A Novel Mobile Antenna for Ku-Band Satellite Communications

Ung Hee Park, Haeng Sook Noh, Seong Ho Son, Kyong Hee Lee, and Soon Ik Jeon

A mobile antenna for multimedia communications with Ku-band geostationary satellite KOREASAT-3 and JSAT-2A is presented. The forward link of the satellite communication is 11.7 to 12.75 GHz, and the return link is 14.0 to 14.5 GHz. The mobile antenna is designed to be a stair structure using 24 active phased array elements in order to provide a low profile, and to be at a non-periodic array distance using the genetic algorithm. Also, the designed antenna uses the double beam forming method for stable satellite tracking. The fabricated mobile antenna is examined using various experiments to confirm its capability for practical application. From the measured results, the fabricated mobile antenna system is confirmed to have a good performance.

Keywords: Phased array antenna, genetic algorithm, satellite communication.

I. Introduction

Satellite communication is not affected much by the communication distance or configuration of the ground. And satellite communication, which is compared to terrestrial communication, has an easiness of line facility, profitability of long distance telecommunication, and resistance to various disasters. For this reason, satellite communications have developed dramatically during recent years. Satellite communications can be classified according to communication link (unidirectional and bidirectional communication) and mobility (fixed and mobile communication). In particular, bi-directional communication using a satellite has been recently studied in many satellite companies and laboratories [1]-[5].

On behalf of fixed bi-directional communication, a Very Small Aperture Terminal (VSAT) can guarantee the radiation characteristics for international regulations such as ITU-R S.580-5 and ITU-R S.728-1 [6], [7]. However, a mobile antenna for bi-directional communication has difficulty in satisfying the above requirements due to many factors such as beam scanning, satellite tracking, and vehicle speed due to moving conditions. Until now, a mobile antenna for satellite communication generally uses two types, a mechanically tracking antenna and a fully electronic tracking antenna. The former has the main disadvantage of a slow tracking speed and the latter has high cost.

In this paper, a prototype antenna is proposed. The suggested antenna, a Mobile Antenna (MANT), is operated electronically in elevation and semi-electronically in azimuth. This antenna has low cost compared to a fully electronic tracking antenna and easily tracks the target satellite in mobile conditions. This antenna is designed with a three-stacked structure, which is capable of Tx (transmitting) and Rx (receiving), to improve the

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radiating efficiency. In particular, the array of the antenna is spaced with a non-periodic distance to optimally reduce the antenna sidelobes. Also, the proposed dual beam forming for satellite tracking can realize stable tracking. This antenna can be utilized on mobile conditions such as a ship, bus, train, and so forth.

II. Mobile Antenna (MANT) Design

The design specification of a mobile antenna system for satellite communications is determined by various applications such as application purpose, communication method, frequency, coverage area, satellite property, and so on. MANT is designed to be low weight, small in size, and high in power efficiency for loading on a vehicle in Korea and Japan. The required specification of MANT is shown in Table 1. The forward link, from satellite to MANT, uses a quadrature phase shift keying (QPSK) modulation method and time division multiplexing (TDM) at 11.7 to 12.75 GHz (11.7 to 12.0 GHz: circular polarization for broadcasting, 12.25 to 12.75 GHz: linear polarization for communication), while the return link, from MANT to satellite, uses the QPSK modulation method, multi channel/code division multiple access (MC/CDMA), at 14.0 to 14.5 GHz (linear polarization for communication). For the above communication method, the required antenna gain to noise temperature ratio (G/T) and effective isotropic radiated power (EIRP) of MANT are above 7.0 dB/K and 34.0 dBW, respectively. These values can support CDMA communication with a 384 kbps return link and 10 Mbps forward link. The transmission radiation pattern of MANT is requested to satisfy the VSAT regulation of ITU-R S.728-1. Also, MANT for satellite communication in Korea and Japan must be able to track a satellite within a 45 ± 10^{o} range in elevation and unlimited rotation in azimuth.

Table 1. The required specifications of MANT.

