Implementation of Direction Finding Processor Based on the Novel DOA Estimation with Channel Mismatch Self-calibration

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Abstract. In order to solve the problem that the channel gain-phase mismatch would deteriorate the performance of direction of arrival (DOA) estimation in actual direction finding (DF) system, a novel efficient gain-phase calibration algorithm based on the self-checking signal is proposed in this paper. By injecting a self-checking signal into the actual DF system, the whole calibration process could divide into the off-line pre-calibration and the auto-calibration part. Thus, it could realize the real-time auto-calibration efficiently during the DOA estimation process. Moreover, in order to verify the effectiveness of the proposed method, a practical DF signal processor based on the FPGA and DSP is implemented in this paper, and the experiments are carried out in the anechoic chamber. The experiment result shows that the proposed method could calibrate the gain-phase mismatch in real-time and have higher DOA estimation accuracy.

Keywords: Direction of arrival · Direction finding system · Array calibration Self-calibration · Multiple signal classification algorithm

1 Introduction

The direction of arrival (DOA) estimation of multiple targets is the most fundamental aspect in array signal processing [1] and has aroused great concern in radar, sonar and wireless communications. The spectrum estimation algorithm with super-resolution performance, such as multiple signal classification (MUSIC) [2] and estimation of signal parameters via rotational invariance techniques (ESPRIT) [3], have been developed greatly for decades. However, these algorithms will fail if the array manifold is not perfectly known due to the gain-phase mismatch between the antennas. Thus, a number of approaches have been proposed to calibrate the mismatch so as to improve the DOA estimation performance [4, 5]. [6] proposed the least squares (LS) array calibration method by using a set of calibration sources whose location are exactly known. Then, the distance between the calibration source and the direction finding (DF) system is investigated in [7].

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However, these methods mentioned above would calibrate the array well when the locations of the calibration sources are precisely known, but in practice, the calibration sources may not available in real system. As a result, the self-calibration algorithm has been developed [8, 9]. [8] proposed an alternative iterative method, which could estimate the signal DOAs and the gain-phase error of each channel. And in [9], Kim proposed a blind calibration method by using independent component analysis. In generally, the researches based on self-calibration techniques are difficult to be realized in real time system.

This paper proposed a real-time calibration method based on the self-checking signal. First of all, the calibration work is divided into two parts: the pre-calibration and the real-time self-calibration, separately. The pre-calibration matrix is obtained by setting a signal with the DOA is 0°. Then, the self-calibration matrix will be updated with the help of self-checking signal in the DF system. Moreover, the real DF signal processor is implemented based on the FPGA and DSP. At last, the effectiveness of the proposed method is verified by the practical DF system.

2 Signal Model and the Proposed Method

Consider a scenario in which P narrowband far-field sources are observed by M ($P < M$) elements, as shown in Fig. 1. The antenna array is assumed to have an UCA structure with the radius d. The noise is assumed to be the additive white Gaussian noise (AWGN).

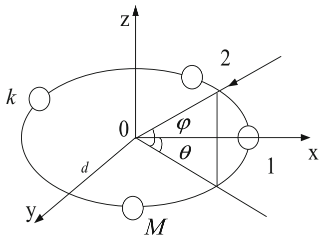


Fig. 1. Uniform circular array diagram.

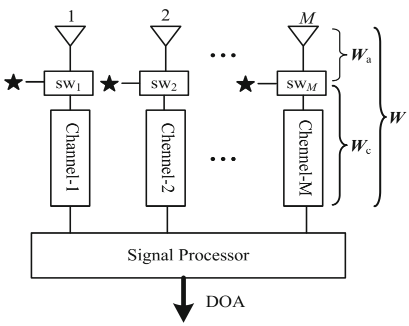


Fig. 2. Diagram of data receiving in DF system.

