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Development and performance analysis of satellite communication system for real-time river monitoring

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ABSTRACT

K-water uses its Koreasat No. 5-based communications network for remote acquisition and provision of hydrological information on rainfall, water levels, water quality, and warnings via its hydrological observation network. The satellite is greatly affected by the rainfall attenuation during heavy rainfall seasons and typhoons since it is using the Ku-band frequency. K-water used the site diversity (SD) technology and developed a duplexing system that involved the setup of its main hub station at its headquarters and its auxiliary hub station at Gunnam Dam located at 200 km away, to smoothly use its data during rainfall attenuation and satellite malfunctions. In this paper, we proposed an online monitoring SD system in the communications satellite equipment and manual/automatic switching algorithms. We examined the SD effects in the projected site to improve the stability and reliability of K-water's hydrological communications satellite. Data reliability was found to be improved to 96.7% through the comparative study of the existing and SD systems, in which present data observation failure occurred in all 418 terminal stations, but proposed method occurred only in 14 terminals.

Keywords: Satellite; Communication; Site diversity; Rain attenuation; Switchover

1. Introduction

Currently, communication media are growing in diversity, speed, reliability, and low cost due to development of communication infrastructure. Communication method is most essential in constructing a information-oriented society. There is demand for a system that can inexpensively and conveniently provide various services such as data collection and dissemination. Satellite communication technology that satisfies such requirements is rapidly developing.

Communication and broadcasting using satellite is coming to an age of bi-directional service. Satellite infrastructure goes beyond the concept of back-up communications network to being portable, establishing

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on-ground infrastructure and providing foundation for wide area communication and broadcasting in regions and facilities with difficulty in operation. Also, Satellite communication and broadcasting is being used as a supplementary or backbone network with on-ground infrastructure in cases of disaster prevention and emergency restoration, industry facility surveillance and measured data monitoring [1].

K-water has established floodgate observation network in 16 multipurpose dams and only water dams basin of six rivers for operation. Floodgate observation network is composed of district center facilities in headquarters (HQ), control station facilities in dam offices, and central terminals in the field such as, water-level gaging station, rainfall gaging station, and warning station.

In the case of transferring data that uses frequency of 10 GHz or more, the signal is harmed considerably while passing through the atmosphere due to precipitation. Harm due to precipitation has a serious impact on the quality of circuits, especially causing effects such as reduction of amplitude, increase of thermal noise, and increase of interference in case of polarized use.

In case of data transmission using the upper 10 GHz frequency, rain results in attenuation of radio waves. And the most serious atmospheric effect in a satellite link is the rainfall. The attenuation of rainfall very seriously affects the quality of transmission line. Because the rain increases thermal noise and interference, the amplitude of the signal decreased.

K-water has been using Koreasat No. 5, which uses Ku-band, since 1998 to transmit data such as precipitation, water level, and warnings. Especially in periods of concentrated rainfall, this data are in even greater need. Also, the frequency used by Koreasat No. 5 is the range that is most severely affected by rainfall; therefore, it requires detailed analysis and measures to address this issue.

In this study, to stabilize the operation of the hydrological communications satellite under the heavy influence of rainfall attenuation, the site diversity (SD) method was applied in the duplexing of the hub station. It resolved the rainfall attenuation problems. The diversity effects of planned site before the development of SD system were also examined. Algorithms were formulated to develop, operate, and manage the online monitoring method for the communications satellite equipment. Performance of the developed SD system was also assessed.

2. Hydrological observation satellite communications network

2.1. Overview

K-water's hydrological observation communications satellite network, which is shown in Fig. 1, has two hub stations (the main and the auxiliary), 25 dam control stations, 131 rainfall gaging stations, 53 water-level gaging stations, 124 warning stations, 8 water-level

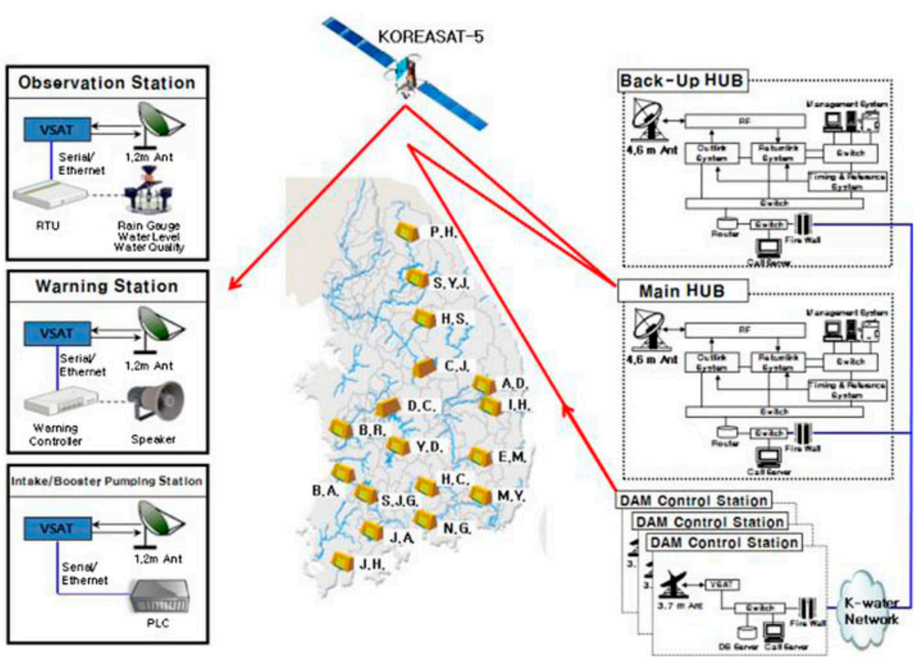

Fig. 1. Diagram of K-water's satellite communications network.

gaging/warning stations, 23 water-level/rainfall gaging stations, 2 water-quality monitoring stations, 27 other stations, and 25 external Han River flood control stations, for a total of 420 terminal stations [2–4].

