3-2 Experiment Report for Rain Attenuation Compensation

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Satellite communication in the K_a band (a microwave band of a frequency range from 27 to 40 GHz) is effective in conserving limited satellite frequency resources, and for providing wide-band and high-speed satellite services. However, rain degradation in the K_a band is larger than in the C/Ku-band. A rain degradation compensation technique would be effective to increase satellite link availability under rain conditions. This report provides the effectiveness of rain degradation compensation by an experiment using the WINDS satellite.

In addition, the correlation between rain attenuation and rain rate, rain attenuation and rain attenuation rate are provided coming from the K_a band rain attenuation measurements.

1 Introduction

K_a band rain attenuation compensation experiments were conducted on a regenerative link [1] using the WINDS on-board asynchronous transfer mode baseband switch (ABS), and its validity was confirmed. This paper reports its experimental results. In addition, the rain attenuation characteristics of the TDMA reference burst (RB) signal in the K_a band for the WINDS on-board regenerative link and the rain attenuation characteristics of the WINDS network information signal residual carrier were measured. The correlation between the rain attenuation and the rainfall, and the correlation between the rain attenuation and the change rate in rain attenuation were obtained. These results were also reported [2].

The WINDS regenerative link uses 1.5 M/6 M/24 M/51 M mode TDMA for its uplink, and 155 M mode TDMA for its downlink [1]. Both a fixed multi-beam antenna (MBA) and an active-phased array antenna (APAA) were used for the experiments. As the regenerative link privies mutually independent satellite link for downlink and uplink, because the on-board function performs processing of demodulation, exchange, and modulation, the rain attenuation compensation experiments were able to be conducted separately for the uplink and the downlink.

A 1 m portable earth station, a 1.2 m antenna very-small-aperture terminal (VSAT), and a 2.4 m antenna VSAT were used for MBA experiments, and a 1.8 m antenna VSAT, and a 2.4 m antenna VSAT were used for APAA experiments. In addition, the 4.8 m antenna Kashima large earth station was used for both MBA and for APAA experiments. The final stage power amplifiers used in the experiments were respectively a 40W solid state power amplifier (SSPA), a 75 W traveling wave tube amplifier (TWTA), and a 250 W TWTA.

The necessary rain attenuation compensation depends on the antenna size and/or the final stage output power. In this article, as the standards, the compensation amount of the case of 1.2 m antenna/40 W SSPA VSAT for MBA, and the compensation amount of the case of 2.4 m antenna/250 W TWTA VSAT for APAA are reported. Note that for a larger size earth station antenna and/or a larger power of transmitter final stage amplifier, the necessary rain attenuation compensation value becomes larger depending on the characteristics of the antenna and/or the amplifier.

Also note: in the MBA experiments reported here, the Kanto Beam is used at an earth station placed in Kashima, so the WINDS satellite performance value under the above geographic conditions was approximately 3.5 dB lower in uplink satellite performance index (G/T) than the beam center value, and approximately 1.5 dB lower in the downlink Effective Isotropic Radiated Power (EIRP). On the other hand, with regard to the experiments using APAA, because the beam is directed to Kashima, there is no such performance grade-down in satellite characteristics.

Figure 1 shows the outdoor equipment of the 1.2 m VSAT and the 1 m portable earth station for MBA experiments, and the 2.4 m VSAT and the large earth station for APAA experiments.

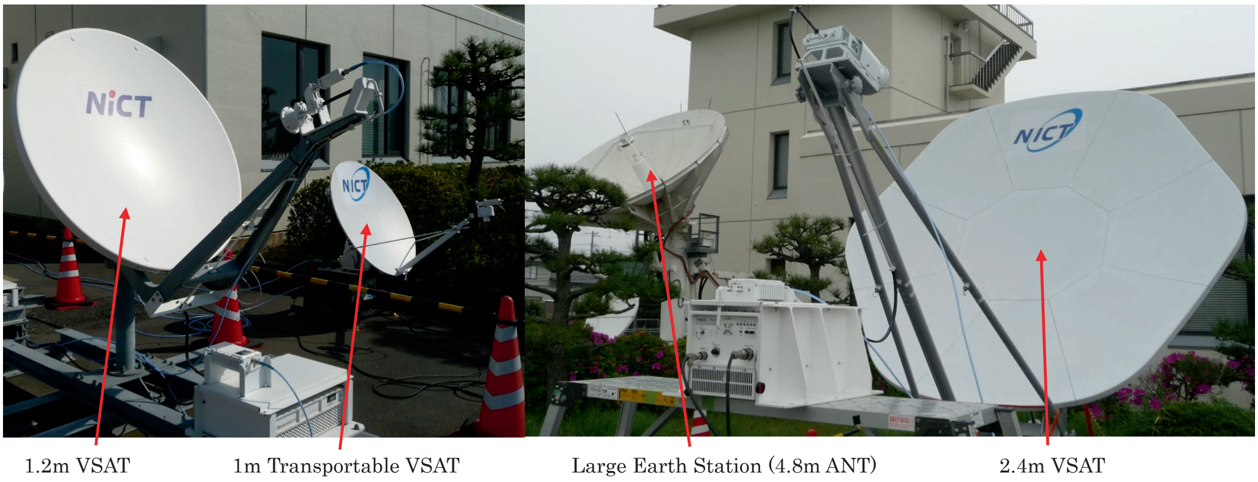


Fig. 1 Outdoor equipment for experiment of regenerative link rain attenuation compensation

2 Uplink rain attenuation compensation

Uplink rain attenuation compensation is accomplished in the following two different ways: controlling the final stage amplifier radiation power of the transmitting earth station, so-called Uplink Power Control (UPC); and controlling the required EIRP of the transmitting earth station through alternating the uplink transmission mode.

2.1 Rain attenuation compensation by uplink power control (UPC)

UPC is widely used for rain attenuation compensation in satellite communications; among UPC methods, such a method is well-known that uses, as a standard signal, the beacon signals of a satellite or the pilot signals transmitted from hub stations or standard stations.

