A Self-Calibration Antenna Array System with Moving Apertures

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***Abstract* — In this paper, an antenna array system with self-calibration capability to the antenna element position errors is proposed. The essential concept of self-calibration is to detect the element positions by using near field reference sources. The estimated position information is further substituted into the beamforming process to correct the distorted pattern of the antenna array. To validate the proposed concept, a test bed with a "distorted" eight element array is set up. With the proposed calibration architecture, the estimation of the position errors is within 7% of the free space wavelength, Based on the estimation information, the array pattern can thus be synthesized**

I. Introduction

Calibration of the antenna array system has become an important part of the array system because the system performance is usually very sensitive to the phase errors. Such errors may significantly shift the direction of antenna beams and nulls, thus affect the system SNR performance [1]. Generally, the error existing in the phased array system comes from two parts— circuit error and element location error or position error. A majority of work has been done to calibrate the circuit error [2-3]. The element position error usually exists in some special communication systems called distorted phased array, such as balloon communication systems, in which the antenna array is built on the balloon's surface, with changing spacing between the elements all the time. Some researchers have proposed their own calibration methods in [4-5]. however, most of those ideas are developed for certain scenarios and can not be extended for general applications. Real world phased array systems usually require a fast, simple, compact and robust calibration process.

In this paper, a self-calibration scheme for both the position error and circuit error has been presented. The essential idea is to use near field reference sources. A few advantages are associated with the proposed configuration. First, the existence of self-calibrating sources brings the calibration scheme more adaptability, even for battlefield systems in a hostile environment. Second, only very limited number the reference sources are required and these sources can be practically mounted on rigid frames. Third, the approach is insensitive to the absolute delay and phase error of the reference source, which make the approach more robust. The calibration process is divided into two steps—first, an estimation algorithm is used to estimate the position error. The basic principle is somewhat like that of GPS receivers. A special technique is employed in this algorithm so that the circuit error's affect can be cancelled out. The second step includes a circuit error calibration.

The key technique of this system is to separate the position error and circuit error with near field sources. Orthogonal coding technique makes it possible for the near field sources to share one frequency channel. Finally, the output information from the calibration system can update the old weighting coefficients to restore the correct far field pattern.

This paper is organized as follows. Section II presents the basic theory of this calibration algorithm. To test the effectiveness of the proposed approach, a test bed is developed with an 8-element distorted array. Section III provides the overview of such a test bed. Section IV presents the measured results to demonstrate the performance of the proposed approach. Finally, conclusions are made in section V.

II. CALIBRATION THEORY

A. Position calibration:

To calibrate the three dimensional moving of the antenna element, four sources are needed.

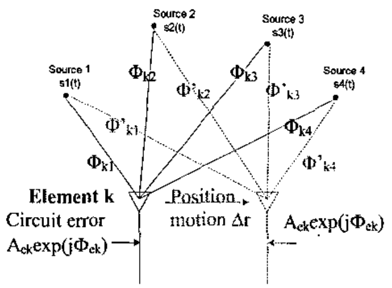

Fig.1 Geometry of array calibration

Fig.1 describes the basic idea of this position calibration algorithm. The four calibration sources are fixed in the positions close to the receiving antenna array. Element k is the kth element in the smart antenna array and because of mechanic moving, this element has a three dimensional

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position motion Δr. Furthermore, there is circuit phase error Φ_{ek} in the branch k., caused by element's aging or circuit connectors and solders. $\Phi_{k\xi}$, ξ=1,2,3,4 is the phase shift created by the distance between sources and element k. In order to make the algorithm more robust, three basic assumptions have to be made.

1) Four calibration sources are fixed in the near field of the antenna array but still far field of the each antenna.

2) Four sources are synchronized or the phase difference is known.

3) The position motion is very small compared with the distance between sources and the element.

