4-3 High-Speed Burst Modem for Bent-Pipe Relay Mode

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The 622 Mbps/1244 Mbps dual rate SS-TDMA terminal is developed for the high-speed network of the WINDS bent-pipe mode. This terminal is consisted of a high-speed burst modem, a digital terminal that is a burst and communication controller, a router and a TCP accelerator. In additional at Kashima earth station, the receiver of the 155 Mbps reference burst transmitted JAXA standard station is provided.

We had been developed the high-speed burst modem and digital terminal. The 155 Mbps reference receiver are supplied same equipment using JAXA standard station. The router and the TCP accelerator will be supplied from commercial goods.

The high-speed burst modem is a digital modem of Quadrature Phase Shift Keying and the transmission rate of 1648 Mbps as the user data rate of 1244 Mbps. And the modem has another mode working a half rate clock for the transmission rate of 824 Mbps as the user data rate of 644 Mbps. In this mode, two carriers can be used for upper and lower band of the WINDS transponder.

The ground tests using 622 Mbps prototype burst modem with RF equipments of the earth station and the WINDS transponder showed good results that the E_b/N_0 is less than 10 dB at the BER of 10^{-10}.

Keywords

High-speed burst modem, Turbo product code, SS-TDMA, Digital signal processing, Digital modem

1 Introduction

The high-speed network terminal mainly consists of a high-speed burst modem and a digital terminal, and is also equipped with a router and a TCP accelerator. The Kashima experimental earth station (referred to simply as the “Kashima earth station” hereafter) is equipped with an additional receiver for the 155-Mbps bent-pipe reference burst transmitted from the standard station (Network Management Center, NMC) of the Japan Aerospace Exploration Agency (JAXA).

The National Institute of Information and Communications Technology (NICT) began a development study of a high-speed network terminal in 2003. In this context we decided to develop a high-speed burst modem, with an additional digital terminal to provide burst control and user data interface functions. In fiscal 2004, we initiated a principal focus on the development of the high-speed burst modem. Development studies and design of the digital terminal have been underway since fiscal 2005.

When we began work on the high-speed burst modem, we intended to achieve a transmission rate of 1,244 Mbps using two sets of modems at a user data rate of 622 Mbps, due to the limitations of the digital analog converter (MUX-DAC) that can be used in the modulator. The MUX-DAC thus represented the bottleneck in increasing the transmission rate. In fiscal 2005, in parallel with the development of the 622-Mbps high-speed burst modem, we developed a new high-speed MUX-DAC that can provide a sample rate of 2 G-samples per second. In fiscal 2006, based on the 622-Mbps high-speed burst modem, we developed a 622-Mbps/1,244-Mbps dual-rate high-speed burst modem using this high-speed MUX-DAC to increase the user data rate to 1,244 Mbps.

In fiscal 2007, we plan to complete the digital terminal, combine it with the high-speed burst modem, and complete the core section of the high-speed network terminal.

Taking development time and costs into consideration, we will prepare a 155-Mbps reference burst receiver equivalent to the 155-Mbps burst demodulator that JAXA developed for the standard station. We will use commercially available products for the router and the TCP accelerator.

2 Overview of high-speed network

We are developing the high-speed network to provide a broadband access environment equivalent to that provided by optical lines, with the aims of using the backbone patch and access patch of the Internet and the dissolution of digital divide on islands and in other isolated locations via satellite link.

Figure 1 shows the configuration of the WINDS transponder system[1][2]. In the WINDS bent-pipe mode, six channels are available, four of which can use the multi-beam antenna (MBA) and the active phased array antenna (APAA); the remaining two channels can use only the APAA. Two channels with the MBA and the two channels with the APAA provide wideband transponder functions with a bandwidth of 1,100 MHz. The remaining two channels with the MBA use upper half-band bandpass filters and can be used in combination with regenerative mode, which employs the lower frequencies. Each channel combines the functions of the IF switch matrix subsystem (IFS), the MPA, and the APAA—all components of the onboard transponder system—and switches the transmitting and receiving beams arbitrarily by slot. The WINDS bent-pipe mode combines this onboard switching function and the TDMA (Time Division Multiple Access) system to constitute an SS-TDMA (Satellite Switched TDMA) system.

In an SS-TDMA system, each earth station needs to transmit and receive signals in synchronization with satellite beam switching. The timing of satellite beam switching is controlled by the standard station. Each earth station synchronizes with the reference burst from the standard station to synchronize the transmitting and receiving signals between the earth station and the satellite. The WINDS development plan assumes that two or more systems use the bent-pipe mode, and thus, the reference burst transmitted from the standard station uses a data transmission rate of 155 Mbps, with which it is relatively easy to implement the demodulator. As the high-speed burst modem cannot directly demodulate the 155-Mbps reference burst, a separate receiver is installed at the Kashima earth station to receive a 155-Mbps reference burst from the standard station and to transmit a 622-Mbps reference burst using the high-speed burst

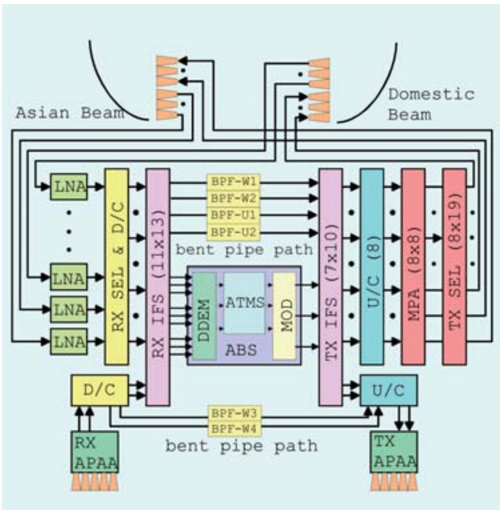

Fig.1 Configuration diagram of WINDS transponder

modem in synchronization with the 155-Mbps reference burst. Other high-speed network earth stations receive this 622-Mbps reference burst to synchronize with the satellite.