The regenerative link TDMA reference signal is used as a reference for the UPC in the WINDS regenerative link rain attenuation compensation method, because the regenerative link TDMA burst signals are radiated with constant power. The regenerative link earth station indoor unit (IDU) estimates the reception C/N_0 using the strength of the received reference burst signal and the strength of guard-time noise, calculating the C/N_0 margin—difference between the estimated C/N_0 and the predefined value of Downlink C/N_0 limit. The IDU, when the C/N_0 margin is lower than the clear sky margin, raises the transmission power to compensate for the rain attenuation [1]. The IDU has parameters for controlling UPC operations, including THR rain fade (K1/K2), Coefficient (K1) and Coefficient (K2), raising the transmission power by the rate of those coefficients against the loss of C/N_0 margin. Those coefficients are the ratios of 28 GHz band transmission power gains to the losses in 18 GHz reception C/N_0, and THR rain fade (K1/K2) specifies the thresholds for alternating those coefficients—for example, under the setting of THR rain fade (K1/K2) to 5, K1 to 1, and K2 to 2, the transmission power is increased as follows: until the C/N_0 loss reaches 5 dB, the transmission power is increased by the amount of C/N_0 margin loss; when the loss goes beyond 5 dB, the transmission power is increased by twice the amount of C/N_0 loss. Figure 2 show such transition in transmission power.

Note that the VSAT EIRP will not grow limitlessly along with the increase in the transmission power—the input-output characteristics and saturation output power of the VSAT Final power amplifier limit the VSAT EIRP.

The abovementioned UPC operation was tested by simulating rain attenuation where shield boards made of

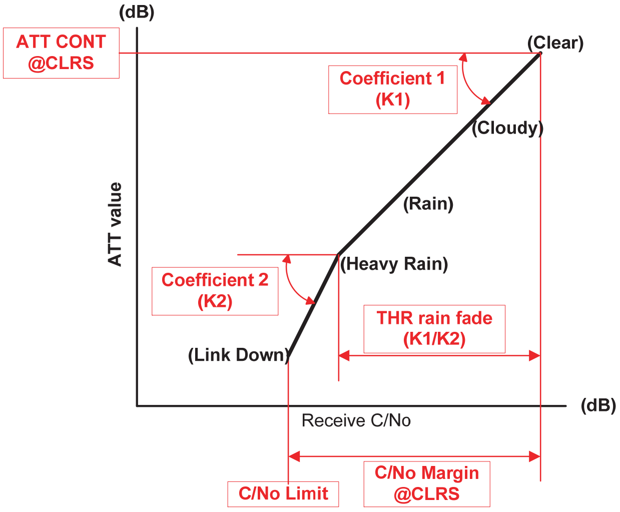


Fig. 2 Rain attenuation compensation scheme in WINDS regenerative link IDU

sheets of carbon fluid (black writing fluid) applied to sheets of paper were used—the amount of attenuation is adjustable by changing the density of the applied carbon fluid. The method causes wave absorption in two directions—transmission and reception. So, two-way rain attenuation—uplink and downlink—is simulated at one time. In addition, with this method, downlink rain margin losses are simulated very closely to actual situations because both rain attenuation and reception system noise temperature increase, simultaneously. However, note that, because such a shield board absorbs waves in a very short distance, the attenuation amount for the reception band (18 GHz band) is almost equal to the amount for the transmission (28 GHz band)—in such a sense, simulated situations by shield boards are different from actual situations.

Figure 3 shows the simulation arrangement where a shield board is attached to a 1.2 m VSAT horn, and an example of a shield board.

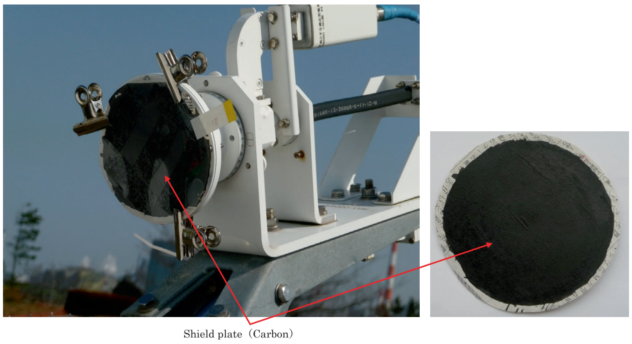


Fig. 3 Experimental arrangement in which a shield board is attached to a 1.2 m VSAT horn

Figures 4 and 5 show the results of UPC operation tests conducted using a 1.2 m antenna and a 40 W SSPA VSAT. Figure 4 shows how the UPC operations in 6 M mode were verified to work, where IDU's parameters were set as follows:

C/N_0 limit = 83 dB;

C/N_0 margin @CLRS = 23 dB

(Note: C/N_0 margin @ CLRS is not directly settable. Instead, set ATT CONT @ CLRS to 29 dB, which is the value for the satellite link establishment request signal form an earth station for 1.5 M mode. So, when 6 M mode is used, the effect is deduced by the difference of 6 M to 1.5 M—6 dB, the ratio of 6 M to 1.5 M—, and C/N_0 margin is adjusted to 23 dB.);

THR rain fade (K1/K2) = 7:

Coefficient (K1) = 0;

Coefficient (K2) = 1.

Note that estimated EIRP (e/w UPC) and estimated EIRP (w/o UPC) are the estimated EIRP of 1.2 m VSAT with UPC and that without UPC, respectively. Such EIRPs were obtained on the assumption that the uplink loss is equal to the loss in the downlink reference burst signal level. Also, packet loss (e/w UPC) and packet loss (w/o UPC) is respectively the packet loss for the data sent from 1.2 m VSAT to the target station in the cases of with UPC and without UPC. Those settings of parameters indicate the following for the UPC operation: the UPC is not in operation until the reception C/N_0 goes down to 7 dB from 116 dB, the sum of C/N_0 limit of 93 dB and C/N_0 margin @ CLRS of 23 dB,—this means that Estimated EIRP (e/w UPC) and Estimated EIRP (w/o UPC) have the same value; when C/N_0 goes down below the point, IDU transmission power goes up in the case of "with UPC," for compensating the uplink rain attenuation. However, in the case of "without UPC," because IDU transmission power stays at a constant level even when the C/N_0 goes down, the estimated EIRP decreases along with the decline in C/N_0, and

