme

group with higher power is more resistant to noise, and high reception accuracy can be guaranteed. In addition, the spreading process improves the noise immunity of the entire signal and further reduces the number of retransmissions.

The rest of this paper is organized as follows: Section II presents the system model and the signal processing model. In Section III, antenna modeling is presented assuming that the GEO satellite is ETS-9 and the earth station is an AESA antenna. In Section IV, the simulation results of the DSSS-PDMA scheme are given. The verification on the reduction of the peak power required by the transmitting terminal by the spreading process and the data rate for the widened bandwidth are examined. Finally, Section V draws the conclusion of this paper.

II. SYSTEM MODEL

In this paper, we consider an uplink satellite communication system. As illustrated in Fig.1, there are N terrestrial users which are deployed within one of multi-beam with coverage area as a circle of radius R . Users within a beam are assigned the power level $m \in \{1, \dots, M\}$ according to the distance from the central beam axis, and the number of users at each power level is defined as N_m , that is $N = \sum_{m=1}^M N_m$. Users of each power level applies direct spreading process to reduce the interference power to the surrounding terminals. At this time, the same spreading code can be used between power levels. After transmitting the signal, the satellite receives all the user's signals synchronously and simultaneously while sharing the frequency band and the time slot. If the receiver fails to demodulate the signal, then the user retransmits the signal with a higher power level allocated, based on [5]. In DSSS-PDMA uplink communication, the signal is modulated in the order of DSSS and PDMA to create user clusters according to the QoS requirements at the satellite side.

A. Channel Model

In this model, we consider user $k \in \{1, \dots, N_m\}$ of level m transmits signal for GEO satellite. Then, the channel coefficient can be written as [6]

$$h_{m,k} = g_{m,k} \sqrt{\frac{G_t G_r(u_{m,k})}{PL_{m,k}}} \quad (1)$$

where G_t and $G_r(u_{m,k})$ are the antenna gain of the user and the antenna gain of the GEO satellite, respectively. $PL_{m,k}$ is the propagation loss, which can be caused by the large-scale fading and the small-scale fading. The large-scale fading represents the free space path loss, atmospheric absorption loss and rain attenuation because satellite-terrestrial communication in the Ka band is greatly attenuated by the rainfall. The small-scale fading is a Rician distribution which can be expressed as

$g_{m,k} = \sqrt{\frac{K}{K+1}} + \sqrt{\frac{1}{K+1}} \tilde{g}_{m,k}$ where $\tilde{g}_{m,k} \in \mathcal{CN}(0,1)$ and K is Rician factor. Employing the Bessel function model for a typical tapered aperture antenna, the receive antenna gain can be expressed as [7]

$$G_r(u_{m,k}) = G_{r,\max} \left(\frac{J_1(u_{m,k})}{2u_{m,k}} + 36 \frac{J_3(u_{m,k})}{u_{m,k}^3} \right)^2 \quad (2)$$

where $G_{r,\max}$ is the maximum antenna gain of GEO satellite, and $J_1(\cdot)$ and $J_3(\cdot)$ are the Bessel functions of the first kind of order 1 and 3, respectively. Using $r_{m,k}$ which denotes distance from the beam center to the user k of level m , $u_{m,k}$ can be written as

$$u_{m,k} \approx 2.07123 \frac{r_{m,k}}{R} \quad (3)$$

where $r_{m,k}$ and R is much less than the distance from satellite to terrestrial users.