2.1 Network configuration

Figure 2 shows a schematic diagram of the high-speed network. We have developed the high-speed network such that it can be operated with other systems that use the WINDS bent-pipe mode. The network consists of the satellite that provides the bent-pipe links, the JAXA standard station, and the high-speed network earth stations—including the Kashima earth station and others—and high-speed network terminals. The onboard transponder can operate six channels simultaneously. In addition, the numbers of beams which can be used for the same experiment period are Kanto beam and seven beams in the maximum of other areas by MBA, and are eight beams by APAA. The high-speed network earth stations are connected according to the combination of beams and transponder channels. The high-speed network terminal does not feature an initial connection function, and thus employs the pre-assignment method, through which signals are transmitted and received based on slot assignment information set in advance.

2.2 Frame format

Figure 3 shows an example of the frame format used in the WINDS bent-pipe mode. A slot represents 2 ms, and 20 slots constitute a frame. A frame thus represents 40 ms; 16 frames constitute a super frame. A super frame consists of 320 slots and represents 640 ms. The guard time between the bursts is 75 μs or more. Communication is controlled in super-frame units.

The 155-Mbps reference burst is placed in the first slot in each frame by default. Although six channels of communication signals can be handled, but reference burst is simultaneously transmitted by one channel in order to use high power. As the WINDS system comprises an SS-TDMA system and as the transmission beam of the reference burst is switched every frame, an earth station can receive one reference burst per super frame.

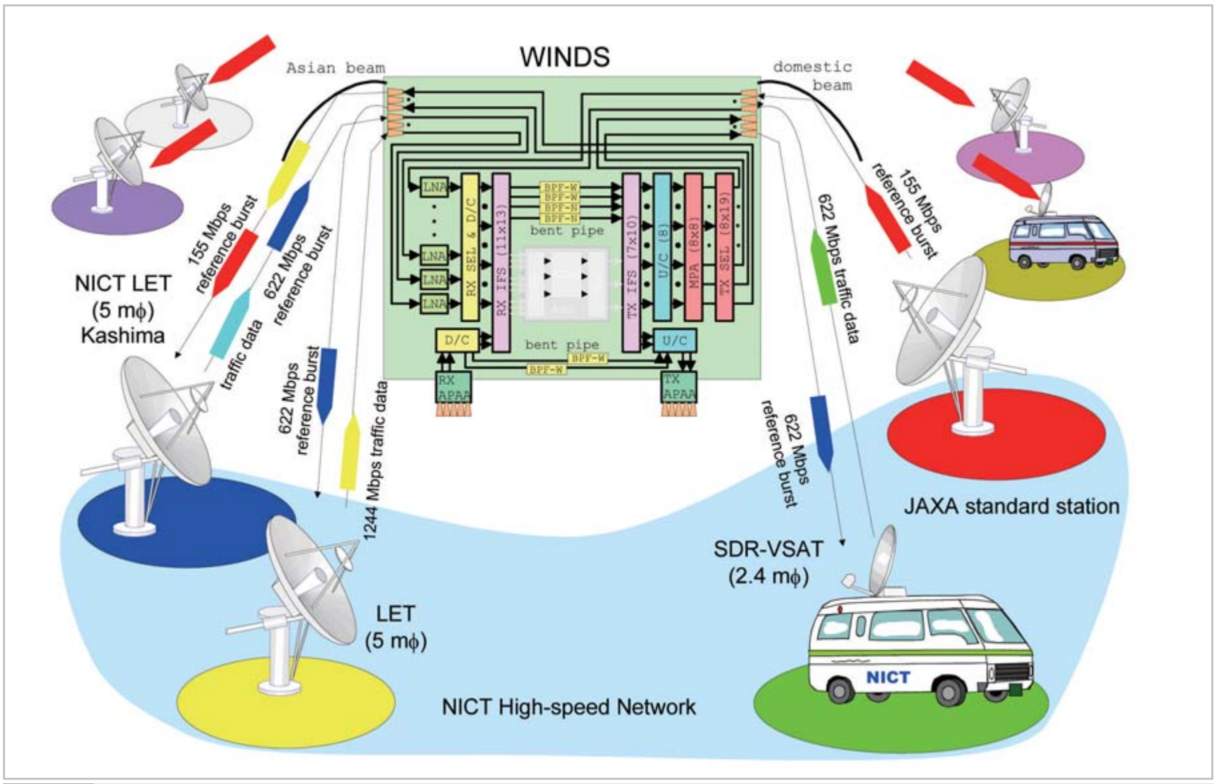

Fig.2 *Schematic diagram of high-speed network*

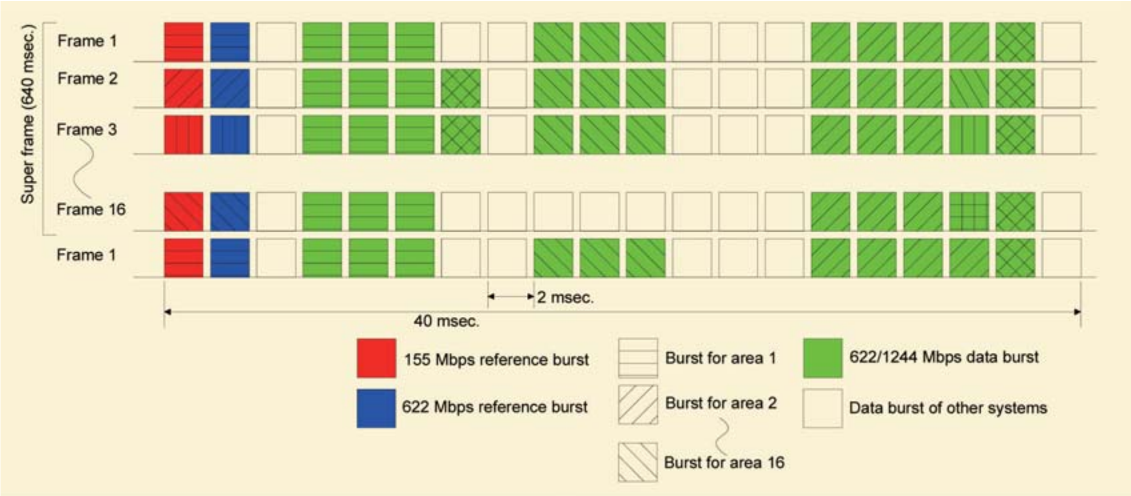

Fig.3 *Example of frame format*

The reference burst conveys the following information:

(1) Satellite orbit information
(2) Reference burst beam information
(3) Slot assignment information (for 6 channels)
(4) Emergency operation information

Table 1 shows the format of each type of information. The notification information is put together in a block as an item of bent-pipe notification information, and the content is stored under the sub-header attached to each item of information. Each earth station acquires the position of the reference burst slot from the reference burst beam information and determines the timing of burst transmission and reception based on the reception timing of the reference burst and the amount of delay calculated from satellite orbit information. The earth station refers to the slot assignment information and uses the slot assigned to the station as the transmission and reception slot. JAXA will compile the information on the frame format for the WINDS bent-pipe mode and the 155-Mbps reference burst and will distribute it to the participants in the experiments as an air interface specification sheet.

The high-speed network has been developed based on the bent-pipe mode air interface specification sheet. The network uses two types of reference bursts: a 155-Mbps reference burst transmitted from the JAXA standard station and a 622-Mbps reference burst unique to the high-speed network. The 622-Mbps reference burst is by default transmitted in the next slot to the 155-Mbps reference burst, directing the same beam. The notification information is also transmitted with the same information as the 155-Mbps reference burst and the additional message for the high-speed network.

Table 1 *Content of notification information*

Header of Bent Pipe Mode Announcement Information
Orbit Information and Urgent Message
RB Beam Information
BPM transmission path information (Block 1)
BPM transmission path information (Block 2)
BPM transmission path information (Block 3)
BPM transmission path information (Block 4)
BPM transmission path information (Block 5)
BPM transmission path information (Block 6)

Here it is noted that the WINDS development plan also defines a mode that mixes the regenerative and bent-pipe modes. In this case, the system uses three reference bursts: 155-Mbps (for regenerative mode), 155-Mbps (for bent-pipe mode), and 622 Mbps (for the high-speed network). To conduct multiple

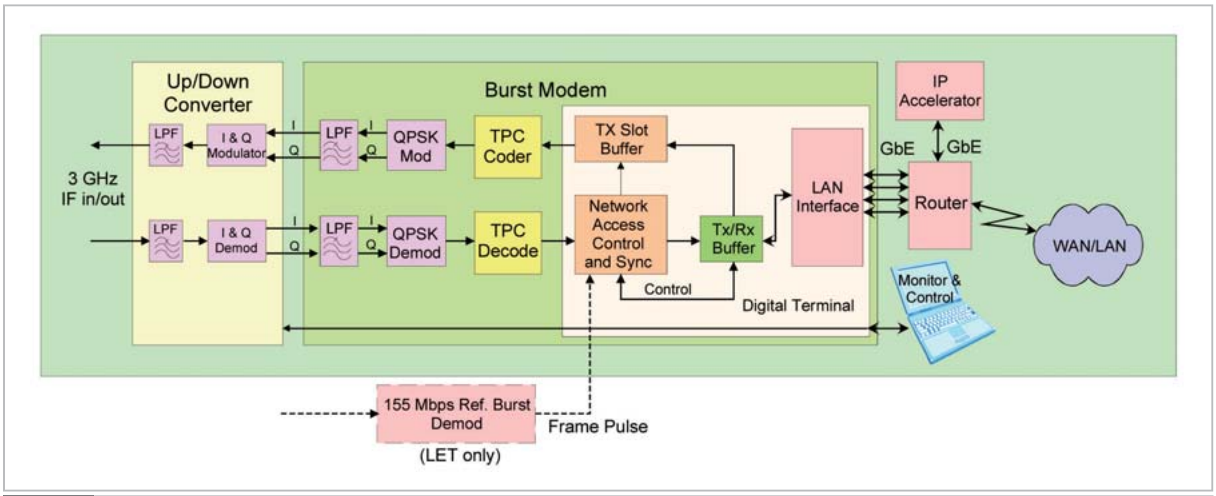

Fig.4 *Configuration of 622–Mbps/1,244–Mbps dual-rate high-speed burst modem*

experiments efficiently, multiple reference bursts are used. Consequently, throughput suffers. However, we expect that the system will be integrated in the stage of practical application and that the same reference burst will be used for all cases.

3 High-speed network terminal

The high-speed network terminal consists of the high-speed burst modem as the core component, as well as a digital terminal, a router, and a TCP accelerator, which are add-on devices. The Kashima earth station is also equipped with a 155-Mbps reference burst receiver.

Figure 4 shows the configuration of the 622-Mbps/1,244-Mbps dual-rate high-speed burst modem. Table 2 shows the specifications of the high-speed burst modem.