2.2. Hub station

The hub station (Table 1 and Fig. 2), installed at K-water's HQ, controls all the observation stations and monitors their outputs and operational status, Fig. 2 shows the diagram of a hub station while its characteristics are shown in Table 1. It automatically calls and recalls terminals on time, and stores the data received after calls in the Telemetering server and the DataBase (DB) server. It receives and stores event data from terminal stations, changes its communication speeds, automatically allocates data to terminal stations, copes with rainfall attenuation, and manages the communications satellite network via Network Management System. It also ensures the data integrity and protects the data from external attacks via firewalls and encryption equipment items.

Table 1
Characteristics of the hub stations

Item	Parameter	Specification
System	Access protocol	TDM/TDMA
	Symbol rate	128 kbps (1–36 Mbps)
	Service	Data, multimedia
RF	RF frequency	Tx: 14.0–14.5 GHz, Rx: 12.25–12.75 GHz
	HPA output	16 W max.
Base band modem	System interface	RS-232, DB-9, Ethernet
	Modulation	QPSK
	Information rate	128 kbps (max. 20 Mbps)
Antenna	Size	4.6 m

2.3. Dam control stations

The dam control station as shown in Fig. 3 controls its assigned terminal stations and gathers data from them. One dam control station has a few terminal stations. It uses a 3.7 m antenna and consists of the satellite modem In Door Unit (IDU), the Radio Frequency (RF) receiving unit Block Up Converter (BUC), and the receiving units that encompass Low Noise Amplifier (LNA), Block Down Converter (BDC), and Low Noise Block Controller.

2.4. Observation stations

Observation stations (Table 2 and Fig. 4) are classified into water-level gaging stations, rainfall gaging stations, water-quality monitoring stations, and warning stations. They use a 1.2 m antenna and consist of the satellite modem IDU, the RF receiving unit BUC, and the receiving units that include Low Noise Block and Out Door Unit (ODU).

Observation stations receive call commands from their hub station and control station; send them response calls; store rainfall, water level, and other events monitored from their sensors; and immediately send such event data to their hub station and control station.

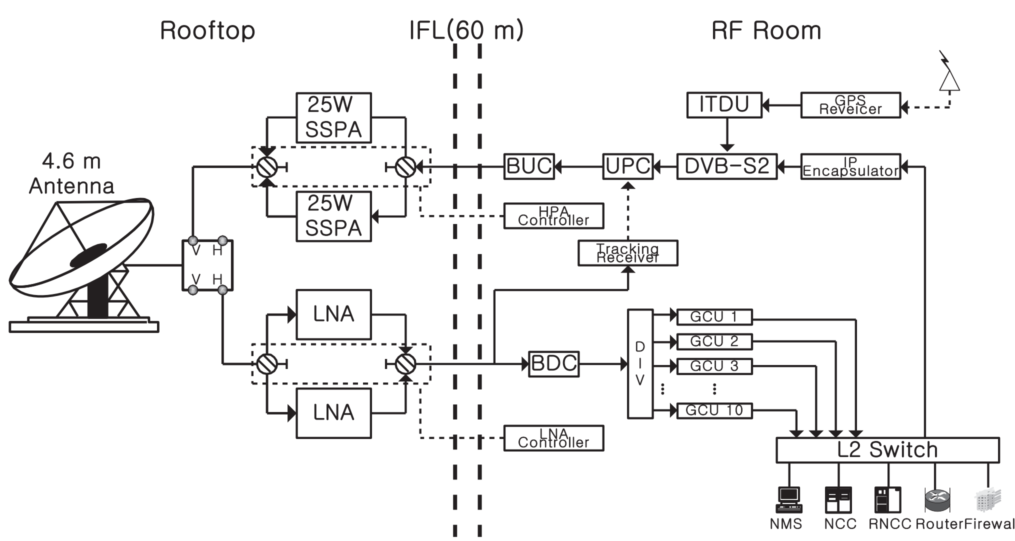

Fig. 2. Diagram of a hub station.

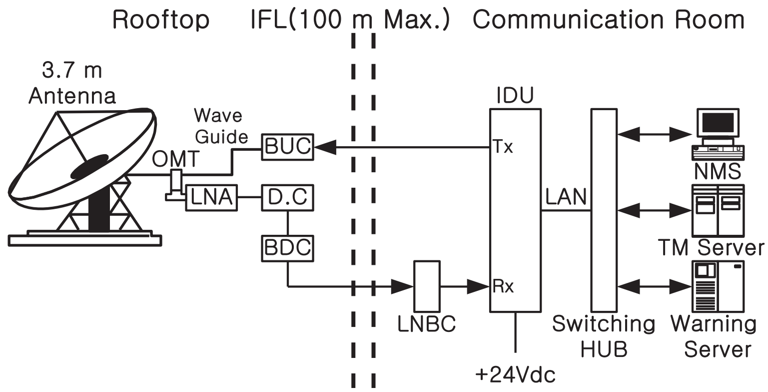

Fig. 3. Diagram of a dam control station.

Table 2
Characteristics of observation stations

Item	Parameter	Specification
System	Output frequency	Tx (14.0–14.5 GHz), Rx (12.25–12.75 GHz)
	IF frequency	950–1,450 MHz
	Topology	Star
	Data rate	128 kbps, Tx: 1–45 Mbps, Rx: 125 kbps–3 Mbps
	Modulation	QPSK
	Access protocol	TDM/TDMA
	Consumption power	IDU: 8 W, ODU: 20 W (Tx), 2 W (Rx)
Antenna	Size	1.2 m

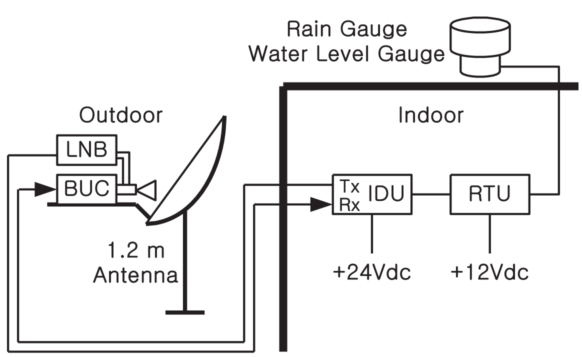

Fig. 4. Diagram of an observation station.