B. Signal Model

After modeling the link budget and estimating the channel coefficient, we consider the signal models of DSSS-PDMA scheme. As indicated in Fig. 2, the user applies the spreading process to reduce the interference power. Let $c_k = (c_k^1, \dots, c_k^{N_c})$ be Gold sequences of length N_c . Gold sequences are generated by using two M-sequences called preferred pairs. A set of Gold codes consists of $N_c + 2$ sequences with a period of N_c . The k -th user's spreading signal $\alpha_k(t)$ is a sequence of unit amplitude rectangular pulses of the chip duration T_c , which can be expressed as

$$\alpha_k(t) = \sum_{l=-\infty}^{\infty} c_k^l \rho_{T_c}(t - lT_c) \quad (4)$$

where ρ_x is the pulse waveform given by

$$\rho_x(t) = \begin{cases} 1, & 0 \leq t < x \\ 0, & \text{otherwise.} \end{cases} \quad (5)$$

For simplicity, we assume BPSK modulation. The binary data sequence for user k of level m can be expressed as

$$\beta_{m,k}(t) = \sum_{l=-\infty}^{\infty} b_{m,k}^l \rho_{T_b}(t - lT_b) \quad (6)$$

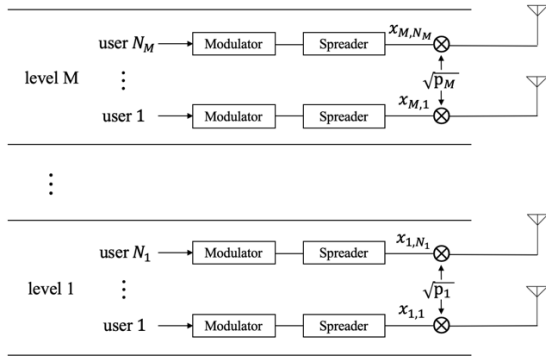


Figure 2. Block diagrams of DSSS-PDMA transmitter

where $b_{m,k}^l \in \{-1, 1\}$. T_b is the bit duration. From (4) and (6), the user signal after spreading for user k of level m is expressed as

$$x_{m,k}(t) = \alpha_k(t)\beta_{m,k}(t). \quad (7)$$

Gold code sequence is shared between transmitter and receiver, and the same code can be used for different power levels. Each user monitors the surrounding radio environment and the visibility of the communication link, and transmits the signal to the GEO satellite in line of sight (LoS) propagation. The signals pass through their respective propagation paths and are received simultaneously at the GEO satellite side. Assuming that the signals are synchronized, the received signal y is represented as

$$y(t) = \sum_{m=1}^M \sqrt{p_m} \sum_{k=1}^{N_m} h_{m,k}(t) x_{m,k}(t) + n(t) \quad (8)$$

where p_m denotes the transmit power of level m subjected to $p_1 \leq \dots \leq p_M$. Without loss of generality, the channel gains are assumed to be ordered as $|h_1|^2 \geq \dots \geq |h_M|^2$, where $|h_m| = \sum_{k=1}^{N_m} |h_{m,k}| / N_m$, based on NOMA concept. However, it should be noted that satellite communication in LoS propagation is not easily affected by the distance between the GEO satellite and the ground, which makes it difficult to create a difference in channel gain between users of each power level. $n(t)$ denotes the additive white Gaussian noise (AWGN) with zero mean and σ_c^2 variance.

C. DSSS-SIC scheme

We assume that perfect channel state information (CSI) is known at the satellite. Fig. 3 shows the procedure of our proposed DSSS-SIC scheme. First, the received signal is despread following the normal CDMA decoding to demodulate a cluster of users with power level m . Next, the signal of each user is re-modulated and re-spread just like the transmitter to reproduce the received signal. Finally, the received signal is cancelled with all the received signals of power level m reproduced with power adjustment, which can be expressed as

$$y_{m-1}(t) = y_m(t) - \sqrt{p_m} \tilde{h}_{m,k}(t) \sum_{k=1}^{N_m} x_{m,k}(t) \quad (9)$$

where $\tilde{h}_{m,k}(t)$ denotes the estimated channel coefficient. This is followed by a similar procedure to demodulate the sig-