3.1 High-speed burst modem

When we began development of the high-speed burst modem, our aim was to arrive at 1,244-Mbps transmission using two sets of modems at a user data rate of 622 Mbps, due to the limitations of the digital analog converter capable of use in the 1,244-Mbps transmission modulator[3][4]. In parallel with the 622-Mbps modem, we developed a new digital analog converter, as this device represented the bottleneck in terms of transmission rate, resulting in the successful development of a high-speed MUX-DAC featuring a sample rate of 2 G-samples per second. We then modified the developed 622-Mbps modem[5]-[7] to a 622 Mbps/1,244 Mbps dual-rate high-speed burst modem. In this process, we modified the system such that a modulator/demodulator pair can transmit and receive signals at two user data rates: 622 Mbps and 1,244 Mbps. We also enabled the system to transmit and receive data while changing the frequency and the modulation rate by the slot. This development in turn allowed for use of the upper or lower frequencies of the WINDS transponder band in 622 Mbps transmission, and use of the central frequencies of the band in 1,244 Mbps transmission. In this modification, we developed a new modulator board with wiring modified to accommodate the high-speed MUX-DAC. Excluding the RF unit that handles three-frequency transmission and receiving, the system is established with modifications only in the FPGA programs of the modulator

Table 2 *Specifications of high-speed burst modem*

	622 Mbps/1244 Mbps Dual Rate	622 Mbps
IF Frequency	2726.4, 3000.0, 3273.6 MHz	2725.0, 3275.0 MHz
Modulation	QPSK	
Access Method	SS-TDMA	
User Data Rate	622/1244 Mbps	622 Mbps
Modulation Rate (before coding)	824/1648 Mbps (724.2/1448.4 Mbps)	824 Mbps (724.2 Mbps)
Forward Error Correction	Turbo Product Code, 4 bit soft decision	
Roll off	Root raised cosine, roll-off factor =0.35	
User Data Interface	Giga bit Ethernet, external router and TCP accelerator used	

and the demodulator. For the decoder, the only modification consists of the addition of a clock corresponding to 1,244-Mbps transmission.

The high-speed burst modem consists of the modulator, the demodulator, the RF unit, and the decoder. A digital terminal attached as an add-on device provides TDMA burst control as well as user data input and output.

The modulator, the demodulator, the decoder, and the digital terminal are each implemented on a 280 × 311 mm board, the standard size under the Advanced Telecom Computing Architecture (Advanced TCA), and are stored in an Advanced TCA case. The FPGAs used consist of the Virtex-2 and Virtex-4 series from Xilinx. As these FPGAs read in the program from the ROM, their functions can be modified by updating the ROM data. The 2-Gbps high-speed serial link of these FPGAs—referred to as the Rocket I/O Multi Gigabit Transceiver (MGT)—connects each section and each FPGA and exchanges the data. As the modulation rate is high—1,648 Mbps—each section uses extensive parallel processing to implement the required functions.

Figure 5 shows the boards of the modulator, the demodulator, the decoder, and the digital terminal, as well as the high-speed MUX-DAC.

3.1.1 Modulator

The modulator employs Quadrature Phase Shift Keying (QPSK) and can switch between two user data rates—622 Mbps and 1,244 Mbps—in each burst. Specifically, the device is a digital modulator consisting of FPGAs. Figure 6 shows a functional block diagram of the modulator. The device receives communication data from the digital terminal,

