Field Tests of 348 Mbps High Speed Downlink System for 50-kg Class Satellite

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A high-speed downlink communication system is required to meet various applications for nano/small satellites. Therefore, it is essential to implement a transmitter with small weight and power in such satellites. We have developed high speed communication system capable of 300 Mbps downlink for small satellite. In the onboard transmitter, RF power amplifier consumes large power. In order to reduce DC power consumption of transmitter, we have developed GaN-HEMT power amplifier for X band downlink. Since this amplifier has not only high power efficiency but also high amplitude and phase linearity, we can use amplitude-phase modulation schemes such as 16-QAM. The developed communication system complies with CCSDS 131.2-B-1 standard. This standard provides adaptive coding and modulation schemes. By combining various modulation schemes with variable coding rate of error correction code, the developed communication system provides user data rate from 72 to 540 Mbps depending on the pass condition. The Hodoyoshi-4 satellite equipped with this communication system was launched in 2014 successfully and we demonstrated 348 Mbps downlink from 50-kg class satellite with 16-QAM modulation scheme. The measured bit error rate was less than 1.7×10^{-9}. By using 64-APSK modulation, downlink speed of over 500 Mbps with 50-kg class satellite will be available in the future.

Key Words: Small satellite, downlink, X band, GaN, 16-QAM, 64-APSK

1. Introduction

Recent small satellites for earth observation are equipped with high-resolution sensors. However, it is true that small satellite missions still have limitations of satellite functions compared with large satellites. One of the main limitations is downlink capability. Since high-resolution sensors generate large quantities of data, high-speed downlink capabilities are needed.

Table 1 shows the specifications of two famous small satellites. Both satellites use 8-PSK modulation with 3 bits per symbol and X band for mission data downlink. Since the signal of 8-PSK modulation is constant envelope, nonlinear amplifiers can be used with high power efficiency. In other words, by using 8-PSK modulation, the power consumption of the onboard transmitter can be reduced. To achieve a higher speed communication in X band satellite downlink channel, a higher order modulation scheme is a possible candidate for increasing frequency efficiency. Since higher order modulation schemes use not only phase modulation but also amplitude modulation, power efficiency of RF amplifier degrades in general.

The purpose of our research is to develop a high data rate (over 300 Mbps) communication system which can be applicable to small satellites of 50-kg class using amplitude-phase modulation schemes such as 16-QAM. We have been developing the communication subsystem for the flight hardware as well as the ground system, paying attention to reduce the DC power consumption and mass of onboard instruments.[4)-6)] In order to achieve both high power efficiency and linearity for amplitude-phase modulation, a new RF power amplifier using GaN-HEMTs (High Electron Mobility Transistors) is developed. This system has been demonstrated on orbit using Japanese Hodoyoshi-4 Satellite launched in 2014. In December 2014, the 3.8 m antenna station at ISAS, Sagamihara received 348 Mbps data with 16-QAM modulation and successfully demodulated/decoded them without bit error.[7)] This communication speed is as high as a half of one of Daichi 2 (ALOS-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.

Table 1. Specifications of recent small satellites for earth observation.[1)]

	SkySat-1[2)]	Flock 1[3)]
Operator	Skybox Imaging	Planet Labs
Launch date	21 Nov. 2013	9 Jan. 2014
Mass	100 kg	5 kg
Spatial resolution	1 m	3-5 m
Downlink system		
Number of channels	3	1
Frequency	8 GHz	8 GHz
Transmitter Power	1.0 W × 3 ch.	3.2 W
Modulation	8-PSK	QPSK, 8-PSK
Maximum data rate	101 Mbps × 3 ch.	120 Mbps

2. High Speed Communication System

Table 2-5 and Fig. 1 summarize our novel communication system with high data rate for small satellites.