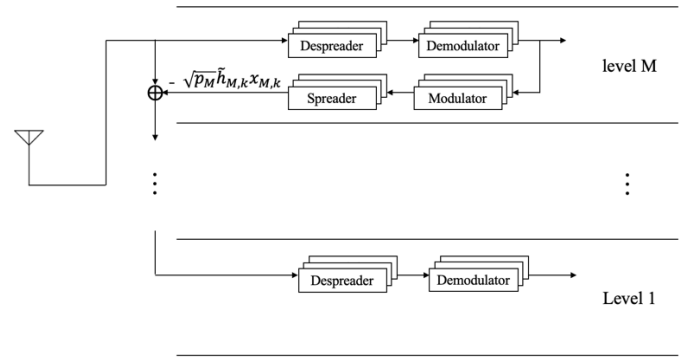


Figure 3. Block diagrams of DSSS-PDMA receiver

nals of users with lower power levels.

D. Spectral Efficiency

Focusing on the cluster of level m to analyze the reception quality for each QoS requirement, the achievable signal-to-interference-plus-noise ratio (SINR) can be given by

$$\gamma_m^D = \frac{p_m H_m}{\sum_{i=1}^{m-1} p_i H_i + \sigma_c^2} \quad (10)$$

where $H_m = \sum_{j=1}^{N_m} |h_{m,j}|^2$ and $m > 1$. This is equivalent to the M -user NOMA method. By employing perfect DSSS-SIC, the achievable SINR of a cluster at the lowest level is expressed as

$$\gamma_m^D = \frac{p_m H_m}{\sigma_c^2} \quad (11)$$

where $m = 1$. Then, we define the achievable spectral efficiency of DSSS-PDMA system, which is derived as [8]

$$R_D = \sum_{m=1}^M \log_2(1 + \gamma_m^D). \quad (12)$$

Now we consider FDMA and NOMA schemes for comparison. We define $N = UM$, i.e. U is the number of users per power level, and define $\sigma_c^2 = N_0 B_c$ where N_0 is the power spectral density (PSD) of the AWGN and B_c is the spreading bandwidth. Due to uplink communications, the received signal from each user can be represented by the same transmission power and channel coefficient. However, FDMA and NOMA schemes do not spread the signal, so the variance of AWGN can be expressed as $\sigma_b^2 = N_0 B_b = N_0 B_c / G_p$ where B_b and G_p denote the subcarrier bandwidth, i.e. the bandwidth before spreading, and processing gain, respectively. The processing gain for a full coded DSSS systems is defined as

$$G_p = \frac{B_c}{B_b} = \frac{T_b}{T_c}. \quad (13)$$

Therefore, the achievable spectral efficiency of FDMA scheme can be expressed as [8]

$$R_F = \frac{1}{N} \sum_{m=1}^M \sum_{k=1}^U \log_2 \left(1 + \frac{p_m |h_{m,k}|^2}{\sigma_b^2} \right). \quad (14)$$

To compare with NOMA scheme, we use different subcarrier bandwidths but the same number of power levels, i.e. user k is divided by code in DSSS-PDMA, but it is divided by bandwidth in NOMA. The achievable SINR is expressed as

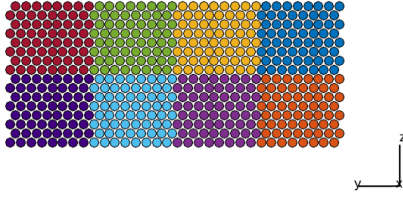


Figure 4. 512-element AESA antenna divided into subarrays

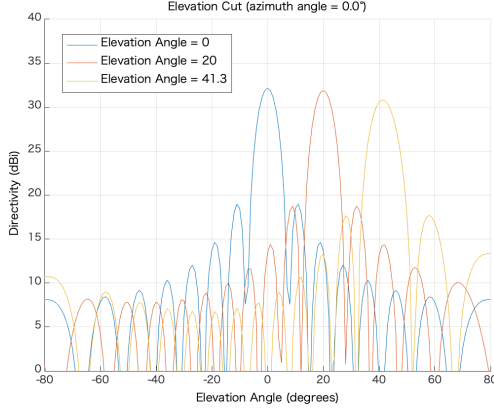


Figure 5. Radiation pattern of 512-element AESA antenna at 29.5 GHz

$$\gamma_{m,k}^N = \begin{cases} \frac{p_m |h_{m,k}|^2}{\sum_{i=1}^{m-1} p_i |h_{i,k}|^2 + \sigma_b^2}, & m > 1 \\ \frac{p_m |h_{m,k}|^2}{\sigma_b^2}, & m = 1. \end{cases} \quad (15)$$