Items	Specifications
Satellite	KOREASAT-3 and JSAT-2A
Rx frequencies	11.7-12.0 GHz : Left hand circular polarization (LHCP) 12.25-12.75 GHz : Horizontal polarization
Tx frequencies	14.0-14.5 GHz : Vertical polarization
Rx signal type	QPSK TDM
Tx signal type	QPSK MC/CDMA
G/T	Over 7.0 dB/K
EIRP	Over 34.0 dBW
Tx antenna beam pattern	Satisfaction of ITU-R S.728.1 (VSAT regulation)
Satellite tracking range	±10° in elevation direction, 360° in azimuth direction
Tracking loss range	Below ±0.2°
Satellite tracking speed	Elevation : Over±45°/second Azimuth : Over±45°/second

To satisfy these design specifications, ETRI designed MANT as a new type of antenna. MANT is designed to steer its beam electronically in elevation and semi-electronically in azimuth using 24 active phased array elements. The block diagram of MANT is shown in Fig.1. MANT consists of 24 antenna subarrays, an Rx part, Tx part, control part, and a mechanically driven part. Each subarray of the three-stacked layer structure has a vertical feed for Tx (return link on the satellite communication) and a horizontal feed for Rx (forward link on the satellite communication). The Rx part consists of 24 Rx active channel modules, an Rx module, and a satellite tracking module. The Tx part consists of 24 Tx active channel modules, a Tx module, two duplexers, and a block up-converter. The channel part is in charge of the operation and channel of MANT using the output of the satellite tracking module. The mechanically driven part stably controls MANT within the maximum speed of 45 °/s in azimuth direction. For a more effective antenna system, MANT makes use of three main technologies, a three-stacked microstrip patch antenna, non-periodic array distance, and double beam forming method.

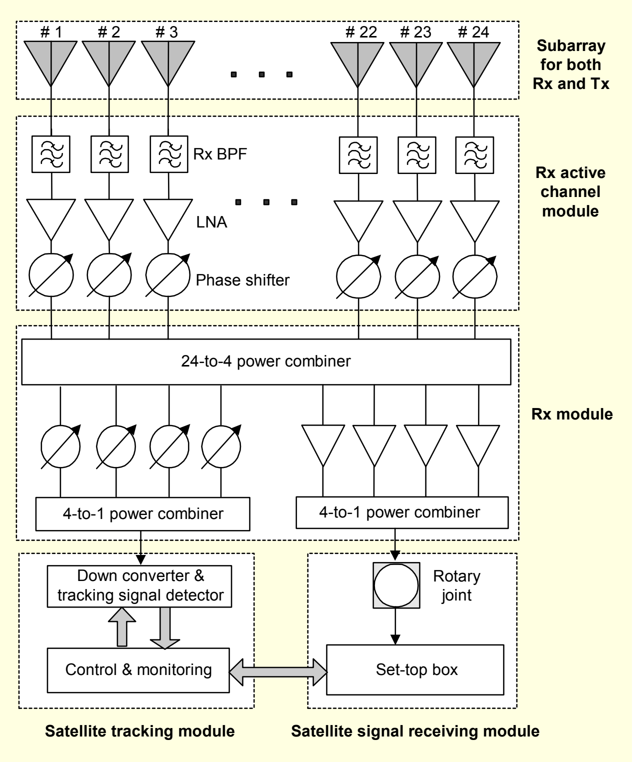


Fig. 1. A block diagram of MANT.

The antenna of MANT consists of 24 three-stacked subarrays, and each subarray consists of 8 × 1 microstrip patch elements as shown in Fig. 2 and Table 2. In each subarray, the horizontal feed for Rx is in the form of parallel feeding and the vertical feed for Tx is in the mixed form of parallel feeding and series feeding. The gain of each subarray in the Rx band (11.7 to 12.75 GHz) is above 17.1 dBi, and the gain in the Tx band (14.0 to 14.5 GHz) is above 17.5 dBi. Also, the isolation between the Tx and Rx ports is below –27 dB over the band of 11.7 to 14.5 GHz. The patch dimension in each subarray is listed in Table 3.

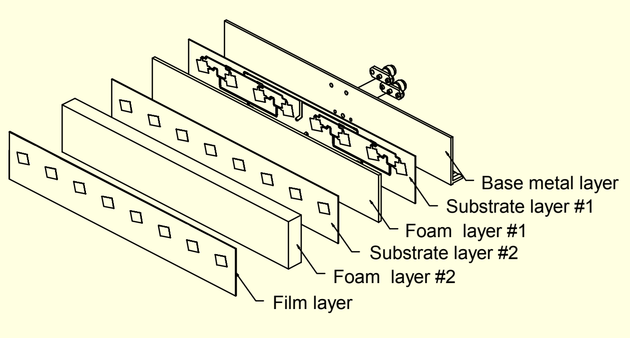


Fig. 2. The configuration of the 8 × 1 subarray antenna.