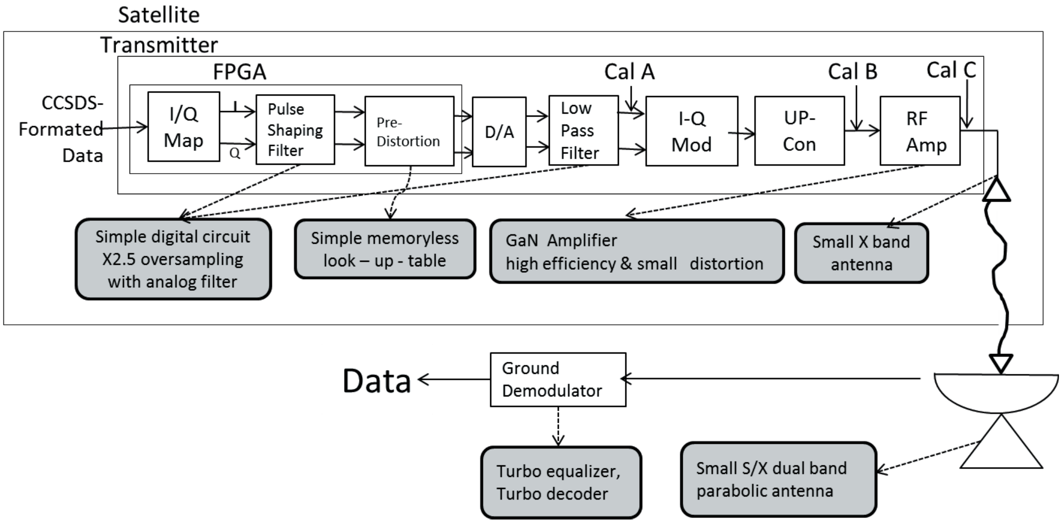

Fig. 1. System diagram of communication system.

Table 2. Onboard transmitter spec.

Frequency band	8160±60 MHz
RF output power	2 W
Symbol rate	100 Msps
Modulation schemes	QPSK, 16-QAM, 8-PSK, 16-APSK, 32-APSK, 64-APSK, 64-QAM
Data rate (user)	72 to 540 Mbps
Error correction code	SCCC based on CCSDS 131.2-B-1 [8)]
Data input interface	LVDS
DC power	28 V, 22 W
Volume	$12 \times 10 \times 7.3$ cm
Weight	1330 g
Operating temperature	-20 to +50 °C
Radiation test	20 kRad

Table 3. Onboard antenna spec.

Type	2×2 patch array
Peak gain	13.5 dBi
Beam width	Approx. 20°
Size	$7 \times 7\text{cm}^2$
Weight	69 g

2.1. Onboard instruments

We have developed the X band high-speed transmitter of over 300 Mbps downlink capacity for small satellite (Fig. 2). This transmitter consists of the baseband unit and the RF unit. The baseband unit converts input binary data streams into output baseband IQ signals, followed by the RF unit. The signaling format conforms to the Consultative Committee for Space Data Systems (CCSDS) 131.2-B-1. The CCSDS 131.2-B-1 defines the serial concatenated convolutional code (SCCC) and the variety of modulation schemes (QPSK, 8-PSK, 16-APSK, 32-APSK and 64-APSK). In addition to these modulation schemes, we implemented the 16-QAM and 64-QAM. We adopt a 2.5 times oversampling technique and a parallel processing to reduce power consumption. Specifically, clock frequency of the FPGA is 125 MHz even though the symbol rate is 100 Msps. This symbol rate is higher than SkySat-1 [2)] (45 Msps) or Flock 1 [3)] (4-45 Msps). In the RF unit, RF power amplifier consumes large power. We applied the GaN-HEMT class AB amplifier (Fig. 3) with high power efficiency of 47% to this transmitter. Fig. 4 shows AM-AM and AM-PM characteristics of the amplifier. The nonlinear phase change of this amplifier is less than 2 degrees at output backoff of 1 dB. Therefore it is possible to achieve amplitude-phase modulation such as 16-QAM with low backoff driving. By integrating these technologies, the transmitter consumes only 22 W. The baseband FPGA supports digital predistortion (DPD) scheme using lookup tables to linearize the power amplifier and improve the power-added efficiency. The performance of DPD using experimental data was reported in 6). The implemented lookup table can be reconfigured by the uplink command whenever the modified table is required. However, the downlink signals are now transmitted without the predistortion scheme. The reason is that the cost of received signal distortion due to the power amplifier is smaller than that of our expectation when comparing an error vector magnitude (EVM) value of 16-QAM.

Table 4. Ground antenna spec.

Type	3.8 m Cassegrain with ring focus
Frequency	S/X dual band
Peak gain	36 dBi (S), 47.5 dBi (X)

Table 5. Ground receiver spec.

Type	Software receiver with IF sampling
A/D converter	400 MS/s, 14 bit
Modulation schemes	QPSK, 16-QAM [Under development] 8-PSK, 16-APSK, 32-APSK, 64-APSK, 64-QAM

We also developed small onboard X band middle gain antenna (Fig. 5). This antenna is mounted on satellite body and directed to ground station by attitude control system. In addition to this antenna, the iso flux antenna (Fig. 6) was developed for earth pointing mode.