Thus, the achievable spectral efficiency of NOMA scheme is given by

$$R_N = \frac{1}{U} \sum_{m=1}^M \sum_{k=1}^U \log_2(1 + \gamma_{m,k}^N). \quad (16)$$

III. ANTENNA DESIGN

Since our model assumes that AESA antennas will be placed on top of vehicles for GEO satellite-terrestrial mobile communication, we used MATLAB to design a 512-element AESA antenna and calculate its antenna characteristics [9]. As shown in Fig. 4, the AESA antenna has an additional 64 element antenna in a sub-array, and the 8 sub-arrays work together to adjust the beam scanning angle. We define the individual antennas called elements as the isotropic antenna setting the backbaffled property, which is described as restricting the antenna response to azimuth angles in the interval from -90 to 90 degrees in MATLAB. AESA antennas on vehicles are essentially mounted perpendicular to the ground and need to scan their main lobes in the satellite direction. Assuming that the earth is a perfect sphere, the elevation angle of the earth station can be approximated as [10]

$$E_{el} = \arctan \left[\frac{\cos(\lambda_s - \lambda_e) \cos(\varphi_e) - \delta}{\sqrt{1 - \{\cos(\lambda_s - \lambda_e) \cos(\varphi_e)\}^2}} \right] \quad (17)$$

where λ_e , φ_e and λ_s denote the earth station longitude, the earth station latitude, and satellite longitude in degree, respectively.

TABLE 1. SIMULATION PARAMETERS

Parameter	Value
Carrier frequency	29.5 GHz
System bandwidth	250 MHz
Subcarrier spacing	120 kHz
Modulation	QPSK
Satellite altitude h	35786 km
AESA antenna gain G_t	30.8 dBi
Satellite antenna gain $G_{r,max}$	42.5dBi
AWGN power density N_0	-174 dBm/Hz
Processing gain G_p	31
Difference of each power level	8 dB
Total number of bits transmitted	100000

$\delta = R_e / (R_e + h)$ where R_e is the equatorial earth radius, and h is the altitude of the satellite. The azimuth angle is also expressed as

$$E_{az} = 180 + \arctan \left[\frac{\tan(\lambda_s - \lambda_e)}{\sin(\varphi_e)} \right]. \quad (18)$$

Since ETS-9 is located at 143 degrees east longitude and Japan is located at 35.3 degrees north latitude and 138 degrees east longitude, we can calculate the elevation angle and azimuth angle of the ground AESA antenna to be 48.7 degrees and 171.4 degrees, respectively, using (17) and (18). The radiation pattern of a 512-element array antenna cut at the azimuth angle $E_{az} = 0$ is shown in Fig. 5. When the angle between the vertical plane and the LoS is 41.3 degrees, the maximum gain of the AESA antenna is 30.8 dBi.

IV. SIMULATION RESULTS AND ANALYSIS

In this section, simulations are provided for the effect of interference reduction by spread spectrum and the spectral efficiency performance. We assume the GEO satellite to be ETS-9 and the ground terminal to be AESA. Some parameters used in GEO satellite communication are given in TABLE 1. We set the satellite antenna gain, referring to [3]. The irradiation radius of the satellite beam is $R = 400$ km. Considering the LoS propagation, we set $K = 40$.

