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Ka-band Multi-Gbps High Speed Downlink with Electrically Steerable Beam

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ABSTRACT

With advances in sensor technology and data services, the latest earth observation missions tend to require substantial amounts of remote sensing data to be downlinked to earth stations with shorter delivery times. To meet these demands, AXELSPACE is developing a Ka-band downlink system (AxelLink-Ka) in cooperation with Tokyo Institute of Technology[1] that combines a broadband Ka-band transmitter and an active phased array antenna.[2] The prototype of the AxelLink-Ka was found to achieve a data rate of up to 4.2 Gbps with using dual polarizaion of Right- and Left-Handed Circular Polarization (RHCP/LHCP) in the Ka-band (25.5—27.0 GHz) and electrical beam steering covering ±66-degree range with the small enough Size, Weight and Power (SWaP) to be installed on a microsatellite: the size $\sim 220 \times 170 \times 100$ mm, the weight $< 2,300$ g, and the power consumption < 60 W. This paper provides an overview of the entire system, simulation results of link budgets, and design and measurement results of the hardware and software.

INTRODUCTION

AXELSPACE is a company that manages satellites from design to manufacturing to operation and has a record of nine satellites. As the progress of sensor technologies and data services, the latest earth observation missions tend to require higher speed to downlink a substantial amount of remote sensing data to earth stations in shorter latencies. In addition, conventional microsatellites usually have to use body-fixed directional antennas under conditions of weight and size, which requires maneuvers to switch attitudes between an observation mission and tracking a ground station for data downlink.

In the above-mentioned context of the need for high-speed satellite communication, a number of studies have been conducted. Dual polarization system which potentially doubles the channel capacity,[3,4] and the Ka-band system which enables higher data rate due to the higher frequency and smaller antenna due to the shorter wavelength compared to conventional X-band system[5] were studied and demonstrated.

In response to these requirements and previous research, AXELSPACE and Tokyo Institute of Technology are developing "AxelLink-Ka" (See Fig. 1). The Ka-band system which enables higher data rate due to the higher frequency and smaller antenna due to the shorter wavelength. The development issue for a broadband Ka-band transmitter is how to generate a broadband modulation signal, and we have developed a broadband transmitter using the latest electronic components by testing and adopting COTS products. The development issues for phased array antennas were power efficiency and beam scanning angle, and there were no commercially available products that could meet these requirements. Therefore, we collaborated with Tokyo Institute of Technology to develop an original RFIC and antenna, and developed a phased array antenna with low power consumption (26.6 W at EIRP 63.8 dBm)[2] and a wide beam scanning angle (±66deg).

