Estimation of delay time difference through space for phased array antennas with true time delay

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Abstract: Large aperture and wideband phased array antennas use both phase shifters for each element and true time delay for each subarray to avoid squint. Thus both phase shifter calibration and true time delay calibration are required. In this paper, we focus on true time delay calibration, and propose a method that conducts measurements through space to estimate the delay difference between two subarrays. Our method is essential in systems for which wired measurements are impossible. Additionally, phase measurement is not required in our method because the delay difference is estimated from just the level variation. Experiments and their results are detailed. Delay difference could be estimated with error of 0.37\(\lambda\) or better.

Keywords: true time delay, phased array antenna, delay calibration

Classification: Antennas and Propagation

References


1 Introduction

Wireless communications systems and radars tend to use phased array antennas (PAAs) with electrical beam scanning [1]. In order to control the exciting phase of antenna elements, each antenna element generally employs a phase shifter. However, trying to realizing large aperture and wideband is hindered by the squint of the main beam [2]. Squint arises because the ideal exciting phase of each element differs within the frequency bandwidth, but the standard phase shifter outputs constant phase within the bandwidth. If signal transmission or reception timing used instead of phase shift, the squint can be avoided. Timing control demands knowledge of the true time delay (TTD).

Some methods to realize TTD have been proposed; (1) to simply select line length, (2) to use an optical switch, and (3) to digitally control signal timing by using direct digital synthesizer (DDS) [3]. If the exciting phases of all elements are controlled by TTD, squint is completely eliminated. However, in general, such system are overly complicated and expensive. Thus All antenna elements use phase shifters, while TTD is imposed on each subarray consisting of multiple elements. While squint can not be perfectly eliminated by this arrangement, compensation methods of TTD error by adjusting the phase shifters have been proposed [4].

Calibrating such PAAs demands both phase calibration for each element and delay calibration for each subarray. For the phase calibration, several methods have been proposed. One example is the rotating element electric field vector (REV) method [5]. It utilizes the cosine-shaped level of the summed electrical field versus the phase variation. Delay calibration may not be needed if delay error is not predicted, e.g., TTD and antenna are connected directly. On the other hand, when TTD and antenna are connected by a long cable, delay calibration is required. Though, of course, the cable delay can be measured in wired section, it is impossible to measure it in systems that can not be overhauled.

In this paper, we propose an method of estimating the delay difference between two subarrays through space. The method transmits a signal from two subarrays with an already-known delay difference. A cosine-shaped response is observed at the receiver when the frequency is swept. Total delay difference is estimated from the cycle of the response. Subtracting the already-known delay difference from the total delay difference yields the delay error of the wired section between subarrays. Our method suits systems for which wired measurements is difficult. Moreover, phase measurements are not required because delay is estimated from just the level variation. Thus a vector network analyzer is not needed matching the characteristic of REV.

We explain the method and show the results of experiments conducted to confirm that the delay difference could be estimated within practical error limits.
2 System configuration and formulation

The assumptions of this study are introduced. Fig. 1(a) shows the PAA system with TTD and phase shifter. It has TTD for each subarray and phase shifters for all elements. The delay and frequency are taken to be variable and ideal. This is realistic when DDS is used. In this system, the factors causing delay error remain such as individual differences in the analogue circuits of each subarray and cable length. A receiver to measure power level is deployed. Our goal is to realize delay estimation through space.

Two subarrays are used and only one element of each subarray is driven as per Fig. 1(a). Vectors of each component are as per Fig. 1(b). \( \rho_i \) is antenna position of the PAA. Summed electrical field from the two antennas at the receiver is given by

\[
E = A_1 e^{j\Phi_1} \frac{e^{-jr_1}}{r_1} a_1(\mathbf{u}_r) + A_2 e^{j\Phi_2} \frac{e^{-jr_2}}{r_2} a_2(\mathbf{u}_r),
\]

where \( A_i \) is excitation amplitude of element \( i \), \( \Phi_i \) is excitation phase, and \( a_i(\mathbf{U}_r) \) is array element pattern. We assume that the excitation amplitude of two elements is 1, excitation phase of one element \( (i = 1) \) is 0 deg. Distance is converted into units of time, (1) is rewritten as

\[
E = e^{-j2\pi f t_1} \frac{1}{r_1} a_1(\mathbf{u}_r) + e^{j\Phi} \frac{e^{-j2\pi f t_2}}{r_2} a_2(\mathbf{u}_r)
\]

where \( t_1 \) and \( t_2 \) are propagation time from element 1 and 2 to the receiver, respectively. \( \Phi \) is excitation phase difference \( \Phi_2 - \Phi_1 \). Because we define \( \Phi_1 = 0 \) deg, \( \Phi \) equal to \( \Phi_2 \). Breakdown of \( \Phi \) is

\[
\Phi = -2\pi f(t_{TTD} + t_{system})
\]

where \( t_{TTD} \) is the delay difference between two TTDs. One TTD may be assigned 0 sec. \( t_{system} \), the parameter to be estimated, is the delay error difference due to cable length or individual difference of analogue circuits of each subarray. Substituting (3) into (2),

\[
E = \frac{1}{r_1} a_1(\mathbf{u}_r) + e^{-j2\pi f(t_{TTD} + t_{system})} \frac{e^{-j2\pi f t_2}}{r_2} a_2(\mathbf{u}_r)
\]

is obtained. Propagation time difference between \( r_1 \) and \( r_2 \) is
Substituting (5) into (4), yields amplitude as

\[ |E| \propto |1 + e^{-j2\pi fT}| \]  