3. Rainfall attenuation and SD technology

3.1. Rainfall attenuation phenomenon

Rainfall attenuation is the phenomenon in which radio waves sent from the satellite hit falling raindrops and weaken due to absorption and scattering. Radio waves with a frequency of over 10 GHz, when passing through the atmosphere, experience attenuation due to various atmospheric elements, such as steam, fog, oxygen particles, and rainfall, the most influential of which is rainfall [5–7].

3.2. Rainfall attenuation compensation technology

The SD method is designed to simultaneously operate two or more base stations that are far away from each other, so that when communication at one base station is disabled due to rain or snow, another station can be used. This technology is possible because these base stations are located at distances that can sufficiently secure their respective areas' weather independence [8,9] (Fig. 5).

K-water's current Koreasat No. 5 uses the Ku-band frequency and thus experiences great rainfall attenuation and suffers from poor communication quality. In recent years, local brief heavy rainfall occurred quite frequently, thus new methods needed to be developed to reduce the influence of the rainfall attenuation [10,11].

3.3. Analysis of SD system gains

In Korea, the seasonal rain front pattern involves the rain front lying across east to west in the July–August rainy season and vibrating north to south. K-water developed the SD system to reduce its communication problems due to attenuation and equipment malfunctions. K-water's main hub station, which comprehensively operates and manages its hydrological observation communications satellite, is located in its HQ in Daejeon. To maximize the effect of the SD system, its site was selected by assessing the SD gains of candidate multipurpose dams.

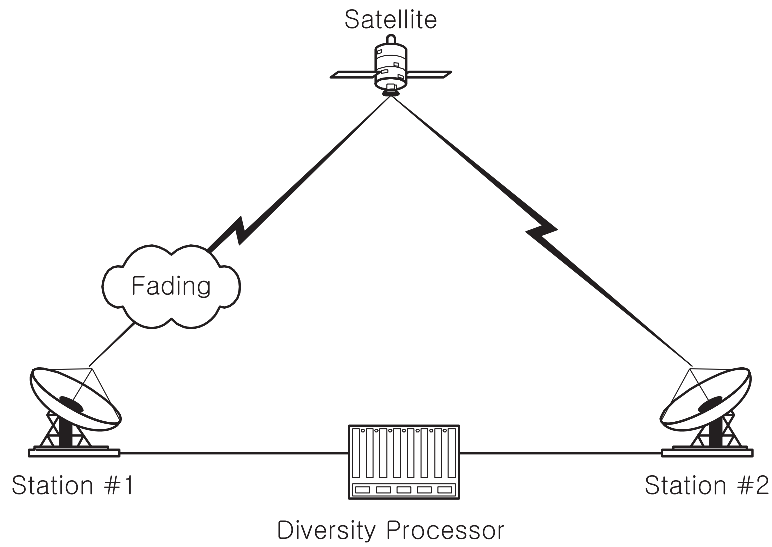

Fig. 5. Diagram of SD.

The path diversity gain (G_D) of the Daejeon main hub station to the four candidate auxiliary hubs (G_D) was calculated using the following ITU-R rainfall attenuation model in Fig. 6, that was based on a single earth station rainfall attenuation ($A_{0.01}$), earth-to-earth station distance (d), link frequency (f), area station latitude (φ), elevation angle (θ), and baseline path angle (ψ) [12–18].

Applied herein were the ITU-R Climate Region's K area 42 mm/h rainfall attenuation ($A_{0.01}$), an above-sea level of 38 m, an uplink frequency of 14.335 GHz, and a downlink frequency of 12.587 GHz. The relational Eq. (1) between the rainfall rate ($R_{0.01}$) of a specific area that is 0.01% higher than the average and the specific attenuation parameter (γ_R) that shows attenuation per 1 km is outlined as follows:

$$\gamma_R = k(R_{0.01})^{\alpha} \text{ (dB/km)} \tag{1}$$

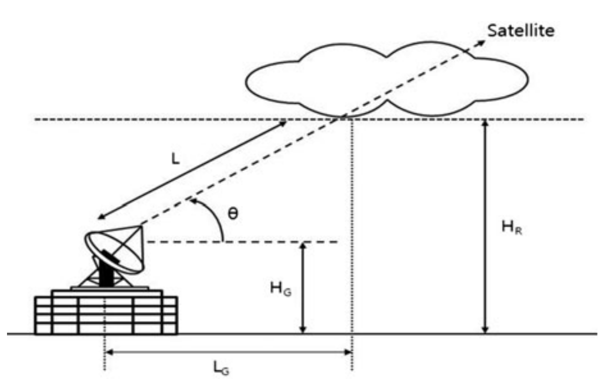

Fig. 6. Diagram for the calculation of the rainfall path.

where in the k and α values are 12–15 GHz band, $k_H = 1.094 \times 10^{-5} f^{2.9977}$, $k_v = 7.718 \times 10^{-6} f^{3.0929}$, $\alpha_H = -0.6501 \log f + 1.9186$, $\alpha_v = -0.74301 \log f + 2.0018$.

(1) Contour line altitude at 0 (°) in the rainfall state: H_0

$$H_0 = 5 - 0.075 \times (\varphi - 23) \text{ (km)}, \quad \varphi \geq 23^{\circ} \tag{2}$$

(2) Effective rainfall altitude: H_R

$$H_R = H_0 + 0.36 \text{ (km)} \tag{3}$$

(3) Actual path slope length: L

$$L = \frac{H_R - H_G}{\sin \theta} \text{ (km)}, \quad \theta \geq 5^{\circ} \tag{4}$$

where in H_G: The earth station's above-sea altitude.