Assume the incident signals are independent with each other, (θ_i, φ_i) is the azimuth and elevation of the ith ($i < P$) signal. Therefore, the received array matrix $\boldsymbol{X}$ is modeled as

$$\boldsymbol{X} = \boldsymbol{A}(\theta,\varphi)\boldsymbol{S} + \boldsymbol{N} \tag{1}$$

where $\boldsymbol{A}$, $\boldsymbol{S}$ and $\boldsymbol{N}$ denote the manifold matrix, signal and noise, respectively. However, when the effect of gain-phase mismatch error is taken into consideration, the actual received array matrix is rewritten as

$$\tilde{\boldsymbol{X}} = \boldsymbol{WX} = \boldsymbol{WA}(\theta, \varphi)\boldsymbol{S} + \boldsymbol{WN} \tag{2}$$

where $\boldsymbol{W} = \mathrm{diag}[g_1 \exp(j\phi_1) \quad g_2 \exp(j\phi_2) \cdots g_M \exp(j\phi_M)]$ is the gain-phase mismatch matrix, and g_i and ϕ_i (i = 1, 2, …, M) denote the gain and phase of ith channel, respectively. Then the covariance matrix of $\tilde{\boldsymbol{X}}$ can be expressed as

$$\tilde{\boldsymbol{R}} = \tilde{X}\tilde{X}^{\mathrm{H}} = \begin{bmatrix} \tilde{\boldsymbol{x}}_1\tilde{\boldsymbol{x}}_1^{\mathrm{H}} & \tilde{\boldsymbol{x}}_1\tilde{\boldsymbol{x}}_2^{\mathrm{H}} & \cdots & \tilde{\boldsymbol{x}}_1\tilde{\boldsymbol{x}}_M^{\mathrm{H}} \\ \tilde{\boldsymbol{x}}_2\tilde{\boldsymbol{x}}_1^{\mathrm{H}} & \tilde{\boldsymbol{x}}_2\tilde{\boldsymbol{x}}_2^{\mathrm{H}} & \cdots & \tilde{\boldsymbol{x}}_2\tilde{\boldsymbol{x}}_M^{\mathrm{H}} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{\boldsymbol{x}}_M\tilde{\boldsymbol{x}}_1^{\mathrm{H}} & \tilde{\boldsymbol{x}}_M\tilde{\boldsymbol{x}}_2^{\mathrm{H}} & \cdots & \tilde{\boldsymbol{x}}_M\tilde{\boldsymbol{x}}_{1M}^{\mathrm{H}} \end{bmatrix} = \begin{bmatrix} g_1^2\boldsymbol{x}_1\boldsymbol{x}_1^{\mathrm{H}} & \cdots & g_1 g_M \exp(j(\phi_1 - \phi_M))\boldsymbol{x}_1\boldsymbol{x}_M^{\mathrm{H}} \\ g_1 g_2 \exp(j(\phi_2 - \phi_1))\boldsymbol{x}_2\boldsymbol{x}_1^{\mathrm{H}} & \cdots & \\ \vdots & \ddots & \vdots \\ g_1 g_M \exp(j(\phi_M - \phi_1))\boldsymbol{x}_M\boldsymbol{x}_1^{\mathrm{H}} & \cdots & g_M^2\boldsymbol{x}_M\boldsymbol{x}_M^{\mathrm{H}} \end{bmatrix} \tag{3}$$

where $\tilde{\boldsymbol{x}}_i$ and $\boldsymbol{x}_i$ denote the received data vector of ith channel when with phase-gain error mismatch and without phase-gain error mismatch, respectively. Assume there is only one signal impinging on the array and the DOA is 0°, if there is no mismatch between each channel, it is easy to get $\boldsymbol{x}_1\boldsymbol{x}_1^{\mathrm{H}} = \boldsymbol{x}_i\boldsymbol{x}_j^{\mathrm{H}}$. Let $\tilde{\boldsymbol{R}}_1$ denote the first column of $\tilde{\boldsymbol{R}}$, then from (3), we can get

