HIGH SPECTRAL-EFFICIENCY COMMUNICATION in X BAND for SMALL EARTH OBSERVATION SATELLITES - RESULT of 505 Mbps Demonstration and PLAN for 2 Gbps LINK -

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ABSTRACT

A compact 64APSK X band transmitter for small satellites with maximum 538 Mbps, mass of 1.3 kg, and power consumption of 22 W has been developed. This transmitter was onboard on Hodoyoshi 4 satellite with 66 kg mass and 505 Mbps downlink was demonstrated. The main characteristics of this downlink system are as follows: i) GaN HEMT X band power amplifier with a high power efficiency and a small nonlinear distortion, ii) application of an error correction code with high coding gain. We present a plan of 2-3 Gbps downlink system in X band.

1 INTRODUCTION

Technologies of small satellites have so rapidly developed [1] that many earth observation missions with small satellites are discussed. Especially a constellation of small earth observation satellites seems promising. In proposed ideas with small satellite constellations [2], several tens to several hundred small earth observation satellites are launched to observe any places on the earth with very short observation intervals. Then image data taken from the orbit have to be transmitted quickly to earth stations with a low cost. Since the number of satellites is very large, frequency-band-efficient downlink seems critical at any frequency bands. Small satellites have only limited mass and power resources and onboard instruments should be light-weighted and low-power consumed.

In most cases medium/large earth observation satellites utilize radio frequency X band (8025-8400 MHz) for their observation data downlink with 300-600 Mbit per second. Their modulation methods are mainly quadrature phase shift-keying (QPSK), and 8 phase shift-keying (8PSK) [3, 4] since these phase modulations have an advantage of constant envelop and can avoid a problem of nonlinearity of RF power amplifiers. A large earth observation satellite, Worldview 3 utilizes dual polarization (RHCP and LHCP) channels in X band with 8PSK modulation and symbol rate of 200 Msps, achieving totally 1.2 Gbps downlink [3]. A small earth observation satellite, Skysat has three downlink channels of 8PSK modulation with 45Msps, achieving totally 303 Mbps[4]. In 2014, Japan launched two earth observation satellites ALOS-2 [5] and ASNARO [6], which utilize 16 quadrature amplitude modulation (16-QAM) with 800 Mbps in X band with use of wider than 220 MHz.

The purpose of this research is to develop a high-data-rate (typically 300-600 Mbps), high frequency-band efficiency modulation such as 64 Amplitude Phase Shift Keying (64APSK) communications system which can be applicable to small satellites of 50 kg class. Advantages of this system are newly developed GaN HEMT power amplifier with a high efficiency and a small nonlinear distortion, a powerful error correction code, and a software demodulation/ decoding system. In this communication system, the occupied frequency band width is only 125MHz out of full width allocation of 375 MHz in X band.

This system has been demonstrated on orbit using Japanese Hodoyoshi-4 Satellite launched in 2014 [7]. In September of 2015, the 3.8 m antenna station at Sagamihara received 505 Mbit per second data with 64APSK modulation and the signals were successfully demodulated / decoded with software [8]. This is the world-first demonstration of 64APSK from an earth-orbiting observation satellite. Also, this downlink speed is the world fastest as a small satellite.

2 HIGH SPEED COMMUNICATIONS SYSTEM

In this section we describe high-data-rate downlink system, including a modulation scheme, an onboard RF amplifier and a transmitter, onboard small antennas, a small S/X dual band ground station, and a high performance demodulator. Table 1 summarizes our novel communication system with high data rate for small satellites.

Table 1 Performance of High-Data Rate Downlink

Instruments	Mass (g)	Power (W)	Remarks
On-board			
Transmitter	1330	22	64APSK, 538Mbps GaN Power Amp.
Antenna			
MGA	69	0	13.5 dBi, RHCP
Iso-flux	150	0	5dBi(60°) , -2dBi(0°)
Ground Station			
Antenna	3.8m Dia. S/X, 47.5dBi(X), 36dBi(S), Sys. Noise temp. 120K		
Demodulator	100 Msps, (71-538 Mbps), QPSK～64APSK, 16QAM, 64QAM, SCCC CCSDS 131.2-B-1		

2.1 Modulation scheme

Consultative Committee for Space Data Systems (CCSDS) 131.2-B-1 recommendation [9] supports a wide range of spectral efficiency values and rates for high-data-rate telemetry applications. Comprehensive coding and modulation schemes are defined as adaptive coding and modulation (ACM) modes including serially concatenated convolutional turbo coding (SCCC) with various

