World Fastest Communication from a 50kg Class Satellite

- Micro Satellite Hodoyoshi 4 Succeeds in 348 Mbit Per Seconds -

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1. Introduction

Recently technologies of small satellites have been so matured that many earth observation missions are proposed. However, it is true that small satellite missions still have limitations of satellite functions compared with large satellites. Their main limitations are earth sensing capabilities as well as down link capabilities.

The purpose of this research is to develop a high-data-rate (typically 300-500Mbps) communication system which can be applicable to small satellites of 50 kg class. We have been developing the communication subsystem both for the flight hardware as well as the ground system, paying attention to reduce the DC power and the mass of onboard instruments. This system has been demonstrated on orbit using Japanese Hodoyoshi-4 Satellite launched in 2014[1]. In December, 2014, the 3.8m antenna station at ISAS, Sagamihara received 348 Mega bit per second data with 16 QAM modulation and successfully demodulated/decoded them without error. This communication speed is as high as a half of one of Daichi 2, a Japanese earth observation satellite with about 2 tons mass and is the world fastest as a 50kg class small satellite. This result indicates that the capability of data transmission from a small satellite approaches to capability of a large satellite. The remaining issues are the improvement of sensor capabilities compatible to a small satellite.

2. High Speed Communications System

2. 1 Problems of conventional high speed down link system

Figure 1 indicates down link data rates of low earth orbiting satellites as a function of satellite mass [2]. The figure shows that down link data rates are proportional roughly to linear or square of satellite mass. This is because in general a down link with a high data rate requires high power consumption and large mass.

Conventional communication systems of large satellites have capability of hundreds Mbps through 1Gbps and in most cases they utilize X band (8025-8400MHz) for earth observation. The maximum bandwidth is 375MHz and in most cases a convolution coding with r=1/2 is applied. Therefore multi phase-shift-keying and amplitude-phase modulation are necessary to achieve higher bit rates than 300 Mbps.

These modulations, however, are sensitive to nonlinear distortion of RF power amplifiers. RF power amplifiers have to operate in linear region, which causes reduction of power efficiency. Also they require digital processing circuits with several hundred MHz clock. Space-qualified devices for these purposes require high power consumption, high cost, and special care for ball grid array (BGA) devices. Figure 2 shows power consumptions as a function of data bit rate for onboard X-band transmitters with high data rates. Their power consumptions increase as the data bit rates increase with bandwidth-effective modulations. The conventional high-data-rate communication system of large satellite requires 100W or 200 W as a whole for DC power consumption.

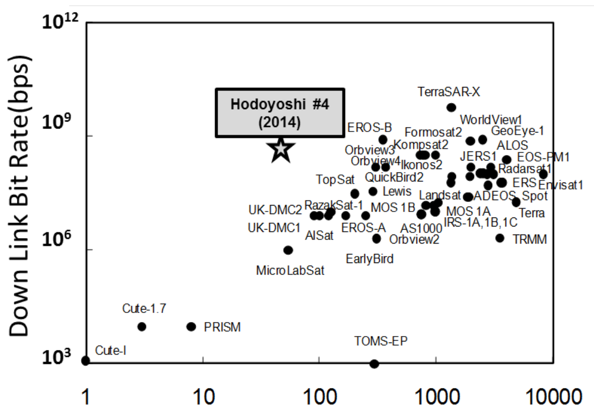

Fig.1 Down link bit rate vs. satellite mass for low earth orbit. ★denotes our novel technology.

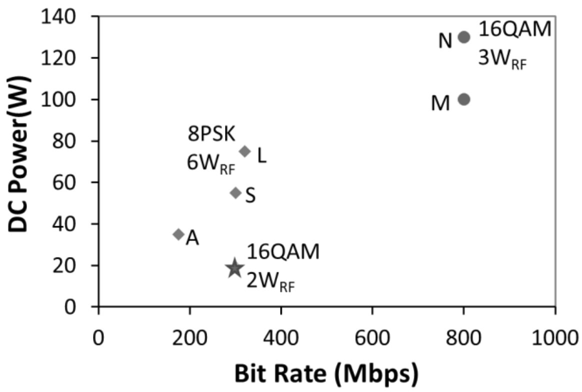

Fig. 2 DC power consumption vs. data bit rate for onboard high-data-rate transmitter.◆and ●correspond to conventional transmitters with 8PSK and 16QAM, respectively. ★ denotes our novel transmitter with 16QAM. RF power levels are also indicated.