(4) Horizontal projection length: L_G

$$L_G = L \cos \theta \text{ (km)} \tag{5}$$

(5) Horizontal attenuation parameter: $r_{0.01}$

$$r_{0.01} = \frac{1}{1 + 0.78\frac{\sqrt{L_G \times \gamma_R}}{f} - 0.38(1 - e^{-2L_G})} \tag{6}$$

Expression (10) can be evaluated using Eqs. (7)–(9).

$$\zeta = \tan^{-1} \frac{H_R - H_G}{L_G \times r_{0.01}} \text{ } (^{\circ}) \tag{7}$$

Table 3
Analysis of the candidate SD gains

Dam	Latitude (°)	Distance (d, km)	Elevation (θ, °)	Baseline (ψ, °)	Length loss (dB)		Diversity gain (dB)	
					D/L	U/L	D/L	U/L
HUB	36.24	0	45.33	–	8.38	9.99	–	–
C.J.	36.50	90	45.00	13.00	8.38	9.98	6.12	5.86
S.J.	35.33	100	46.34	7.00	8.40	10.01	5.04	5.84
S.Y.	37.56	170	43.89	13.00	8.37	9.95	5.02	5.81
G.N.	38.06	200	43.53	34.00	8.35	9.93	5.21	6.02

$$L_R = \frac{L_G \times r_{0.01}}{\cos\theta}\ (\text{km})\ \zeta > \theta \tag{8}$$

$$\chi = 0\ (^\circ)\ |\theta| \geq 36^\circ \tag{9}$$

(6) Vertical adjustment parameter: $v_{0.01}$

$$v_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - e^{-\theta/(1+\chi)}\right)\frac{\sqrt{L_R \times \gamma_R}}{f^2} - 0.45\right)} \tag{10}$$

(7) Effective rainfall length: L_{eff}

$$L_{\text{eff}} = L_R \times v_{0.01}\ (\text{km}) \tag{11}$$

Thus, the rainfall path loss $A_{0.01}$ can be calculated as shown in Eq. (12) via Eqs. (1) and (11).

$$A_{0.01} = \gamma_R \times L_{\text{eff}}\ (\text{dB}) \tag{12}$$

Using the path loss $A_{0.01}$ as calculated in Eq. (12), the diversity gain by the SD system can be calculated via the following procedure.

(1) Gain according to the spatial separation

$$G_d = a\left(1 - e^{-bd}\right)\ (\text{dB}) \tag{13}$$

where $a = 0.64\ A - 1.6\left(1 - e^{-0.11A}\right)$, $b = 0.585\left(1 - e^{-0.98A}\right)$.

(2) Frequency dependent gain: G_f

$$G_f = 1.64\left(e^{-0.025f}\right)\ (\text{dB}) \tag{14}$$

(3) Elevation angle gain: G_e

$$G_e = 0.00492\,\theta + 0.834\ (\text{dB}) \tag{15}$$

(4) Baseline gain: G_ψ

$$G_\psi = 0.00177\,\psi + 0.887\ (\text{dB}) \tag{16}$$

(5) Diversity gain: G_D

$$G_D = G_d \times G_f \times G_e \times G_\psi\ (\text{dB}) \tag{17}$$

The calculation results are shown in Table 3. Among the candidate SD sites, Gunnam Dam had the best diversity gain.

Thus, based on Table 3, the SD system was developed by installing the hub station at the Daejeon HQ, and the auxiliary station, at Gunnam Dam in Yeoncheon-gun, Gyeonggi-do, 200 km away to the north as shown in Fig. 7

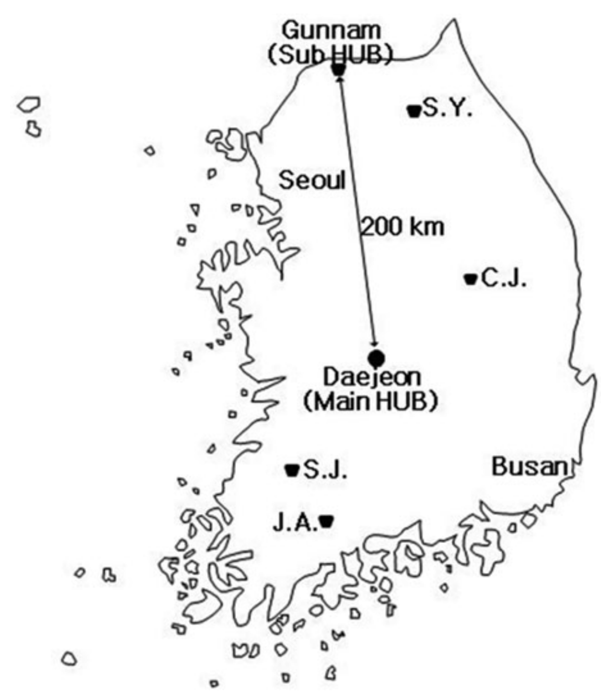

Fig. 7. K-water SD system installation location.

4. Development of the SD system and performance test

4.1. Development of the SD system

HQ's main hub station and Gunnam Dam's auxiliary hub station were equipped with a switching server and software to enable the switching of a disabled hub station they were connected to the K-water network.

Under the existing SD system, the automatic switching method activated the system when the satellite signal reception level fell below the critical value and remained for a specific time in that state, and when the number of malfunctioning observation stations reached or exceeded the defined number [19].

Herein, the SD system was developed so that it can switch not only when the satellite signal reception level falls below the critical level, but also to monitor problems in the hub station's communications satellite transmission equipment, including Up Power Controller (UPC), BUC, and Solid State Power Amplifier (SSPA), as well as in the receiving equipment, including LNA, BDC, and Transmit Receive Unit (TRU), carrier and beacon, in real time.

The SD system was developed so that it can be connected to the serial server, the switching server, Local Area Network, and the switching software to enable the main/auxiliary hub stations to monitor the communications satellite equipment in real time.

