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Synthesis of Algorithms and Procedures for Real-Time Internal Calibration of Receiving Channels in Digital Phased Antenna Arrays

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Abstract

Introduction. Real-time calibration is essential for maintaining the performance of modern digital phased antenna array (DPAA) systems. Previous papers have proposed a method of real-time internal calibration for all receiving channels. This method uses a calibration signal (CalSig) of the same frequency spectrum as the received signal, modulated in phase and amplitude by the binary phase-shift keying (BPSK) and on–off keying (OOK) codes, respectively. With the purpose of improving the method, we propose an algorithm for estimating the phase and amplitude parameters of each receiving channel on the basis of continuous phase correlation accumulation of CalSig samples.

Aim. Synthesis of algorithms and procedures for real-time internal calibration of receiving channels in digital phased antenna arrays.

Materials and methods. Calibration algorithms and calibration procedure were analyzed and synthesized using the methods of systems analysis. In addition, the methods of systems engineering and technology, digital processing of radar signals and synthesis of building test models close to actual requirements were applied.

Results. The advantage of the proposed calibration algorithm and calibration procedure consists in using CalSig modulated by the BPSK and OOK codes. The results obtained on a small DPAA system with four receiving channels gave the error of phase and amplitude lower than 0.3° and 0.05 dB, and the error of main beam direction lower than 0.2°. The results of testing the developed DPAA model confirmed the simplicity and high calibration accuracy of the approach under study.

Conclusion. The proposed calibration algorithm and calibration procedure have the advantage over those proposed in previous research in terms of simplicity and resource efficiency. This fact determines the prospects for using the obtained results.

Keywords: digital phased antenna array, real-time internal calibration, calibration signal, calibration procedure, digital beamforming

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Introduction. The method of real-time internal calibration method for all receiving channels is attracting wide research interest and is implemented in many digital phased antenna array (DPAA) systems [1–6]. With the development of integrated circuits technologies, the calibration problem can be solved entirely in the digital domain. The method of real-time internal calibration of the receiving channel is a calibration process that takes place continuously and simultaneously with the process of receiving signals, exerting little influence on the received signal [7–9]. Various extensions of this method have so far been published. However, some problems associated with calibration signals (CalSig) and their processing remain to be solved [9, 10]. Our previous papers [11, 12] proposed using a CalSig with the same frequency as the received signal, modulated in phase and amplitude by the binary phase-shift keying (BPSK) and on–off keying (OOK) codes, respectively. This solution has shown several advantages over other methods. Using such a CalSig structure, this paper proposes an algorithm for estimating the phase and amplitude parameters of the receiving channels, which may serve as a basis for performing the calibration procedure. The proposed algorithm and calibration procedure are characterized by implementation simplicity, low resource consumption and high reliability. The obtained results confirm the advantages of the proposed solution over those published in literature.

Synthesis of an algorithm for estimating the parameters and calibration procedures of receiving channels. Fig. 1 presents the structure of a typical DPAA system with an integrated internal calibration subsystem. The system consists of Transceiver Modules (A), Signal Generation and Distribution Block (B), Analog to Digital Converter (ADC) Block (C), and the Signal Processing Block (D). The structure and function of transceiver modules (TRM) are specified in [11, 12]. The output received signal of the TRM is a signal at the mid-frequency IF, which is amplified and digitized in the ADC Block to obtain the output digital mid-frequency signal IFs. Next, the IFs signal is fed to the Signal Processing Block, which is digitally demodulated in the Digital Down Converter (DDC) Unit to receive the complex baseband I/Q signal $S_{TH}(n)$. This I/Q signal $S_{TH}(n)$ contains CalSig samples modulated according to the BPSK and OOK codes as illustrated in Fig. 2 [11]. Then, all receiving channels are calibrated in the Calibration Unit (D4). Each receiving channel has an independent "Measure and Calibration" unit, whose diagram is shown in Fig. 3. This unit has