2.2 Down link system for small satellite

In this section we propose several improvements for high-data-rate down link system as described in Fig.3, 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.

Consultative Committee for Space Data Systems (CCSDS) 131.2-B-1 recommendation is published to support 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 convolution turbo coding (SCCC) with various data rates using a punctured code and amplitude-phase shift keying (APSK).

Table 1 Performance of High-Data Rate Down Link

Instruments	Mass (g)	Power (W)	Remarks
On-board			
Transmitter	1330	20	16QAM, 348Mbps GaN Power Amp.
Antenna			
MGA	69	0	13.5 dBi
Iso-flux	150	0	5dBi(60°)，-2dBi(0°)
Ground Station			
Antenna	3.8m Dia. S/X Cassegrain, 47.5dBi(X), 36dBi(S), Sys. Noise temp. 120K(X)		
Demodulator	100Msps, (348-144Mbps), 16QAM, QPSK SCCC Turbo Equalizer CCSDS 131.2-B-1		

Our symbol rate f_s is selected as 100Msps, taking into consideration the onboard digital hardware, frequency-band allocation of 150MHz, and the requirement for the data rates. We can change the data rate R (144-348 Mbps) by changing the coding rate r (0.36-0.87) or ACM 1-17.

The performances of this high-data-rate downlink system shown in Fig.3 are simulated [3,4] by the signal processing work system (SPW) [5].

Let C be a received power at an input of a low noise amplifier at a ground station. Required C/No can be calculated as

$$\text{requied C/No} = (\text{required Eb/No}) \times R, \quad (1)$$

where R is a bit rate given as (symbol rate) x mod. multiplicity x (coding rate) .In this system symbol rate is 100Msps, and modulation multiplicity is 2 for QPSK and 4 for 16QAM. The required Eb/No is given at [6] for ideal cases. The realistic required Eb/No value may be degraded due to nonlinearity of the transmitter and

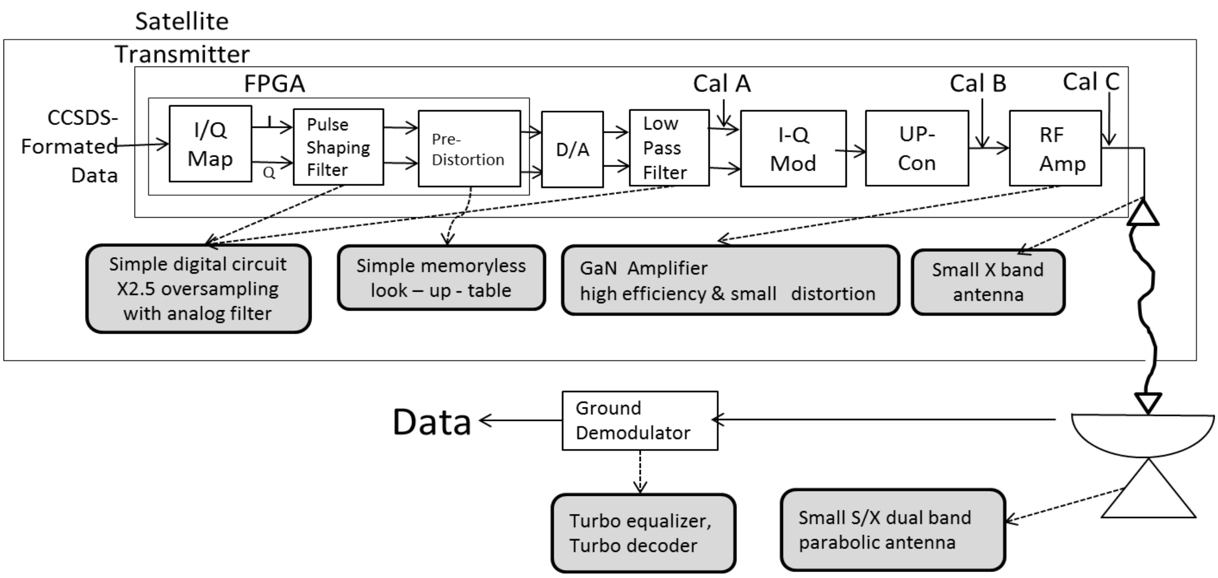

Fig.3. System block diagram of high-data-rate on-board transmitter.