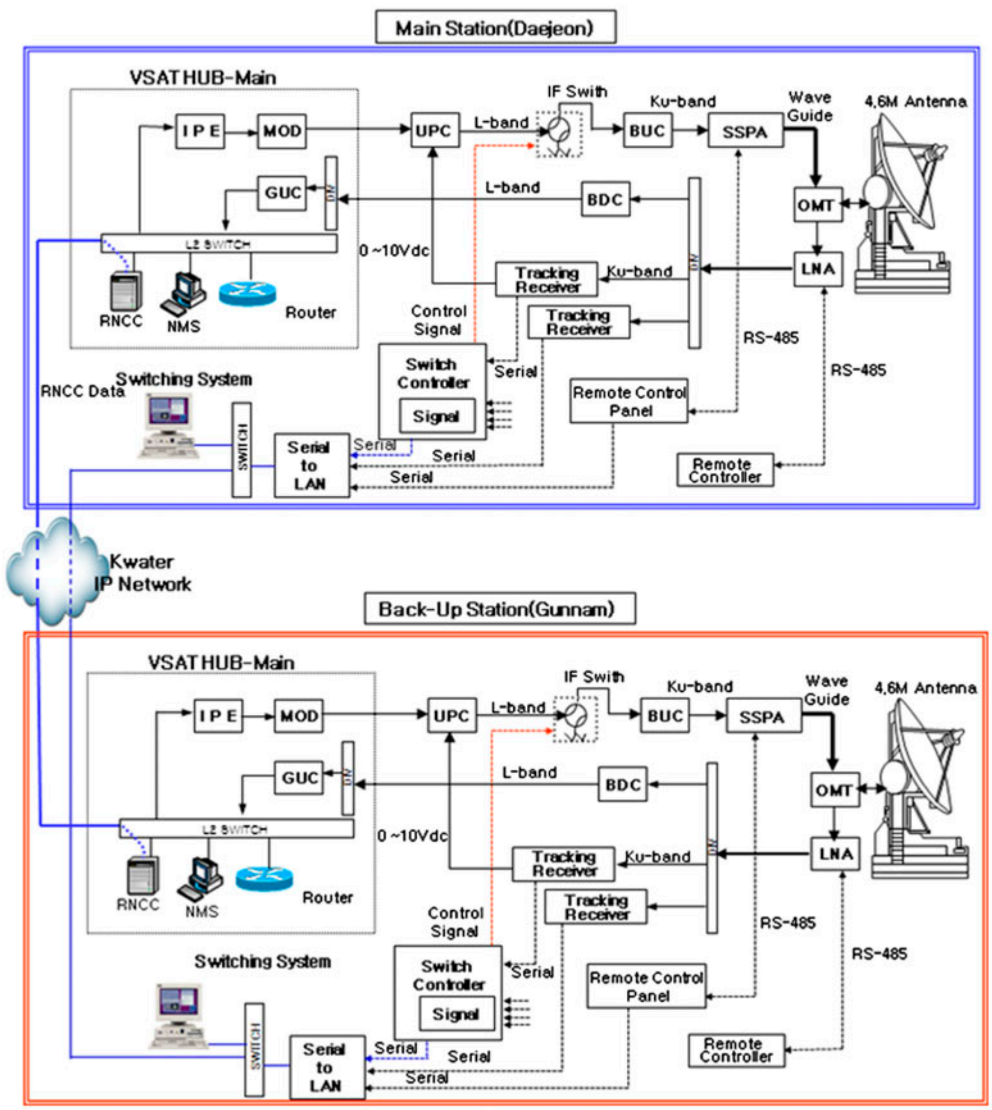

Fig. 8. Diagram of the SD system.

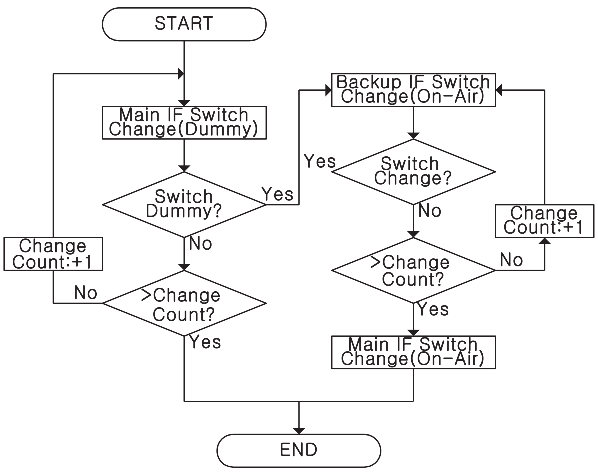

Fig. 9. Manual switching algorithm.

The diagram of the SD system is shown in Fig. 8 and its functions are as follows:

- Displays the main hub/sub-hub status;
- Allows the operator to manually switch;
- Automatically switches based on the switching parameter set by the operator;
- Monitors the UPC status;
- Monitors the BUC/BDC status;
- Monitors the SSPA status;
- Monitors the TRU (carrier and beacon) status;
- Controls the switch controller;
- Stores monitoring information; and
- Detects faults and issues alarms.