Table 2. Characteristics of the substrate layers of the 3-stacked patch antenna.

Item	Permittivity	Thickness (mm)
Film layer	2.25	0.04
Foam layer #2	1	10
Substrate layer #2	2.17	0.508
Foam layer #1	1	2.5
Substrate layer #1	2.17	0.508

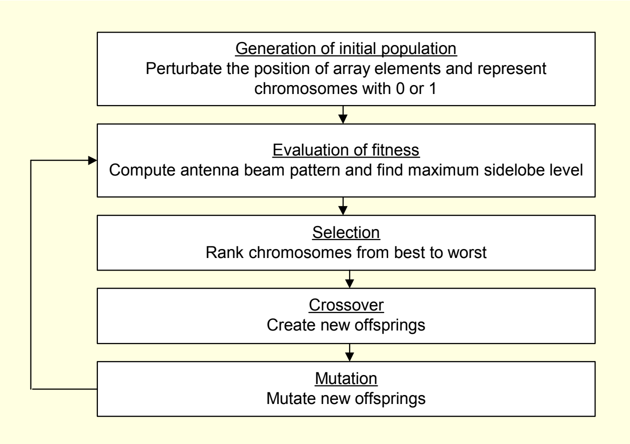


Fig. 3. The position perturbation algorithm of array elements based on the genetic algorithm.

Table 3. Dimension of the patches of the 3-stacked patch antenna.

Item	Width (mm)	Length (mm)
Radiation patch	7.86	6.56
1st patch	8.02	5.88
2nd patch	7.46	6.24

Another characteristic of MANT is that the spacing of the subarray is non-periodic. Generally, equal-spaced arrays bring about high-level sidelobes, while perturbed arrays can suppress sidelobe levels effectively. MANT uses the proposed genetic algorithm (GA) to get an optimal distance between array elements [8]. The position vectors are perturbed and optimized to produce the lowest sidelobe by using GA as shown in Fig. 3. Each chromosome of the initial population involves the information of spacing between array elements expressed with binary strings. Then, the antenna beam pattern is computed according to the given element spaces which are decoded from chromosomes. After that, the fitness of the chromosomes is evaluated from the maximum sidelobe level. Finally, the optimum element spacing is derived from the iteration of selection, crossover, and mutation. This iteration is processed until the termination criteria are satisfied. A non-periodic array distance according to the above result generates a new array factor in radiation patterns. If the element spacing of MANT is periodic, a radiation pattern of MANT can be expressed [9], [10] by

$$\begin{aligned} E(\vec{r}) &= \frac{\exp(-jkR)}{R}\cdot f(\theta,\phi)\cdot AF(\theta,\phi) \\ &= \frac{\exp(-jkR)}{R}\cdot f(\theta,\phi)\cdot AF_{SA}(\theta,\phi)\cdot AF_{tot}(\theta,\phi), \quad (1) \end{aligned}$$

where $f(\theta,\phi)$ is an element pattern, $AF_{SA}(\theta,\phi)$ is the array factor for the subarray, $AF_{tot}(\theta,\phi)$ is the array factor for the entire planar array, and the wave number k is $2\pi/\lambda$. In (1), the array factor for the subarray can be written as follows:

$$\begin{aligned} &AF_{SA}(\theta,\phi) \\ &= \sum_{l=1}^{8}|a_l|\exp\{j(l-1)k_0 D_{xa}(\sin\theta\cos\phi-\sin\theta_0\cos\phi_0)\}, \quad (2) \end{aligned}$$

where the weight amplitude of the l-th unit element is $|a_l|=1$, and D_{xa} is the element spacing between unit elements. And the array factor for the entire planar array can be written as

$$AF_{tot}(\theta,\phi)=\sum_{m=1}^{2}\Bigg[\sum_{n=1,2,13,14}|a_{mn}|\exp\{j(m-1)k_0D_xb_1\}\cdot\exp\{j(n-1)k_0D_yb_2\}+\sum_{n=3}^{12}|a_{mn}|\exp\{j(m+1/2)k_0D_xb_1\}\cdot\exp\{j(n-1)k_0D_yb_2\}\Bigg], \qquad (3)$$