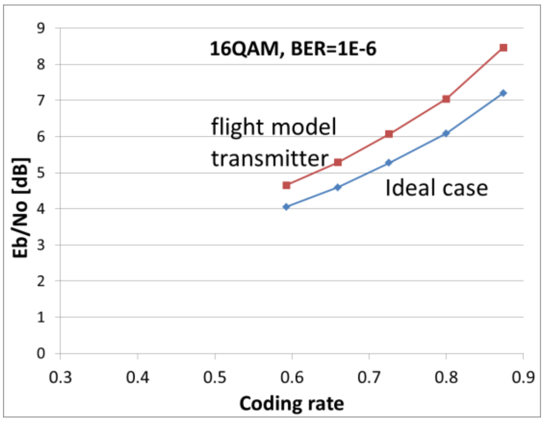

Fig.4 Simulation results of required Eb/No with error correction as function of coding rate for ideal case as well as flight model of transmitter. 16QAM, BER=10^{-6}.

Table 2 Link Calculation

Items	Values	Comments
Satellite		
TX Power [dBW]	3.0	2W
TX Cable Loss [dB]	-1.0	
TX Ant Gain [dBi]	13.5	MGA
EIRP [dBW]	15.5	
Propagation		
Propagation Loss [dB]	-177.9	El=5° (2320km)
(altitude 600km)	-173.9	El=30°(1460km)
Rain & Atm. Loss [dB]	-2.1	incl. noise
Gnd Station		
RX Ant Gain [dBi]	47.5	3.8m diameter
Sys. Noise Temp [dBK]	20.0	100K
G/T [dB/K]	27.5	
Received C/No [dBHz]	91.6	El=5°
	95.6	El=30°

synchronization errors at the demodulation. Figure 4 shows the required Eb/No for bit error rate 10^{-6} with the ideal case as well as the flight model of the transmitter. In the latter case, we recorded the waveform of the transmitting signal from the flight model and added noises to the signal.

The onboard antenna for high speed down link at Hodoyoshi-4 satellite is a medium gain antenna with 13.5dBi gain and 2x2 patch array. Its beam width is about 20°and is directed toward a ground station with about 5 °accuracy.

Link calculation was performed for Hodoyoshi-4 with 600 km altitude. Table 2 summarizes the link calculation. The link margins can be calculated based on the received C/No, the required Eb/No and the data rate.

3. Onboard Instruments

3.1. GaN-HEMT power amplifier

X band power amplifiers on satellites have widely used GaAs devices. Recently GaN HEMTs (high

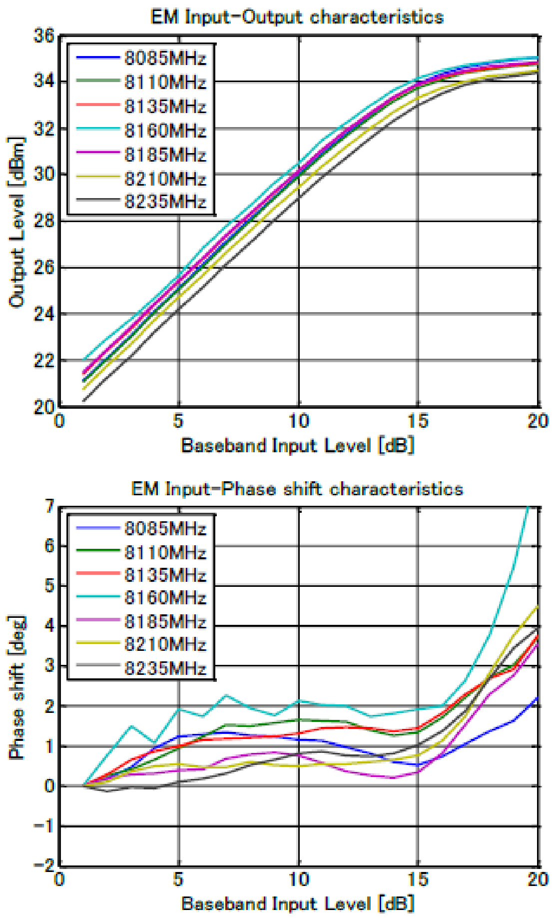

Fig.5 Input-output characteristics of RF power amplifier in high speed transmitter. Upper: AM-AM characteristics, Down: AM-PM characteristics.

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 modulation such as 16QAM requires linearity of RF amplifier. We have developed an AB class and a F class power amplifier with GaN-HEMT devices. It is found that an AB class is more suitable for our purpose than F class [4].