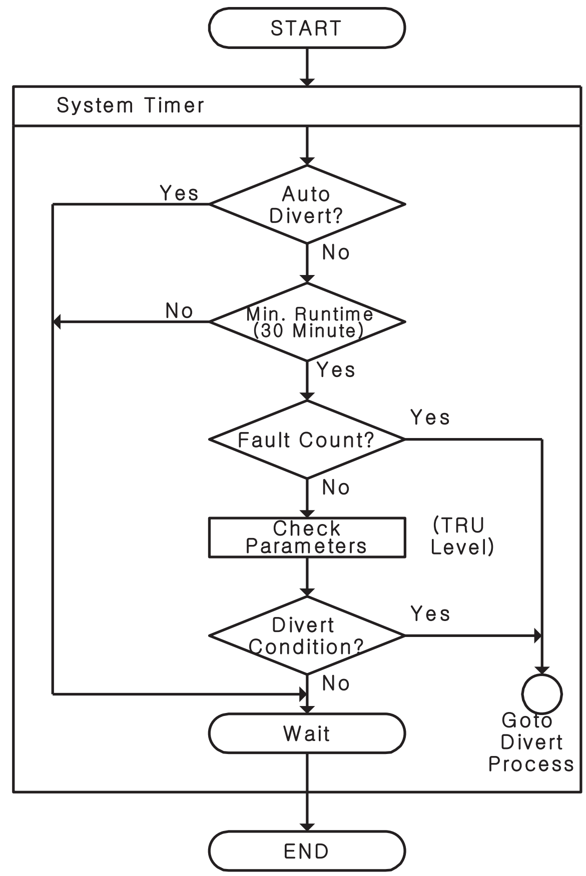

Fig. 10. Automatic switching algorithm.

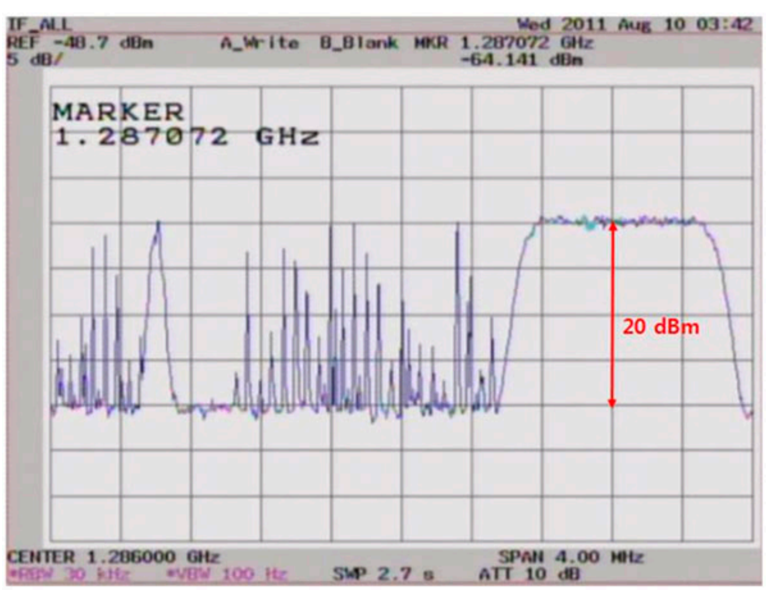

Fig. 11. K-water's satellite signal reception in its normal state.

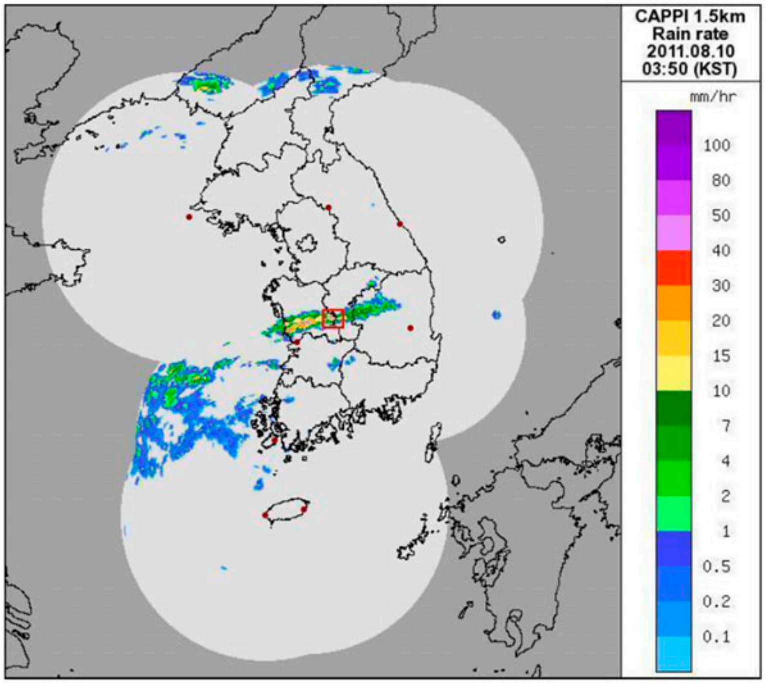

Fig. 12. Radar images of the HQ and the Daecheong Dam basin.

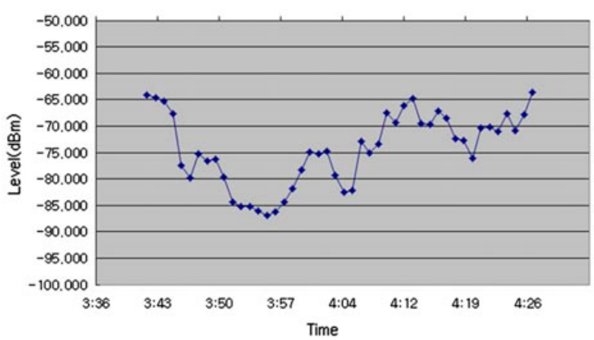

Fig. 13. Changes in the received satellite signal levels.

4.2. SD system switching algorithm

As for manual switching, the authorized operator of the satellite hydrological observation system, at his discretion, switches from the main hub station to the auxiliary hub station when the activated hub station system is disabled. The manual switching process is outlined in Fig. 9. When the manual switching process is activated, the operator should first check the auxiliary hub station's SSPA status, check if the RF output can be transmitted, and lift the RF Inhibition. Thereafter, switching is performed according to the switching process, and the system will recover the previously set communications satellite equipment status if errors occur in the process and will issue switching failure alarms to the operator.

The switching process was developed so that it can be regularly monitored by the switching server timer and can be activated when necessary. The automatic switching process is outlined in Fig. 10. Conditions for automatic switching are outlined as follows:

- When a transmission equipment malfunction is monitored;
- When the SSPA output voltage continues to be lower than the predetermined value;
- When no transmission equipment malfunction has been monitored; and
- When the TRU receiving level is lower than the predetermined value.