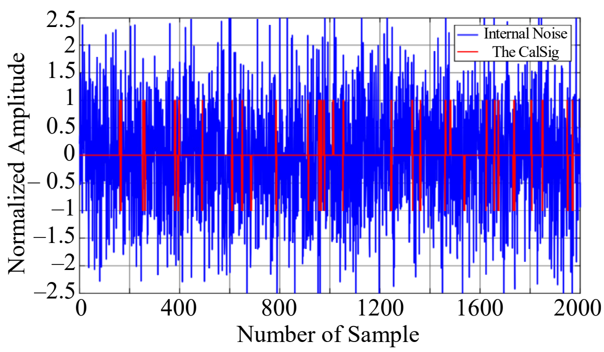


Fig. 2. CalSig and internal noise in each receiver channel

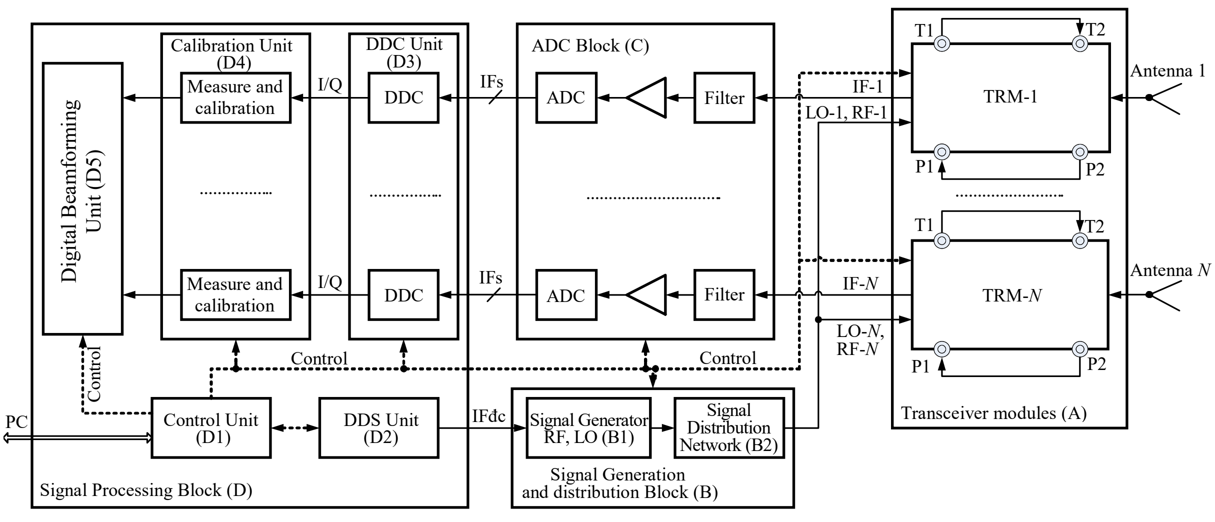


Fig. 1. Typical structure schema of DPAA system

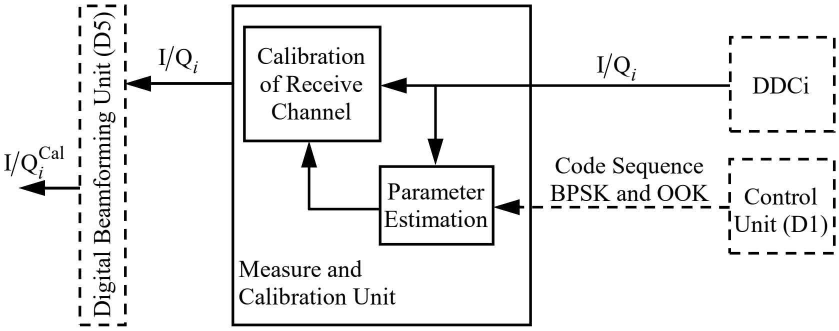


Fig. 3. Measure and Calibration Unit in each receiver channel

the function of estimating the phase and amplitude parameters of receiving channels and performing calibration procedures, which will be detailed in the following sections.