The AB class amplifier has saturated power of 35dBm at 8160MHz and output backoff is adjusted to 1-2dB. The power added efficiency reaches to 47%. Figure 5 shows input-output characteristics of AB class GaN-HEMT power amplifiers, AM-AM characteristics and AM-PM characteristics. Nonlinear phase change is less than 2 °around the average output power level of 33-34dBm, which is operating point of the FM transmitter. This GaN-HEMT AB class amplifier is provided with both of high efficiency and small distortion characteristics.

3.2 Flight model of transmitter

We have developed the 16QAM onboard transmitter with the AB class GaN-HEMT power amplifier. As the block diagram in Fig.3 indicates, in a FPGA input baseband signals are mapped in a 16QAM constellation and I, Q signals are pulse-shaping filtered. The clock frequency of the FPGAs reduces to 125MHz with assists of 2.5 oversampling technique and parallel processing, even though the symbol rate is 100Msps.

It is found that the output power of the transmitter decreases by 1.2dB at 50℃,compared with one at 0 ℃. This fact means that output backoff or distortion characteristics change as the temperature changes. We provide the transmitter with an automatic level controller that keeps output backoff constant in order to keep almost constant quality of the communication link.

Figure 6 is a photograph of the onboard transmitter. The mass is 1.3kg and the power consumption is 22W, which is significantly small, compared with conventional products as indicated in Fig.2.

As an evaluation of the flight model of the transmitter, bit error rates (BER) were measured without error corrections. Figure 7 is the measured and the ideal bit error rate of 16 QAM. The measured bit error is degraded compared with the ideal one due to nonlinear effects of the amplifier on amplitude-phase modulation. Simulations shown in 2.2 indicate that SCCC of CCSS.131.2-B-1 and turbo equalizer and decoder can improve the bit error rate to less than 10^{-6} in condition that uncoded bit error rate is less than $5x10^{-2}$ at around Eb/No=10dB. Figure 6 indicates that the uncoded bit error rate is $2x10^{-2}$ at Eb/No=10dB, which satisfies this condition of BER<10^{-6} with decoding and equalizing.

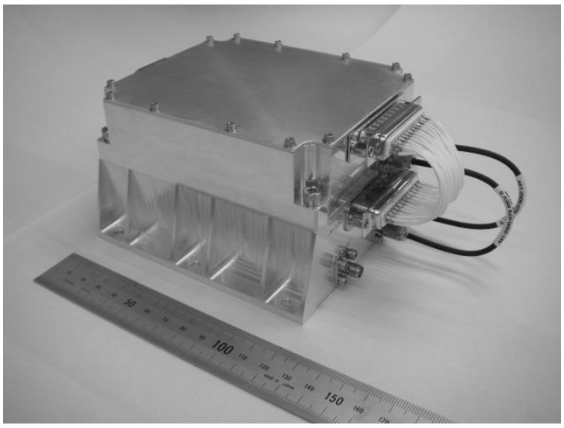

Fig.6 Photograph of high-data-rate X-band 16QAM transmitter. Maximum data rate is 348 Mbps, RF output is 2W, DC power is 22W, and mass is 1330g and size is 120 x 120 x 73 mm^3.

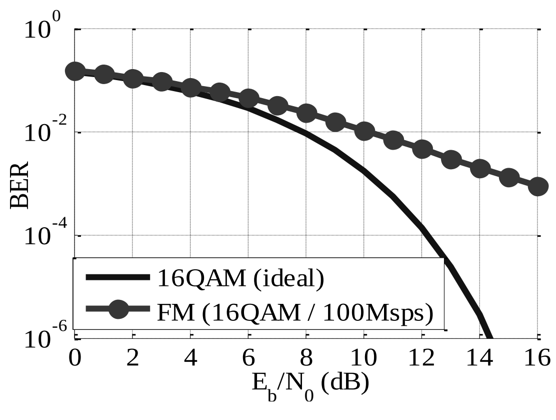

Fig.7 Bit error rate without error correction. Solid line: ideal case. Circles : transmitter flight-model.

4. Ground Station

Operation and data reception of small 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 (Fig. 8) [7].

For demodulation and decoding processing there are hardware system with FPGAs or gateways [3] and software system. For the former system real time processing is possible. However, required hardware is very high performance and expensive especially for higher bit data rates than several 100Mbps.