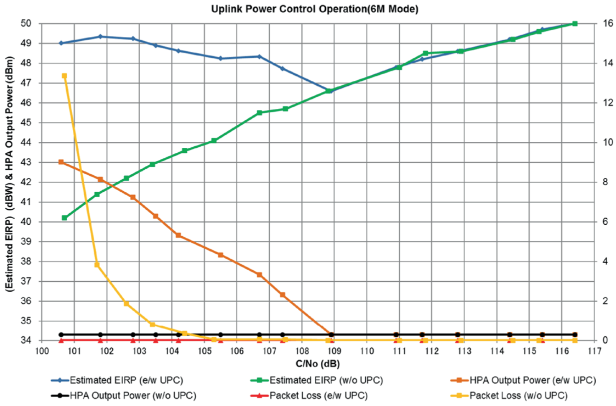


Fig. 4 Verification of UPC operation (6 M mode)

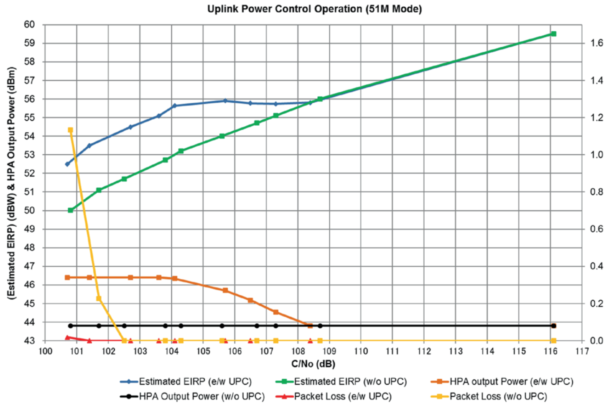


Fig. 5 Verification of UPC operation (51 M mode)

consequently, as Packet Loss (w/o UPC) indicates, packet losses are inevitable when the C/N$_0$ is below the level of around 105 dB. HPA Output Power (e/w UPC) and HPA Output Power (w/o UPC) are respectively the output power of 1.2 m VSAT HPA output power with UPC and that without UPC. At the C/N$_0$ level below 109 dB, in the case of "with UPC," the HPA output power goes up as the C/N$_0$ goes down; this indicates that UPC works normally. Figure 5 shows the UPC operation in 51 M using the same parameter settings as mentioned above. Figure 5 shows that, in 51 M mode, VSAT EIRP does not go up in the C/N$_0$ region of the level below 104 dB even with UPC due to the saturation of 40 W SSPA; consequently, even in the case of with UPC, the estimated EIRP shown in Estimated EIRP (e/w UPC) goes down in the C/N$_0$ region below the level of 104 dB, with packet losses occurring.

Figures 4 and 5 suggest that the effective work of UPC as designed is well verified.

For the validity verification of the assumption that the estimated EIRP uplink attenuation is equivalent to the decrease in the downlink reference burst received signal, the packet loss characteristics are compared with both cases, one uses shield boards to simulate the decrease in VSAT EIRP, and the other lowers the IDU output power to lower the VSAT EIRP. Figure 6 shows the results of the two different methods' measurements.

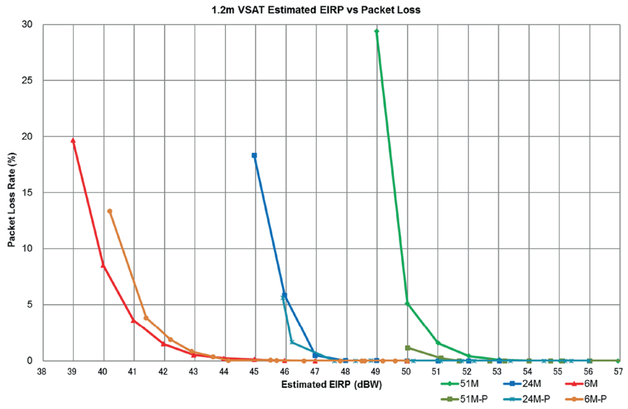


Fig. 6 Validity verification of uplink attenuation using shield boards

In Figure 6, the cases denoted by "51M," "24M," or "6M" are the cases where VSAT EIRP is lowered by adjusting IDU output power, and the cases denoted by "51M-P," "24M-P," or "6M-P" are the cases where VSAT EIRP is lowered by applying shield boards. The correlation of estimated EIRP and packet loss is almost equivalent for different operation modes; this means that the abovementioned experiment method is verified as appropriate.

Note that in this measurement, experiment-dedicated special IDU operation parameters were applied because the amount of attenuation due to the insertion of shield boards is almost equivalent for the reception frequency band and the transmission frequency band. Therefore, in the actual situations, because the uplink rain attenuation is approximately twice larger than the attenuation of downlink, THR rain fade (K1/K2), Coefficient (K1), and Coefficient (K2) shall be determined taking account of such difference in attenuation amount.

2.2 Rain attenuation compensation by altering uplink transmission mode

In the WINDS regenerative link, the following uplink transmission modes of TDMA are used: 1.5 M, 6 M, 24 M, and 51 M. According to the communication link critical design review report (CDR) of June 2006, the C/N$_0$ required for the abovementioned modes are respectively 73.6, 79.7, 85.7, and 88.6 dB/Hz. For instance, in the case where 51 M Mode TDMA is used on a clear day, the communication link can be kept available in rain by degrading the transmission mode, even if the available transmission speed or quantity can go down. Theoretically, the attainable rain attenuation compensation is 15.1 dB—this corresponds to 88.7 dB minus 73.6 dB.

Figure 7 shows the earth station estimated EIRP versus packet loss measurements conducted in the Kanto MBA using 1.2 m VSAT, where the earth station estimated EIRP is obtained by conversion using the earth station estimated EIRP diagram.