where

$b_1=\sin\theta\cos\phi-\sin\theta_0\cos\phi_0$ and $b_2=\sin\theta\sin\phi-\sin\theta_0\sin\phi_0$; D_x and D_y are the element spacing between subarrays; and the weight amplitude $|a_{mn}|$ of the (m,n)th subarray element is 0 (if m=1 and n=1, 2, 13, 14) or 1 (otherwise). When applying GA, a new array factor can be easily acquired by the change of array distance ($\Delta y_n/n$) such as in (4) [11]. Then, if D_y in (3) is substituted by the value of this new array factor, we can obtain a radiation pattern with low-level sidelobes.

$$Dy' = Dy + \Delta y_n/n \qquad (4)$$

Figure 4 shows the optimized Tx radiation pattern in elevation direction by this proposed GA. The dashed line is a radiation pattern of the equally spaced array before GA optimization. However, the solid line is a radiation pattern of the perturbed array after GA optimization. The optimized sidelobe peak is –12.1 dB, while the initial sidelobe peak is –5.6 dB. In this way, the sidelobe level is suppressed 6.5 dB after optimization and satisfies ITU-R S.728-1.

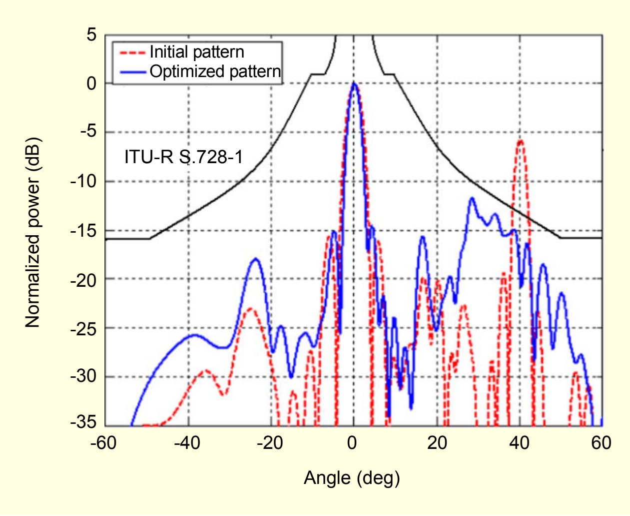


Fig. 4. The MANT-optimized transmitting beam pattern by GA (simulation result).

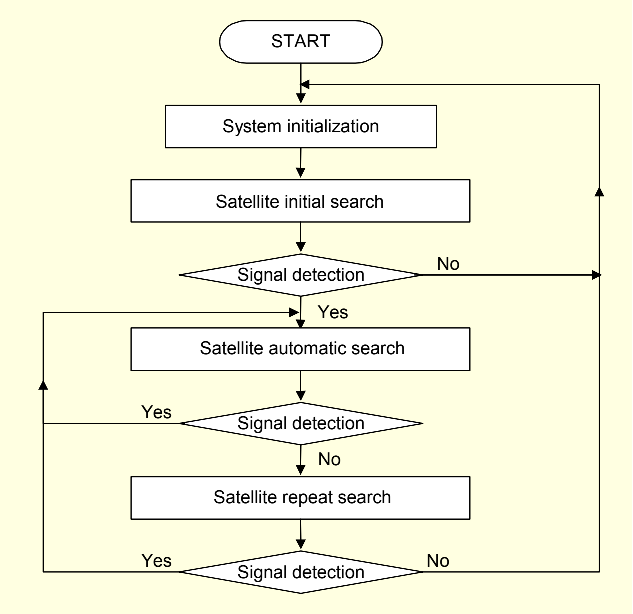


Fig. 5. Event chart of satellite tracking algorithm.

