A Novel Digitally Polarization Tracking Antenna for Ku-band Mobile Satellite Communication Systems

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This paper presents a novel electrical polarization tracking method for mobile satellite communication systems that use linear polarization. It consists of two main technologies; the first estimates the mobile station antenna’s relative polarization angle against that of the satellite’s onboard antenna, the second forms counter polarization against the estimated value. We use a Ku-band communication satellite to evaluate the polarization tracking characteristics and BER performances. These results show that the proposed antenna offers the desired performances.

Nomenclature

\[ G_{ri} = \text{transmission coefficient of a DPT receiving antenna polarization plane } i (i = 1 \text{ or } 2) \]

\[ G_{hi} = \text{transmission coefficient of a DPT transmitting antenna polarization plane } i (i = 1 \text{ or } 2) \]

\[ \mathbf{P} = \text{propagation matrix} \]

\[ \mathbf{R} = \text{polarization angle rotation matrix} \]

\[ R_{H} = \text{amplitude of polarization reference signal of horizontal polarization} \]

\[ R_{H}^{i} = \text{received amplitude of } R_{H} \text{ in a DPT antenna polarization plane } i (i = 1 \text{ or } 2) \]

\[ R_{V} = \text{amplitude of polarization reference signal of vertical polarization} \]

\[ R_{V}^{i} = \text{received amplitude of } R_{V} \text{ in a DPT antenna polarization plane } i (i = 1 \text{ or } 2) \]

\[ r_{ij} = \text{input signal amplitude of channel estimator } (i = 1 \text{ or } 2, j = H \text{ or } V) \]

\[ S = \text{modulated signal} \]

\[ S_{i} = \text{output signal from a DPT antenna polarization plane } i (i = 1 \text{ or } 2) \]

\[ S_{H} = \text{received signal of reference antenna at horizontal plane} \]

\[ S_{V} = \text{received signal of reference antenna at vertical plane} \]

\[ w_{i} = \text{calibration coefficient for the RF front-end path } i (i = 1 \text{ or } 2) \]

\[ \omega = \text{carrier angular frequency} \]

\[ \theta = \text{rotated polarization angle value} \]

\[ \theta_{0} = \text{relative polarization angle against satellite onboard antenna} \]

I. Introduction

Broadband mobile satellite communications services are already being offered to passengers on airplanes, trains, and vessels via the Ku-band1-4. However, the earth stations are quite expensive because highly accurate auto-tracking antennas are required. They must track not only satellite direction but also polarization precisely so as not to interfere with other satellite users and/or other polarization users. Polarization tracking makes it difficult to realize the low-profile antennas desired for airborne and/or train communication. Insufficient polarization tracking yields harmful cross-polarization interference and degrades frequency utilization efficiency.

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To tackle these problems, we focused on the electrical polarization tracking antenna approach. It can eliminate the rotation mechanism of the antenna feed and attendant rotary joints and so can be expected to improve tracking speed while lowering costs. To realize electrical antenna polarization tracking, two main technologies are needed. The first estimates the shift in the mobile station antenna’s relative polarization angle against that of the satellite’s onboard antenna. The second forms counter polarization against the estimated value.

In general, relative polarization angles against the satellite’s onboard antenna are calculated by antenna position information and target satellite information. However, due to low-frequency disturbances, the polarization angle estimates become less accurate.

Airborne antennas, a typical application of electrical polarization tracking, employ an analog-controlled polarization former in the RF band. It consists of some RF components such as phase-shifter and variable gain amplifier. As highly accurate polarization forming must be realized by exciting orthogonal two polarization planes with appropriate weights, they suffer from the control errors triggered by the frequency and temperature dependence of the RF components.

This paper presents a novel digital polarization tracking (DPT) antenna that achieves high-speed and high-accuracy polarization tracking. Our proposal digitally implements a relative polarization angle estimation function and a counter polarization forming function.

Our polarization angle estimator, unlike the conventional polarization angle estimator, estimates the relative polarization angle from the estimated propagation factors of vertical and horizontal polarization signals from a base station whose antenna is precisely aligned in terms of direction and polarization. Our polarization angle estimation method dispenses with high-precision sensors needed by the conventional approach to calculating polarization angle. Furthermore, to achieve high accuracy polarization forming, our antenna is equipped with a digital polarization controller and calibrator for RF components’ characteristics. As our calibrators can offset the RF components’ characteristics such as transmission gain and phase, manual adjustment of the RF circuit is unnecessary.

To evaluate the proposed polarization tracking function, we built several earth stations and carried out several experiments using a Ku-band communication satellite. As a result of satellite experiments, it was confirmed that the proposed polarization tracking technique satisfied the regulatory value on XPD (Cross Polarization Discrimination) and dual polarization sharing transmission among independent earth stations was available in Ku-band mobile satellite communications.