1. Synthesis of an algorithm for estimating the parameters of receiving channels. CalSig is modulated by two codes – BPSK and OOK. These two codes are precisely time-synchronized by the DDC Unit, the result of which is illustrated in Fig. 4. The amplitude and phase parameters of receiving channels are estimated by correlating CalSig samples. CalSig sampling is carried out simultaneously with the OOK code; the continuously cumulative addition phase correlated with the BPSK code sequence. After accumulating the required number of M pulses, the cumulative total value is determined, and two parameters of phase and amplitude for each receiving channel are estimated. These two parameters are further used for the calibration procedure. The block diagram of the Parameter Estimation Module is shown in Fig. 5. The "Correlation multiplier" element is essentially the change of sign according to the phase code sequence $C(n) = \pm 1$ such that the CalSig samples have the same sign. In addition, in order to ensure measurement quality, the detected samples with large received signals are rejected.

To ensure an optimal resource efficiency of the method, the correlative accumulative process is performed in parallel with the acquisition process without using data buffers. This solution consumes less resources as there is no need to use large data buffers

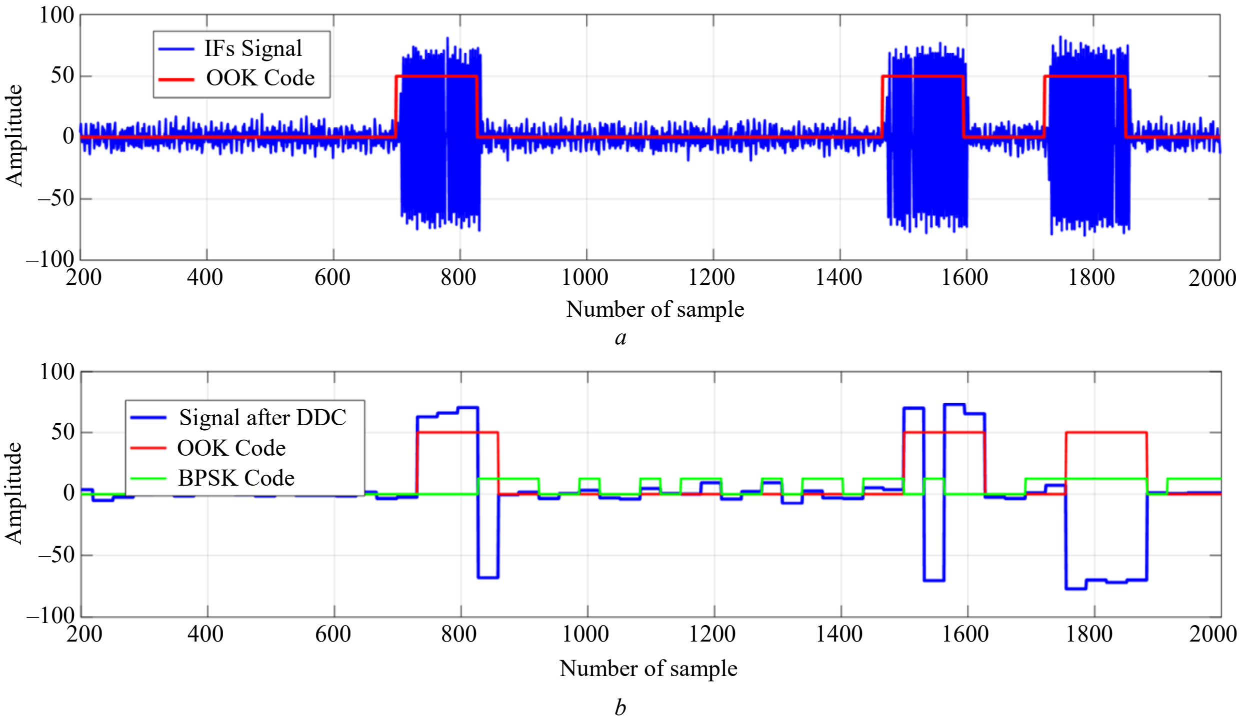


Fig. 4. CalSig after DDC synchronized with code BPSK and OOK: *a* – digital mid-frequency signal IFs; *b* – signal after DDC