The purpose of this algorithm is to use the phase information to calibrate the position. However, the circuit phase error Φ_{ek} does always exist in the receiving signals. Here, the phase difference between two sources' signal at the receiving element k is calculated so that Φ_{ek} is cancelled.

$$\Delta\Phi_{k\xi} = (\Phi_{k\xi} + \Phi_{ek}) - (\Phi_{k\xi+1} + \Phi_{ek}) = \Phi_{k\xi} - \Phi_{k\xi+1}$$

$$\Delta\Phi'_{k\xi} = (\Phi'_{k\xi} + \Phi_{ek}) - (\Phi'_{k\xi+1} + \Phi_{ek}) = \Phi'_{k\xi} - \Phi'_{k\xi+1} \qquad (1)$$

Where ξ=1,2,3.

$\Delta\Phi_{k\xi}$ and $\Delta\Phi'_{k\xi}$ represents the phase difference before and after motion.

Thus the circuit phase error term is removed. The next step is to construct the relationship between phase information and position motion Δr. Due to the assumption (3), a linear relationship can be easily found:

$$(\Delta\Phi_{k\xi} - \Delta\Phi'_{k\xi}) + n_{k\xi} \propto \Delta r \qquad \xi=1,2,3 \qquad (2)$$

Obviously, the position motion is proportional to the difference of the phase difference. Here, a random phase noise term $n_{k\xi}$ is added to simulate the random error in extracting the phase information from the receiving signals. Using proper DSP algorithm, such as Kalman filters, will give the best estimation of the unknowns under the noisy condition.

The reason we need four calibration sources is that the position motion is three-dimensional and at least three equations like (2) can solve for the three unknowns (Δx, Δy, Δz).

$$\begin{pmatrix} \Delta x_k \\ \Delta y_k \\ \Delta z_k \end{pmatrix} = \mathbf{H}(x_k, y_k, z_k) \begin{pmatrix} \Delta\Phi_{k1} - \Delta\Phi'_{k1} \\ \Delta\Phi_{k2} - \Delta\Phi'_{k2} \\ \Delta\Phi_{k3} - \Delta\Phi'_{k3} \end{pmatrix} \qquad (3)$$

Where **H** is the coefficients matrix which is only the function of element k's original position (x_k ,y_k ,z_k) and source positions. Thus the new position of the element k can be easily obtained.

After detecting the new position of the each antenna element, the new weighting coefficients can be calculated with the adaptive beamforming technique such as sample matrix inversion (SMI).One thing needs to mention is that the original position of the element can be either previous calibration position or virtual position. The meaning of virtual position is that we can assume the element is moving around a center point. In each time step, the position motion according to the virtual position is detected so that we can "position" the antenna element.

B. Source coding:

The four near field sources share the same channel, so that special coding technique is needed to separate them in the receiving antenna. Here, orthogonal sequence is used. The four synchronized sources send out four modulated orthogonal digital signals --s1(t), s2(t), s3(t) and s4(t). These four digital signals share the same period M, and inside one period, they satisfy:

$$\begin{aligned} &\sum_{m=1}^{M} s_i(m\Delta t)s_j(m\Delta t) = 0 \qquad i \neq j \\ &\sum_{m=1}^{M} s_i(m\Delta t)s_i(m\Delta t) = M \end{aligned} \qquad (4)$$

Hence, we can assume the total base band signal after A/D converter at the receiving antenna k becomes:

$$x(n\Delta t) = \sum_{i=1}^{4} s_i(n\Delta t)\frac{\exp(\Phi'_{ek})}{R'_{k\xi}} A_{ek}\exp(j\Phi_{ek}) \quad (5)$$

We can use the DSP algorithm like matched filter to separate the information coming from the four sources:

$$\sum_{m=1}^{M} s_j(m\Delta t)x(n\Delta t) = M \cdot \frac{\exp(\Phi'_{ek})}{R'_{k\xi}} A_{ek}\exp(j\Phi_{ek})$$

$$m = n, j = 1,2,3,4 \qquad (6)$$

Hence, the formulations (1-3) can be used to do the position calibration.

The length of the orthogonal codes will affect the calibration's precision. Usually, the longer sequence will give the better results. However, the longer sequence will take more data collection time and DSP calculation time. The code length must be carefully selected according to the moving speed of element and the required precision.

