Interferometric angle-of-arrival estimation using a simple weight network

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Abstract: This paper presents a method to estimate the Angle of Arrival (AOA) for incident waves, using an RF-based interferometric monopulse technique. We used an AOA network to yield a weight function for the received signals, in which the phase of the received signals for each element is delayed in accordance with the coordinate of the elements using the differing lengths of microstrip transmission lines. Based on electromagnetic field analysis and experimental results, it is clarified that the proposed method achieves a high degree of accuracy for AOA estimation.

Keywords: interferometric angle of arrival estimation, circular array, weight network, connected car

Classification: Antennas and Propagation

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1 Introduction

In the automotive industry, there is a significant interest in realizing new technologies such as self-driving cars, Internet of Things (IoT) for automobiles, and commercial vehicle management [1]. The direction of the incoming wave, i.e. the communications counterpart, such as another connected car or traffic signal, changes significantly according to the dynamic movement of the automobile. Therefore, the connected car must estimate the direction of incident wave autonomously. We are currently developing a multiple-input multiple-output (MIMO) antenna system that utilizes the circular phased array technology for use in connected cars [2]. This MIMO antenna system is realized using the capability of the angle of arrival (AOA) estimation function [3].

As for an AOA network, a Butler matrix is commonly used for giving an appropriate phase delay to the received signals [4]. However, a Butler matrix has the drawback of being a bulky microwave component, which leads to hardware complexity. The AOA antenna proposed in this paper employs an RF-based interferometric monopulse technique without a Butler matrix, which reduces hardware complexity [5].

This paper presents an experimental verification of AOA estimation that employs an RF-based interferometric monopulse technique. We used an AOA network for yielding a weight function to the received signals, in which their phase for each element is delayed in accordance with the coordinates of the elements, using the differing lengths of microstrip transmission lines. The experimental results are in good agreement with the results obtained from the geometrical relationship between the direction of incoming waves and the location of antenna elements.

2 Principle of the AOA estimation

As shown in Fig. 1(a), the AOA antenna is composed of nine elements, eight of which (#1–#8) are arranged at equal angular intervals of 45° on a circle of radius a , with the final element (#9) located at the center of the circle. When a radio wave originates from the ϕ direction, measured from the x -axis, the voltage induced on the i^{th} element located on the circle with radius a is calculated using the following equation:

$$V_i = e^{j\frac{2\pi}{\lambda}a \cos(\frac{2i-1}{8}\pi - \phi)} \quad (1)$$

where all the elements are assumed to be isotropic antennas, and λ denotes the wavelength of the received signal.

The voltage V_i is multiplied by the weight function W_i defined by the following equation:

$$W_i = e^{-j\frac{2i-1}{8}\pi} \quad (2)$$

The summation of the total voltage induced on the eight elements can therefore be written as:

$$E_{\Delta} = \sum_{i=1}^8 e^{j\{\frac{2\pi}{\lambda}a \cos(\frac{2i-1}{8}\pi - \phi) - \frac{2i-1}{8}\pi\}} \quad (3)$$

Now, we consider the case where the number of elements is infinite and E_{Δ} converges to the Bessel function expressed by the following equation:

$$E_{\Delta} = e^{-j(\phi - \frac{\pi}{2})} \cdot 2\pi J_1\left(\frac{2\pi}{\lambda}a\right) \quad (4)$$

The received signal at the ninth element is represented by E_{Ω} . Furthermore, phases of E_{Δ} and E_{Ω} are denoted by $\angle E_{\Delta}$ and $\angle E_{\Omega}$, respectively. The phase difference is calculated as follows:

$$\phi_m = \angle E_{\Delta} - \angle E_{\Omega} \quad (5)$$

The phase difference expressed by Eq. (5) is approximately proportional to ϕ (the actual direction of an incident wave).

Fig. 1(b) shows the summation of the whole voltage denoted by Eq. (3) as a function of the array radius, together with the Bessel function. The frequency used in the analysis is 2 GHz. The magnitude of E_{Δ} reaches the maximum value when the radius is 4.4 cm. This configuration of narrow element spacing may lead to a significant gain reduction in the antenna, due to a strong electromagnetic mutual coupling. However, the effect of mutual couplings is not adequately considered in the theoretical formula.

To investigate the effects of mutual couplings on the characteristics of the AOA antenna, half-wavelength dipole antennas are used for the nine array elements. All dipoles are terminated at 50 Ω . The complex field pattern is calculated using the method of moments.

The analytical results reveal that even in the presence of mutual couplings, the radiation gain of the antenna is nearly the same as that of a half-wavelength dipole antenna [6]. We have verified that this phenomenon is attributed to the decoupling mechanism caused by the cancellation of signals, with the weighted phase excitation induced in 50 Ω terminals.