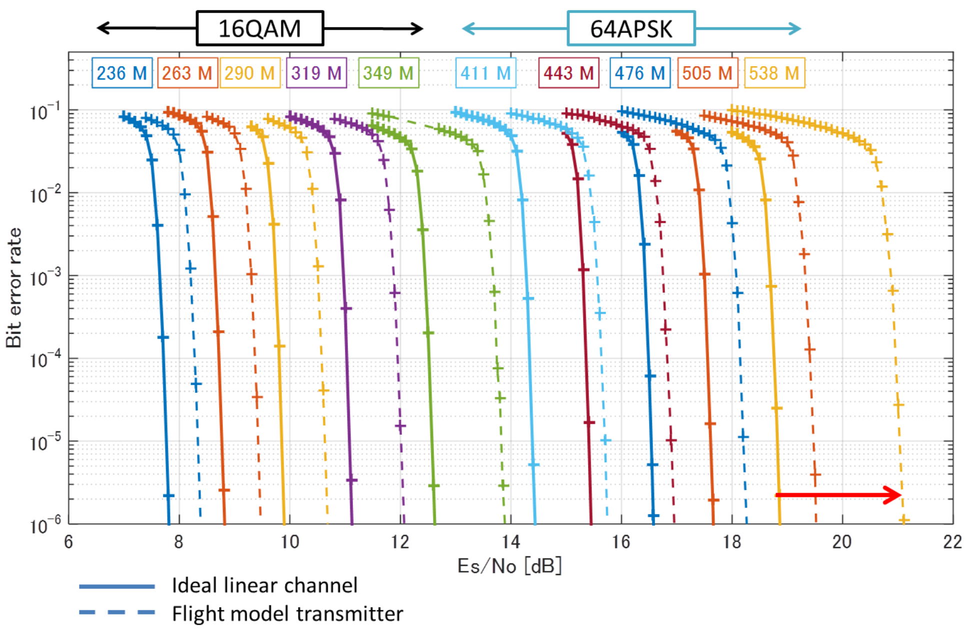

Fig. 1 Bit error rate as functions of required E_s/N_o. Solid lines are for an ideal, linear channel. Broken lines are for a flight mode of transmitter including power amplifier nonlinearity. Numbers indicated in figure are bit rates in case of 100 M symbol per second.

data rates R using a punctured code and QPSK, 8PSK as well as 16, 32, 64APSK.

Our high bit rate downlink system is based on this CCSDS 131.2.B-1 mode. The symbol rate is selected as 100 Msps, taking into consideration the on-board digital hardware, frequency-band, and the requirement for the data rates. We can change the data rate R from 71 Mbps to 538 Mbps by changing ACM modes. The required value of E_s/N_o is given at [10] for ideal, a linear channel case. Here E_s and N_o are energy per a symbol and noise spectral density, respectively. This error-correction code is very powerful compared with classical error-correction code such as Reed-Solomon code. For example, the SCCC ACM 17 has about 13dB of the required E_s/N_o for 10^{-6} BER while the conventional Reed-Solomon code (255, 223) has about 18 dB of the required E_s/N_o for 10^{-6} BER.

In the case of the flight model transmitter, the required E_s/N_o value may be degraded due to nonlinearity of a transmitter. We will discuss on these factors later. Figure 1 shows the bit error rate by solid lines as functions of required E_s/N_o with a linear channel case [8].

2.2 Onboard GaN-HEMT power amplifier

X band power amplifiers on satellites have widely used GaAs devices. Recently GaN HEMTs (high electron mobility transistors) achieve high efficiencies as high frequency and power devices. We have developed X band GaN-HEMT amplifiers in order to reduce power consumption.

Amplitude-phase modulations such as 16QAM and 64APSK require linearity of RF amplifier. We have developed an AB-class and an F-class power amplifier with GaN-HEMT devices [11]. The F-class amplifier is found to have power added efficiency up to 60%. However, the nonlinear phase change reaches to 15° in the working power region of 16QAM.