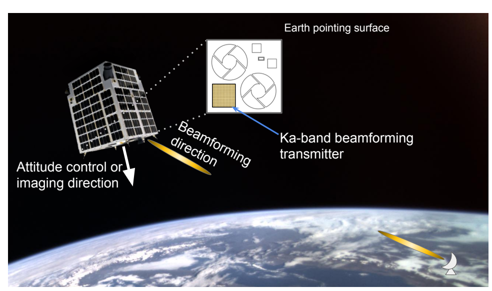

Figure 1: Illustration of AxelLink-Ka system

OVERVIEW OF KA-BAND TRANSMITTER

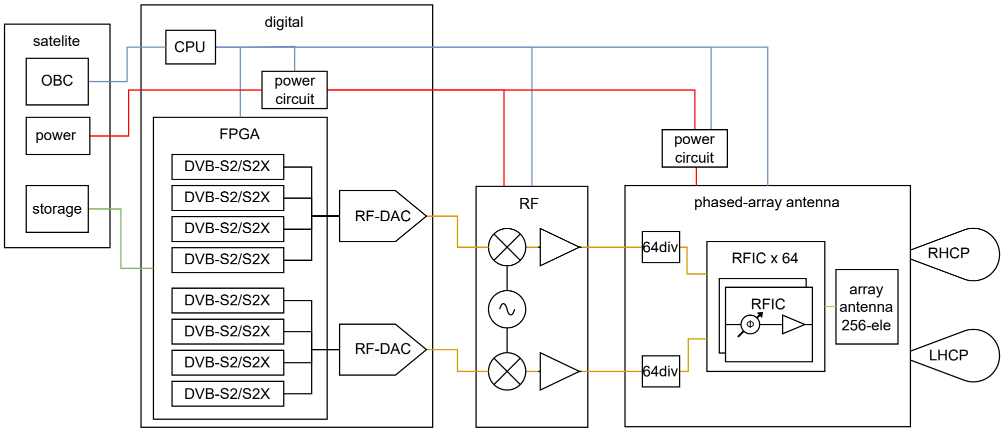

Figure 2: Block diagram of AxelLink-Ka transmitter

Figure 2 shows the block diagram of AxelLink-Ka transmitter. AxelLink-Ka is divided into three major blocks. The digital section controls the entire subsystem and generates digital signal processing modulation signals; the RF section upconverts the signals from IF signals to the RF band and amplifies the signal level. The antenna section consists of an original RFIC that integrates a phasor and power amplifier, and an array of patch radiation elements. The digital section performs signal processing on data received from the satellite bus side via high-speed data lines and outputs DVB-S2(X)[6,7] compliant IF signals. The blue line indicates the control signals for the entire "AxelLink-Ka". The control signals include various parameters for upconverters, status checks of currents, voltages, temperatures, anomaly monitoring and control signals for phase values that determine the beam direction of phased array antennas.

Table 1 shows the SWaP of AxelLink-Ka transmitter. and its size and weight are such that it can be mounted on a microsatellite. The power consumption is less than 60W, which is low for a Ka-band transmitter system. This is due to the use of a highly power-efficient phased-array antenna with RFIC developed by Tokyo Tech and a broadband radio system with the latest COTS electronic components.

AxelLink-Ka uses the Ka band, with four 200—270 Msymb/s per carrier channel per polarization and a total symbol rate ideally reaching 2.16 Gsymb/s/ when both polarizations are used. The occupied bandwidth at this time can be less than 1.5 GHz including the guard band. DVBS2(X)-compliant communication systems are available for many ground station sharing services,[8] and adoption of the standard is expected to reduce the cost of AxelLink-Ka deployments because it does not require construction of its own ground stations.

Table 1: SWaP of AxelLink-Ka transmitter

Parameter	Value
Size [mm]	Digital : 220 x 170 x 30 RF/antenna: 150 x 150 x 50
Weight [g]	Total < 2,300 Digital : < 1,100 RF/antenna: < 1,200
Power [W]	55—60

LINK BUDGET ANALYSIS

To determine the target specifications of the AxelLink-Ka transmitter, the link budget of the communication system was investigated. Figure 3 shows the arrangement of subcarriers. The full bandwidth from 25.5 to 27 GHz is potentially available bandwidth for the downlink of earth observation satellite communication. It indicates the maximum spectrum of four subcarriers for frequencies. The symbol rate of each subcarrier is 262.5 Msymb/s, the center frequencies of each subcarrier are 25.69/26.06/26.44/26.81 GHz, respectively. The roll-off rate is 0.35.

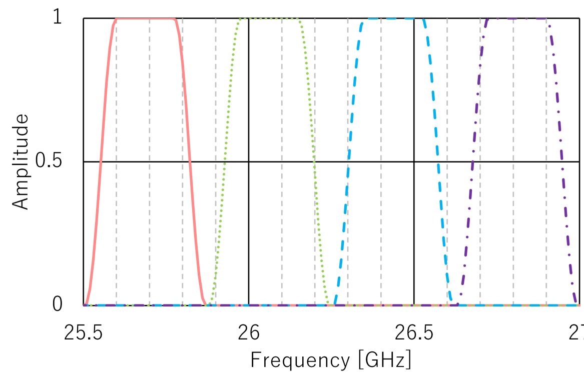

Figure 3: Arrangement of subcarriers

Table 2 shows the specifications of AxelLink-Ka transmitter. The operational frequency settings are consistent with the arrangement of subcarriers. To increase the data rate and mitigate the development cost, dual polarization with the Left- and Right-Handed Circular Polarization (LHCP and RHCP) and the modulation and coding standard DVB-S2(X) has been adopted.