Fig. 2. Flight model of X band transmitter. DC power consumption is 22 W and mass is 1330 g.

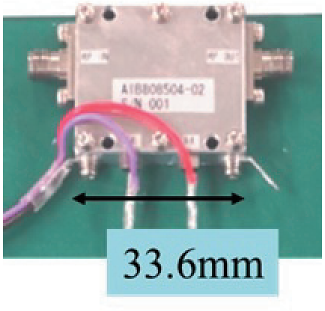

Fig. 3. Engineering model of GaN-HEMT power amplifier.

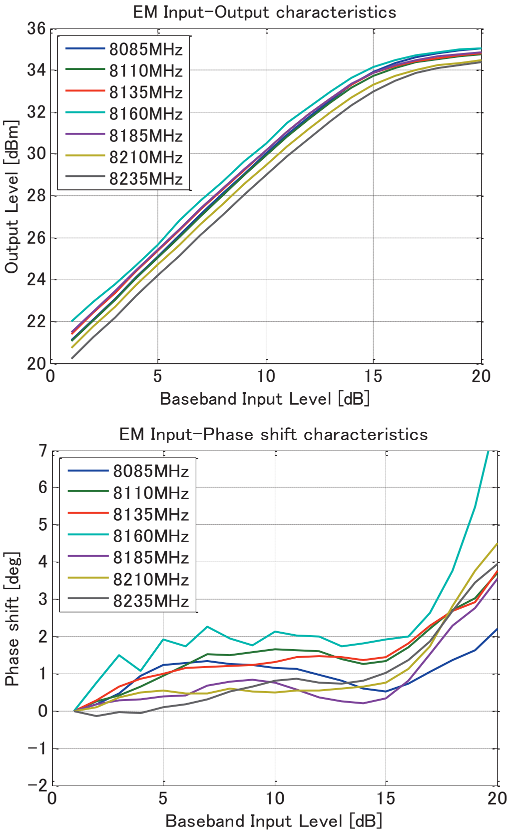

Fig. 4. Input-output characteristics of RF power amplifier. Above: AM-AM characteristics, Below: AM-PM characteristics.

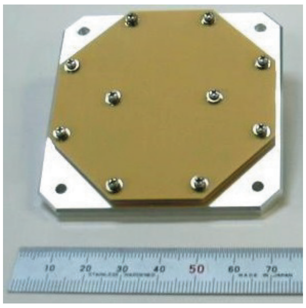

Fig. 5. Onboard middle gain antenna. Peak gain is 13.5 dBi and mass is 69 g.

Fig. 6. Onboard iso flux antenna. Peak gain is 5 dBi and mass is 149 g.

2.2. 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. 7). There are some commercial ground receivers which support high data rate and SCCC error correction. 9), 10) However, since these receivers were developed for large satellites, they are expensive in general. Therefore, it is difficult to use existing commercial receiver in low-cost small satellite missions. Since our research is not considered any real-time communications application, we have developed offline receivers. 5)

In the ground station, downconverted IF signals are digitally processed by developing offline receiver. The modulation symbol rate is a fixed 100 Msps regardless of different modulation and coding formats, and then four times oversampling scheme with raised-cosine filtering, called the Nyquist pulse, is adopted to avoid inter-symbol interference. All of the received samples during each satellite's field of view are stored in a data recorder. The recoded samples are demodulated and decoded by the offline receivers. We have developed two types of receiver, a field-programmable gate array (FPGA)-based hardware, 5), 6) and MATLAB-based software. The FPGA may be implemented real-time processing to design parallel processing circuits, but the development cost and complexity is increased. We then develop the receiver based on the software due to flexibility and better performances. The performance of the software receiver is better than that of hardware one, since the software can implement digital modules by using a floating-point signal processing. Comparing with a quantized signal processing of hardware, the floating-point one has some advantages, such as dynamic range and quantization error. Fig. 8 shows the system diagram of ground receiver. Since current version of software receiver supports QPSK and 16-QAM modulation schemes only, the current maximum user data rate of our communication system is 348 Mbps (16-QAM, coding rate = 0.87).

Fig. 7. S/X dual bands 3.8 m antenna. Peak gain of X band is 47.5 dBi.