$$\tilde{\boldsymbol{R}}_1/\tilde{\boldsymbol{R}}_1(1) = [1 \;\; g_2/g_1 \exp(j(\phi_2 - \phi_1)) \cdots g_M/g_1 \exp(j(\phi_M - \phi_1))]^{\mathrm{T}}, \tag{4}$$

$$g_i/g_1 \exp(j(\phi_M - \phi_1)) = \tilde{\boldsymbol{x}}_i\tilde{\boldsymbol{x}}_1^{\mathrm{H}}/\tilde{\boldsymbol{x}}_1\tilde{\boldsymbol{x}}_1^{\mathrm{H}}. \tag{5}$$

It is seen that from (5), if we utilize the classical 0° calibration method and consider the first channel as the reference, then (5) is the gain-phase mismatch error of the ith channel. Even though the 0° calibration method is an off-line method by utilizing an assistant source, and we only need to obtain the calibration matrix once before estimating the DOA. However, in actual DF system, the channel mismatch is mainly caused by active devices, e.g. amplifier, whose performance would fluctuate with surrounding environment, such as temperature, running hour, etc. As a result, we could divide the error matrix $\boldsymbol{W}$ into two parts, $\boldsymbol{W}_{\mathrm{a}}$ and $\boldsymbol{W}_{\mathrm{c}}$, as shown in Fig. 2. $\boldsymbol{W}_{\mathrm{a}}$ denotes the error matrix caused by the passive devices, while $\boldsymbol{W}_{\mathrm{c}}$ caused by the active devices. $\boldsymbol{W}$, $\boldsymbol{W}_{\mathrm{a}}$ and $\boldsymbol{W}_{\mathrm{c}}$ are diagonal matrix and they have the following relationship,

$$\boldsymbol{W} = \boldsymbol{W}_{\mathrm{a}}\boldsymbol{W}_{\mathrm{c}}, \tag{6}$$

$$\boldsymbol{W}_{\mathrm{a}} = \mathrm{diag}[g_{\mathrm{a}1} \exp(j\phi_{\mathrm{a}1}) \quad g_{\mathrm{a}2} \exp(j\phi_{\mathrm{a}2}) \cdots g_{\mathrm{a}M} \exp(j\phi_{\mathrm{a}M})] = g_{\mathrm{a}1} \exp(j\phi_{\mathrm{a}1}) \cdot \boldsymbol{W}'_{\mathrm{a}}, \tag{7}$$

$$\boldsymbol{W}_{\mathrm{c}} = \mathrm{diag}[g_{\mathrm{c}1} \exp(j\phi_{\mathrm{c}1}) \quad g_{\mathrm{c}2} \exp(j\phi_{\mathrm{c}2}) \cdots g_{\mathrm{c}M} \exp(j\phi_{\mathrm{c}M})] = g_{\mathrm{c}1} \exp(j\phi_{\mathrm{c}1}) \cdot \boldsymbol{W}'_{\mathrm{c}} \tag{8}$$

where $\boldsymbol{W}'_{\mathrm{a}} = \mathrm{diag}[1 \cdots g_{\mathrm{a}M}/g_{\mathrm{a}1} \exp(j(\phi_{\mathrm{a}M} - \phi_{\mathrm{a}1}))]$, $g_{\mathrm{a}i}, \phi_{\mathrm{a}i}$ (i = 1, 2,…, M) denote the gain error and phase error between the antenna and received channel, respectively. And $\boldsymbol{W}'_{\mathrm{c}} = \mathrm{diag}[1 \cdots g_{\mathrm{c}M}/g_{\mathrm{c}1} \exp(j(\phi_{\mathrm{c}M} - \phi_{\mathrm{c}1}))]$, $g_{\mathrm{c}i}, \phi_{\mathrm{c}i}$ (i = 1, 2,…, M) denote the gain error and phase error between received channel and the digital signal processor, respectively. Then, (6) could be rewritten as