We first analyze the interference reduction effect of the DSSS method based on MATLAB simulation. Fig. 6 shows the comparison between DSSS-PDMA, i.e., the method with spread spectrum, and PDMA, i.e. the method without spread spectrum, with $N = M = 4$, i.e. one user for each power level. The horizontal axis shows the minimum transmit power, which means the transmit power of the user at power level 1. The distance from user to the central beam axis of each level is set as $r_{1,1} = 10$ km, $r_{2,1} = 100$ km, $r_{3,1} = 250$ km, and $r_{4,1} = 380$ km. In subsequent simulations, the same distance set is used for the same power level. From Fig. 6, bit error rate (BER) of the method with spreading is better at the same power level. This means that the peak power has been reduced by the spreading process, and the required received power at the receiver side has been relaxed accordingly. And thus, it can be said that DSSS-PDMA contributes to the improvement of the overall performance of the 5G system by lowering the interfer-

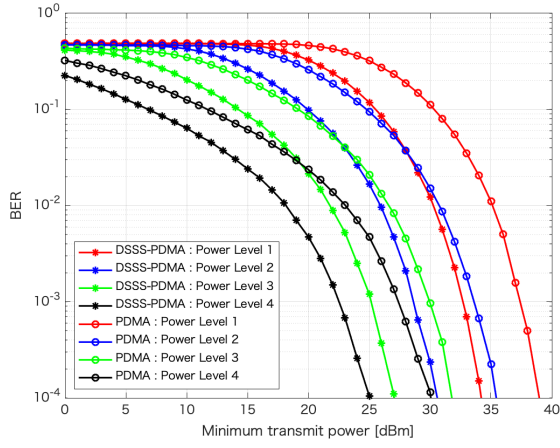


Figure 6. BER performance versus Minimum transmit power for DSSS-PDMA scheme and PDMA scheme with $N = M = 4$

ence power given by the terrestrial user to the surroundings.

Fig. 7 shows the spectral efficiency when the number of power levels M and the number of user U for each power level are increased. It can be seen that the spectral efficiency when U is fixed and the number of power levels is increased is larger than that when M is fixed and the number of users is increased. However, the more the number of power levels is increased, the larger the maximum transmit power becomes. As a result, AESA antenna causes a large amount of interference to the ground terminals, which will easily lead to communication failure. To maintain harmony with the terrestrial networks, we should set an appropriate number of power levels.

Similarly, there is a limit to the number of users for the spreading process. Assuming the Gold code sequence with period $N_c = G_p = 31$ set in Table 1, the upper limit is 33. Thus, Fig. 8 shows the spectral efficiency of FDMA, NOMA, and DSSS-PDMA schemes when the transmission power of level 1 is 30 dBm and U is increased from 15 to 33 with the power level fixed at $M = 4$, i.e. U is near the upper limit. Since the power level M is fixed, the spectral efficiency of FDMA and NOMA with increasing number of subbands does not change. In contrast, the DSSS-PDMA scheme multiplexes the signals in the same bandwidth, so the spectral utilization efficiency increases. In particular, it is greater than the NOMA scheme when U is larger than 31.

V. CONCLUSIONS

In this paper, we proposed and evaluated a DSSS-PDMA scheme that combines direct spreading and power level division schemes. By simulation, we have shown that our proposed scheme reduces the peak power by applying DSSS and achieves a spectral efficiency advantage over existing techniques by increasing the number of users. Since the spreading codes and power assignments used in this paper are simple, further improvement of spectral efficiency and BER can be expected with limited resources by applying various techniques that have been studied so far, such as advanced spreading/despreading and demodulation techniques, optimization of transmit power, fairness, and increasing the number of antennas. The simulation was conducted as a perfect SIC, but by introducing an imperfect

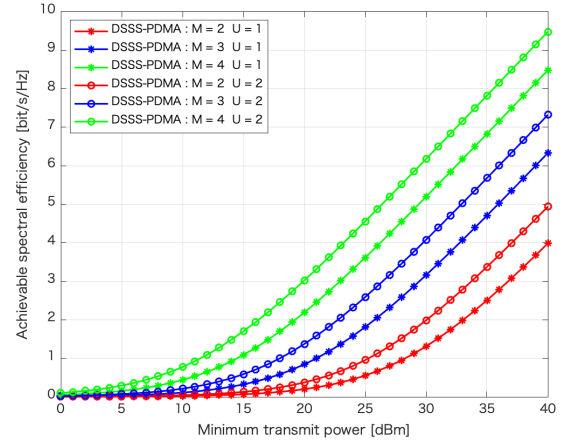


Figure 7. Achievable spectral efficiency versus Minimum transmit power for different M and U in DSSS-PDMA