Table 2: RF specifications of AxelLink-Ka transmitter

Parameter	Value
Center frequency	26.25 GHz
Frequency band	25.5 — 27 GHz
Occupied bandwidth	1.5 GHz
Symbol rate /subcarrier	200—270 Msymb/s
Number of subcarriers	4
Number of polarizations	2 (LHCP/RHCP)
Total symbol rate	1.6 ∼ 2.16 Gsymb/s
Maximum data rate	∼ 10.8 Gbps
Modulation standard	DVB-S2(X)
EIRP	∼ 63.8 dBm
G/T of ground station	29 dB/K

The standard has too many MODCODs (Modulation and Codings) to use in our satellite communication. Therefore, some are picked out of them as shown in Table 3. The MODCODs in the list are selected so that the required E_b/N_0 and spectral efficiency specified in the standard are evenly distributed between the highest and lowest values as much as possible. These are supposed to be changed during the linked one-time pass of a satellite flying over a ground station. The switching timing would be scheduled in advance depending on the precalculated distance between them. This method is called Variable Coding Modulation (VCM) in the satellite communication system.

Table 3: List of selected MODCODs

No.	MODCOD	Required E_b/N_0 [dB]	Spectral efficiency
1	QPSK 2/9	0.766695142	0.434841
2	QPSK 9/20	0.730322938	0.889135
3	8APSK 5/9-L	2.562507662	1.647211
4	16APSK 3/5-L	3.662437745	2.370043
5	16APSK 25/36	4.883415384	2.745734
6	32APSK 2/3-L	5.92546242	3.291954

Under the above-mentioned specifications and a few additional information about our satellites and ground stations in operation, link budget analysis has been performed. Figure 4 shows the orbital simulation and beamforming. The phased array antenna mounted on a satellite is supposed to pinpoint the ground station to communicate with. From this simulation, the slant range, and the gain of the phased array antenna to time are calculated, and then the Free-Space Path Loss (FSPL), received isotropic power (RIP) can be calculated by post-processing. The satellite attitude is always fixed to point the earth center and the ground station is electrically tracked by the phased array antenna.

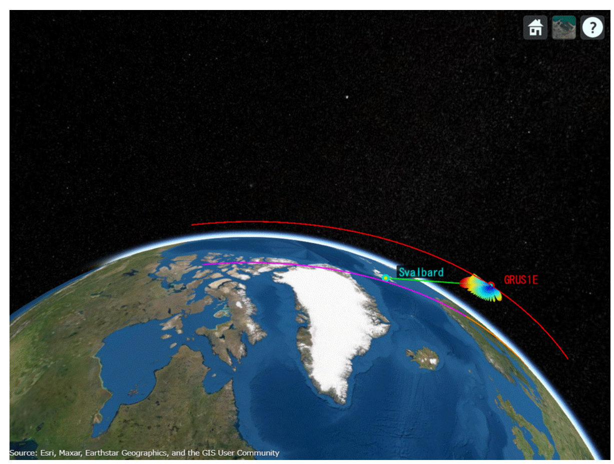

Figure 4: Orbital simulation and beamforming

Figure 5 shows the throughput and data amount to time. The assumed situation corresponds to Fig. 4. The timing on the orbit indicated with the red line in Fig. 4 corresponds to the period from 0 to 20 minutes in Fig. 5. Since VCM with the set of MODCODs listed in Table 3 is used, the bitrate indicated with the blue line is stair-stepping. The dotted line and the solid line are the values obtained by a single and dual polarizations, respectively. The bit rate hits 8.07 Gbps at the maximum. As a result, the red lines represent the cumulative data capacities as an integration of the bit rate, which achieves 265 GB for one pass of the satellite flying over a ground station. Each number from 1 to 6 in the figure indicates the timing when the MODCOD number (see Table 3) is switched to each number. The numbers are symmetric between the increasing and decreasing phases in the bit rate. To investigate this link budget analysis, the breakdown of the link budgets at the two times when the MODCOD is switched to the MODCOD number 1 and 6 are investigated.