$$\boldsymbol{W} = \boldsymbol{W}_{\mathrm{a}}\boldsymbol{W}_{\mathrm{c}} = g_{\mathrm{a1}}g_{\mathrm{c1}}\exp(j(\phi_{\mathrm{a1}} + \phi_{\mathrm{c1}})) \cdot \boldsymbol{W}'_{\mathrm{a}}\boldsymbol{W}'_{\mathrm{c}} = g_1\exp(j\phi_1) \cdot \boldsymbol{W}' \tag{9}$$

where $\boldsymbol{W}' = \boldsymbol{W}'_{\mathrm{a}}\boldsymbol{W}'_{\mathrm{c}}$, and $\boldsymbol{W}'_{\mathrm{a}} = \boldsymbol{W}'\boldsymbol{W}'^{-1}_{\mathrm{c}}$. Because $\boldsymbol{W}'$, $\boldsymbol{W}'_{\mathrm{a}}$ and $\boldsymbol{W}'_{\mathrm{c}}$ are all diagonal matrix, then

$$\boldsymbol{W}'_{\mathrm{a}}(i,i) = \boldsymbol{W}'(i,i)/\boldsymbol{W}'_{\mathrm{c}}(i,i). \tag{10}$$

It is seen from (10), $\boldsymbol{W}'_{\mathrm{a}}$ will be obtained once we got $\boldsymbol{W}'$ and $\boldsymbol{W}'_{\mathrm{c}}$. Hence, in order to obtain $\boldsymbol{W}'_{\mathrm{c}}$ and realize real time self-calibration, a self-checking signal denoted by "★" is injected into the DF system, shown as in Fig. 2. It is seen that, when to receive the signal from the antenna is decided by a Single-pole Double Throw Switch (SPDT) $\mathrm{sw_i}$ (i = 1, 2…, M), and the self-checking signal would be received at the following edge of the signal pulse that we interested. As the self-checking signal is injected into each channel at the same time, we could utilize the received self-checking signal data to calibrate the gain-phase mismatch between channels. Thus, the received data of self-checking signal with mismatch error could be presented as

$$\tilde{\boldsymbol{X}}_{\mathrm{c}}(t) = \boldsymbol{W}_{\mathrm{c}}\boldsymbol{X}_{\mathrm{c}}(t). \tag{11}$$

From (3) and (4), we could get

$$g_{\mathrm{c}i}/g_{\mathrm{c1}}\exp(j(\phi_{\mathrm{c}M} - \phi_{\mathrm{c1}})) = \tilde{\boldsymbol{x}}_{\mathrm{c}i}\tilde{\boldsymbol{x}}^{\mathrm{H}}_{\mathrm{c1}}/\tilde{\boldsymbol{x}}_{\mathrm{c1}}\tilde{\boldsymbol{x}}^{\mathrm{H}}_{\mathrm{c1}}. \tag{12}$$

Then,

$$\begin{aligned}\boldsymbol{W}'_{\mathrm{c}} &= \mathrm{diag}[1 \quad g_{\mathrm{c2}}/g_{\mathrm{c1}}\exp(j(\phi_{\mathrm{c2}} - \phi_{\mathrm{c1}}))\cdots g_{\mathrm{c}M}/g_{\mathrm{c1}}\exp(j(\phi_{\mathrm{c}M} - \phi_{\mathrm{c1}}))] \\ &= \mathrm{diag}[1 \quad \tilde{\boldsymbol{x}}_{\mathrm{c2}}\tilde{\boldsymbol{x}}^{\mathrm{H}}_{\mathrm{c1}}/\tilde{\boldsymbol{x}}_{\mathrm{c1}}\tilde{\boldsymbol{x}}^{\mathrm{H}}_{\mathrm{c1}}\cdots\tilde{\boldsymbol{x}}_{\mathrm{c}M}\tilde{\boldsymbol{x}}^{\mathrm{H}}_{\mathrm{c1}}/\tilde{\boldsymbol{x}}_{\mathrm{c1}}\tilde{\boldsymbol{x}}^{\mathrm{H}}_{\mathrm{c1}}]\end{aligned}. \tag{13}$$