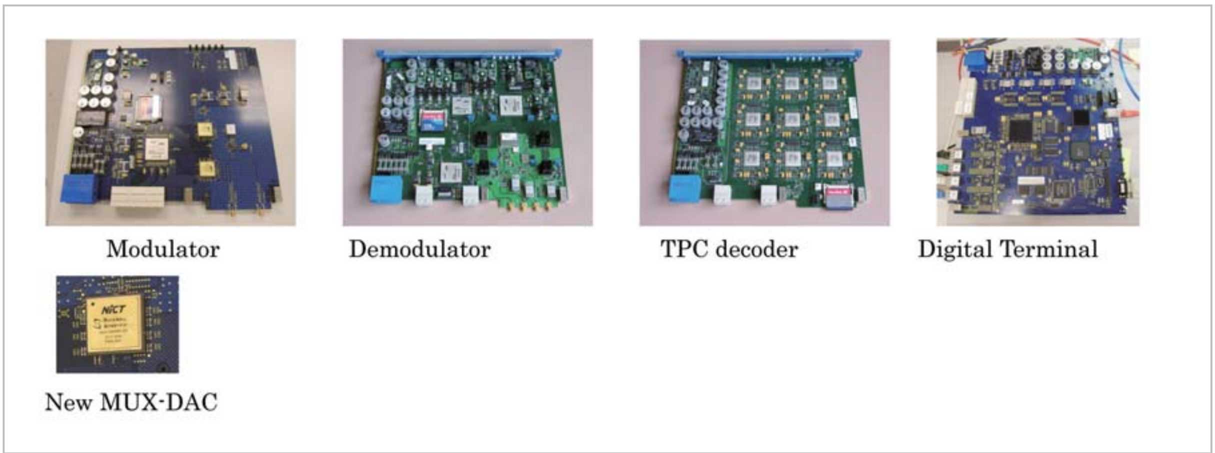

Fig.5 Boards of high-speed burst modem

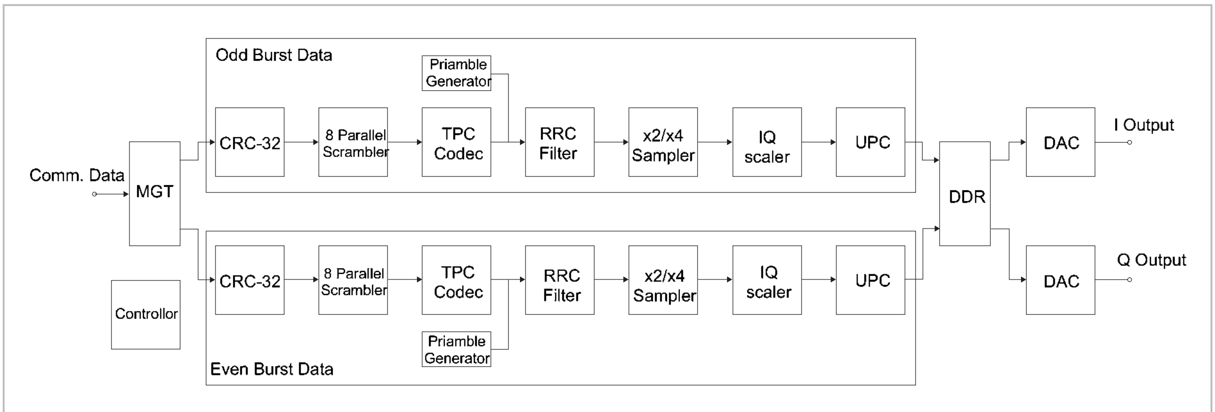

Fig.6 Functional block diagram of modulator

calculates CRC-32, scrambles the data with an 8-parallel scrambler, and converts the data into turbo product codes (TPC). When decoding, the modulator interleaves the data by changing the readout order from memory for turbo product coding, a method of two-dimensional coding. The data is attached with preamble data and reconfigured as transmission burst data. The data for 622-Mbps transmission are converted to quadruple-sample data and data for 1,244-Mbps transmission are converted to I and Q orthogonal signal data for the double-sample QPSK. The data for 622-Mbps transmission are frequency-offset from the baseband, in the form of digital signals, with the local oscillator signal provided by the NCO at plus or minus 273.6 MHz for the upper or lower frequencies of the transponder band. The data are then output through the band limiting filter, converted into analog signals by the high-speed MUX-DAC, and sent to the RF unit.

To provide user data rates of 622 Mbps or 1,244 Mbps, the modulation rates are set at 412 M-symbols per second (824 Mbps) and 824 M-symbols per second (1,648 Mbps), respectively, taking into account the time during which communication is not possible due to the reference burst and the guard time, as well as the additional bits required for the preamble and error correction.

The data section uses the coding unit of the TPC, 14,400/16,384 bits, as the block and consists of 192 blocks in 1,244-Mbps transmission and 96 blocks in 622-Mbps transmission. The CRC-32 data are included in the last block.

3.1.2 Demodulator

Similarly to the modulator, the demodulator employs Quadrature Phase Shift Keying (QPSK) and can switch between two user data rates, 622 Mbps and 1,244 Mbps, in burst units. The demodulator is also digital and also consists of FPGAs. Figure 7 shows a functional block diagram of the demodulator. The I and Q signals transmitted from the RF unit are sam-

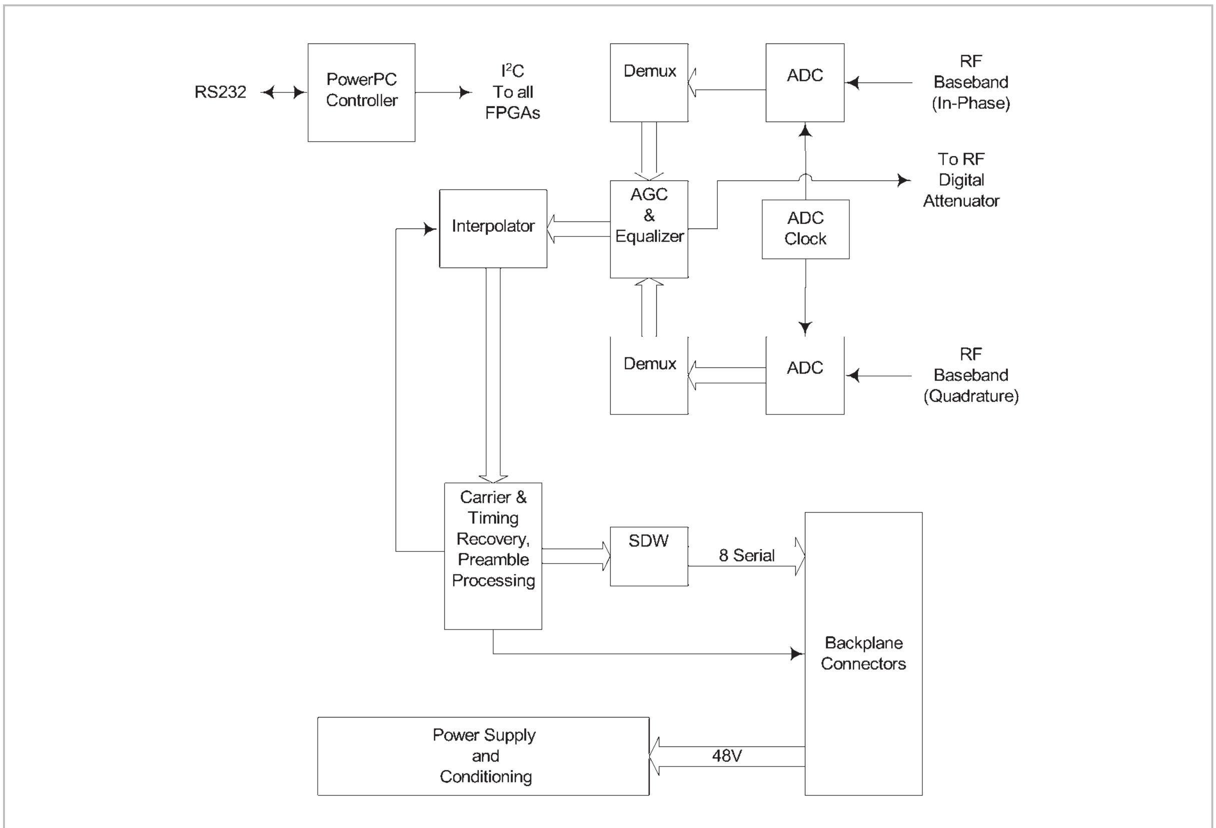

Fig.7 *Functional block diagram of demodulator*

pled by the 10-bit analog digital converter at a sampling rate of 1,648 M-samples per second. When the signal is received at 1,244 Mbps, there is no large frequency offset. However, when the signal is received at 622 Mbps, the sampling signal is shifted by ± 273.6 MHz, such that the signal is converted to the baseband using the NCO local oscillator signal and the digital mixer. The signal is then cut out by a root-raised cosine filter with a roll-off factor of 0.35. This filter operates quadruple sampling when the transmission rate is 622 Mbps and double sampling when the transmission rate is 1,244 Mbps. In this manner, it is possible to use the same circuit for the two rates. By modifying the characteristics of this filter, it is also possible to add line-equalizer operations. It is essential that a burst modem perform carrier recovery and clock recovery in the preamble section of the receiving signal, to ensure that the modem is instantly prepared for the data demodulation.