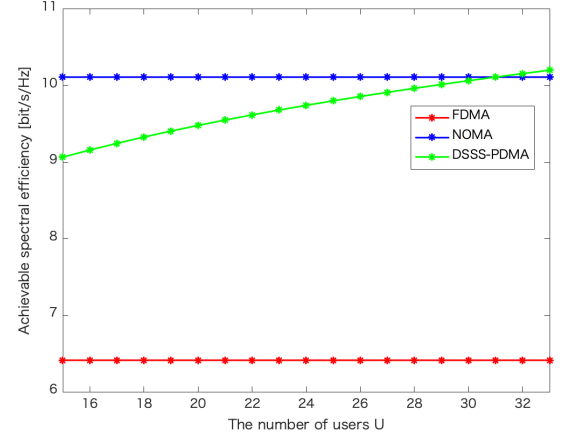


Figure 8. Achievable spectral efficiency versus the number of users U for three different schemes with $M = 4$ and $p_1 = 30$ dBm

SIC, a more realistic evaluation considering long-distance communication between the GEO satellite and the earth station will be possible. In the future, we will improve the reception quality by incorporating the advanced techniques mentioned above, and optimize the scheme based on actual measurements by conducting demonstration experiments of the DSSS-PDMA scheme.

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Yosuke Higasa received B.S. degree in Communications and Computer Engineering from Waseda University, Tokyo, Japan in 2020. Currently, he is pursuing the M.S. degree with the department of Computer Science and Communications Engineering. his research interests are the Satellite Communication system and multiple access system.

Kazutoshi Yoshii (M'19) received B.S. and M.S. degree in Communications and Computer Engineering from Waseda University, Japan, in 2018 and 2020, respectively. He is currently the Research Associate with the department of Computer Science and Communications Engineering, School of Fundamental Science and Engineering, Waseda University, Japan. His research interests include HF communication and ionospheric propagation.

Megumi Saito (S'15) received M.S. degree from Graduate School of Global Information and Telecommunication Studies, Waseda University, Japan in 2014. She is a Ph.D. candidate at Department of Computer Science and Communications Engineering, School of Fundamental Science and Engineering. She is also a research associate Waseda University, Japan. Her research interest includes D2D, Cooperative Access scheme in Cellular Networks.

Jiang Liu (S'05, M'09, SM'18) received the B.E. degree in electronics engineering from Chong Qing University of Technology, China, in 2001, and the M.S. and Ph.D. degree in information and telecommunications from the Graduate School of Global Information and Telecommunication Studies (GITS), Waseda University, Japan, in 2006 and 2012 respectively. She was a research associate from 2009 to 2012, and an assistant professor from 2013 to 2017 at Waseda University. Currently, she is an associate professor at Faculty of Science and Engineering, Waseda University. Her main fields of research interests include optical wireless communication, cellular system design, sensor network, and smart grid systems.

Shigeru Shimamoto (M'94) received the B.E. and M.E. degrees from the University of Electro-Communications, Tokyo, Japan, in 1985 and 1987, respectively. He received the Ph.D. degree from Tohoku University, Sendai, Japan, in 1992. He joined NEC Corporation from 1987 to 1991. From 1991 to 1992, he was a research associate in the University of Electro-Communications, Tokyo, Japan. He was a research associate in Gunma University, Gunma, Japan, from 1992 to 1993. From 1994 to 2000, he was an associate professor in the Graduate School of Global Information and Telecommunication Studies (GITS), Waseda University, Tokyo, Japan. Since 2001, he has been a professor in the Graduate School of GITS, Waseda University. He was a visiting professor of E.E. at Stanford University in 2008. His main fields of research interests include satellite communications, mobile communications, optical wireless communications, ad-hoc networks, sensor networks, and body area networks.