The AB-class amplifier has saturated power of 35 dBm at 8160 MHz. The power-added-efficiency reaches to 47%. Figure 2 shows input-output characteristics of AB-class GaN-HEMT power amplifiers, AM-AM characteristics and AM-PM characteristics. The output back-off is adjusted to

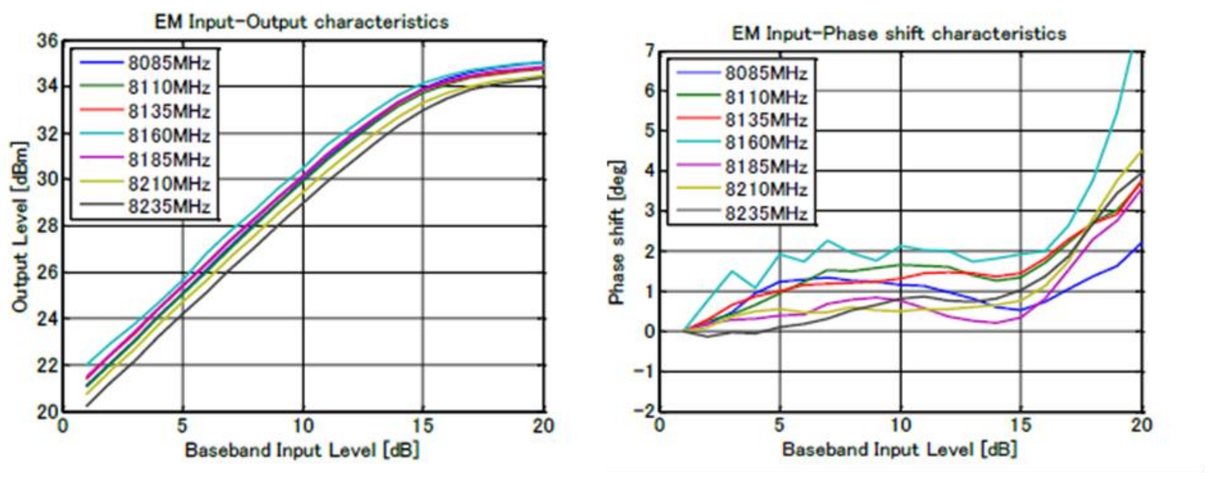

Fig.2 Input-output characteristics of RF power amplifier in high speed transmitter.
Left: AM-AM characteristics, Right: AM-PM characteristics.

1-2dB. Nonlinear phase change is less than 2° around the average output power of 33-34 dBm, which is operating point of the transmitter. This GaN-HEMT AB-class amplifier is provided with both of high efficiency and small distortion characteristics. We applied this AB-class GaN-HEMT power amplifier to our QPSK/16QAM/64APSK transmitter.

2.3 On-board transmitter and antenna

This section describes outline of the transmitter and the on-board antenna. The transmitter consists of the digital section and the analogue section. Input digital data from a data recorder are mapped in a constellation and I, Q signals are pulse-shaping filtered in FPGAs of the digital section. Although the symbol rate is 100 Msps, a clock frequency of the digital-analogue converter is selected to be 250 MHz with assists of 2.5 oversampling technique. The clock frequency of a large part FPGA gate is reduced to be 125MHz with assist of parallel processing. This is effective to reduce a consumption power. We also can use a FPGA device with a low cost, a medium performance and robust quad plat package (QFP) instrumentation instead of fragile ball grid arrays (BGAs) devices.
Then the digitally-processed I and Q signals are converted to analogue signals. In the analogue section, aliasing spectrum components caused by 2.5 oversampling are eliminated by an analogue low pass filter. The I and Q components are orthogonally modulated. Then the intermediate signal (IF) are upconverted to X band. The center frequency is 8160MHz and the band width is 125 MHz. The X band signal is power amplified up to 34-35 dBm by the GaN HEMT AB class amplifier described in Sec.2.2. It is observed that output power of the transmitter decreases by 1.2 dB at 50 ℃, compared with one at 0 ℃. We provide the transmitter with an automatic level controller (ALC) in which the target output level depends on the measured temperature in order to keep output back-off value almost constant at about 1.5 dB. This ALC maintains almost constant distortion quality of the communication link at wide range of the temperature.
Figure 3 is a photograph of the onboard transmitter. The mass is 1.3 kg and the power consumption