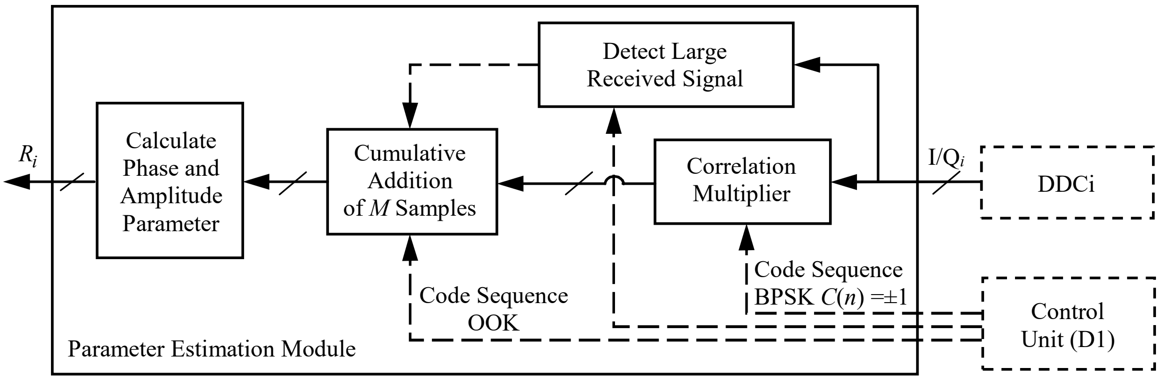


Fig. 5. The block diagram of the Parameter Estimation Module

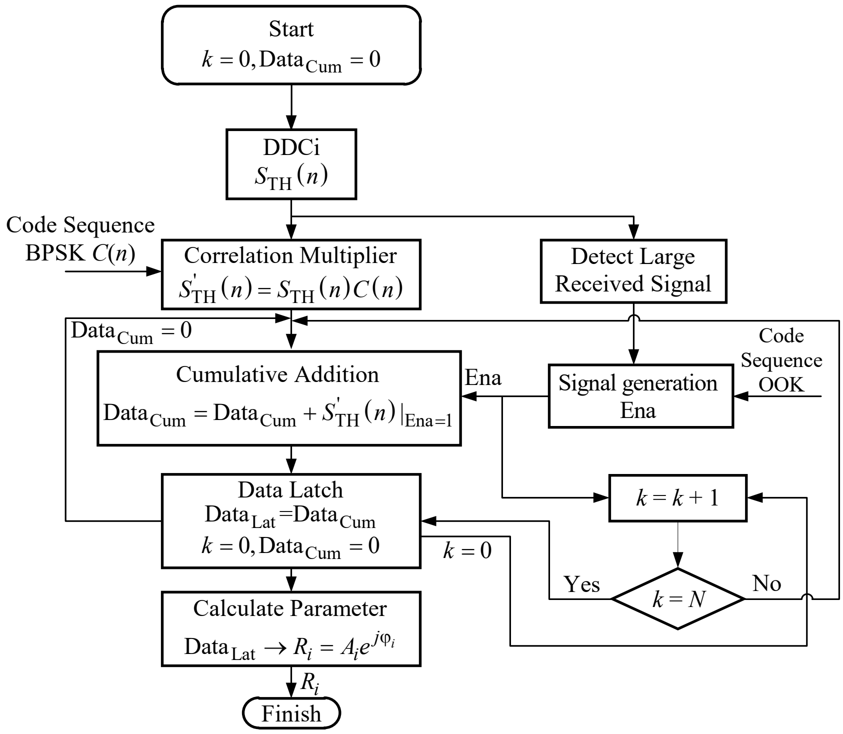


Fig. 6. The algorithm diagram of the Parameter Estimation Module

along with specialized signal processing cores, such as Fast Fourier Transform (FFT) or Finite Impulse Response (FIR) [2–6], to perform the measurements.