The preamble section contains 968 symbols (1,936 bits). The Barker correlator detects the burst and roughly adjusts the carrier and the clock. Carrier recovery and clock recovery are implemented by reverse modulation loops. Carrier recovery is performed by canceling frequency and phase errors using the NCO and is controlled based on the phase error in four symbols of the reverse modulation data as well as on the frequency offset information transmitted from the Barker correlator. In the standby state, the correlator uses a wideband loop filter. After locking, this device reduces the loop bandwidth to increase precision. Clock recovery is similarly controlled by setting the initial clock value based on the correlation period of the Barker correlator, obtaining the zero-cross point from eight samples of data, and averaging the error information using the second order filter.

The start data word in the preamble section is detected in the recovered data, and the communication data that follow are transmitted to the decoder.

3.1.3 RF unit

The RF unit converts and outputs the I and Q signals from the modulator to the 3,000-MHz-band IF signal using the quadrature modulator. The unit also converts the received 3,000-MHz band IF signal to the baseband using the quadrature modulator and transmits the converted signal to the demodulator.

In 1,244-Mbps transmission, the IQ signal does not have a frequency offset and is converted to a signal centered at 3,000 MHz with the 3,000-MHz local oscillator signal. In 622-Mbps transmission, the IQ signal has a frequency offset of ± 273.6 MHz, and thus is converted to a signal centering at 2,726.4 MHz or 3,273.6 MHz, respectively.

3.1.4 Turbo product code decoder

To process the 1,648 Mbps × 4 bit soft-decision data transmitted from the demodulator, parallel processing is employed with eight FPGAs to increase speed. After the data divided and processed in each FPGA are gathered in the collector, the data is deinterleaved, and the data is unscrambled. The data are then subject to error checking by the CRC-32 and are output.

The turbo product code used is a two-dimensional code with 8 bits of error code added to the 120 bits of data, as shown in Fig. 8. This code is expressed as $(128, 120)^2$. The encoding ratio is $120^2/128^2$, or 0.879.