Setting the incident signal angle is 0°, and according to (10), (12) and (13), the pre-calibration matrix $\mathbf{W}'_{\mathrm{a}}$ could be expressed as

$$\mathbf{W}'_{\mathrm{a}}(i,i) = \mathbf{W}'(i,i)/\mathbf{W}'_{\mathrm{c}}(i,i) = (\tilde{\boldsymbol{x}}_i\tilde{\boldsymbol{x}}^{\mathrm{H}}_1/\tilde{\boldsymbol{x}}_1\tilde{\boldsymbol{x}}^{\mathrm{H}}_1)/(\tilde{\boldsymbol{x}}_{\mathrm{c}i}\tilde{\boldsymbol{x}}^{\mathrm{H}}_{\mathrm{c1}}/\tilde{\boldsymbol{x}}_{\mathrm{c1}}\tilde{\boldsymbol{x}}^{\mathrm{H}}_{\mathrm{c1}}). \tag{14}$$

As a result, the proposed calibration method can be summarized as follows: (1) Set an incident signal with the DOA is 0°, and record the received data of the incident signal and the self-checking signal. (2) By (14), calculate the pre-calibration matrix $\mathbf{W}'_{\mathrm{a}}$. (3) According to (13), calculate $\mathbf{W}'_{\mathrm{c}}$ by considering the first channel as the reference, and obtain $\boldsymbol{W}$ by (9). (4) Obtain $\tilde{\boldsymbol{X}}$ with (2), and estimate the DOA with MUSIC algorithm. Repeat step (3)–(4), we can estimate the DOA with a higher accuracy in real time.

3 Design and Implementation of the DF Signal Processor

As shown in Fig. 3, the DF system consists of two parts: microwave front-head and digital signal processor. The microwave front-head, which contains 5 channels, is responsible to process the received analog signal. The digital signal processor is comprised of 4 processors, which are wide-band digital channelizer, signal sorting processor, narrow-band digital receiver and DF signal processor, respectively. It is worth to note that, the DF signal processor is the mainly contribution in this paper and in the next, we will introduce the processor based on the hardware and software design, respectively.

