Direction Finding and Calibration Method Based on Time Modulated Array

Chong He, Ronghong Jin, Xianling Liang, Junping Geng, Jingfeng Chen
Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, 200240, P. R. China
Email: rhjin@sjtu.edu.cn

***Abstract*—The applications of the time modulated array (TMA) in the direction finding and the array calibration are discussed. First, the fundamental idea to implement the direction-of-arrival (DOA) by the TMA is analyzed. Second, the parallel and fast array calibration method by the time modulation is introduced. Last, the paper is summarized, and some further discussion about the applications of the TMA in the direction finding is provided.**

I. Introduction

Time modulated array (TMA) was first proposed by Shanks and Bickmore in 1959 [1], which introduced the time-domain degree of freedom (DOF) to traditional antenna arrays. The new DOF was realized by periodically controlling the 'ON-OFF' state of the switches added in the RF front end. However, the application of the TMA was restricted by the technological level of RF switches at that time. After 2000, it attracted attention again due to the progress in microelectronic and integrated circuit technology. Recently, the research for the TMA mainly concentrated on two aspects. One devotes to obtain the ultra-low sidelobe level, and to suppress the unwanted harmonic radiation simultaneously. It is implemented by optimizing the periodical time sequences added to the RF switches. The evolutionary algorithms, such as the differential evolution algorithm (DE) [2], the simple genetic algorithm (SGA) [3], and the particle swarm optimization (PSO) [4] were exploited to achieve this goal. The other aspect, however, exploits the harmonic radiation to implement beamforming. The amplitudes and initial phases of the harmonic radiation are synthesized by altering the time sequences added in the RF switches, which are the complex weights in the beamforming. Plentiful work was done in the pattern synthesis and adaptive beamforming of the traditional TMA. *i.e.*, G. Li *et al* used the differential evolution algorithm to optimize the 'ON-OFF' sequences of the TMA, for the beam steering in the first harmonic component [5]. L. Poli *et al.* optimized multiple patterns at the fundamental and the first harmonic components with the PSO algorithm [6]. Yizhen Tong *et al* proposed the TMA with multiple output channels to obtain multiple steering beams at the same time [7].

Because of the additional freedom, the TMA has the ability to decide the direction of RF source. If the RF signals enter the TMA from different directions, the received signals have different fundamental and harmonic components. Therefore, the direction of the RF source can be calculated by analyzing their mathematical relationship. On the other hand, if the direction of the RF source is known, the mismatches among the RF channels can be calculated in parallel by analyzing the harmonic characteristic of the modulated signal. Therefore, the time modulation can be exploited in the fast calibration of the active phased array.

In this conference paper, we introduce the application of the TMA in the direction finding and array calibration. Their fundamental principle is analyzed, and some recent experiment results are provided. Finally, the further research about the applications of the TMA in direction finding of coherent sources and blind calibration is discussed.

II. Direction Finding Method by the TMA

The concept of direction finding by the TMA was first proposed in 2007 [8], which exploits the relationship between the pattern of the first harmonic component and the mark-to-space ratio the modulation signal. In 2010, an experiment result about the direction finding by the TMA was reported [9]. The authors developed a two-channel TMA, and a co-axial line stretcher was inserted to one channel to change its phase shift. If the phase shift caused by the stretcher can counteract the phase shift caused by the location of two channels, the first harmonic component can vanish totally. Therefore, by adjusting the phase shift caused by the stretcher and measuring the pattern of the first harmonic component, the direction of the RF source can be estimated. However, it requires much time to adjust the stretcher to the needed phase shift and to measure the pattern of the first harmonic component. In [10], the direction finding method based on the TMA by harmonic characteristic analysis is proposed, which calculates the direction of the RF source by analyzing the mathematical relationship between the incident direction θ, the fundamental component α_0 and the positive first harmonic component α_1. Assume that a two-element TMA works on the receiving state, and the element spacing is D. The RF signals received in the two elements are alternatively selected by a single-pole double-throw (SPDT) RF switch, and the duty cycle is 50%. After the time modulation, the fundamental and the harmonic components are generated simultaneously. The mathematical relationship between the incident direction θ, the fundamental component α_0 and the positive first harmonic component α_1 is as follows

$$\theta = \arcsin\left(\frac{2}{KD}\arctan\frac{\pi\alpha_1}{2\alpha_0}\right), \tag{1}$$

where K is the wave number corresponding to the carrier frequency F_c. Therefore, if we analyze the spectrum of the received modulated signal, the direction of the RF source can be calculated directly.