C. Circuit error calibration:

Circuit calibration can be realized after the position calibration. Since the position error has been calibrated, which means $\Phi'_{k\xi}$ and $R'_{k\xi}$ are known, the circuit error information $A_{ek}\exp(j\Phi_{ek})$ can be extracted from equation (6).

$$error_k = A_{ek}\exp(j\Phi_{ek}) \qquad (7)$$

Change the weighting coefficients, the pattern can be compensated:

$$W'_k = W_k / error_k \qquad (8)$$

III. Circuit Overview

A system including one receiver and two calibration sources is constructed to test the technique described in section II. Assume that a mechanic motion causes the smart antenna receiver to distort from a uniform half-wavelength array to a non-uniform array. As a result, the original weighting coefficients which are calculated from the uniform array are no longer suitable to the distorted array. With the two fixed near-field sources, the element spacing error of the non-uniform array can be detected then the new weighting coefficients can be calculated to calibrate the main beam direction and null direction. The reason to use only two transmitters instead of four is that only one-dimensional motion of the antenna element needs to be calibrated.

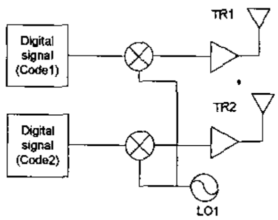

Fig. 2 Near-field calibration sources

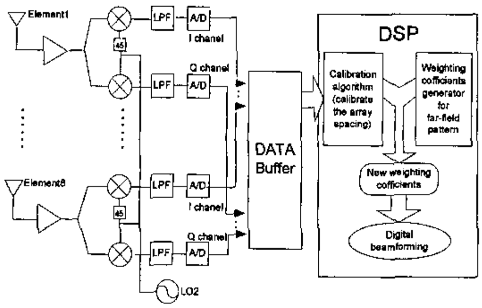

Fig. 3 Receiver with distorted array

Fig.2 shows the circuitry of two near-field calibration sources. Two synchronized digital sources generate 100KHz orthogonal sequences "1100" and "1010". These two digital signals are modulated with 5.828GHz synchronized LO carrier. Two transmitter antennas are quasi-Yagi antennas, which are broad bandwidth and broad beam width. Because the RF signals coming out of the mixers pass the same length of transmission line or cables then are transmitted out by the same antenna, the RF signals from the antenna can be considered as synchronized signals.

Fig.3 shows the receiver with the distorted array. The distorted array is constructed by eight compact subdivided square microstrip patch antennas, which has a size reduction of 60% compared to the conventional square microstrip patch antenna [6]. This advantage can make the patch array to have low mutual coupling and larger position motion. Each element has a 20dB gain block and a sub-harmonic I/Q mixer, which converts C-band RF signals directly to IF signals. Since the same LO frequency used as the transmitter, those IF signals actually are base band signals. An anti-parallel diode mixer with low DC offset is designed for this system. The LO power of each mixer is 2dBm. In order to implement in-phase and quadrature-phase mixers, 45° delay line is applied to LO signal path in order to achieve uniform quadrature IF signals over the RF bandwidth. As a result, the base band signals before low pass filter in element k can be written as:

$$
\begin{aligned}
I_k(t) &= s_1(t)\sin(\Phi_{k1} + 2\Phi_{rLO} - \Phi_{sLO}) \\
&\quad + s_2(t)\sin(\Phi_{k1} + 2\Phi_{rLO} - \Phi_{sLO}) \\
Q_k(t) &= s_1(t)\cos(\Phi_{k1} + 2\Phi_{rLO} - \Phi_{sLO}) \\
&\quad + s_2(t)\cos(\Phi_{k1} + 2\Phi_{rLO} - \Phi_{sLO}) \qquad (9)
\end{aligned}
$$

Notice that in (9), the amplitude information is neglected. After low pass filter, I and Q signals enter the digital oscilloscope to realize the A/D converters' sample function. Then the sampled data are collected and transferred to PC. A matlab code works as a DSP to realize the calibration and digital beamforming functions.