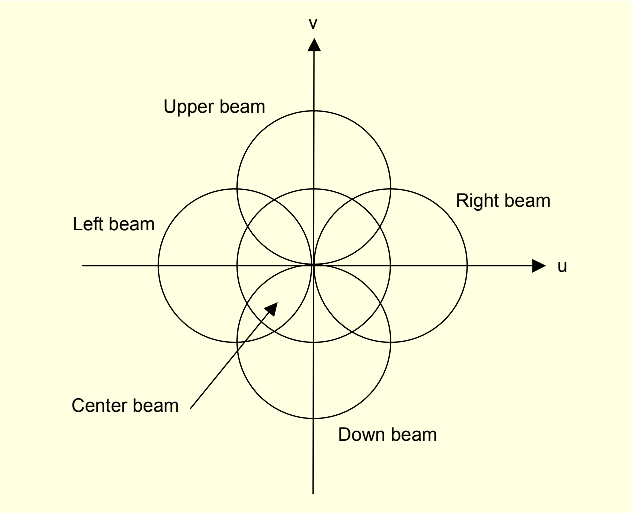
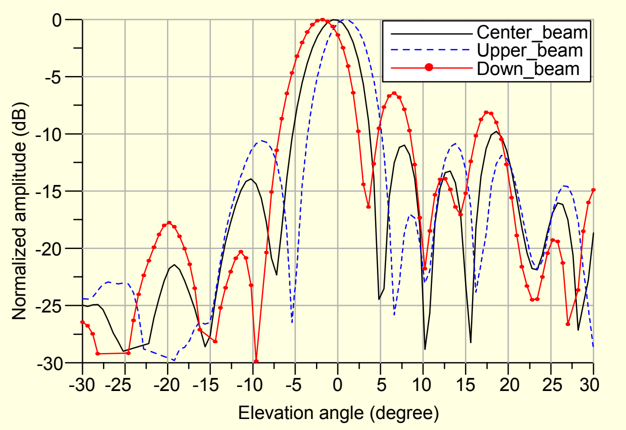
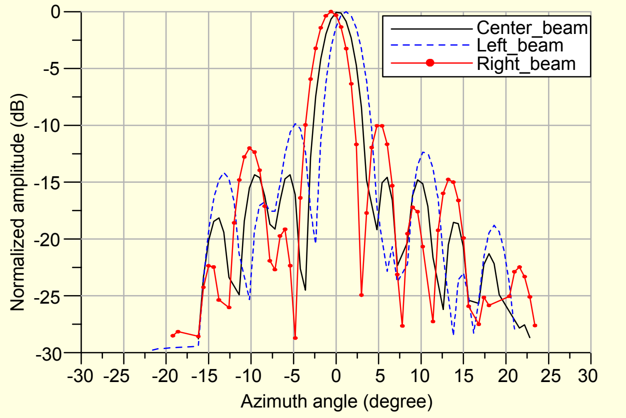


Fig. 6. Tracking beam squinting scheme.

The original satellite tracking system of the double beam forming method in MANT is as follows. An event flow chart of the satellite tracking algorithm in Fig. 5 consists of satellite initial search mode, automatic tracking mode, and repeat search mode. The satellite tracking algorithm in the initial search mode searches the signal of the target satellite with a mechanical and electronic scan in azimuth and electronic scan in elevation. If the signal is detected, the satellite tracking algorithm changes to the automatic tracking mode. MANT in automatic tracking mode tracks the satellite with squinted tracking beams unless the signal is lost due to blocking, shadowing, and so on. MANT in repeat search mode sweeps the search zone for specific duration from the point where the satellite is lost. If the signal of the target satellite is detected, the satellite tracking algorithm goes to the automatic tracking mode; otherwise it returns to the initial search mode. For the stable satellite tracking in MANT, the original satellite tracking algorithm is a double beam forming method that makes an additional beam, a tracking beam, at various points around the Rx beam of MANT using a well-timed phase control of a phase shifter in a beam forming circuit. In MANT, the tracking beam from a double beam forming circuit is sequentially steered to compare the signal intensity of five positions (center, upper, down, left and right of the Rx beam) as shown in Fig. 6. Each measured tracking beam pattern is presented in Fig. 7. In the case of automatic tracking of MANT, the tracking beam is sequentially squinted into the five positives previously mentioned. At that time, the strengths of the acquired satellite signal are compared to find the highest signal strength. Then, the main beam is tilted into the more exact direction of the target satellite. In this way, MANT can stably and accurately auto-track the target satellite on moving vehicles.



(a) Elevation pattern



(b) Azimuth pattern

Fig. 7. Satellite tracking beam pattern.