The measurements reveal the following: in 51 M mode, due to less performance of the re-constructer, packet loss

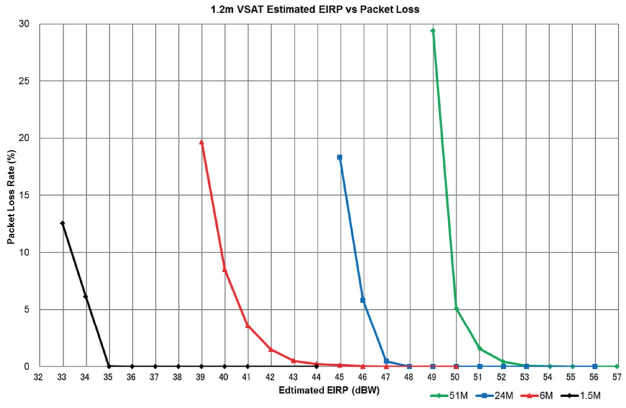


Fig. 7 Packet loss rates versus earth station estimated EIRP (MBA)

occurs earlier than expected; in 1.5 M mode, the re-constructor seems to have better performance, and attains performance of 1 dB error than the 15.1 dB theoretically expected.

The 1.2 m VSAT earth station estimated EIRP was verified by comparing between the 1 m portable VSAT estimated EIRP. Figure 8 shows the verification results, where each of the transmission modes has almost identical packet loss versus estimated EIRP to each other; it means that the earth station estimated EIRPs are appropriately obtained.

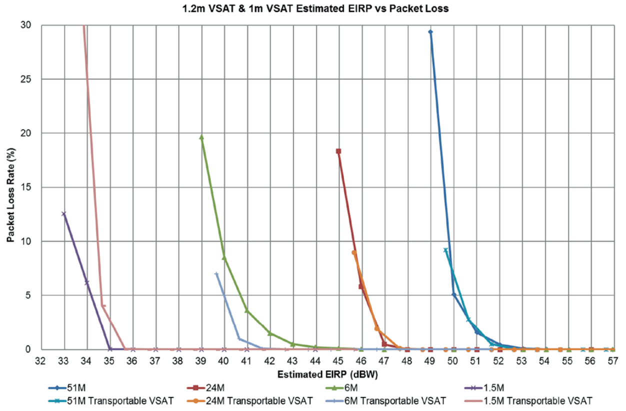
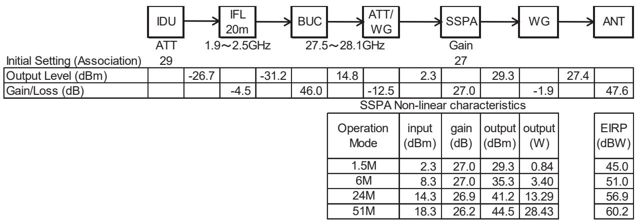


Fig. 8 1.2 m VSAT/1m portable VSAT estimated EIRP versus packet loss rates (MBA)

Figure 9 and Table 1 show the 1.2 m VSAT standard level diagram for the case where only MBA Kanto 1 beam is used and the satellite output power is 280 W.

Figure 10 shows the packet loss versus earth station estimated EIRP—converted by using an earth station level diagram—in the case of using APAA and 2.4 m VSAT by the same method as that used for MBA. By comparing two characteristics between of APAA (Fig. 10) and MBA (Fig. 7), the packet loss versus earth station estimated EIRP characteristics of the APAA is very close to the MBA with a shift of about 11 dB. This shift matches the G/T difference of APAA and MBA. Such a difference naturally occurs because the re-constructer in the WINDS onboard baseband switch (ABS) is commonly used for APAA and MBA.



	IDU		IFL 20m		BUC		ATT/WG		SSPA		WG		ANT
Initial Setting (Association)	29								27				
Output Level (dBm)		-26.7		-31.2		14.8		2.3		29.3		27.4	
Gain/Loss (dB)			-4.5		46.0		-12.5		27.0		-1.9		47.6

SSPA Non-linear characteristics

Operation Mode	input (dBm)	gain (dB)	output (dBm)	output (W)	EIRP (dBW)
1.5M	2.3	27.0	29.3	0.84	45.0
6M	8.3	27.0	35.3	3.40	51.0
24M	14.3	26.9	41.2	13.29	56.9
51M	18.3	26.2	44.5	28.43	60.2

Fig. 9 1.2 m VSAT standard level diagram (MBA)

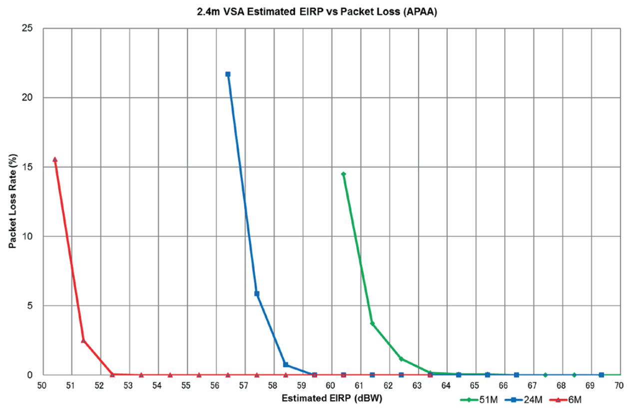


Fig. 10 Earth station estimated EIRP versus packet loss rates (APAA)

As the uplink rain compensation conclusion, both the compensation by UPC and the compensation by transmission mode alteration work ware successfully verified almost as well as the theory predicted. In addition, when both methods are used for uplink rain attenuation compensation in MBA, the maximum compensation of 26.7 dB is obtained by the difference between the VSAT maximum EIRP 61.7 dBW and 35 dBW which is the EIRP for MBA just before packet loss emergence as shown in Fig. 7. On the other hand, for APAA, 31.2 dB compensation is obtained, by the difference between 2.4 m VSAT with a higher saturation output power HPA EIRP 77.2 dBW and 46 dBW which is approximately 11 dB shifted from 35 dBW of 1.5 M mode MBA packet loss start estimated EIRP.

3 Downlink rain attenuation compensation

The mode 155 M is solely used for the WINDS regenerative link signal transmission. WINDS has an 8-port multiport amplifier (MPA) on board to simultaneously provide eight regions, domestic or international, with fixed communication links. The output power of each port is independently adjustable; however, the total output power of the eight ports is limited to 280 W. The standard station performs its downlink rain attenuation compensation by adjusting each port's MBA output power within the range of surplus power using the data obtained through the statistically processing of the reference burst signal's C/N_0 margin which is periodically transmitted from a VSAT existing in the service area to standard stations [4]. Note that the satellite MBA EIRP depends on the number of spot beams, for example, with regard to Kanto Beam 1 beam having power of 72.6 dBW, the C/N₀ margin, as shown in Table 1, is 20.8 dB when received by a 1.2 m VSAT on a clear sky. Also, the number of MBA spot beams, although depending on how many service areas the satellite covers, is eight at maximum; this means that, if it is assumed simply that an identical volume of power is supplied to each of the eight beams, the 1.2 m VSAT reception margin on a clear day is 11.3 dB. Also, Table 2 shows another example of downlink satellite link design in an 8-beam operation, where the whole surplus power is allocated to an area under heavy rain and the other areas are under a weather condition that allows applying 6 dB rain margin power.