Takuya Okura received the B.E., M.E., and D.E. degrees in electrical and computer engineering from Yokohama National University, Yokohama, Japan, in 2012, 2013, and 2016, respectively. Since 2017, he has been with the National Institute of Information and Communications Technology (NICT), and has been engaged in research on antennas and satellite communications, including several satellite communications experiment projects. He has also been a Researcher of the Space Communication Systems Laboratory, Wireless Networks Research Center, NICT, since April 2021. His current research interests include phased array antennas, systematic error calibration technique of array antennas, and active electronically scanned array antenna for aircraft.

Naoko Yoshimura received her B.E. and M.E. degree in electrical engineering from Nihon University, Japan in 1991 and 1993, respectively. In 1993, she joined the Communications Research Laboratory (CRL, Ministry of Posts and Telecommunications), now part of the National Institute of Information and Communications Technology (NICT). She was engaged in the research of mobile and fixed satellite communication systems and high data rate satellite communications for the Engineering Test Satellite VI (ETS-VI) and Communications and Broadcasting Engineering Test Satellite (COMETS). Since 1998 she joined the Wideband Inter Networking test and Demonstration Satellite (WINDS) project and she took charge of development of on-board switching system for WINDS. Currently, she is a researcher manager of the Space Communication Systems Laboratory, Wireless Networks Research Center, NICT.

Amane Miura received his Ph.D. degree in information sciences from Tohoku University, Sendai, Japan in 1998. Since 1998, he has been with the Communications Research Laboratory, Tokyo, Japan and currently considered as the National Institute of Information and Communications Technology (NICT), to engage in the research on satellite communications and antennas. During 2004-2005, he was a visiting scholar at University of California, Los Angeles, CA, USA. During 2005-2009, he has been transferred to the ATR Wave Engineering Laboratories, Kyoto, Japan. He is currently a senior researcher of the NICT, conducting the research and development on communications mission of the Engineering Test Satellite 9, and space communications in Beyond 5G.

Hiroyuki Tsuji received the B.E., M.E., and D.E. degrees in electrical engineering from Keio University, Tokyo, Japan, in 1987, 1989, and 1992, respectively. In 1992, he joined the Communications Research Laboratory (CRL), now part of the National Institute of Information and Communications Technology (NICT). From 1999 to 2000, he was a Visiting Research Fellow of the University of Minnesota. From 2002 to 2021, he was working at Yokohama National University, Yokohama, Japan, as a Visiting Professor, which is an additional post. He has been the Director of the Space Communication Systems Laboratory, Wireless Networks Research Center, NICT, since April 2021. His research interests include array antennas for wireless communications, unmanned aircraft communication systems, and other satellite communication systems.

Morio Toyoshima received the Ph.D. degree in electronic engineering from The University of Tokyo, Tokyo, Japan, in 2003. He joined the Communications Research Laboratory (CRL), Ministry of Posts and Telecommunications, in 1994, and shortly after was engaged in research for the Engineering Test Satellite VI (ETS-VI) optical communication experiment. He joined Japan Aerospace Exploration Agency (JAXA; formerly, NASDA) to assist in the development of the Optical Inter-orbit Communications Engineering Test Satellite (OICETS), from 1999 to 2003. He spent one year as a Guest Scientist at Vienna University of Technology, Austria, in 2004. In April 2006, he returned to NICT, where he performed ground-to-OICETS laser communication experiments. He was involved in the development of the Small Optical Transponder (SOTA) for 50-kg-class satellites and conducted the satellite-to-ground quantum communication experiments. He was also involved in the development of the communication payloads for the Engineering Test Satellite 9 (ETS-9). He has been the Director General of the Wireless Networks Research Center, NICT, since April 2021.