III. Experimental Results

A photograph and the fabricated characteristics of MANT are shown in Fig. 8 and Table 4. For a bi-directional communication with a satellite, MANT is connected with a set-top box using four cables: a power supply line, data control line, receiving signal line, and transmitting signal line. MANT has a weight of about 34 kg and a size of 860 (major) × 680 (minor) × 210 (height) mm^3. These features are more advantageous than the mechanical parabola antenna. To verify its stable operation, MANT is examined with several characteristics such as return loss , EIRP, G/T, beam pattern, satellite tracking speed, satellite tracking range, and so on. Figure 9 is the measured results of return loss and isolation characteristics for the fabricated 8×1 subarray antenna. In these results, the impedance bandwidth (<–10dB) is over 11% for the Tx band and about 10 % for the Rx band, and the isolation characteristics is below –25 dB. The measured EIRP at the Tx frequency and G/T at the Rx frequency of MANT in a fixed environment are over 34.4 dBW and 7.1 dB/K. The Tx/Rx pattern in the azimuth direction is shown in Fig. 10. In this figure, we know that the Tx/Rx patterns have low sidelobe

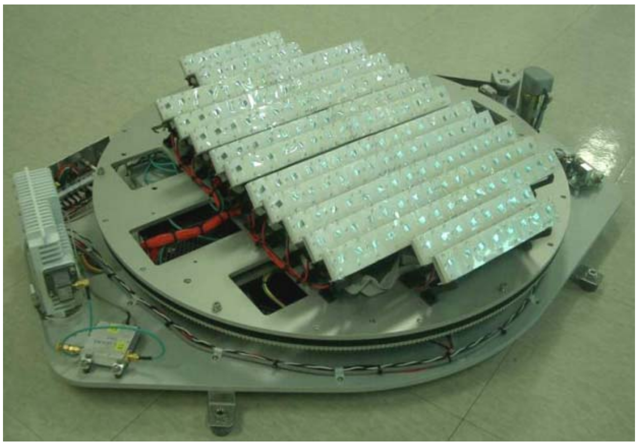


Fig. 8. A photograph of a fabricated MANT.

Table 4. The fabricated MANT characteristics.

Items	Characteristics
Rx frequencies	11.7-12.75 GHz (satisfaction)
Tx frequencies	14.0-14.5 GHz (satisfaction)
G/T	Over 7.1 dB/K (satisfaction)
EIRP	Over 34.4 dBW (satisfaction)
Rx/Tx antenna beam pattern	Satisfaction of ITU-R S.728.1 (VSAT regulation)
Tracking range of satellite	±10° in elevation direction (electronically) ±2° at azimuth direction (electronically) 360° at azimuth direction (mechanically)
Tracking loss range	Below ±0.15°
Power consumption	195 W
Weight	34 kg
Tracking speed	Elevation : Over ±45°/second Azimuth : Over ±45°/second

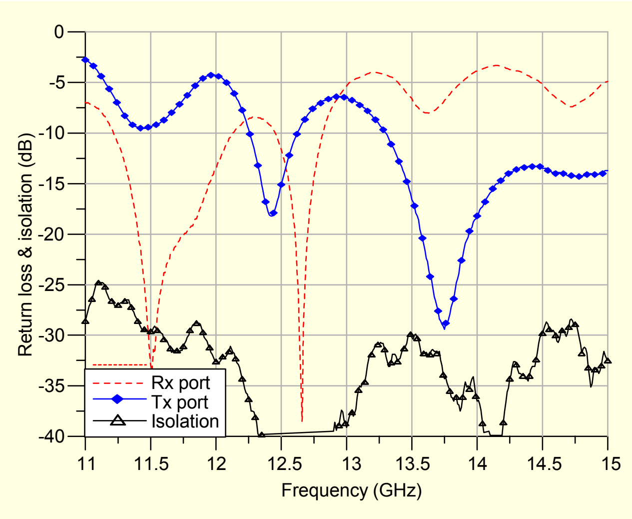
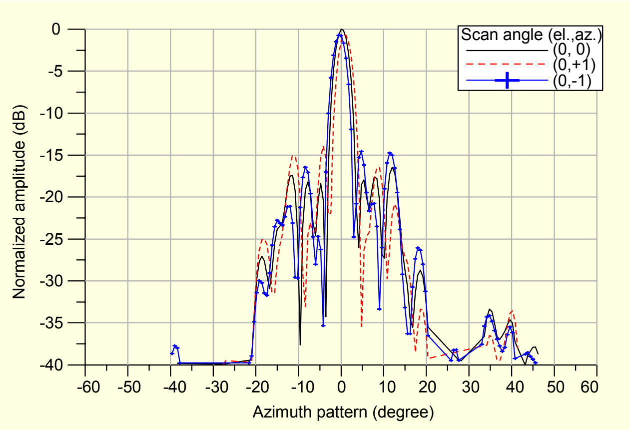
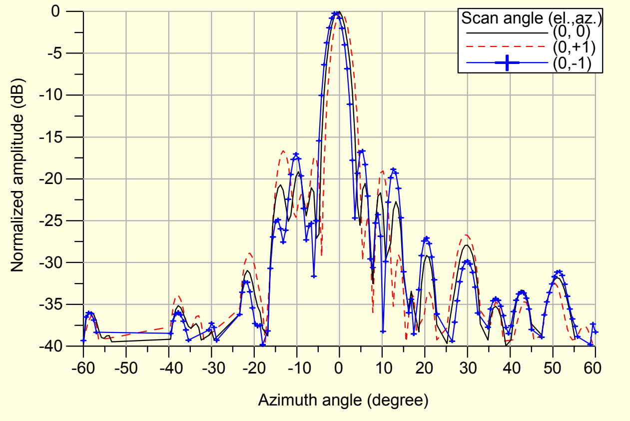