2.3. Link simulations

Our communication system complies with CCSDS 131.2-B-1 standard. Current our ground receiver only supports QPSK and 16-QAM modulation. The bit error rate performances of variable data rate formats according to CCSDS 131.0-B-2 were simulated by using the measured X band downlink channel conditions, as shown in Fig. 9. The nonlinearity and frequency dependence of the transmitter and receiver RF electronics causes increase in BER. Achievable bit rate in the measured X band downlink channel conditions were also simulated as shown in Fig. 10. When BER of 1×10^{-6} with margin of one decibel is required, our communication system can transmit up to 32.5 GBytes per pass from 600 km sun-synchronous orbit with a 3.8 m ground antenna.

3. Experiments with Hodoyoshi-4 Satellite

The Hodoyoshi-4 is Japanese small satellite with 64 kg mass. Our high speed transmitter and small antenna are installed to this satellite. Hodoyoshi-4 was launched at June 20th, 2014, 4:11 (JST) from Yasny, Russia by Dnepr rocket. Sagamihara 3.8 m antenna station controls the satellite via S band link as a main station. We have performed high speed downlink experiments with 16-QAM, 100Msps for 348 Mbps data downlink. The satellite is equipped with attitude control system toward the ground station continuously at coarse accuracy of 5° during high speed communications. However, the attitude control system has not yet work sufficiently. Instead we performed high speed data downlink 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 onboard middle gain antenna. The transmitter sent repeatedly a fixed known data (PN code). The received signals were demodulated and decoded by software-based receiver. Figs. 11 and 12 show I-Q constellation diagram of received signals. Estimated received C/No based on received IF spectrum is about 96 dBHz at ground antenna elevation angle of 84.5° and slant range of 622 km. The measured BER is 1.2×10^{-3} without error correction. After turbo decoding process, the measured bit error rate is less than 1.7×10^{-9}.

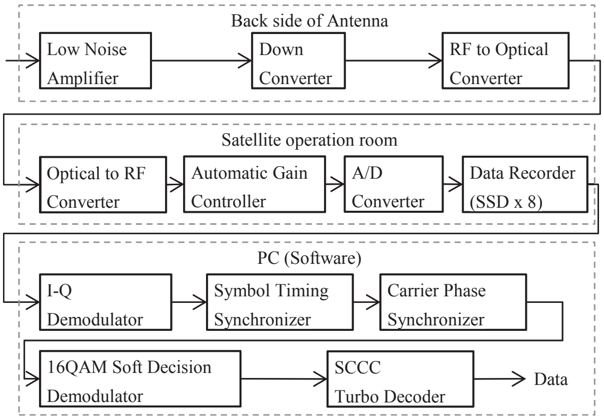

Fig. 8. System diagram of ground receiver.

4. Conclusion

We have developed high speed downlink system for small satellite. The Hodoyoshi-4 satellite equipped with our communication system was launched successfully and we demonstrated 348 Mbps downlink from 50-kg class satellite with 16-QAM modulation scheme and forward error correction of SCCC. Until May 2015 after the launch, our communication system is operating without any problems. In the future, we will try 400 Mbps to 500 Mbps downlink with 32-APSK or 64-APSK using Hodoyoshi-4.

Acknowledgments

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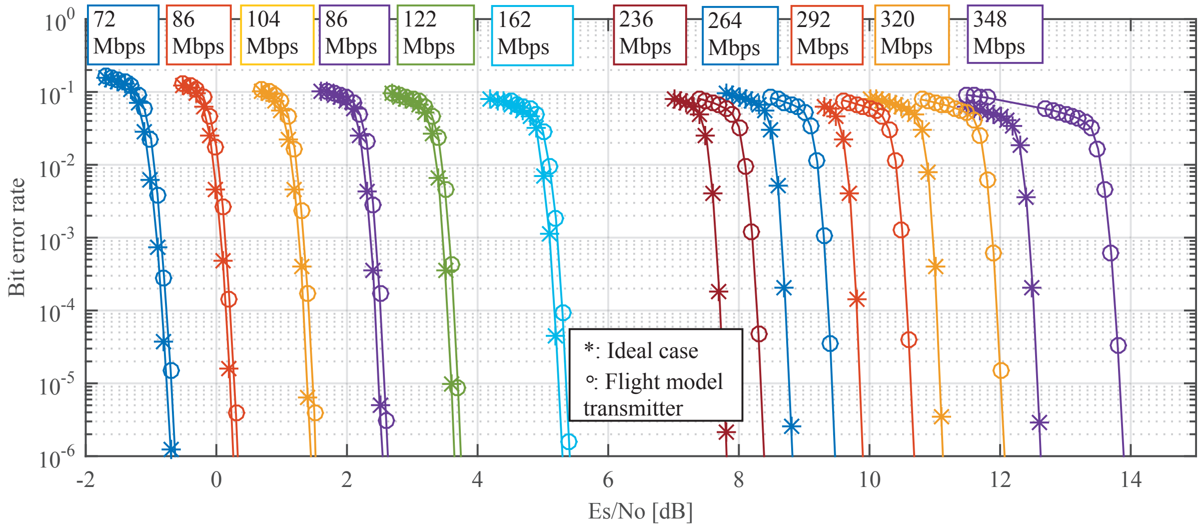