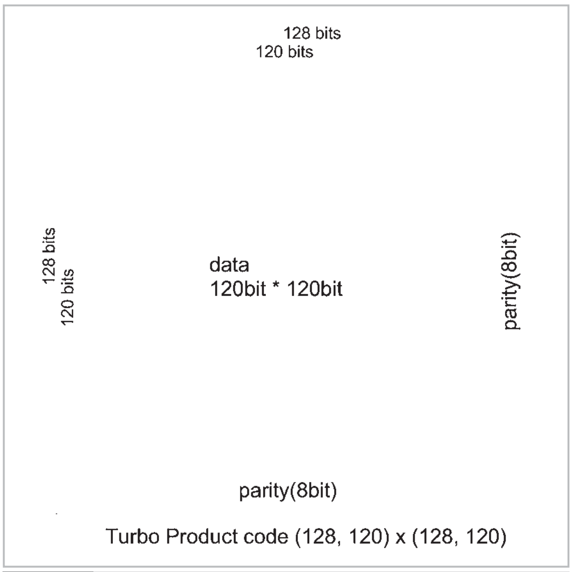

Fig.8 Structure of turbo product code

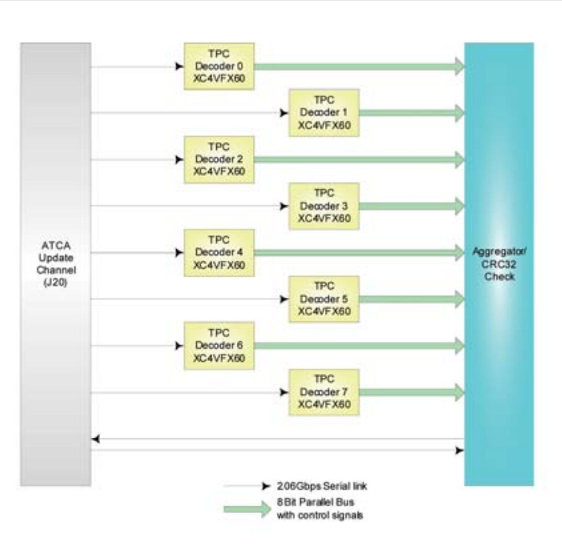

Fig.9 Configuration of turbo product code decoder

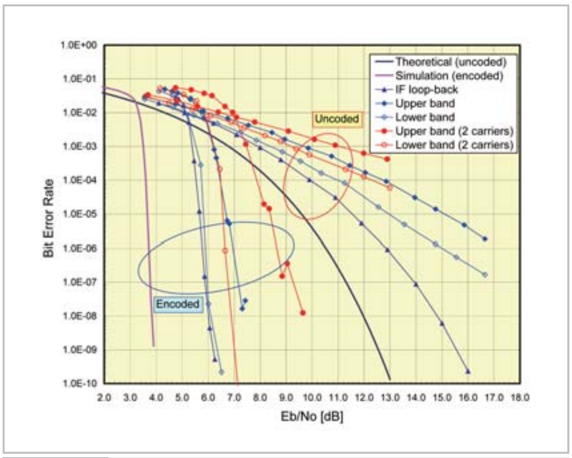

Fig.10 Results of mission combination test

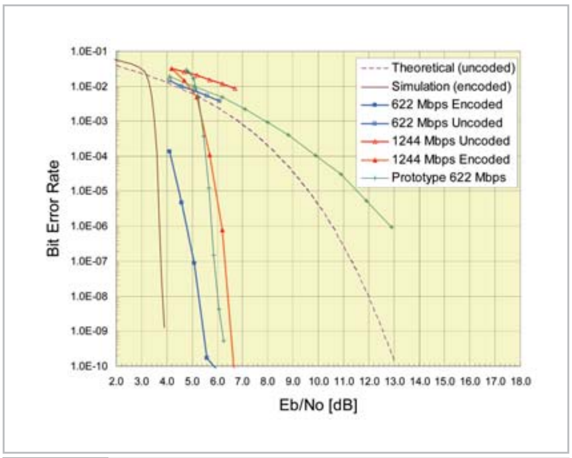

Fig.11 Stand-alone characteristics of 622–Mbps/1,244–Mbps dual-rate high-speed burst modem

3.1.5 Test results for high-speed burst modem

In the fall of 2006, we performed an integrated test using the 622-Mbps high-speed burst modem, combining the WINDS satellite mission system and the earth station RF unit[8]. Figure 10 shows the results of the test. The BER characteristics after error correction at a BER of 10^{-10} are degraded by approximately 2 dB compared with the simulation results in the IF loop-back and in the earth station loop-back. The degradation by the satellite link is 1 dB to 3 dB relative to the values of the earth station loop-back, and the E_b/N_0 is 10 dB or less. When we compare the upper and lower frequency bands, signal degradation in the upper frequency band is larger, particularly with two-carrier transmission. This phenomenon is considered to be due to the band limiting at the upper edge of the transponder frequency band, which is performed in order to avoid disturbing the network information link; this link serves as the mission telemetry in the Ka band. The IF connection unit (IF patch) in the earth station features an amplitude equalizer, and this equalizing adjustment is expected to improve the situation. However, given the multiple routes in the onboard transponder, we need to consider other solutions—for example, adjustment of settings to average characteristics.

Figure 11 shows the BER characteristics of the stand-alone 622-Mbps/1,244-Mbps dual-rate high-speed burst modem. In 622-Mbps transmission, the error rate is approximately the same as the error rate of the 622-Mbps high-speed burst modem. In 1,244-Mbps transmission, slight degradation is noted, but the E_b/N_0 for acquiring a BER of 10^{-10} is 7 dB or less.

3.2 Digital terminal

The digital terminal provides the burst, communication control, and the user data interface, as an add-on device of the high-speed burst modem.

3.2.1 Hardware

Figure 12 shows a functional block diagram of the digital terminal. The terminal is connected to a router with four GbE interfaces and then connected to network devices such as servers, which serve as the external experimental devices. The communication data from GbE are stored in a buffer memory and transmitted to the MGT toward the modulator under the control of the CPU. The reception data transmitted from the MGT is sent to the GbE interface for each source station. The digital terminal is connected to the controller PC by a 100 BASE-T or RS232C interface and can be controlled by a Web browser or via Telnet.

As the Kashima earth station receives the notification information from the receiver of the 155-Mbps reference burst transmitted from the JAXA standard station, the digital terminal is connected with the 100 BASE-T interface. The Kashima station is also equipped with an interface to receive the frame synchronization signal at an electrical signal level in compliance with RS422. The digital terminal also constructs and transmits the 622-Mbps reference burst.

3.2.2 Software

The digital terminal provides the control functions listed below.

(1) Sends communication data from the four GbE interfaces to the burst for each destination station

(2) Sends communication data from the destination station to the GbE interface assigned to each station

(3) Receives the reference burst and extracts the notification information

(4) Calculates the distance to the satellite from the satellite position information

(5) Synchronizes the frame timing based on the beam information

(6) Calculates the position of the transmission and receiving bursts from the slot assignment information and configures the GbE interfaces with the destination stations

(7) Transmits and receives the burst data to and from the MGT interface in synchro-