From the above analysis, the algorithm diagram of the Parameter Estimation Module is synthesized and presented in Fig. 6.

2. Synthesis of calibration procedures. Calibration of a phased network antenna system consists of two stages: static calibration and dynamic calibration [2, 13]. In [13], the basic steps for general phase network antenna systems are presented. For a DPAA system, which integrates the internal calibration subsystem as shown in Fig. 1, the connection diagram and parameter symbols of some main components are shown in Fig. 7.

The main components include the following:

– *Receiving Channel* represents all components constituting the receiving route from the input of the TRM to the output of the DDC Unit;

– *Transmission Structure* represents the CalSig path from the signal distribution network to the receiving channel input;

– *Parameter Estimator* module is responsible for estimating the receiving channel parameters as de-scribed above;

– *Receiver input signal feed element* is used to supply the input signal to the TRMs. It can be a $1:N$ power divider or antenna elements.

The coefficients with symbols in Fig. 7 are as follows:

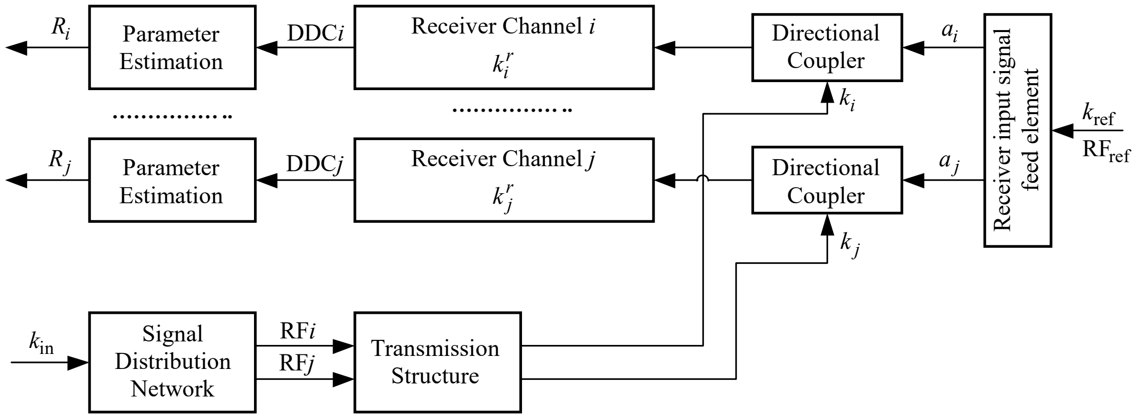


Fig. 7. Connection diagram of some key components in calibration

$k_{i(i=1...N)}$ – parameter of the entire CalSig feedline from the Signal Distribution Network input to the receiving channel input (including Directional Coupler);

k_i^r – receiving channel transfer function;

$R_{i(i=1...N)}$ – receiving channel parameter after performing parameter estimation;

a_i – parameters of receiver input signal feed element;

k_{ref}, k_{in} – parameter of an individual input signal.

Let us describe each calibration stage in detail.