On the other hand, the latter has merits of low cost of the hardware and flexibility of the software. The demerit is latency of processing. However, down link of earth observation data does not necessarily require real-time processing. Typically a visible time and an orbit period are 10 and 100 minutes, respectively. It is acceptable that the processing has finished by the next visible pass. In this high speed communication experiment, received signals are demodulated and decoded with software processing after a visible pass.

Intermediate frequency of 720MHz is digitalized at 400MS/s and is stored during a visible time. Then after the visible time the data is demodulated and decoded. Communication software SPW[5] is partially in use.

Fig.8 S/X dual band 3.8 m antenna at Sagamihara campus of ISAS/JAXA

5. Experiments with Hodoyoshi-4 Satellite

Hodoyoshi-4 satellite was launched at June 20th, 2014, 4:11 (JST) from Yasny, Russia by Dnepr rocket. Sagamihara 3.8 m antenna station controls the satellite through S band as a main station from its first visible pass of June 20, 8:36. At the pass of June 22, 9:20, medium speed X band down link (10Mbps, QPSK, RS/Conv) from iso flux antenna (5dBi gain) was received at first time. Observed optical images were successfully down-linked.

We have performed high speed down link experiments with for 16QAM, 100Msps for 237Mbps (ACM13) and 348Mbps (ACM17). The medium gain antenna (MGA, 13.5dBi, beam width of 20 °) was utilized to satisfy its communication link. 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 pointing mode is available. We performed high speed experiments when the satellite passed at higher elevation than 70° with earth-pointing attitude mode. In this condition, the earth station is inside a half beam width of the MGA.

We uploaded the down link test pattern data to the transmitter of Hodoyoshi 4. The test pattern was stored in the memory of the transmitter. The test pattern can be transmitted repeatedly to the ground. The down link test with 16 QAM of ACM 17, coding rate 0.87, 348 Mbps data rate was performed in December, 2014. The received data were digitalized and stored in the ground data recorder. After the visible pass a software process of blind demodulation and turbo-decoding were performed. Figure 9 shows the I/Q constellation at elevation of 84.5° , slant range of 622km. The four symbol points at the square corners are shifted inside due to the nonlinear AM-AM effect of the transmitter. However there is no AM-PM effect as indicted in Fig.4.

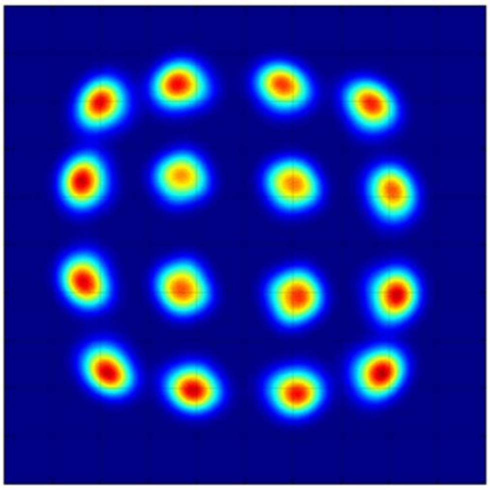

Fig.9 Demodulated I Q constellation of 16QAM when satellite Hodoyoshi 4 achieved the world fastest down link speed as a 50 kg class satellite.

Measurement at the intermediate frequency 720MHz found the ratio between the received power and the noise spectral density is C/No=96dBHz and the ratio between the energy per a symbol and the noise spectral density is Es/No=16dB. The measured bit error rate was 1.2×10^{-3} at 400Mbps uncoded signal and bit error rate after turbo decoding was less than 1.7×10^{-9}. There was no error bit in this test. This communication speed is the world-fastest one from 50 kg class satellite at present.

The simulation for bit error rates (Fig.4) shows that the required Eb/No is 8.5dB for BER after decoding $<10^{-6}$ with the flight model of the transmitter. This means the required Es/No=13.9dB. We have still 2dB margin in this experiment.

6. Conclusion

We have developed a compact 16QAM transmitter for small satellites with maximum 550Mbps, mass of 1.3kg and power consumption of 22W. This transmitter was onboard on Hodoyoshi 4 satellite with 66kg mass. The 348Mbps down link signal were received by 3.8m antenna and successfully demodulated. This communication speed is the world-fastest one from 50 kg class satellite at present. Soon we will test the 64APSK modulation with 500Mbps bit rate.

This research will enhance very much the performance of earth observation with a 50 kg class small satellite.

7. Acknowledgement

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