Fig. 9. Return loss and isolation characteristics of a fabricated 8 × 1 subarray antenna.

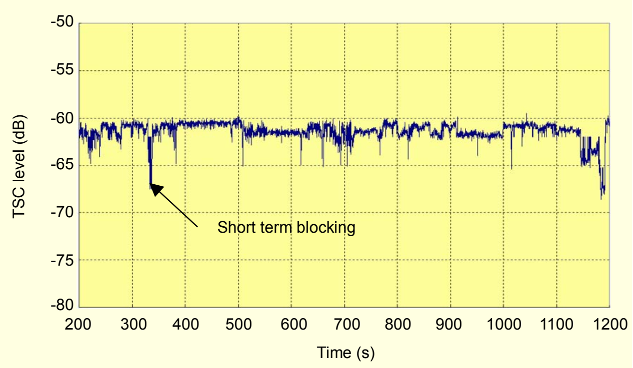


(a) Tx pattern at 14.25 GHz

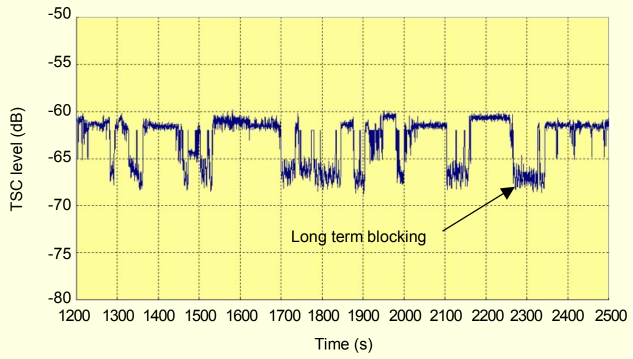


(b) Rx pattern at 12.25 GHz

Fig. 10. Transmission and receiving patterns of MANT in azimuth direction (scan range: ± 1 degree).



(a) Highway



(b) Downtown

Fig. 11. The tracking signal levels for field test.

levels. Also, MANT using the double beam forming method for the satellite tracking system is stably operated within the range and speed of a desired satellite tracking performance.

To confirm the performance of satellite tracking and signal reception in mobile conditions, MANT is tested on a vehicle using a broadcasting signal of KOREASAT-3 in Korea and a communication signal of JSAT-2A in Japan. The experimental results using JSAT-2A are shown in Fig. 11. These graphs present the tracking signal level versus time traveling on roads including a highway and downtown street for about 20 minutes. As the main experimental set-up, MANT was installed on the roof of a test vehicle, and antenna monitoring units such as a notebook PC and spectrum analyzer were equipped inside the vehicle. After these installations, the satellite tracking test of MANT was performed on the traveling conditions. According to this result, we knew that the tracking system of MANT was stably operated within only 3 dB of the tracking loss at the line-of-sight area, and the tracking system of MANT could recapture the target satellite as soon as any obstacles disappeared.

IV. Conclusion

ETRI designed and fabricated the mobile antenna system, MANT, for multimedia communications via the Ku-band satellite. MANT can support the CDMA communication system with a 384 kbps return link and 10 Mbps forward link.