Static calibration procedure. Static calibration to determine the relationship of the static coefficients $k_{i(i=1...N)}$ and $a_{i(i=1...N)}$. Subsequently, these parameters are recorded for use in dynamic calibration. The static calibration diagram is shown in Fig. 8. The input reference signal to the TRMs is supplied through a 1: N power divider, which is a CalSig extracted from the Signal Distribution Network. The procedure is performed via the following steps:

Step 1. Measuring the receiving channel parameters $R_{i(i=1...N)}$ when the reference signal is fed to the TRM input through the 1: N power divider. It should be noted that the CalSig is not issued according to the dedicated calibration curve. The coefficients are calculated as follows:

$$R_i = k_{\text{ref}} a_i k_i^r;\ R_j = k_{\text{ref}} a_j k_j^r. \quad (1)$$

From (1),

$$F_{ij}^r = R_i / R_j = \left(a_i k_i^r\right) / \left(a_j k_j^r\right). \quad (2)$$

Step 2. Measuring the receiving channel parameters when only CalSig is fed according to the dedicated calibration line. The coefficients are calculated as follows:

$$R_i = k_{\text{in}} k_i k_i^r;\ R_j = k_{\text{in}} k_j k_j^r. \quad (3)$$

From (3),

$$K_{ij}^r = R_i / R_j = \left(k_i k_i^r\right) / \left(k_j k_j^r\right). \quad (4)$$

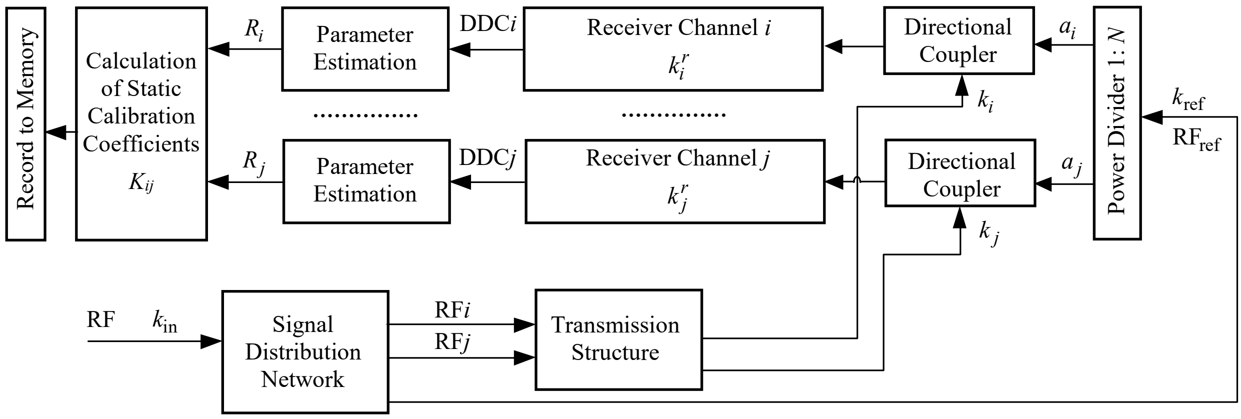


Fig. 8. Connection diagram when static calibration

Step 3. Estimating static calibration coefficients. Under N receiving channels, $(N-1)$ static coefficients with channel 1 as standard are obtained; these coefficients are stored in memory to compensate for dynamic calibration. From the two expressions (2) and (4), an expression to calculate the static calibration coefficient $K_{1j(j=2...N)}$ can be derived:

$$K_{1j(j=2...N)} = (a_1 k_j)/(a_j k_1). \quad (5)$$

Dynamic calibration procedure. Dynamic calibration for compensating amplitude and phase changes of the elements constituting the receiving channel due to component ageing and operating temperature variations. CalSig is supplied continuously from a dedicated calibration line. Let us assume that, over time, the transfer functions of the receiving channel change. The changed parameters are denoted by a sign ('). Fig. 9 presents the diagram of system connection.