Fig. 1(c) shows the error of the estimated angle as a function of the array radius. The error is reduced by decreasing the array radius, with an error of less than 0.1° when the array radius is 4.9 cm. The maximum error decreases with a decrease in the distance between the adjacent elements. Hence, we determined the array radius to be 4.9 cm, based on the performance of the MIMO array [2]. Therefore, the distance between the adjacent elements is 3.75 cm, which is equivalent to a quarter wavelength at 2 GHz. In this case, the directivity of the subarray is expected to have a cardioid radiation pattern.

Fig. 1. Circular array arrangement for interferometric angle of arrival estimations.

3 Network used for estimating the AOA

In this paper, we introduce the weight functions defined by Eq. (2), allowing the use of a simple AOA network. Fig. 2 shows the network used for estimating the AOA that processes the received signals [7]. Fig. 2(a) is a diagram, and Fig. 2(b) depicts a fabricated microwave circuit using a double-sided printed circuit board (an FR4-based PCB) with a thickness of 1 mm and a relative permittivity of 4.2.

In Fig. 2(b), the phase of the received signals for each element is delayed in accordance with Eq. (2), using the differing lengths of microstrip transmission lines. The use of a 180° rat-race hybrid in Fig. 2(b) allows a 180° phase reversal to be involved in the two signals combined by the three Wilkinson power combiners located on the right and left side of Fig. 2(b), enabling a small-sized AOA network to be realized.

Fig. 2(c) shows the phase characteristics of the fabricated AOA network. The phase difference between Port $\#i$ ($i = 1, 2, \dots, 8$) and Port E_Δ was measured at 2 GHz using a vector network analyzer. In Fig. 2(c), Port $\#1$ is used as a reference of the phase. In Fig. 2(c), the measured phase decreases by 45° intervals with an increase in the element number. Furthermore, the difference between the measured and designed phases is 5.3° on average. These facts indicate that the fabricated AOA network works properly to achieve the operation of the weight function given by Eq. (2).

Fig. 2. Network used for estimating the AOA.

4 Experimental results

In our previous study [7], the impact of the array radius on the operating characteristic has not been investigated because the radius was fixed at 4.9 cm. In this paper, an experimental verification of the proposed AOA estimation method with regard to the different array radius was conducted in an anechoic chamber. Fig. 3(a) shows a photograph of the AOA antenna, with the network depicted in Fig. 2(b). Hereafter, we consider an AOA configuration where eight half-wavelength dipole antennas (#1–#8), designed at 2 GHz, are mounted on a circle with a radius a and an additional dipole antenna (#9) is located at the center of the circle, as shown in Fig. 3(a).

Fig. 3(b) shows the radiation patterns of E_Δ and E_Ω defined in the xy -plane. The solid and dashed lines depict the measured and calculated results, respectively. The blue lines depict E_Δ , whereas the red lines represent E_Ω with a radius of 4.9 cm, respectively. The black lines depict E_Δ with a radius of 8.5 cm. As shown in Fig. 3(b), the radiation gain of E_Δ at $a = 4.9$ cm is approximately 0 dBd. A larger radiation gain is achieved with a radius of 4.9 cm than with 8.5 cm. This behavior is in good agreement with the results obtained from Fig. 1(b). The amplitudes of E_Δ and E_Ω have omnidirectional patterns, with a radius of 4.9 cm. Hence, the fabricated AOA antenna can be received signal that the communication target radiates.

Fig. 3(c) shows the phase radiation characteristics. The solid and dashed lines depict the measured and calculated results, respectively. The phase of E_Δ is approximately proportional to the actual direction of an incident wave ϕ . On the

other hand, the phase of E_Ω remains constant regardless of the azimuth angle. These facts indicate that the fabricated antenna works well as AOA function.

Fig. 3(d) shows the estimated angle as a function of the AOA for an incident wave. Fig. 3(d) shows that measured results are proportional to the angle of an incident wave. The error in the red and black curves was found to be 6.1° and 11.2° on average, respectively. In Fig. 1(c), the estimated angle is characterized by a higher accuracy when the radius is 4.9 cm than when it is 8.5 cm. The same results as in the analysis were obtained by actual measurements. However, the estimation error is larger in the actual measurements. A possible cause of this error is the phase error arising from the fabricated AOA network, as shown in Fig. 2(c).

Fig. 3. Experimental verification of the AOA estimation.

5 Conclusion

This paper presents an experimental verification of AOA estimation that employs an RF-based interferometric monopulse technique. The experimental results are in good agreement with the results obtained from the geometrical relationship between the direction of incoming waves and the location of antenna elements.

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