A simple S band two-element TMA is constructed to verify the idea. As is shown in Fig. 1, the array is fastened to a tunable, and the incident direction can be changed by a circular scale. Change the incident direction from 0° to +30° with the step 5°. The spectrum of received signals at incident directions $[0°, +10°, +20°, +30°]$ is plotted in Fig. 2. As is shown, if the angle of incident direction becomes larger, the fundamental component α_0 decreases and the first harmonic component α_1 increases step by step. The change of the ratio α_0/α_1 reflects the change of the incident direction θ correspondingly.

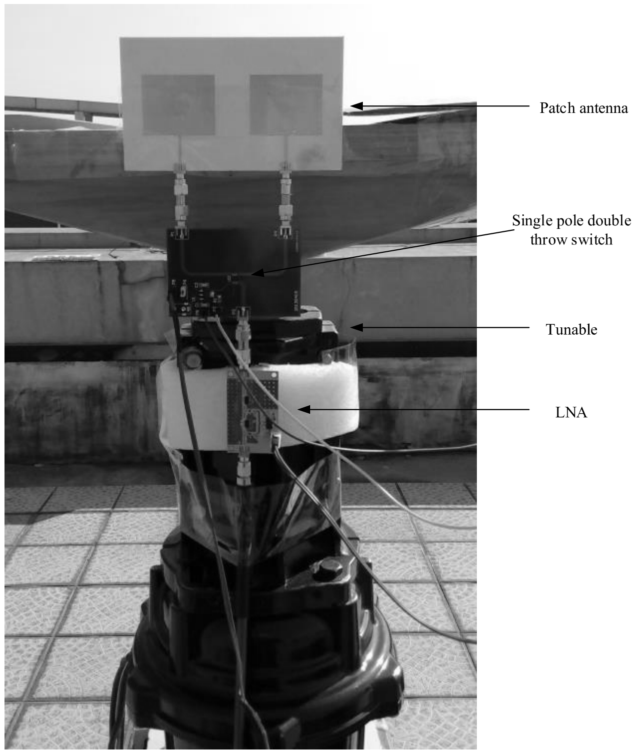

Fig. 1. The S band two-element TMA for direction finding.

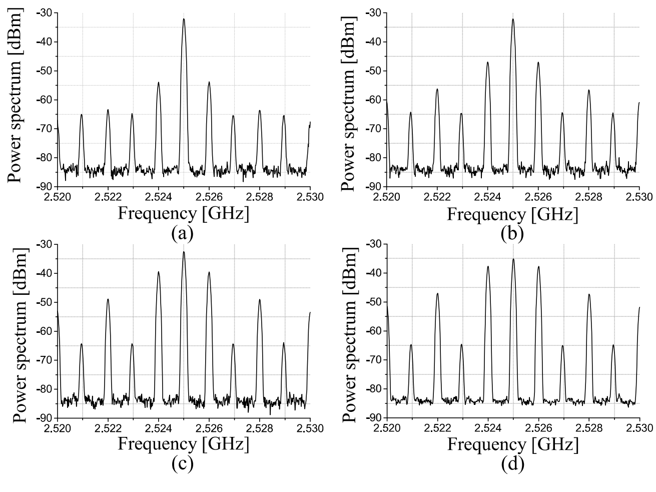

Fig. 2. The block diagram for the direction finding of the TMA with harmonic characteristic analysis.

In TABLE I, the powers of the fundamental α_0 and the first harmonic component α_1 under different incident directions are listed out. They are measured out by the spectrum analyzer. Then, the estimation results for the incident direction are calculated, and the absolute and relative estimation errors are listed out in the last two columns of the table. It can be seen that the estimation errors are less than $5°$, their standard deviation is $3.3°$. The errors of direction finding may be caused by several aspects as follows

1) The amplitude and phase unbalance between the two channels, and the isolation characteristic controlled by the SPDT switch.
2) The multi-paths caused in the surrounding environment.
3) The mutual coupling characteristic between two antenna elements.
4) Power measurement errors caused by the equipment.

TABLE I. EXPERIMENT RESULTS FOR DIRECTION FINDING

Direction [deg]	α_0 [dBm]	α_1 [dBm]	*Estimation* [deg]	*Abso. Error* [deg]	*Rela. Error* [%]
0	-32.02	-53.84	4.7	4.7	-
5	-31.3	-50.36	6.5	1.5	30
10	-32.09	-47.03	10.3	1.3	13
15	-32.16	-41.43	18.9	3.9	16
20	-32.51	-39.48	23.7	3.7	18.5
25	-33.22	-38.91	26.6	1.6	8
30	-35.08	-37.72	34.2	4.2	14

III. PARALLEL ARRAY CALIBRATION METHOD BY THE TIME MODULATION

This section analyzes the application of the TMA in the calibration of the active phased array [11]. The principle is that by periodically modulating the phase shifts of channels in sequence, the channel mismatches can be calculated out in parallel by analyzing the harmonic characteristic of the received calibration signal. The proposed method requires no measurement between the calibration source and sink, and needs no auxiliary calibration element. Its signal processing concentrates on the estimation of harmonic component's spectrum by the discrete Fourier transform (DFT).