The procedure is performed through the following steps:

Step 1. CalSig is fed according to the dedicated calibration line. The coefficients are calculated:

$$R_i^{'} = k_{\text{in}} k_i k_i^{r'};\ R_j^{'} = k_{\text{in}} k_j k_j^{r'}. \quad (6)$$

From (6),

$$K_{ij}^{r'} = R_i^{'}\big/R_j^{'} = \left(k_i k_i^{r'}\right)\big/\left(k_j k_j^{r'}\right). \quad (7)$$

Step 2. Estimating the dynamic calibration coefficients. From the two expressions (5) and (7), an expression to calculate the dynamic calibration coefficient $F^{r'}_{1j(j=2...N)}$ can be obtained:

$$F^{r'}_{1j(j=2...N)} = \left(a_1 k_1^{r'}\right)\big/\left(a_j k_j^{r'}\right). \quad (8)$$

Step 3. Calibrating the receiving channels. The coefficients $F^{r'}_{1j(j=2...N)}$ from (8) are used to calibrate the receiving channels while the system is being operated. Let us denote the complex received signal before calibration as $S_{\text{DDC}j(j=1...N)}$, then the complex signal after calibration $S^{\text{Cal}}_{\text{DDC}j(j=1...N)}$ can be calculated using the following expression:

$$S^{\text{Cal}}_{\text{DDC}j(j=2...N)} = S_{\text{DDC}j(j=2...N)} F^{r'}_{1j}. \quad (9)$$

After step 3, all receiving channel signals are phase and amplitude synchronized according to receiving channel 1 before being sent to a digital beamform compositor. Indeed, $R^{'}_{j(j=2...N)}$ and $R^{\text{Cal}}_{j(j=2...N)}$ are the signal parameters before and after calibration, respectively. By transforming these parameters according to expression (9),

$$R_j^{\text{Cal}} = R_j^{'} F_{1j}^{r'} = R_j^{'}\left(R_1^{'}\big/R_j^{'}\right) = R_1^{'}. \quad (10)$$

It follows from (10) that the parameters of the channels are synchronized with channel 1.

Calibration tests and beamforming:

1. *Development of an experimental model.* The experimental model is a small DPAA system with the basic components shown in Fig. 1, including four TRMs. The system is tested in the L-Band frequency range, the PCBs are designed on FR4 material, the printed circuit thickness is 1.6 mm. The system components for testing the calibration process are shown in Fig. 10.

2. *Calibration procedures.* During calibration, the RF signal has a frequency of 1570 MHz, the IF