(7)

where

\[ T = t_{TTD} + t_{system} + t_r. \]  

(8)

Here, \( t_{TTD} \) is already known. \( t_r \) is propagation distance difference. If the distance between PAA and the receiver is far, it can be calculated from the path length difference based on the plane wave assumption. At shorter distances, it can be measured directly. When frequency is swept, (7) varies cyclically. If \( |E| \) is squared, it becomes cosine-shaped. When \( |E| \) completes one cycle with frequency sweeping, we define its required frequency range as \( F \). \( FT \) becomes \( 1/F \) in (7). Therefore \( T \) is determined as

\[ T = \pm \frac{1}{F}. \]  

(9)

Sign in (9) is determined by the following condition. If the absolute value of \( t_{TTD} \) in (8) is bigger than the absolute value of the sum of \( t_{system} \) and \( t_r \), i.e.,

\[ |t_{TTD}| > |t_{system} + t_r|, \]  

(10)

then the sign of right side in (8) should be the same as the sign of \( t_{TTD} \). (10) depends on system design. For example, (10) holds when \( t_{system} \) is clearly small and large \( t_{TTD} \) is applied. If (10) is used, \( t_{system} \) is determined including the sign,

\[ t_{system} = T - t_{TTD} - t_r = \frac{1}{F} - t_{TTD} - t_r, \]  

(11)

where \( t_{TTD} \) is positive.

The relationship between required frequency bandwidth and resolution and delay difference is shown here. Required bandwidth for one cycle of (7) is simply \( F = 1/T \). When large \( T \) is selected, required \( F \) can be reduced so as to fit the available bandwidth of antennas and RF devices. On the other hand, if available frequency is discrete, estimation resolution will deteriorate due to the large delay variation triggered by each frequency step. We define minimum frequency step as \( \Delta f \) and its delay variation as \( \Delta T \). Their relationship is

\[ \Delta T = T \frac{\Delta f}{F} = \Delta fT^2. \]  

(12)
3 Experiment on delay difference estimation

We conducted an experiment of the delay estimation proposal. The system of Fig. 2(a) was built in an anechoic chamber. Two antennas, assumed to belong to different subarrays, were used at PAA side for simplicity, see Fig. 2(b). The known delay difference $t_{TTD}$ is given by cable length difference. A phase shifter was inserted behind element 2 to simulate delay error $t_{system}$. Because the phase shifter is a trombone type device, it creates some delay time. We define $t_{TTD}$ as the difference between ‘delay between A and B’ and ‘delay between A and C with minimum phase shifter value’ in Fig. 2(a). Wired measurement found that $t_{TTD}$ was 7.698 ns. The wired measurement is not needed in the proposed procedure, and is for a comparison between the true value and the estimated value. We used Ku band and frequency step size was 100 kHz. $T$ is approximated by $t_{TTD}$ because the delay difference was dominated by cable length. Thus the required bandwidth is 130 MHz and delay resolution is 5.9 ps from (12).

Received level variation according to frequency sweep is shown in Fig. 3(a). While antenna spacing was fixed to 215 mm, several phase shifter values were examined. Cyclic patterns were obtained as shown in (7). We used the spacing between adjacent nulls to obtain cycle period from Fig. 3(a). Multiple cycles were averaged to offset the error due to the antennas’ frequency characteristics. Estimated delay is shown in Fig. 3(b). The chain line is overall delay difference $T$ including propagation delay. The solid line is obtained by subtracting propagation distance from overall delay difference estimated. It means the delay difference of the wired section, i.e., $t_{system} + t_{TTD}$. We directly measured the propagation distance because propagation distance was short, about 4 m. Path length difference was 39 mm, 0.13 ns. The broken line is the true delay difference between A-B and A-C in Fig. 2(a) according to wired measurements. All lines are downward-sloping because delay difference decreases as delay is increased by the phase shifter.

Comparing estimated value though space and true value, no difference exceeds 33 ps, and rms error was 19 ps. It was bigger than the theoretical value, 5.9 ps. One cause is the approximation that yields (7) from (6). Strictly speaking, $a_1(U_{r1})$ is not equal to $a_2(U_{r2})$ and $r_1$ is not equal to $r_2$. However,
33 ps corresponds to just $0.37\lambda$ at center wavelength. This error can be mostly eliminated by phase calibration after delay calibration. As a result, beam squint can be suppressed. Estimated $t_{\text{system}}$ can be obtained by subtracting $t_{\text{TTD}}$ (7.698 ns) from the solid line.

### 4 Conclusion

We proposed a method that uses true time delay in estimating delay time difference through space for phased array antennas. In the method, a signal is transmitted from two subarrays with an already-known delay difference. Total delay difference is estimated from the cycle of the cosine-shaped received signal. Our method is applicable to systems for which wired measurement is difficult. Additionally, phase measurement is not required, only the level variation. We described our experiments. Delay difference was estimated with error of 33 ps or lower. This is lower than $1\lambda$ and remaining error can be virtually eliminated by phase calibration.