The antenna beam of MANT can be steered electronically in elevation direction and semi-electronically in azimuth direction. To get a small size and good operation characteristics, MANT, which consists of 24 active phased arrays with a stair structure, is arranged with non-periodic distances determined by the proposed genetic algorithm. Also, MANT uses the original satellite tracking algorithm of the double beam forming method for stable satellite tracking. To verify the performance of MANT, we actually examined several characteristics. From the measured results in a fixed and mobile environment using KOREASAT-3 and JSAT-2A, we verify that the satellite tracking and receiving system shows a good performance. Based on the satisfactory results from the road test with a satellite, we confirm that MANT can stably operate in a real environment such as a vehicle, ship, bus, train, and so on.

References

[1] S.Y. Eom et al., "Active Phased Array Antenna for a Vehicle DBS System of Ku-Band," *Proc. of the XXVIII Moscow Int. Conf. on Antenna Theory and Technol.,* Sept. 1998, pp. 257-260.

[2] S. Egashira and E. Nishiyama, "Stacked Microstrip Antenna with Wide Band and High Gain," *IEEE Trans. Antennas Propagat.,* vol. 44, no. 11, Nov. 1996.

[3] S.H. Son, J.S. Yun, U.H. Park, and S.I. Jeon, "Theoretical Analysis for Beam Pointing Accuracy of Stair-Planar Phased Array Antenna with Tracking Beam," *IEEE Proc. of Antennas and Propagation Symp.*, vol. 4, June 2003, pp. 204-207.

[4] M. Pisaruck et al., "Connexion by Boeing^{SM}-Broadband Satellite Services for Aircraft," *Technical Report of IEICE*, SAT2002-70, Oct. 2004, pp. 105-109.

[5] F. NAGASE et al, "Mobile Multimedia Satellite Communication System," *NTT R&D*, vol. 51, no. 4, 2002, pp. 317-324.

[6] ITU-R S. 580-5, "Radiation Diagrams for Use as Design Objectives for Antennas of Earth Stations Operating with Geostationary Satellites," 1994.

[7] ITU-R S. 728-1, "Maximum Permissible Levels of Off-Axis E.I.R.P. Density from VSAT," 1995.

[8] J.H. Bae, K.T. Kim, C.S. Pyo, and J.S. Chae, "Design of Scannable Non-Uniform Planar Array Structure for Maximum Side-Lobe Reduction," *ETRI J.*, vol. 26, no. 1, Feb. 2004, pp. 53-56.

[9] K. Fujimoto et al., *Mobile Antenna Systems Handbook*, Artech House Press, 2001, pp. 465-481.

[10] Constantine A. Balanis, *Antenna Theory Analysis Design*, John Wiley & Sons, 1982.

[11] J.M. Johnson and V. Rahmat-Samii, "Genetic Algorithms in Engineering Electromagnetics," *IEEE Antennas and Propagation Magazine*, vol. 39, no. 4, Aug. 1997, pp. 7-21.

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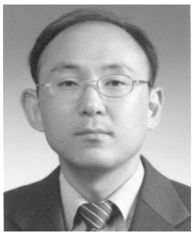
Haeng Sook Noh received the BS and MS degrees in electronics engineering from Dankook University, Korea, in 1995 and 2000. Since 2000, she has been with ETRI, where she has been engaged in research on mobile antenna systems for satellite communications. Her research interests are in phased array antenna and linear array antenna designs.

Seong Ho Son received the BS degree in control and mechanical engineering from Pusan National University, Korea, in 1997, and the MS degree in mechanical engineering from Pohang University of Science and Technology (POSTECH), Korea, in 1999. From 1999 to 2001, he was with the technical research center of Daewoo Motors. Since 2001, he has been with ETRI, where he has been engaged in research on mobile antenna systems for satellite communications. His current research interests are in phased array antenna systems design and satellite tracking control.

Kyong Hee Lee received the MS degree in information and telecommunication engineering from Chonbuk University, Jeonju, Korea. In 2001, she joined ETRI, where was engaged in research on RF power amplifier design for the IMT 2000 repeater. Since 2002, she has been engaged in research on the RF block and MMIC for the Ku-band satellite communication antenna system. Since 2005, she has been a Member of the Research Staff of the RFID/USN group of ETRI. Her research interests include various active RF circuit designs.



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