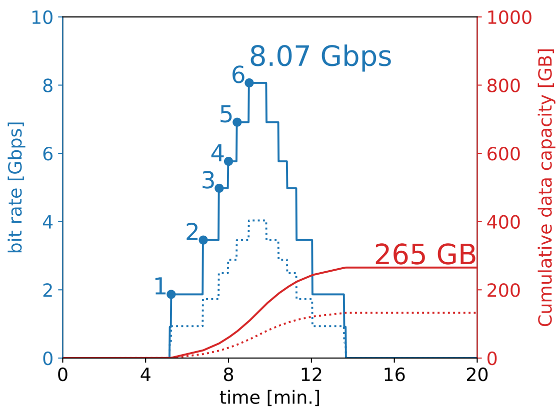

Figure 5: Throughput and data amount

Table 4 shows the downlink budgets from AxelLink-Ka to a ground station. The second and the third columns show the results when the satellite is at the timing 1 and 6 shown in Fig. 5, respectively. As mentioned at the beginning of this section, each subcarrier is 262.5 Msymb/s and then the total symbol rate of four subcarriers is 1,050 Msymb/s. It is supposed that other losses include pointing, polarization, and atmospheric losses. With the lowest MODCOD QPSK 2/9, the bit rate of 0.933 Gbps is obtained. Although the link margin of 3.41 dB is too enough, this is due to the setting of operational elevation angle of 10 degrees. Since these numbers are per polarization, the bit rate becomes around 1.8 Gbps with dual polarization. With the highest MODCOD 32APSK 2/3-L, the bit rate reaches 4.03 Gbps per polarization and 8.07 Gbps for dual polarization with the link margin of 1.8 dB.

HARDWARE AND SOFTWARE DESIGN AND EVALUATION

This section describes two tests: RF signal quality in OTA measurements for the entire system, and compatibility test using the digital part and the ground station emulator.

Table 4: Downlink budgets from AxelLink-Ka to a ground station

Parameters	Timing 1	Timing 6	Unit
Orbit altitude	600	600	km
Elevation angle	10.07	68.15	deg.
Slant range	1955	655	km
Occupied bandwidth	1500	1500	MHz
symbol rate of a subcarrier	262.5	262.5	Msymb/s
Number of subcarriers	4	4	-
Number of polarization	2	2	-
Guard bandwidth	25	25	MHz
Roll-off rate	0.35	0.35	-
Center frequency	26.25	26.25	GHz
MODCOD	QPSK 2/9	32APSK 2/3-L	-
Spectral efficiency	0.434841	3.291954	-
Required E_b/N_0	0.766	5.92	dB
Symbol rate	1,050	1,050	Msymb/s/pol.
Radiated power	0.6918	0.6918	W/pol.
Transimit antenna gain	24.73	28.25	dBi
EIRP	23.13	26.65	dBW
FSPL	186.65	177.16	dB
Implementation loss	1.0	1.0	dB
Other losses	6.17	6.17	dB
RIP at ground station	-164.65	-151.65	dBW
G/T of ground station	29	29	dB/K
C/N_0	91.77	104.78	dB-Hz
E_b/N_0	4.18	7.72	dB
Bit rate	0.933	4.03	Gbps
Link margin	3.41	1.80	dB

HARDWARE AND SOFTWARE DESIGN AND EVALUATION

This section describes two tests: RF signal quality in OTA measurements for the entire system, and compatibility test using the digital part and the ground station emulator.

Over-The-Air (OTA) Measurement

Figure 6 shows the experimental setup for OTA measurement to evaluate Error Vector Magnitude (EVM) with using a spectrum analyzer. In addition to "OTA" measurement, "wired" measurement using a direct cable connection was conducted to check signal quality degradation.

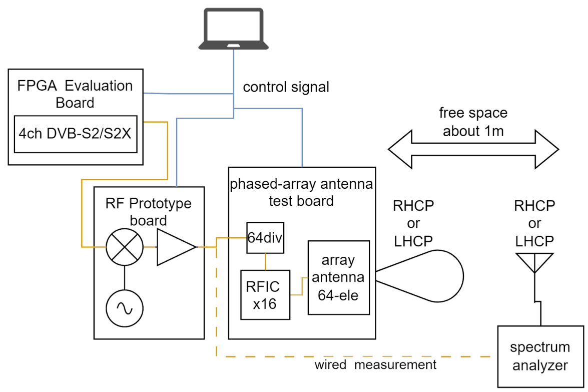

Figure 6: Experimental setup for OTA

Figure 7 shows the measured constellation for each multicarrier. Every constellation clearly shows the 16APSK constellation. The EVM of each constellation is shown in Table 5. The orders of multicarriers in Fig. 7 and Table 5 are the same with each other from top to bottom. The EVMs were around 4% in wired measurement and around 8% in OTA measurement, which are reasonable and acceptable for satellite communication system.