II. Required Performance

As the target value with regard to polarization forming ability, we determined that the XPD had to be at least 27 dB under the ship motion environment. VSAT (Very Small Aperture Terminal) systems, i.e. the well known Ku-band satellite communication system with dual polarization use, must satisfy this value in Japan.

III. Proposed Polarization Tracking Antenna

To realize highly accurate polarization tracking without highly accurate sensors, we propose a novel polarization tracking method. This method consists of two main technologies; the first is estimation of the DPT antenna’s relative polarization angle ($\theta_0$) against that of the satellite’s onboard antenna using a polarization reference signal from the satellite antenna; the second is counter polarization forming against the estimated value.

Figure 1 shows a block diagram of the DPT antenna. It consists of a dual polarization antenna, a relative polarization angle estimator, an electrical polarization forming transmitter, and a maximum ratio combiner. The dual polarization antenna dispenses with a polarization adjustment mechanism and harmonization of the transmission characteristics on the two-path of the RF circuit. The polarization forming transmitter and the maximum ratio combiner counter the polarization mismatch based on $\theta_0$ detected by the relative polarization angle estimator.
A. Relative Polarization Angle Estimation Method

To estimate $\theta_0$, we propose to use a polarization reference signal from the satellite antenna. Figure 2 shows the block diagram of the relative polarization angle estimator. It consists of a dual polarization antenna, a two-path RF front-end, a channel estimator and a polarization angle calculator. Figure 3 shows the principle of polarization angle estimation. When the DPF antenna receives the polarization reference signal, the example is horizontal polarization ($R_H$), the received signal’s amplitude on the DPT antenna’s polarization planes 1 and 2 (pol. 1 and pol. 2) is given by the Eq. (1a) and (2b). $|\theta_0|$ value can be calculated by Eq. (2).

\[ R_{1H} = R_H \cos \theta_0 \]  
(1a)
\[ R_{2H} = -R_H \sin \theta_0 \]  
(1b)
\[ |\theta_0| = \tan^{-1}\left(\frac{|R_{2H}|}{|R_{1H}|}\right) \]  
(2)

However, the actual input signals’ amplitudes at the channel estimator ($r_{1H}, r_{2H}$) are affected by the RF front-end and antenna gain imbalances. These factors are described as follows,

\[ r_{1H} = G_{r1}R_{1H} \]  
(3a)
\[ r_{2H} = G_{r2}R_{2H} \]  
(3b)

where $G_{r1}$ and $G_{r2}$ are transmission coefficient of a DPT receiving antenna polarization plane $i$ ($i=1$ or $2$). $|\theta_0|$ value can be calculated by Eq. (4).

\[ |\theta_0| = \tan^{-1}\left(\frac{r_{2H}G_{r1}}{r_{1H}G_{r2}}\right) \]  
(4)

To calculate $|\theta_0|$ value using Eq. (4), we must specify $G_{r1}$ and $G_{r2}$. However, it is difficult to specify these values accurately due to fluctuation in the characteristics of the RF devices. We propose a $|\theta_0|$ calculation method that dispensed with $G_{r1}$ and $G_{r2}$. Our approach is to use two orthogonal polarization signals as a polarization reference. When the DPF antenna receives a vertical polarization reference signal ($R_V$), input signals’ amplitude at the channel estimator is described as follows. Our proposal is to calculate $|\theta_0|$ value by Eq. (6).

\[ r_{1V} = G_{r1}R_{1V} \]  
(5a)
\[ r_{2V} = G_{r2}R_{2V} \]  
(5b)
\[ |\theta_0| = \tan^{-1}\left(\frac{r_{2H}G_{r1}r_{1V}G_{r2}}{r_{1H}G_{r2}r_{2V}G_{r1}}\right) = \tan^{-1}\left(\frac{|r_{2H}|}{|r_{1H}|}\right) \]  
(6)
In Eq. (6), \(|\theta_0|\) is independent of \(G_{t1}\) and \(G_{t2}\) values, but the sign of \(\theta_0\) is unknown.

Since the initial sign state of \(\theta_0\) can be specified when determining the calibrator’s coefficients, described below, we only have to detect changes in the sign of \(\theta_0\). We focus on the relative phase between received signals on the DPT antenna’s pol. 1 and pol. 2. When \(\theta_0\) is positive, see Fig. 3, the received relative polarization reference signals, \(r_{1H}\) and \(r_{2H}\), are in reversed phase. This phenomenon is also confirmed by Eq. (1a) and (1b). Meanwhile, when \(\theta_0\) is negative, the received signals are in-phase. Therefore, the change in the sign of \(\theta_0\) can be detected by the phase relationship of the received signals.