Table 1 Communication link design example (clear day, MBA Kanto Beam)

		MBA Kantou Beam					Remarks
		1.5M	6M	24M	51M	155M	
Uplink Frequency	GHz	28.05	28.05	28.05	28.05		
Earth Station Transmission							
Output Power	W	0.85	3.39	13.18	28.18		
	dBm	29.3	35.3	41.2	44.5		
Feed Loss	dB	-1.9	-1.9	-1.9	-1.9		
Antenna Gain	dBi	47.6	47.6	47.6	47.6		1.2m ANT
EIRP	dBW	45.0	51.0	56.9	60.2		
Pointing Error	dB	-0.5	-0.5	-0.5	-0.5		
Propagation							
Free Space Loss	dB	-212.7	-212.7	-212.7	-212.7		
Atmospheric Absorption	dB	-0.3	-0.3	-0.3	-0.3		
Rain Attenuation	dB	0.0	0.0	0.0	0.0		
Satellite							
G/T	dB/K	20.3	20.3	20.3	20.3		
Uplink C/No	dB	80.4	86.4	92.3	95.6		
Output Power	W					280.0	
Feed Loss	dB					-1.0	
Antenna Gain	dBi					49.1	
EIRP	dBW					72.6	
Downlink Frequency	GHz					18.25	
Propagation							
Free Space Loss	dB					-208.9	
Atmospheric Absorption	dB					-0.2	
Rain Degradation	dB					0.0	
Earth Station Reception							
Pointing Error	dB					-0.5	
G/T	dB/K					23.1	1.2m ANT
Downlink C/No	dB					114.7	
Modulation Speed	Mbps	2.3125	9.25	37	74.0	203.5	
Symbol Rate	Msps	1.15625	4.625	18.5	37.0	101.75	
User Data Rate	Mbps	1.536	6.144	24	51.8	155.52	
Required C/No	dB	73.6	79.7	85.7	88.7	93.9	
C/N Margin	dB	6.8	6.7	6.6	6.9	20.8	

Table 2 An example of satellite link design during downlink rain attenuation compensation

Regenerative Downlink		Clear Area	Heavy Rain Area
Satellite Transmission			
Output Power	W	10.0	210.0
Feed Loss	dB	-1.0	-1.0
Antenna Gain	dBi	49.1	49.1
EIRP	dBW	58.1	71.3
Propagation			
Free Space Loss	dB	-208.9	-208.9
Atmospheric Absorption	dB	-0.2	-0.2
Rain Attenuation	dB	0.0	-19.0
Earth Station Reception			
Pointing Error	dB	-0.5	-0.5
G/T	dB/K	23.1	23.1
Downlink C/No	dB	100.2	94.4
Modulation Speed	Mbps	203.5	203.5
Symbol Rate	Msps	101.75	101.75
User Data Rate	Mbps	155.52	155.52
Required C/No	dB	93.9	93.9
C/N Margin	dB	6.3	0.5

Table 2 is a very simple example because the actual situations, satellite antenna gains are different from area to area and also all VSAT do not use over 1.2 m antennas. However, the rain attenuation compensation of about 19 dB is actually applicable to the area under heavy rain. It also should be noted that the compensation 19 dB compensation corresponds to the 13 dB rain attenuation from the C/N₀ margin on a clear day of about 6 dB. The downlink required C/N₀ and C/N₀ margin were verified through the experiments by measuring the packet losses while lowering the reception C/N₀ by inserting shield boards. Figure 11 shows the characteristics of reception C/N₀ versus packet loss measured using the Kanto MBA with 1.2 m VSAT in Kashima, where at the C/N₀ of approximate 95 dB, the packet loss began to increase; the value of 95 dB, having just a difference of 1 dB compared to the downlink required C/N₀ of 93.9 dB, is within the error range.

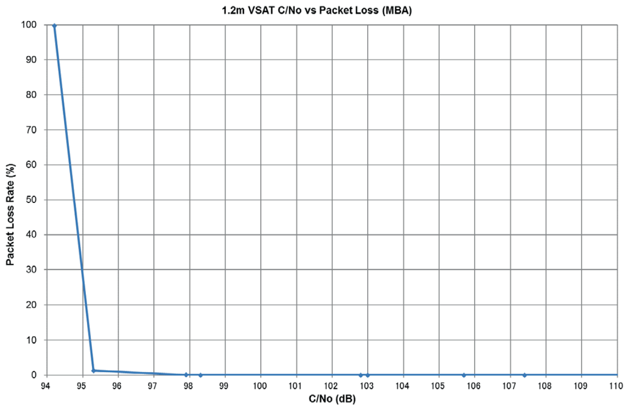


Fig. 11 Packet loss rates versus reception C/N₀ (MBA)

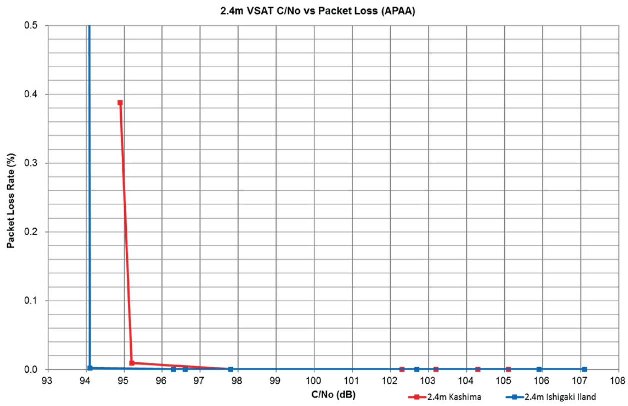


Fig. 12 Characteristics of reception C/N₀ versus packet loss (APAA)

In addition, in Fig. 12 the characteristics of APAA downlink reception C/N₀ versus packet loss are shown; the figure shows similar characteristics as the case of MBA.