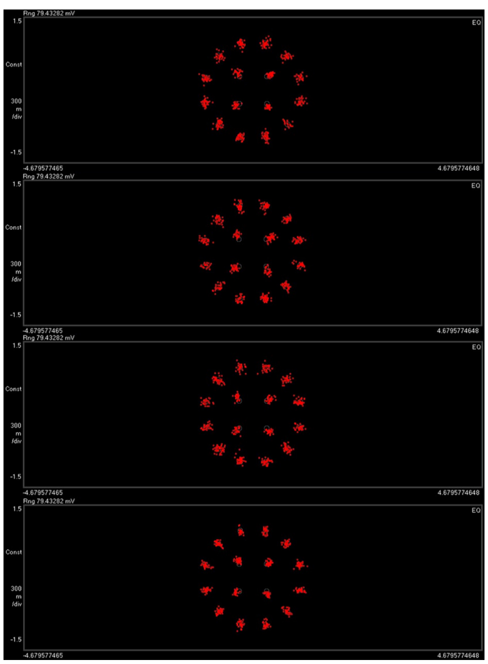

Figure 7: Measured constellation for each multicarrier

Compatibility Test with Ground Station Emulator

Compatibility Test was conducted to confirm the data transmission between the digital section and the ground station equipment. Figure 8 shows the test configuration using the ground station emulator. An FPGA evaluation board was used to generate count-up data as dummy data, encode and modulate the data based on DVB-S2/S2X standard to output the IF signal. The signal was upconverted using an upconverter prototype unit, and the RF signal was connected to an in-house ground station emulator with a coaxial cable to demodulate the signal. The modem in the ground station emulator which is the same as the one used in some ground station equipment enables a simple compatibility test. The data decoded by the modem was stored as a file in the data recorder, and the file was acquired by the control PC and checked to see if the received data matched the sent data.

Table 5: Measured EVMs of each multicarrier

Center frequency	Wired	OTA
25.65 GHz	4.7	8.2
26.05 GHz	3.5	8.8
26.45 GHz	4.9	8.5
26.85 GHz	3.4	7.0

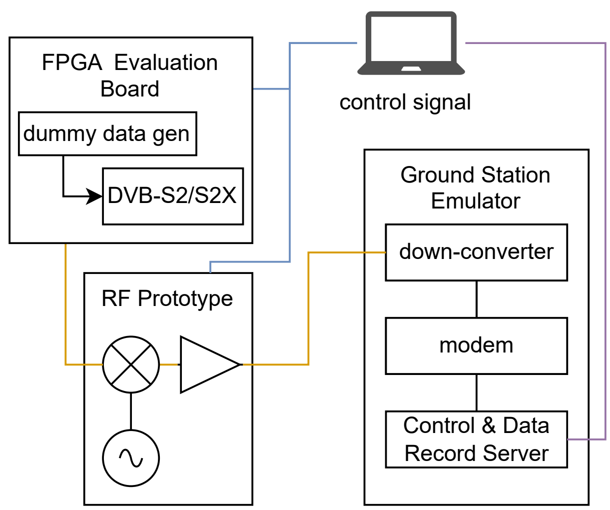

Figure 8: Compatibility test with ground station emulator

The functionality of the digital part was verified using an FPGA evaluation board, on which the signal processing part of DVB-S2/S2X was implemented to confirm that the functionality works as expected. For this test, count-up data was generated in the FPGA as dummy payload data and used as the input signal to the processing part. A prototype RF unit was used to upconvert the signal from IF to RF, and the RF signal was connected to the ground station emulator after adjusting the signal level using a coaxial cable and an attenuator. The data demodulated and decoded by the modem in the ground station emulator can be saved as a file in the data recorder. The recorded data files were retrieved by a control PC and checked to see if they matched the dummy data. The test was conducted with varying the symbol rate (150—250 Msymb/s) and MODCOD (QPSK—32APSK). As a result, it was confirmed that count-up data were correctly received by the ground station emulator under all conditions.

Conclusion

In response to the growing needs for more communication capcity and shorter delivery time to earth observation satellites, the AxelLink-Ka system including the broadband Ka-band transmitter and a phased array antenna were developed and demonstrated. As the results of link budget analysis, communication capabilities with VCM over QPSK to 32APSK was demonstrated, and the prototype of AxelLink-Ka demonstrated OTA transmission with the same MODCOD range. In the future, we plan to develop more detailed parts such as an operation monitoring system, evaluate items that have not yet been verified, and study how to use the system in actual operation based on the link budget design, in order to install it in next-generation earth observation satellites and contribute to the advancement of the microsatellite.

Acknowledgments

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