B. Electrical Polarization Forming Method
(1) Principle
To electrically form the desired polarization, it is necessary to excite the two orthogonal polarization antenna planes with appropriate weights. Figure 4 shows the polarization forming principle. The DPT antenna’s polarization axis is mismatched by \(\theta_0\) from that of the satellite antenna’s polarization axis. In order to output horizontal polarization signal from the DPT antenna, the antenna must be electrically rotated by \(\theta = \theta_0\). For this purpose, the DPT antenna’s pol. 1 and pol. 2 must output reversed phase signals whose amplitude ratio is \(\cos \theta_0\) to \(\sin \theta_0\). These two signals are spatially in-phase combined in the horizontal polarization plane (H. plane), and canceled out in the vertical polarization plane (V. plane).

(2) Implementation and Calibration
However, the output signal errors in each antenna plane due to transmitter gain imbalance cause polarization forming error. Amplitude error causes polarization angle shift error and phase error yields elliptical polarization. Both errors cause signal leakage on the orthogonal polarization plane and XPD degradation. Therefore, harmonization of the transmission characteristics on the two-path of the DPT antenna is very important. Fig. 5 illustrates a promising approach to realize digital polarization forming. It consists of a polarization angle shifter, an RF front-end calibrator, a two-path RF front-end, and a dual polarization antenna.

In order to determine the calibrator coefficients as shown in Fig. 5, we monitored signal level received by a reference antenna which is located at the fixed base station. The reference antenna also transmits polarization reference signals. Figure 6 shows the DPT antenna mathematical model used for determining the calibrator’s coefficients. In this figure, \(R(\theta)\) and \(P\) are the transmission characteristics of the polarization angle rotation matrix and the propagation matrix between the reference antenna and the DPT antenna, respectively. \(R(\theta)\) and \(P\) are given by Eq. (7) and (8).

\[
R(\theta) = \begin{bmatrix} \cos \theta \\ -\sin \theta \end{bmatrix}
\]

\[
P = \begin{bmatrix} \cos \theta_0 & -\sin \theta_0 \\ \sin \theta_0 & \cos \theta_0 \end{bmatrix}
\]
The DPT antenna outputs signals from pol. 1 and pol. 2, $S_1$ and $S_2$, are described by Eq. (9),

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} w_1 G_{t_1} & 0 \\ 0 & w_2 G_{t_2} \end{bmatrix} \mathbf{R}(\theta) S e^{j\omega t} = \begin{bmatrix} w_1 G_{t_1} \cos \theta \\ -w_2 G_{t_2} \sin \theta \end{bmatrix} S e^{j\omega t} \tag{9}$$

where $S$ and $\omega$ indicate the modulated signal and carrier angular frequency, respectively; $w_i$ and $G_i$ are the calibration coefficient of the RF front-end calibrator and the transmission coefficient of the DPT antenna polarization plane $i$ ($i=1 \text{ or } 2$), respectively. The signals received at the reference antenna are given by Eq. (10).

$$\begin{bmatrix} S_{H}(\theta) \\ S_{V}(\theta) \end{bmatrix} = \mathbf{P} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} w_1 G_{t_1} \cos \theta_0 \cos \theta + w_2 G_{t_2} \sin \theta_0 \sin \theta \\ w_1 G_{t_1} \sin \theta_0 \cos \theta - w_2 G_{t_2} \cos \theta_0 \sin \theta \end{bmatrix} S e^{j\omega t} \tag{10}$$

To form H. Polarization, we set $\theta = \theta_0$. The interference signal, $S_t(\theta_0)$, is then given by Eq. (11).

$$S_t(\theta_0) = \sin \theta_0 \cos \theta_0 \left(w_1 G_{t_1} - w_2 G_{t_2}\right) S e^{j\omega t} \tag{11}$$

To minimize the interference signal, $S_t(\theta_0)$, the calibration coefficients should be adjusted to meet Eq. (12).

$$w_1 G_{t_1} = w_2 G_{t_2} \tag{12}$$

We propose a sequential calibration procedure that nulls $S_t(\theta_0)$. At first, the phase of $w_2$ is determined so as to minimize $S_t(\theta_0)$. Next, the amplitude of $w_2$ is determined so as to null $S_t(\theta_0)$.