4 Rain attenuation compensation by changing throughput and TCP/IP uplink transmission mode

Table 3 shows the UDP throughput measured by using iperf which is software for computing network throughputs in different WINDS transmission modes.

Table 3 UDP throughputs in different uplink transmission modes

Transmission Mode	1.5M	6M	24M	51M
No of Slot/Super frame	288	288	288	288
No of Data/Slot	2	8	30	60
Data volume incl. All"0" data (Byte)	223	223	223	223
Data volume excl. All"0" data (Byte)	212	212	212	212
Data volume excl. ATM header (Byte)	192	192	192	192
Data rate excl. ATM header (Mbps)	1.382	5.530	20.736	41.472
Measured Maximum Throughput (Mbps)	1.27	5.1	19.1	38.2

Note1: In the case where No. of Slot is changed, corresponding throughput can be calculated using proportional distribution.

The throughputs listed in Table 3 are the throughputs in the case where 288 traffic slots are used in a super-frame. In the case where a smaller number of slots are allocated to a user, the throughput decreases in proportion to the decrease in the number of allocated slots. In addition, in the case where the transmission mode grade-down is applied for doing rain attenuation compensation, because the uplink transmission speed or information volume decreases in proportion to the value listed in Table 3, the application side would be required to take measures for adjustment.

On the other hand, TCP/IP throughputs, because retransmissions are done, depend not only on transmission path capacity but also on the packet size, window size and others. With regard to satellite communication systems with larger transmission delays in particular, the transmission capacity varies within a wide rage. Figure 13 shows the estimated EIRP versus throughput or packet loss measured using iperf with the following settings: in order to obtain approximately maximum throughput of the WINDS regenerative link, using TCP/IP, and setting the window size to automatic selection mode within the range from 4 Kbytes to 4 Mbytes for 6 / 24 / 51 M mode and within the range from 4 to 128 Kbytes for 1.5 M mode.

Figure 13 shows that TCP/IP throughput drastically decreases on the occurrence of packet loss on satellite links. The figure suggests that the satellite links shall operate with a higher throughput through operating the transmission link under a packet loss condition, by down-stepping the transmission mode on the occasion of packet loss of around 0.2 percent down at 51 M satellite transmission mode and 1 to 2 percent down at 24 M/6 M mode. Therefore, for the transmission services by TCP/IP, it will be more effective to immediately shift the transmission mode down to a low-speed mode on the occasion of rain attenuation exceeding the threshold where packet losses begin to occur.

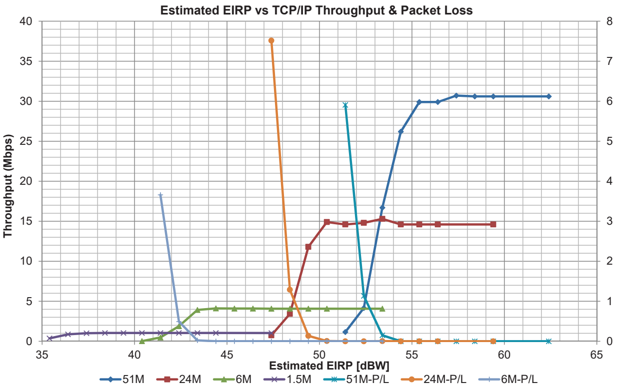


Fig. 13 Estimated EIRP versus throughput and packet loss

5 Satellite link unavailability in rain

The satellite link unavailability due to rain attenuation in the WINDS regenerative link are discussed here, based on the rain attenuation calculated using the UTU-R P.618-8 model. Table 4 lists the uplink rain attenuation versus satellite link unavailability. In addition, the table shows the satellite G/T for the different cities estimated using the distance of the city to the MBA beam center and the maximum attainable value of estimated rain attenuation compensation. Such compensation values for different cities are obtained by converting the uplink rain attenuation compensation of Kashima 1.2 m VSAT of 26.7 dB—adding or subtracting the difference of the satellite estimated G/T in a city to the MBA Kanto satellite estimated G/T in Kashima of 20.3 dB/K to or from the compensation in Kashima of 26.7 dB.

According to Table 4, the following uplink unavailability in different districts is expected: in the districts from Hokkaido to Northern Tohoku, 0.01%; in the districts from Sendai to Kanto, 0.03%; in the districts from Chubu to Kyushu, 0.05%; in Okinawa, 0.1%.

Table 5 lists the downlink rain degradation against satellite link unavailability—the downlink rain degradation is the sum of rain attenuation and degradation in reception

G/T. In addition, Table 5 lists the estimated values of satellite maximum EIRP in different cities estimated using the distance of a city to its MBA beam center location, and the downlink estimated rain attenuation margin for a city—such a downlink estimated rain attenuation margin is obtained shifting the Kanto MBA 1 beam attenuation margin of 20.8 dB in Kashima by the difference of the satellite estimated maximum EIRP at a city to the MBA Kanto satellite estimated maximum EIRP of 72.6 dBW. According to Table 5, the following downlink unavailability in different districts is expected: in the districts from Hokkaido to Tohoku, 0.01%; in the districts from Kanto to Kyushu, 0.03%; In Okinawa, 0.05%.

Table 4 Uplink rain attenuation versus satellite link unavailability

Uplink rain attenuation (ITU-R P.618-8)
Satellite : WINDS **143.0** **degrees East**
Uplink frequency **28.05** **GHz**
Uplink rain attenuation (dB)

City/Area	MBA	Unavailability (% of an average year)							Estimated Satellite G/T (dB/K)	Estimated Uplink Rain Attenuation Compensation (dB)
		1	0.5	0.3	0.1	0.05	0.03	0.01		
Nemuro	Hokkaidou East	0.9	0.9	0.9	2.1	4.1	7.0	21.0	19.4	25.8
Sapporo	Hokkaidou South	0.8	0.8	0.8	1.9	3.7	6.4	19.5	23.1	29.5
Morioka	Touhoku	0.8	0.8	0.8	1.8	3.9	7.1	26.2	23.0	29.4
Sendai	Touhoku	0.7	0.7	0.7	1.7	3.9	7.3	29.0	19.4	25.8
Kashima	Kantou	3.8	5.9	8.0	14.2	19.7	24.6	37.1	20.3	26.7
Nagoya	Cuubu	5.7	8.7	11.6	20.5	28.0	34.6	51.3	24.4	30.8
Oosaka	Kinki	4.8	7.5	10.0	17.7	24.4	30.1	44.9	21.0	27.4
Hiroshima	Chuu-shikoku	4.7	7.2	9.7	17.2	23.7	29.3	43.7	23.2	29.6
Kumamoto	Kyuusyuu	5.0	7.8	10.5	18.5	25.2	31.1	45.9	20.2	26.6
Naha	Okinawa	7.0	11.5	15.6	26.8	35.7	43.2	61.1	22.9	29.3

Table 5 Downlink rain degradation versus satellite link unavailability Satellite estimated maximum EIRPs are the values at MPA output power of 280 W.