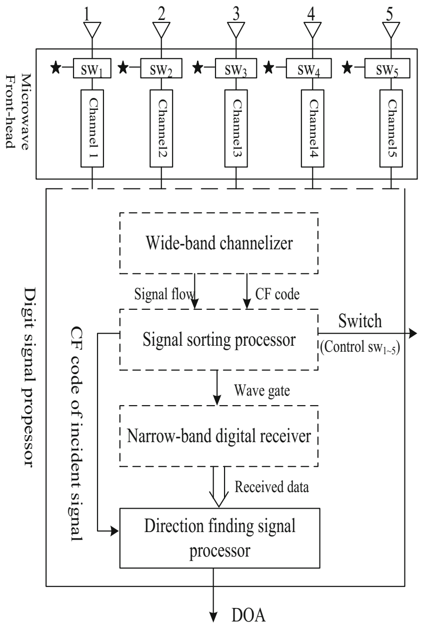


Fig. 3. Block diagram of the DF system

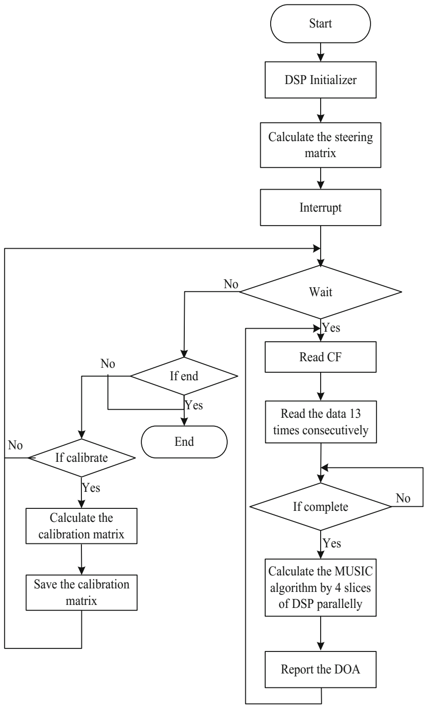


Fig. 4. Software flow chart of the DF signal processor

3.1 Hardware Design of the DF Signal Processor

The task of the DF signal processor is to process the received signal data, estimate the DOA of the incident signal and report the angles to the host finally. The block diagram of the DF signal processor is shown is Fig. 5.

As shown in Fig. 5, the PDS120 is used for the processor to communicate with other processors. In order to improve the calculation speed, four slices of ADSP TS201 process the received data in parallel, besides, they share data and communicate with each other by adopting the tight coupling mode to share the bus line. A slice of FPGA

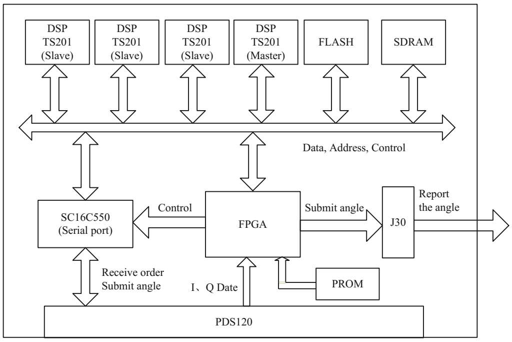


Fig. 5. Diagram of the DF signal processor

Fig. 6. Appearance of the DF signal processor

of virtex-4 is responsible for the logic control, data reception and transmission, and control test, etc. Then, the I, Q data, received from 5 channels, is transferred to FPGA by PDS120, and read by the master DSP after the extension in FPGA. On the one hand, the master DSP is mainly used for data communication, source number estimation, eigen decomposition, spectrum function calculation in the first quadrant, spectrum peak searching, the global extremum judgement, angel transform and result sending. On the other hand, the other three slave DSPs are used to calculate the spectrum function in the other three quadrants, search the peak of the function and transfer the extremum value in each quadrant to the master DSP, and then, the final global extremum value will be decided by the master DSP. At last, the final estimated result (DOA) is converted by FPGA and reported to the servo system through J30. The physic DF signal processor is shown in Fig. 6.

3.2 Software Design of the DF Signal Processor

(1) Work flow of the system

The Fig. 4 is the flow chart of the hardware program. At first, DSP is initialized and load the program from the FLASH. In the next step, enable interrupt and wait order of central computer to start work. However, if the order is not to start work, then judge whether to end the work. If the order is to end the work, then the DF processor will end work. Otherwise, if the order is channel calibration, we will calculate the calibration matrix and save it, then the program will return to the original location and wait order to start. Once receiving the order to start work, it will read the carrier frequency (CF) code from the signal sorting processor, estimate the DOAs and report the final DOA result.

(2) Working principle of the MUSIC algorithm in DSP

As mentioned above, there are four slices of DSP, one master DSP and three slave DSPs. And the three slave DSPs are response for the peak searching of the 2^{nd}, 3^{rd}, 4^{th} quadrant, respectively. When the master DSP start to work, it will calculate the calibration matrix by utilizing the self-checking signal data, and then share the estimated source number, noise subspace and the real-time calibration matrix in the broadcast area for other three slave DSPs to use. As the time efficiency is always an essential problem that we concern, some remarks are given as follows:

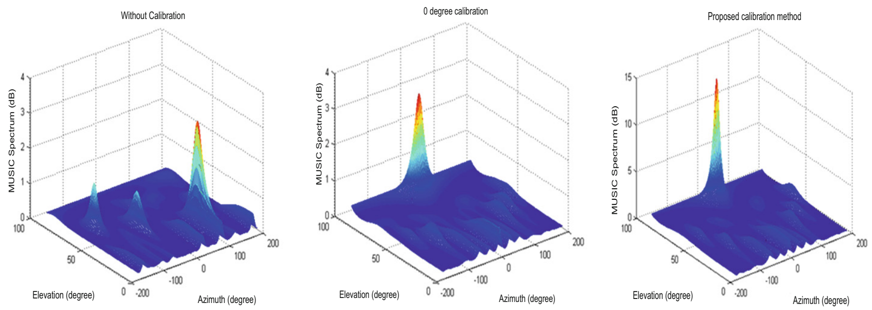
Remark 1: The three slave DSPs first calculate the component of the steering matrix that independent of signal frequency. And then calculate the reminder after the signal frequency is provided by the master DSP.

Remark 2: It is well known that the spectrum peak searching is an exhaustive step. In order to solve this problem, we first find the spectrum peak in a coarse step, e.g. 4°, and then we improve the accuracy of our result with a smaller step, e.g. 2°. In this way, the estimated DOAs will be more accurate and it will consume less time as well.

4 Performance Test and Analysis

In this section, some test results are presented to illustrate the performance of the proposed method based on the actual DF system. The antenna array is a uniform circular array (UCA) with 5 sensors, the radius is 180 mm. Setting the DOA of the incident signal is 0°, according to (14) and the received data, we can get the pre-calibration matrix is diag [1.0, 1.9266exp(j10.0181°), 2.2830exp(j129.4431°), 1.0203exp(−j21.6611°), 1.9311exp(−j16.8094°)].

Figure 7 presents the MUSIC spectrum based on the real data with three methods. They are the method without calibration, 0° calibration method and the proposed method, respectively. The DOA of the incident signal is (0°, 80°), the snapshot is 100. As shown in Fig. 7(a), the estimated DOA is (72.0°, 23.5°), which is far bias from the true angle. Similarly, the estimated DOAs with 0° calibration and the proposed method are (−3.95°, 81.52°) and (−1.02°, 79.52°), respectively. Obviously, the proposed calibration method has a higher accuracy in the actual system.



(a) (b) (c)

Fig. 7. MUSIC spectrum of DOA estimation under the condition of (a) without calibration (b) 0° calibration method (c) proposed calibration method

Table 1 illustrates the DOA estimation results of the two methods with different frequency and one incident angel. The snapshots are 100. As shown in Table 1, the channel mismatch has a great negative influence on the estimation performance. However, compared with the conventional 0° calibration method, the proposed method can realize the dynamic calibration and has better estimation performance.

Table 1. The DOA estimation result of two methods with different frequency (degree)

DOA	2 GHz		4 GHz	
	0° calibration	Proposed method	0° calibration	Proposed method
25	27.00	24.60	26.40	25.40
20	21.40	20.80	19.60	20.20
15	16.20	15.40	15.80	15.80
10	10.80	10.20	10.80	10.60
5	5.60	4.60	5.60	5.40
0	0.80	−0.40	0.40	0.20
−5	−4.80	−5.40	−4.60	−4.80
−10	−11.60	−10.60	−9.20	−10.60
−15	−16.80	−16.00	−15.20	−15.40
−20	−21.00	−20.60	−19.80	−20.20
−25	−26.40	−25.80	−26.00	−24.80

5 Conclusion

In actual DF system, the active device of the receiver would cause the gain-phase mismatch among sensors and that will seriously deteriorate the performance of the DOA estimation algorithm based on the spatial spectrum estimation. In this paper, a novel self-calibration gain-phase mismatch calibration method is presented and the actual DF signal processor based on FPGA and DSP is implemented. Finally, the trial results show that the proposed method could calibrate the gain-phase mismatch effectively and improve the estimation performance greatly. Moreover, this method consumes less energy and it is available for the actual real-time DF system.

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