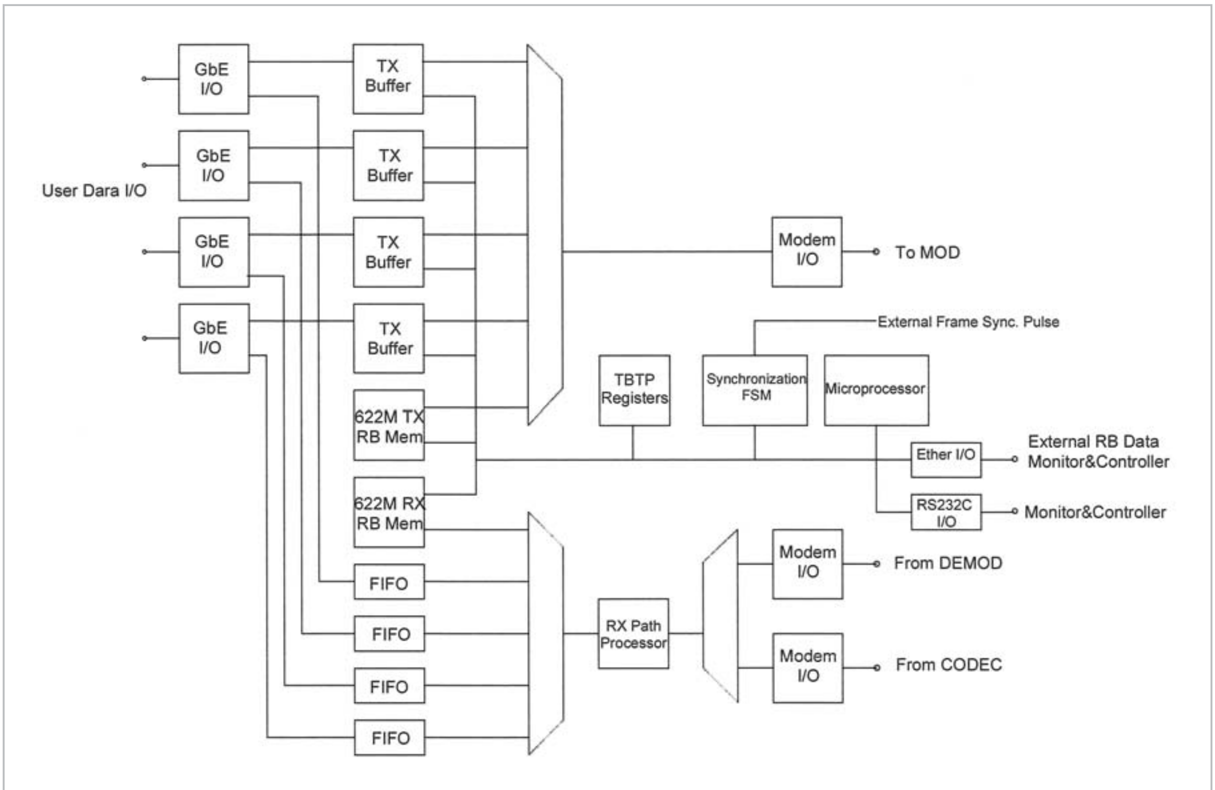

Fig.12 Functional block diagram of digital terminal

nization with the transmission and reception timing

(8) Reads in the notification information from the 155-Mbps reference burst receiver and creates and transmits the 622-Mbps reference burst (Kashima earth station only)

(9) Receives the frame synchronization signal from the 155-Mbps reference burst receiver and performs synchronization (Kashima earth station only)

These functions can be monitored and controlled with a Web browser. It is also possible to perform experiments with modified data.

Telnet control is also supported. Test modes such as self synchronization operation and continuous burst transmission are also available.

3.3 155-Mbps reference burst receiver

The 155-Mbps reference burst receiver is installed only in the Kashima earth station. The device receives the 155-Mbps reference burst transmitted from the JAXA standard station and recovers the frame synchronization signal and the notification information. The frame synchronization signal and the notification information are then sent to the high-speed burst modem.

The 155-Mbps reference burst receiver is equipped with devices equivalent to the 155-Mbps burst demodulator developed by JAXA for the standard station, and is used as the receiver for the 155-Mbps reference burst in bent-pipe mode. A frequency converter is installed to convert the IF frequency of 3,280 MHz, used by the earth stations to receive the 155-Mbps reference burst, to 814 MHz, the input frequency of the demodulator.

The frame synchronization signal, which determines the burst transmission position, is transmitted through the RS422 interface, and the notification information (including slot assignment) that is transmitted by the reference burst, is transmitted through the Ethernet link to the digital terminal.

3.4 Other components

The high-speed network terminal is equipped with a 4-port gigabit Ethernet for the user data interface. Each of the four ports is connected to the port of the destination earth station through the satellite link. Accordingly, one of the four ports is selected with a router according to the communication destination, the earth station. The router monitors the traffic of the links and controls this traffic to ensure that it does not exceed the assigned link capacity.

TCP/IP transfers data in units of the specified window size to guarantee that the data are transmitted correctly upon reception of the response. However, a satellite link requires approximately 500 ms for the response to return, so the window size determines the upper limit of throughput in a broadband connection. The throughput is calculated using the following equation:

Throughput [bit/sec] = window size [bit] / response time [ms].

Assuming a window size of 64 kB, a common value in personal computers, throughput is calculated as

65,535 × 8 [bit] / 500 [ms] = 1,048,560 [bit/sec].

This value indicates that throughput will not exceed 10.5 % even in a10-Mbps satellite link. As the WINDS high-speed network provides 1,944 kbps in a single slot in 622-Mbps transmission, we cannot obtain throughput of 54 % or larger.

We can increase throughput by increasing the window size. However, this size must be supported by all devices communicating via TCP, and required system memory is proportional to window size. Consequently, window size cannot be exceedingly large.

File sharing based on the server message block (SMB) protocol used in many intranets uses a shorter transfer size, and increasing the TCP window size does not improve the results. Thus it is effective to terminate the input and output of the high-speed network terminal with a TCP accelerator / PEP (Performance Enhancing Proxy) supporting TCP and representative applications, and to use different window sizes and protocols for the satellite link and the Ethernet.

The functions of the TCP accelerator are as set forth below.

(1) Alternative protocol for satellite link (For example, SkyX-XTP and SCPS)
(2) Optimization of TCP window size
(3) Termination of TCP
(4) Termination of file sharing protocol
(5) Data compression
(6) Buffering
(7) SSL termination

Combining these functions can improve throughput. Some TCP accelerators offer additional security by encoding the information in the satellite link.

Based on the currently available level of increased security, encoded packets such as IPsec, the use of which is spreading in VPN and other applications, involves encoding of the entire packet (including the contents of the packet and the header). Such packets are difficult to handle the using TCP accelerators. In these applications, the user must handle satellite link delay at the application level-for example, through the use of the UDP.

In a high-speed satellite link, countermeasures against delay are indispensable. It will therefore be necessary to incorporate the TCP accelerator function and the router function into the high-speed burst modem for use in practical applications.

4 Conclusions

We have developed a high-speed burst modem and a digital terminal as devices constituting a high-speed network terminal, and will use the 155-Mbps reference burst receiver developed by JAXA for the standard station. We investigated the router and the TCP accelerator and found that commercially available products are suitable for use. As a result, we have now established the possibility of procuring all component devices.

In terms of 622-Mbps transmission, we performed combination tests in November 2006 with the prototype high-speed burst modem by combining the WINDS satellite and the earth station. We obtained satisfactory results with a BER of 10^{-10} at an Eb/N_0 of 10 dB or less. We plan to perform a combination test for the 622 Mbps/1,244 Mbps dual-rate burst modem with the WINDS satellite in the fall of 2007.

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