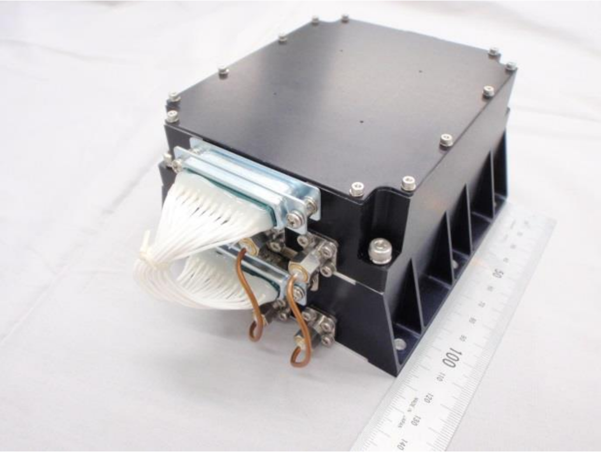

Fig. 3 Photograph of high-data-rate X-band 64APSK transmitter. Maximum data rate is 538 Mbps, RF output is 2 W, DC power is 22 W, and mass is 1330 g and size is 120 x 120 x 73 mm^3.

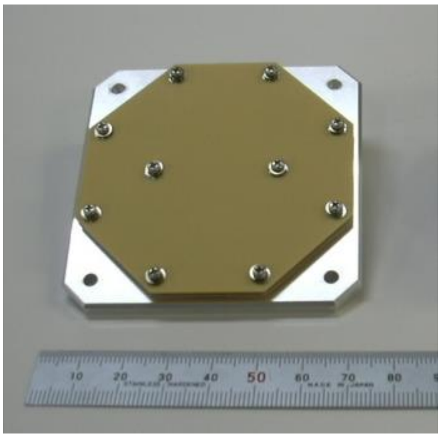

Fig. 4 Photograph of medium gain antenna. Gain is 13.5 dBi for right-handed circular polarization. Mass is 69 g.

is 22 W, which is significantly small, compared with conventional products.

The onboard antenna for high speed downlink at Hodoyoshi-4 satellite is a medium gain, 2x2 patch array antenna (MGA) with 13.5 dBi gain and only 69 g mass. Figure 4 is a photograph of the MGA. Its beam width is about 35°. The MGA is fixed on the satellite body and the satellite performs attitude manoeuvre toward a ground station with about 5° accuracy.

2.4 Ground station

Operation and high-rate data receiving of small earth observation satellites require a compact, low-cost ground station. We have developed S/X dual band 3.8 m antenna at Sagamihara campus of ISAS/JAXA. Figure 5 shows outlook of the S/X dual band antenna with a diameter of 3.8 m. The antenna is a ring-focused Gregorian type. The antenna gain is 47.5 dBi and the aperture efficiency is 56% in X band. The system noise temperature is about 120 K at the zenith.

The received X band signal is amplified by the low noise amplifier and is down–converted to 720 MHz band. Then this IF signal is digitalized with 400 M sample/sec. and is stored in the mass memory.

A conventional method of demodulation and decoding processing of high rate downlink is in use of hardware system with FPGAs. However, required hardware is very high performance and expensive especially for higher bit data rates than several 100 Mbps.

An alternative method is software processing. The merits of software processing are low cost of the hardware and flexibility of the software. The demerit is latency of processing. However, downlink of earth observation data does not necessarily require real-time processing. Typically a downlink time and an orbit period are 10 and 100 minutes, respectively. It is acceptable that the processing has finished by the next downlink time. In this high speed communication experiment, received signals are demodulated and decoded with software processing after a downlink pass. We have developed a demodulation and decoding software based on CCSDS131.2-B-1 [8, 12].

Fig.5 S/X dual band 3.8 m antenna at Sagamihara campus of ISAS/JAXA.

2.5 Analysis of communication link performance

In order to analyze performance of this communication link, nonlinear distortion of the transmitter and performance of demodulation/decoding software have to be taken into consideration. In the performance analysis digitally recorded waveforms of the on-board transmitter are combined with the ground demodulation/decoding software. Figure 1 shows the bit error rate by broken lines as functions of required E_s/N_o for this realistic communication channel [8]. Here E_s and N_o is the energy per a symbol and the noise spectral density, respectively. Degradations of 1-2 dB mainly due to the nonlinear distortion are observed, compared with a linear channel case.