IV. MEASURED RESULTS

A virtual position of each element is set to assume the original array is a half wavelength uniform array. The two near field calibrated sources are fixed in 0.483m away and 0.156m high of the uniform array's center (see Fig.4).

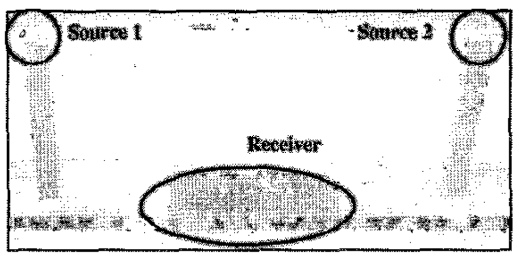

Fig. 4 Location of the calibration sources and array

Fig. 5 shows the measured base band signals at sources and element one of the receiver. Source one transmits the digital signal '1100' with the amplitude 0.5V, while source two transmits '1010' with the amplitude 0.37V and DC offset 0.1V. The base band I/Q signals also have some DC offset, which will affect the precision of the calibration. Equation (9) proposes a good way to remove the DC offset. From (9), in the first and last bit period, I(t) or Q(t) are always equal amplitude but negative sign. With this information, the DC offset can be calculated then be rem

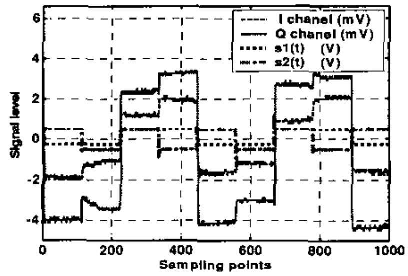

Fig. 5 Measured base band signals at the sources and receiver (element one)

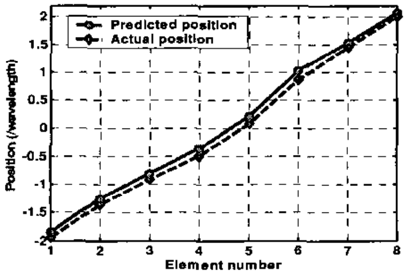

Fig.6 Predicted position and actual position of each element

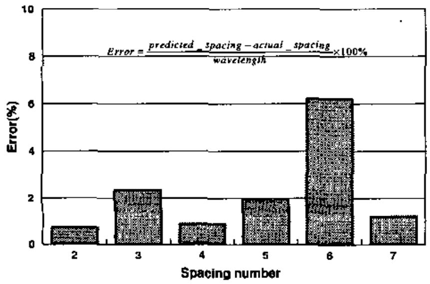

Fig. 7 Array spacing error

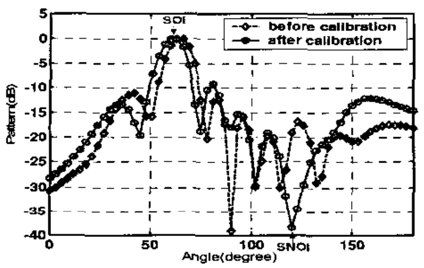

Fig. 8 Synthesized beamforming result (SOI: +30°, SNOI: -30°)

Fig.6 shows the predicted position and actual position of each element. A common position error exists in each element, and this error is caused by position error of the sources. However, this error will not affect the array spacing, which shows our calibration algorithm is robust enough to the calibration sources' position error.

Fig.7 shows the spacing error of each element, normalized the free space wavelength. The maximum error is only about 6% of the wavelength, which is too small to affect the far field pattern. Fig.8 shows the synthesized pattern in SDMA communication, with two far field signals from 30° and -30° respectively. Because of the element moving, the original pattern is highly distorted, with the main beam and null position shifted. After the position calibration and the new weighting coefficients applied, the pattern is restored.

V. CONCLUSION

A novel array calibration scheme has been proposed and a test bed has been set up to validate the concept. The measurement results show that it is a precise and robust calibration can be carried out. The spacing detection error is less than 7%. The distorted array pattern is corrected using the estimated element position. The test bed will be further developed to measure and calibrate the circuit error.

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