### IV. Experiments and Results

To confirm the proposed techniques, we fabricated a DPT antenna that consisted of a dual-polarization auto-tracking, RF front-end, and several kinds of functions for polarization tracking. All polarization tracking functions were implemented on FPGAs (Field Programmable Gate Arrays). For channel estimation, we adopted the MMSE (Minimum Mean Square Error) algorithm and used a pair of orthogonal Gold codes as the V/H unique word. A dual-polarization auto-tracking antenna with RF front-end was also developed. Table 1 shows the specifications of the antenna. This antenna has no polarization tracking mechanism and each path’s transmission gain difference due to no adjustment of the RF devices’ transmission characteristics.

Figure 7 shows the satellite experimental setup. It consisted of a simulated mobile station (MS)

### Table 1. Tracking antenna specification.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture diameter</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Number of polarization</td>
<td>2 (linear)</td>
</tr>
<tr>
<td>Pointing error</td>
<td>&lt; 0.2 degrees</td>
</tr>
<tr>
<td>Antenna gain</td>
<td>TX : 40.3 dBi</td>
</tr>
<tr>
<td></td>
<td>RX : 39.3 dBi</td>
</tr>
<tr>
<td>EIRP</td>
<td>45 dBW</td>
</tr>
<tr>
<td>G/T</td>
<td>15 dB/K</td>
</tr>
<tr>
<td>RF output power</td>
<td>8 W (each pol.)</td>
</tr>
</tbody>
</table>

### Table 2. Simulated ship motion.

<table>
<thead>
<tr>
<th>Motion Type</th>
<th>Small wave</th>
<th>Big wave</th>
<th>Circling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll</td>
<td>1º / 6s</td>
<td>5º / 6s</td>
<td>5º / 7s</td>
</tr>
<tr>
<td>Pitch</td>
<td>0º / 4s</td>
<td>4º / 5s</td>
<td>1º / 10s</td>
</tr>
<tr>
<td>Yaw</td>
<td>35º</td>
<td>5º</td>
<td>170º</td>
</tr>
</tbody>
</table>
employing DPT antenna and a base station (BS). The DPT antenna was mounted on a ship motion simulator, which mechanically creates three dynamic ship motions (Small wave, Big wave, and Circling). Table 2 lists the motion specifications.

First of all, we evaluated the calibration function and static polarization tracking function. In this experiment, we monitored the BS's received signal level. Figure 8 and Figure 9 show received signal spectra of H. and V. polarization before and after calibration, respectively. As shown in Fig. 9, we confirmed that polarization interference less than the noise level by using the proposed calibration. The calibration results indicated that the amplitude and phase differences before calibration were estimated to be 1.8 dB and 72 degrees, respectively.

Next, we evaluated the polarization tracking performance in artificial ship motion environments. For comparison, we also measured a commercial tracking antenna under the same motions. Figure 10 and Figure 11 show the measured XPD performances. Figure 10 confirms both antennas achieved the required polarization tracking performance (XPD > 27 dB). With circling motion, see Fig. 11, the commercial antenna allowed tracking error to creep in. This occurred because the maximum motion around the YAW axis was 15° within 8 sec., more than twice the commercial antenna spec. (6° per 8 sec). The proposed DPT antenna could maintain antenna polarization tracking even in the face of this extreme yaw rate. These results confirm that our method offers high speed and high accuracy polarization tracking.

Next, we measured the BER performance of the link from the MS to the BS. For this measurement, we used a QPSK modulated signal (symbol rate: 1.28 MHz) with turbo product code (R = 0.66). Figure 12 shows the measurement results in three cases; manual polarization adjustment in static condition, polarization tracking mode in static condition and in big wave condition. The degradation in required Eb/N0 was about 0.5 dB in each case. Since no significant difference was observed among these three conditions, it was concluded that the proposed polarization tracking was sufficiently available even in practical moving environments.

Finally, we performed a dual polarization frequency sharing transmission experiment. In this experiment, we measured the BER performance of the BS (H. pol.) loop-back link. We also transmitted a polarization interference signal from the BS (V. pol.) or the MS (V. pol.). Figure 13 shows the results. The degradations imposed by dual
polarization frequency sharing transmission were about 0.3 dB in both cases compared to single polarization transmission. We considered that the degradation was due to the BS’s received antenna’s XPD characteristics. These results show that our polarization tracking technique is feasible for dual polarization sharing transmission using a Ku-band mobile satellite.

V. Conclusion

We described a digitally controlled polarization tracking antenna for Ku-band mobile communication satellite service. To achieve high polarization tracking ability, we proposed two techniques. One estimates the mobile station antenna’s relative polarization angle against that of the satellite’s onboard antenna. The other is counter polarization forming against the estimated value. We evaluated the polarization tracking characteristics and conducted transmission experiments using Ku-band communication satellite. The results showed that the developed antenna offers the desired performance in terms of XPD and BER.

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7Ordinance Regulating Radio Equipment, section 7.2.2, Article 54.3