Fig. 9. Simulation results of bit error rate.

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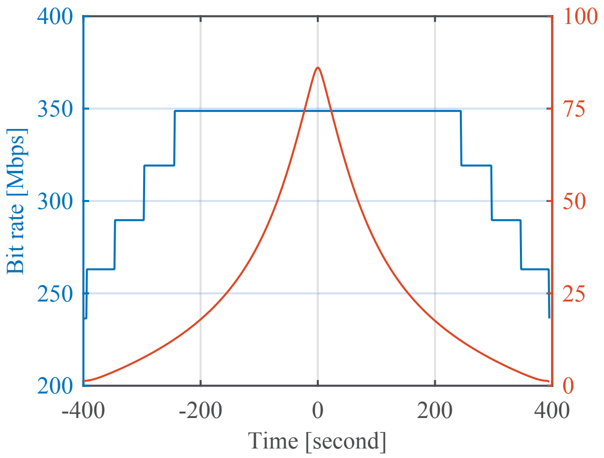

Fig. 10. Simulation result of bit rate with real path condition. The required BER is 1×10^{-6} with margin of one decibel.

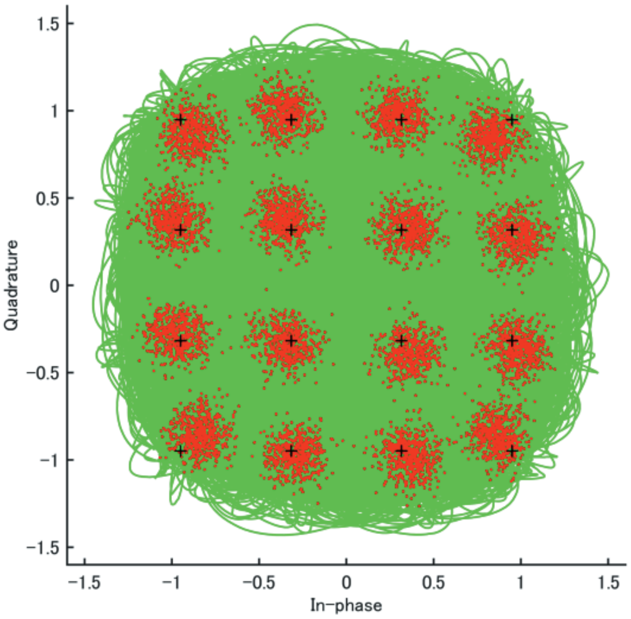

Fig. 11. I-Q constellation diagram of received 16-QAM signals. Raw bit error rate is 1.2×10^{-3}

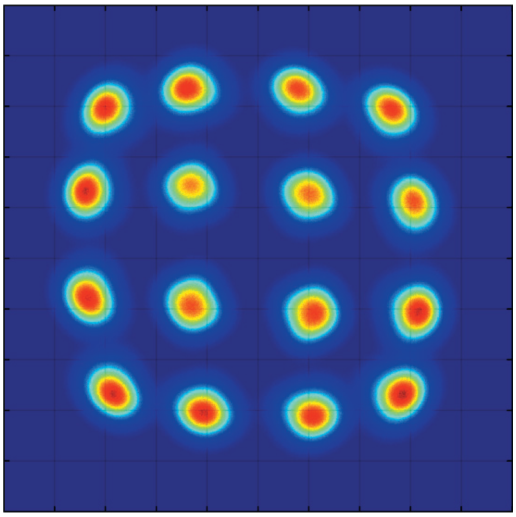

Fig. 12. Density plot diagram of received 16-QAM signals.