4.3. Analysis of the SD system performance

The K-water satellite signal reception level is 20 dBm in its normal state (Fig. 11). The radar images in Fig. 12 show that the main hub station and the Daecheong Dam basin posted the occurrence of rainfall, and Fig. 13 shows the corresponding satellite reception signal changes. Due to the occurrence of rainfall, the satellite reception signal level fell below 2 dBm (Fig. 14). Moreover, the satellite link was disconnected (Fig. 15), which disabled the reception of data from the observation stations.

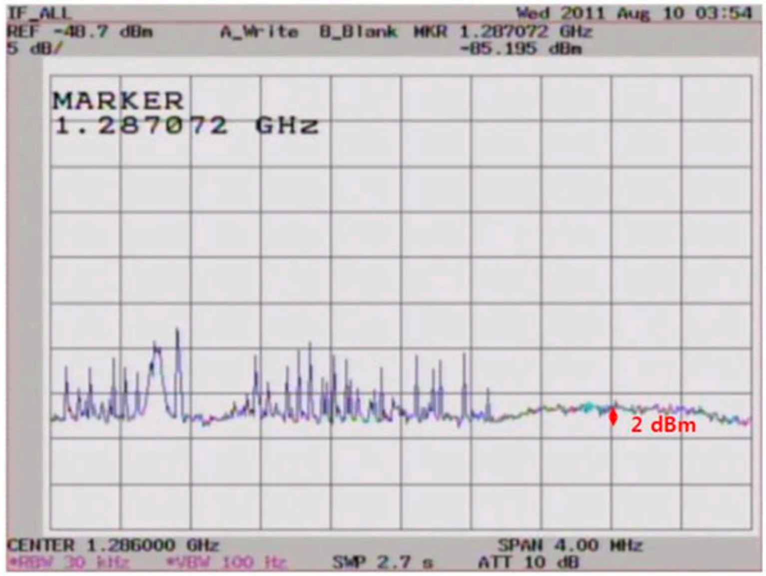

Fig. 14. Attenuation of the received satellite signals according to the rainfall.

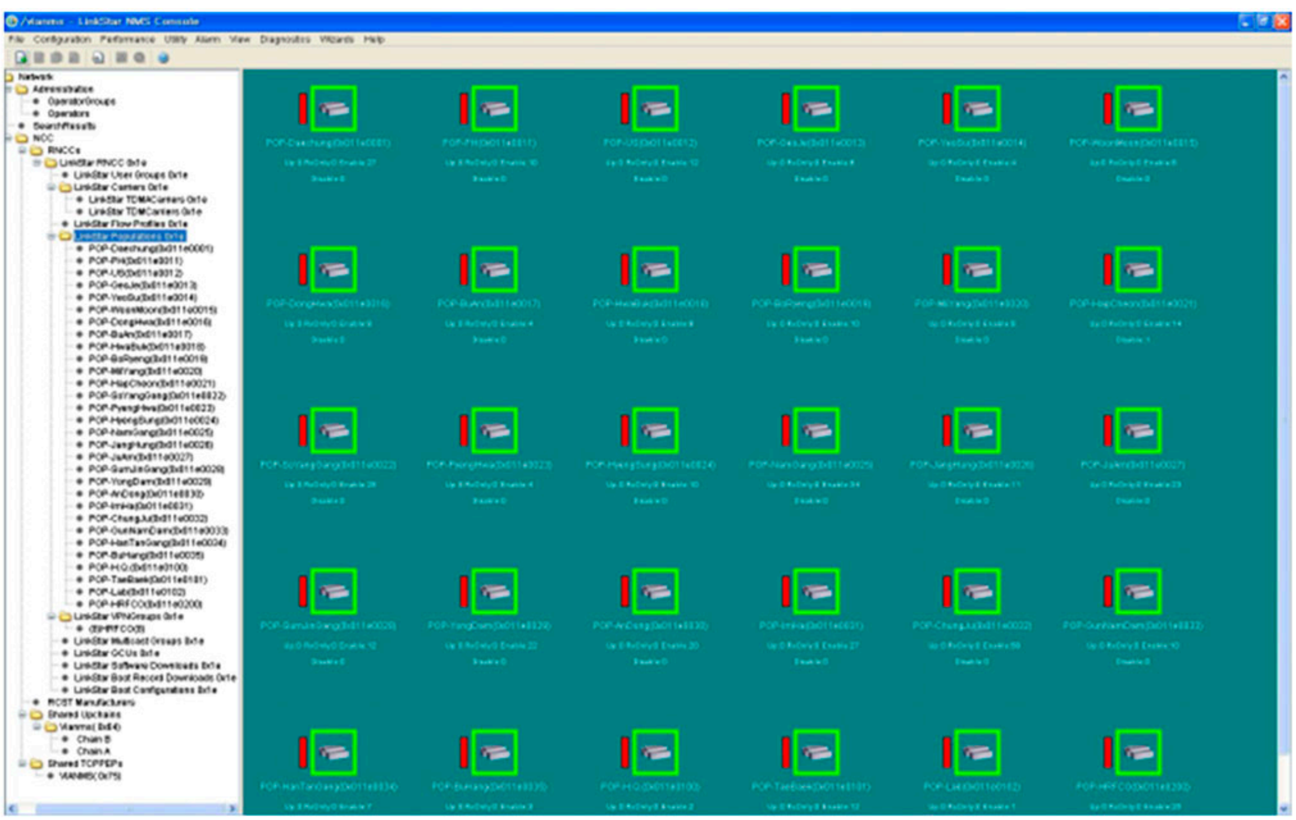

Fig. 15. Observation stations' reception status after rainfall.