Required downlink rain margin
Satellite : WINDS **143.0** **degrees East**
Downlink frequency **18.25** **GHz**
Downlink rain degradation (dB)

City/Area	MBA	Unavailability (% of an average year)							Maximum Estimated Satellite EIRP (dBW)	Downlink Estimated Rain Margin (dB)
		1	0.5	0.3	0.1	0.05	0.03	0.01		
Nemuro	Hokkaidou East	0.5	0.5	0.5	1.6	3.2	5.2	13.3	70.3	18.5
Sapporo	Hokkaidou South	0.4	0.4	0.5	1.4	3.0	4.8	12.5	73.3	21.5
Morioka	Touhoku	0.3	0.3	0.3	1.3	3.0	5.3	16.0	71.4	19.6
Sendai	Touhoku	0.3	0.3	0.3	1.3	3.0	5.5	17.5	69.9	18.1
Kashima	Kantou	2.7	4.2	5.5	9.1	12.1	14.6	21.4	72.6	20.8
Nagoya	Cuubu	3.9	5.9	7.6	12.3	16.3	19.7	28.6	72.2	20.4
Oosaka	Kinki	3.5	5.2	6.7	11.0	14.5	17.5	25.4	72.6	20.8
Hiroshima	Chuu-shikoku	3.3	4.9	6.5	10.7	14.0	17.0	24.6	72.8	21.0
Kumamoto	Kyuusyuu	3.5	5.3	6.9	11.3	14.8	17.9	25.8	72.1	20.3
Naha	Okinawa	4.8	7.4	9.6	15.3	19.9	23.7	33.2	72.3	20.5

Maximum estimated satellite EIRP is the case of MPA output power is 280W。

6 Measuring rain attenuation characteristics

The rain attenuation in the K_a band is measured using the level TDMA reference burst (RB) used in the WINDS regenerative link and the level of the WINDS network information signal residual carrier.

Figure 14 shows the downlink TDMA frame format—a super-frame consisting of 16 basic frames, and a basic frame consisting of 20 slots.

The reference burst is satellite-generated, packed in the first slot of each of the basic frames and transmitted with a constant level of satellite output power. Consequently, by observing the RB reception level, the satellite downlink rain attenuation can be measured independently of the uplink situation. The measurements were conducted at NICT Kashima Space Technology Center, NICT Headquarters (Koganei), and Hino Campus of Tokyo Metropolitan University, where the RB center frequency of the Kanto beam is 17.7925 GHz.

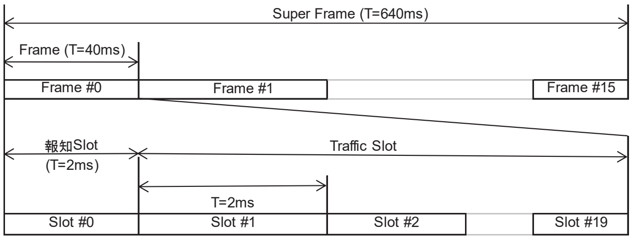


Fig. 14 Downlink TDMA frame format

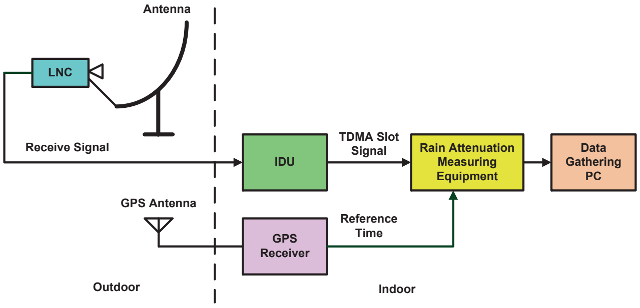


Fig. 15 TDMA RB level measurement system

At the same time, at Kashima Space Technology Center, 1 minute of rainfall is measured, studying the correlation between rain attenuation and rainfall.

Figures 16 and 17 show examples of the measurements conducted at Kashima Space Technology Center. In Figure 16, a big attenuation can be observed between 15:11 and 15:38. Figure 17 shows an enlarged illustration of the corresponding time period. These figures clearly show the correlation of rain attenuation and rainfall. Also, a time lag from the rainfall to the rain attenuation can be found. The time lag is likely to have been caused by wind flowing, in most of the period, from the Kashima WINDS line of sight direction—the rain clouds causing rain attenuation on the slant transmission path to arrive in Kashima later by the delay time. In addition, those figures show that the rate of rain attenuation is about 0.5 dB/s at maximum.