Link analysis was performed for Hodoyoshi-4 with 628 km altitude [8]. Table 2 summarizes the link analysis. Figure 6 shows estimated values of the received E_s/N_o for 10^{-6} BER as a function of the elevation angle of the ground antenna to the satellite. Here antenna pointing error is assumed to be zero. The link performance is evaluated based on the received E_s/N_o given in Fig.6 and the required E_s/N_o given in Fig.1 for bit error rate 10^{-6} . The links of data rate 348 Mbps (16QAM of ACM 17), 505 Mbps (64APSK of ACM 26), and 538 Mbps (64APSK of ACM 27) can be satisfied at El>20 deg, >48 deg, and >65 deg, respectively.

Table 2 Link analysis

Parameter	Value	Unit
General		
Orbit altitude	628	km
Elevation angle	45.0	deg.
Frequency	8160	MHz
Symbol rate	100	Msps
Satellite Transmitter		
Amplifier output power	2	W
Circuit loss	1	dB
Antenna peak gain	13.5	dBi
Antenna pointing loss	0.5	dB
EIRP	15	dBW
Channel Losses		
Free space loss	169.6	dB
Atmospheric loss	0.5	dB
Ground Station Receiver		
Antenna peak gain	47.5	dBi
System noise temperature	120	K
Station G/T	26.71	dB/K
Received C/No	100.2	dB
Received Es/No	20.2	dB

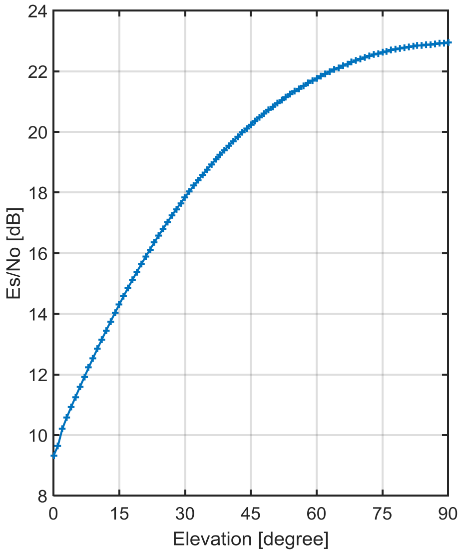

Fig.6 Received E_s/N_o as function of elevation angle for 628 km orbit and 47.5 dBi ground antenna. Link parameters are shown in Table 2.

3 DEMONSTRATION RESULTS of 64APSK MODULATION with 505Mbps DOWNLINK from HODOYOSHI-4

Hodoyoshi-4 satellite with 66 kg mass was launched at June 20th, 2014 at Yasny, Russia by Dnepr rocket. The orbit is nearly sun synchronous orbit with altitude of 628km. Sagamihara 3.8 m antenna station controls the satellite through S band as a main station.

We have performed high speed downlink experiments with 348 Mbps, 16 QAM, coding rate 0.87 of ACM 17 [12, 13], and 505 Mbps, 64APSK, coding rate 0.84 of ACM 26 [8].

The onboard antenna is a body-fixed antenna with beam width of 35°. It is supposed that the satellite is attitude-controlled toward the earth station at coarse accuracy of 5° during high speed communications. However, the satellite was not ready yet for this attitude operation. Only coarse earth center pointing mode was available at this experiment. We performed high speed downlink experiments at a higher elevation angle (>73°) of the satellite from the ground antenna to reduce onboard antenna pointing error.

Figure 7 shows the measured power spectrum of the received signal at 80 MHz IF of 64APSK, ACM26 505 Mbps signal at elevation of 83.3°, slant range of 658 km [14]. It indicates that the full-width-of-half-maximum of the spectrum is about 100 MHz and ratio between the signal peak level and the noise floor is about 20 dB, which means measured value of the received C/N_o =100dBHz and received E_s/N_o=20 dB. On the other hand the link analysis in Fig.6 shows the estimated value of received E_s/N_o =22.5 dB with elevation of 83.3°. The discrepancy 2.5dB may be combination of onboard antenna pointing error due to coarse earth center pointing instead of earth station pointing mode, dynamic control error of the ground antenna, and other factors.