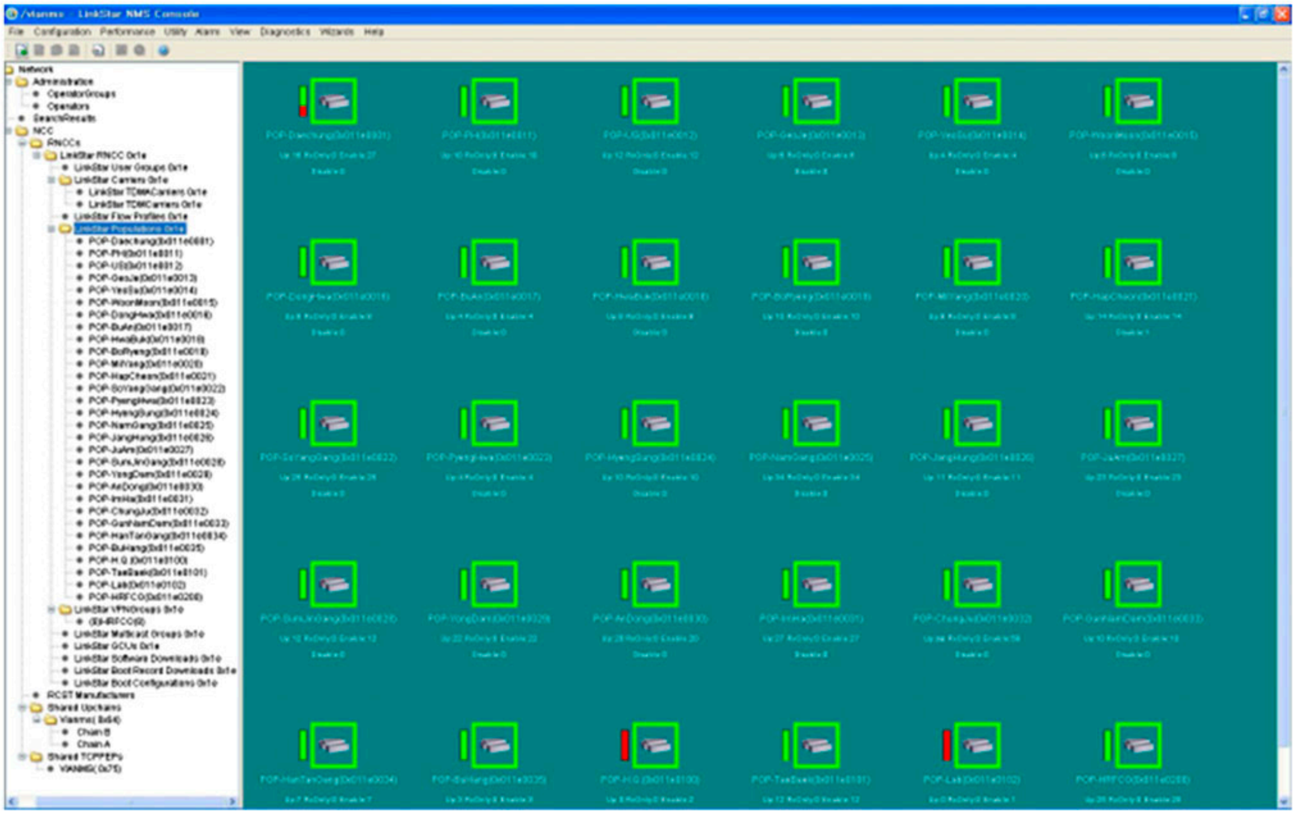

Fig. 16. Observation stations' status after switching.

The data observation failed in all 418 observation stations, so the data reliability is outlined as follows:

$$\text{Reliability} = \frac{\text{NND}}{(\text{NND} + \text{NDD})} \times 100\% \tag{18}$$

where NND: Number of Normal Data and NDD: Number of Defective Data.

$$\begin{aligned}\text{Reliability} &= \tfrac{0}{(418+0)} \times 100\% \\ &= 0\%\end{aligned} \tag{19}$$

The SD system switched from the main hub station (Daejeon) to the auxiliary hub station (Gunnam Dam) according to the automatic switching process. The data reception status is shown in Fig. 16.

The data observation failed in 14 of the 418 observation stations, so the data reliability is outlined as follows.

$$\begin{aligned}\text{Reliability} &= \tfrac{404}{(404+14)} \times 100\% \\ &= 96.7\%\end{aligned} \tag{20}$$

Under the existing system, all 418 observation stations experienced data observation failure. Under the SD system that involves automatic switching, however, only 14 terminals experienced data observation failure, posting a reliability level of 96.7%, and enhanced system stability.

The inability to achieve 100% data reliability in the SD system switching was because the failed observation stations are located 10–20 km away from the main hub station, and thus experienced rainfall attenuation, as did the hub station. To cope with satellite attenuation problems, K-water is also operating landlines, VHF, and CDMA as auxiliary networks, thus duplexing the system.

5. Conclusions

K-water is using Koreasat No. 5 and operating its hydrological observation network designed to transmit data on rainfall, water levels, water quality, and warnings in dam upstream and downstream areas. The system configuration considers multiple regions and the simultaneity, disaster resistance, and flexibility of the line composition. The SD system was developed so that it can smoothly acquire data when rainfall attenuation occurs due to heavy rains in connection with the use of the Ku-band frequency, and when the communications satellite equipment malfunctions. Specifically, the main hub station was installed at the HQ, and the auxiliary hub station, at Gunnam Dam, 200 km away from the HQ, based on the SD analysis that showed the best SD gains for Gunnam. In this way, the duplexing system was developed. In this study, the SD system was developed and its performance was tested and proven. Towards that end, the SD technology was used, the SD effects were analyzed, the switching system was developed, the switching measures based on the online monitoring of the satellite communications equipment were devised, and manual/automatic switching algorithms were developed. Under the existing system, data observation failure occurred in all 418 terminal stations. Under the SD system, however, data observation failure occurred only in 14 terminals after the switching, posting a reliability level of 96.7%, and enhancing the system stability.

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