Also, the rain attenuation was measured by observing the WINDS network information signal residual carrier level at every second using spectrum analyzers. The frequency of the network information residual carrier is 18.9 GHz. The rain attenuation of the network information

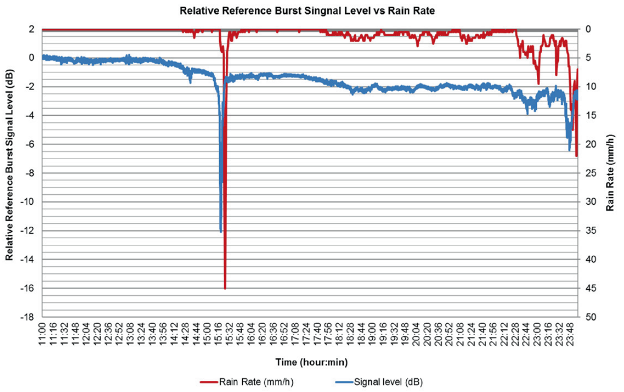


Fig. 16 An example of rain attenuation measurement using TDMA RB (Kashima, April 14, 2009)

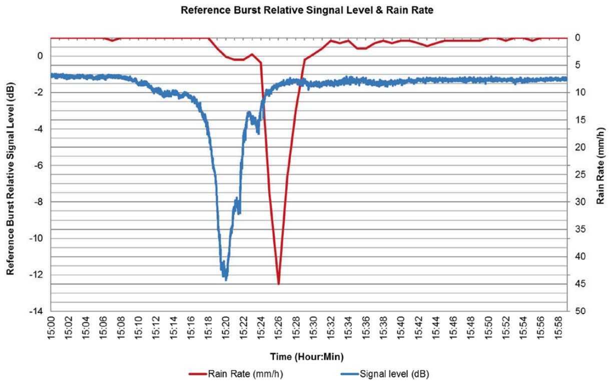


Fig. 17 Time domain enlarged graph of Fig. 16

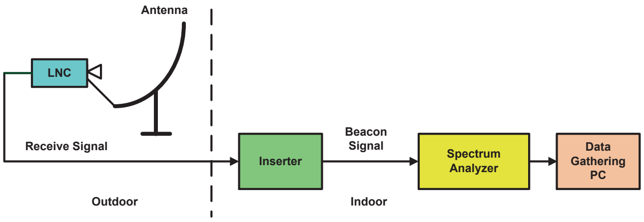


Fig. 18 WINDS network information signal residual carrier measurement system

residual carrier was measured at NICT Kashima Space Technology Center, NICT Headquarters (Koganei), and NICT Okinawa Electromagnetic Wave Technology Center.

Figure 19 shows an example of the results of the measurements conducted at Kashima Space Technology Center of the WINDS network information signal residual carrier level, along with 1 minute of rainfall.

Figures 20 and 21 show the correlation of rain attenuation and rainfall, and the correlation of rain attenuation and rain attenuation variation rate obtained in Kashima from 2009 to 2017. By considering the MBA 1.2 m VSAT

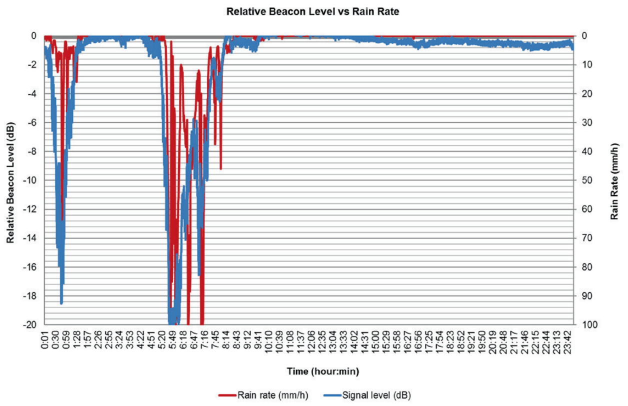


Fig. 19 An example of rain attenuation measurements using WINDS net information signal residual carrier (Kashima, September 11, 2015)

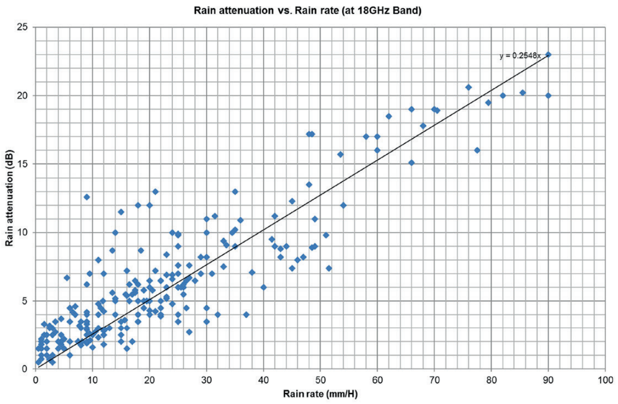


Fig. 20 Rain attenuation versus Rainfall (Kashima)

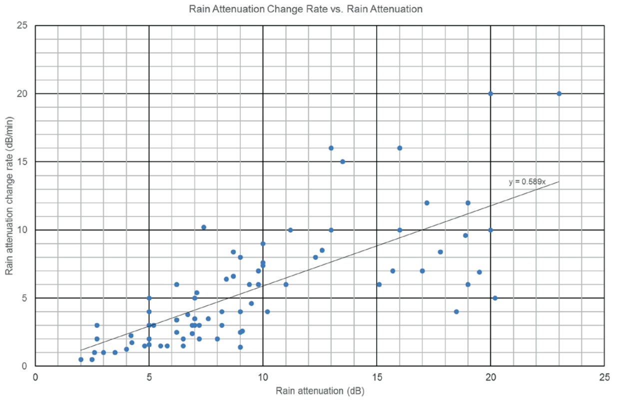


Fig. 21 Rain attenuation variation rate versus rain attenuation (Kashima)

uplink rain attenuation compensation is 26.7 dB, and the ratio of the rain attenuation in a 28 GHz band uplink and the rain attenuation in an 18 GHz band downlink is about 2, the attenuation due to “heavy rain” of up to about 50 mm/hour is expected to compensate in Kashima. On the other hand, the control response speed is one of the important parameters for keeping satellite links available by altering satellite link design characteristics, and it is necessary to determine the response speed according to the link margin and the attenuation variation rate at rainfall. In accordance with Fig. 21, a rain attenuation compensation of 25 dB must be accomplished against the rain attenuation variation rate of about 15 to 20 dB/min. This means that a rain attenuation compensation of 1 dB must be done within about 2 seconds.

On the other hand, for preparing for rainfalls around the destination stations, a delay of at least more than one path travelling time on satellite link (about 250 to 300 ms, one way) shall be considered.

7 Conclusion

The report presented the experiment results of rain attenuation compensation on the WINDS regenerative link, showing that rain attenuation compensation is effective in the K_a band. In addition, the report presented examples of our measurements conducted on K_a band rain attenuation characteristics and statistical analysis thereof. The basic data for determining the algorithm and the response speed of rain attenuation compensation can be collected successfully.

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