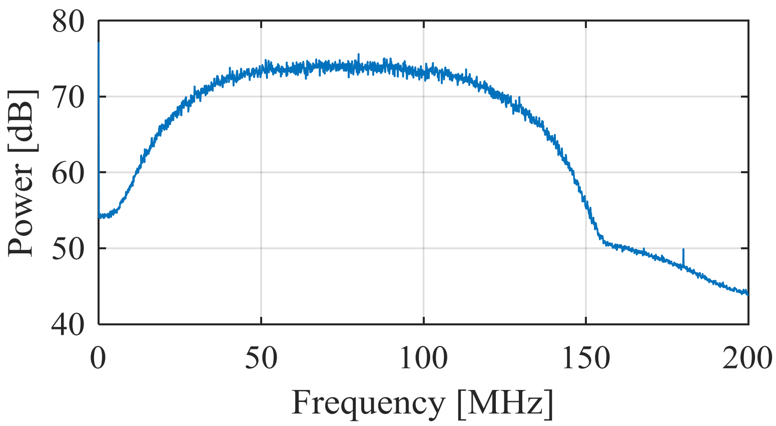

Fig.7 Power spectrum of received 80 MHz intermideate frequency. 64APSK, ACM26 505 Mbps signal at elevation of 83.3°, slant range of 658 km.

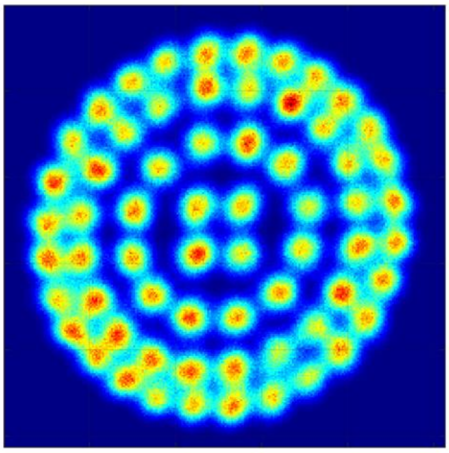

Fig.8 Demodulated I Q constellation of 64APSK, 505 Mbps when satellite Hodoyoshi4 achieved the world fastest downlink speed as a small satellite.

Analysis of the bit error rate described in Fig.1 (broken line of 505 Mbps) section 2.5 shows that the measured value of received E_s/N_o=20 dB corresponds to an almost error-free region.

In order to measure a bit error rate of this communication system, a known PN code data was transmitted repeatedly to the ground station. The received data were digitalized and stored in the ground data recorder. After the downlink pass a software processing of blind demodulation and turbo-decoding is performed.

Figure 8 shows the I/Q constellation after software demodulation [14]. Symbols at the most outer region are shifted inside due to nonlinear AM-AM effect of the transmitter. However there is almost no AM-PM effect as indicted in Fig.1. Bit error rate of demodulated, uncoded bit (600Mbps) is measured to be 2.7 x 10^{-2}.

Seven iterations of turbo decoding process make error-free result for the information bit (505 Mbps).

There was no error bit in this test. This communication speed is the world-fastest one from 50 kg class satellite at present. Bit error rate after decoding is measured to be less than 7.6 x 10^{-7}. This error-free link performance is in agreement with our system design.

4 PLAN of 2 Gbps DOWNLINK with X BAND FREQUENCY

We have described in the previous sections the system and the first demonstration result of a high spectral-efficiency communication in X band for small earth observation satellites. This is the first demonstration of 64APSK modulation for non-stationary satellites as long as the authors know. In this system, a high-speed downlink of 505 Mbps is achieved with only 125 MHz frequency band width, which is a one-third of the full earth observation band width (375 MHz width) in X band allocation for earth observation (8025 - 8400 MHz).

If we use the full frequency bandwidth of 375 MHz, 1-1.5 Gbps link with one polarization becomes possible in X band. There are two methods for this purpose. One is a frequency multiplication of this 505 Mbps channel with 100 M symbol per second. The other is to increase in the symbol rate up to 200-300 M symbol per second. We are comparing these two methods to select a letter method to select a better method.

Another resource of radio wave is polarization of carrier wave. In the present communication system, only right-handed circular polarization (RHCP) is utilized. If we use a left-handed circular polarization (LHCP) independently from RHCP channel, the communication speed becomes double.

These two approaches will provide us with an ultra-high bit rate downlink of 2-3 Gbps in X band. We plan to demonstrate 2-3 Gbps link in 2018 [15].

5 CONCLUSION

We have developed a compact 64APSK transmitter for small satellites with maximum 505 Mbps, mass of 1.3kg and power consumption of 22 W. This transmitter was onboard on Hodoyoshi4 satellite with 66 kg mass. The 505 Mbps downlink k signal were received by 3.8m antenna and successfully demodulated. This communication speed is the world-fastest one from a small satellite at present.

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