Consider an N-channel uniform linear array with the element spacing D. The calibration source transmits a far-field planar sinusoidal wave to the phased array with the direction θ. At the receiving end, the phase shift on each RF channel are periodically modulated from $0°$ to $180°$ sequentially by controlling the digital phase shifters. Assume that g_n represents the complex gain in the nth channel. During the calibration, the periodic phase modulation is sequentially added to each phase shifter. The modulation period T_p is equally divided into N segments, and each RF channel takes over a time slot. During one time slot, the phase shift of the corresponding channel increases by $180°$. After the phase modulation, the complex gain of the nth RF channel is expressed as

$$g'_n(t) = \begin{cases} -g_n, & \frac{(n-1)}{N}T_p + mT_p < t \leq \frac{n}{N}T_p + mT_p \\ g_n, & \begin{array}{l} mT_p < t \leq \frac{(n-1)}{N}T_p + mT_p, \text{or} \\ \frac{n}{N}T_p + mT_p < t \leq (m+1)T_p \end{array} \end{cases} \quad (2)$$

$g'_n(t)$ $(n = 1, 2, \ldots, N)$ can be expanded by Fourier series as the fundamental and the harmonic components. After the combiner, the combined calibration signal contains the fundamental and the harmonic components, which are related to the complex gains g_n of each channel. We can establish the system of linear equations about the g_n, the fundamental component Γ_0 and the harmonic components $\Gamma_1, \Gamma_2, \ldots, \Gamma_{N-1}$. By solving the system of linear equations, the complex gain g_n of each channel can be calculated out in parallel. A four-channel array working at 2.6GHz is modulated with modulation period $4\mu s$, the power spectrum of the received calibration signal is plotted in Fig. 3. The complex gains of the four channels can be calculated by the fundamental component and the first three harmonic components.

The calculated complex gains are compared to the results by the vector network analyzer. In the second column of Table II, the first channel is set to as reference, and its amplitude and phase are 0dB and $0°$, respectively. From the third to the fifth column, the calculation and measurement results are listed for comparison. As can be seen, the amplitude estimation errors are less than 0.1dB, and the phase estimation errors are less than $1°$. The errors may be caused by the reasons as follows

1) the noise in the RF link, the signal-

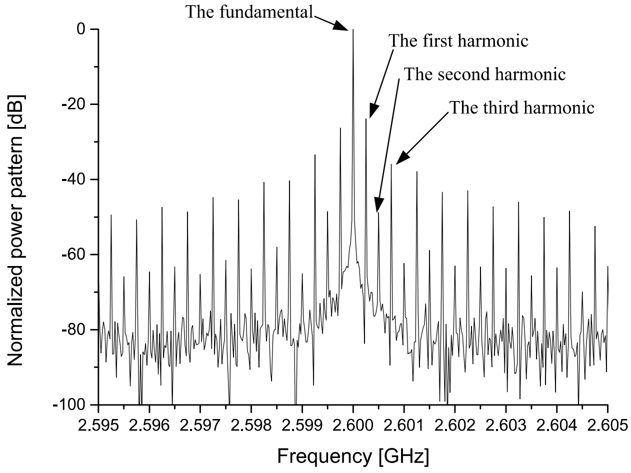

Fig. 3. The normalized power spectrum of modulated calibration signal after the power combiner.

to-noise ratio (SNR) can influence the calculation result.

2) the rising and falling times of RF switches is not ideal, which are not equal to zeros. The non-ideal switching time can influence the harmonic characteristic.
3) the spectrum estimation error caused by the DFT, including the fencing and licking effects.

TABLE II. CALIBRATION RESULTS COMPARISON BETWEEN THE CALCULATION AND THE MEASUREMENT

Channel	*1*	*2*	*3*	*4*
Calculated amplitudes [dB]	0	-0.61	-1.28	-0.59
Measured amplitudes [dB]	0	-0.65	-1.30	-0.64
Calculated phase [deg]	0	-4.17	-11.25	-7.35
Measured phase [deg]	0	-4.42	-11.40	-7.50
Amplitude estimation errors [dB]	0	-0.04	-0.02	0.05
Phase estimation errors [deg]	0	0.25	0.15	0.15

IV. CONCLUSION

The applications of the TMA in the direction finding and the array calibration are discussed. Both the direction finding and the array calibration exploit the harmonic characteristic analysis of the time modulated array. In the further research, the direction finding of coherent sources and the blind calibration with unknown direction of calibration source are concerned.

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