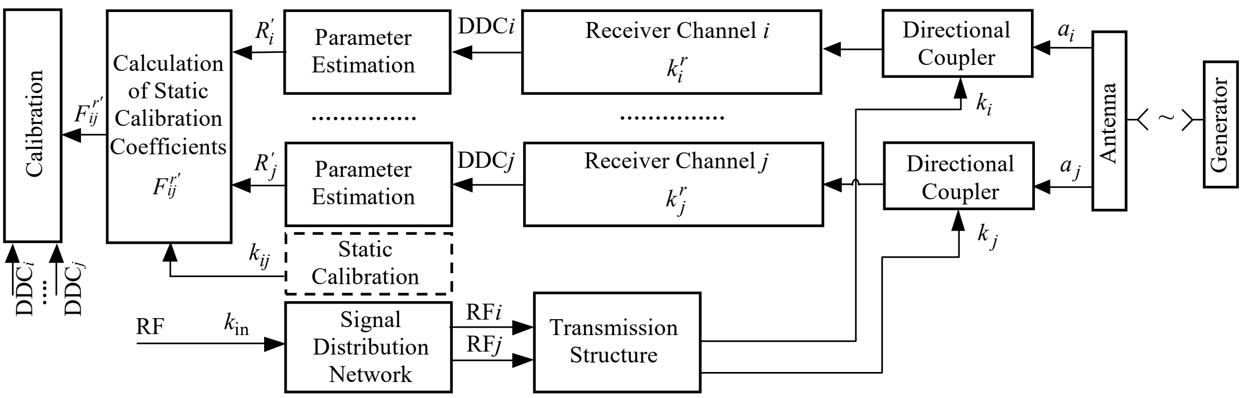


Fig. 9. Connection diagram when dynamic calibration

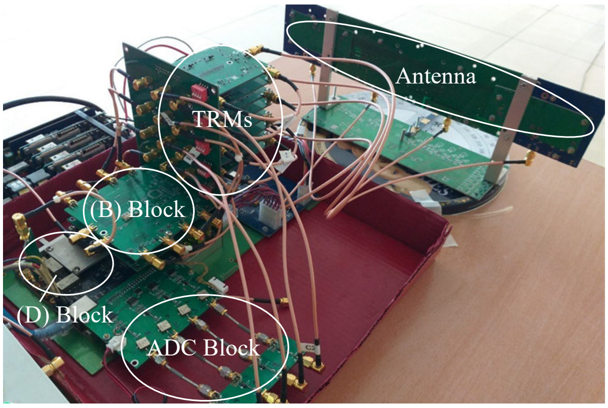


Fig. 10. The system components for the calibration process experiment

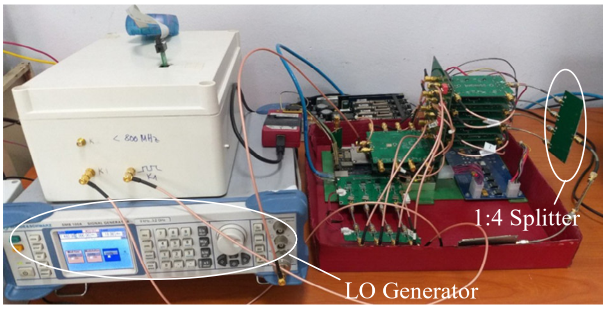


Fig. 11. Diagram of test connection of static calibration procedure

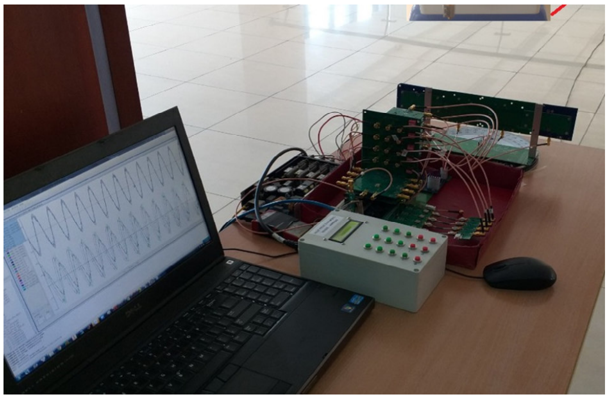


Fig. 12. Diagram of test connection of dynamic calibration procedure

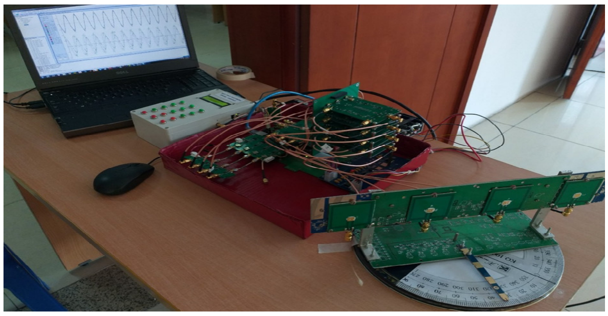


Fig. 13. System image when testing

signal has a frequency of 90 MHz. Calibration cycles are performed as follows.

The static calibration procedure is carried out in a laboratory, with the connection diagram shown in Fig. 11. The static calibration coefficients were found equal: $0.82e^{j9°}, 0.87e^{j3°}, 1.16e^{j4°}$. In principle, these factors should be measured over the entire operating frequency range of the system [13]. Depending on the accuracy requirements and the degree of deviation, the number of frequency points to be measured is selected reasonably.

The dynamic calibration procedure is carried out in field tests, with the connection diagram shown in Fig. 12. It can be seen that the input signal to the channels is received from an antenna with a transmitter located in a far-field zone. The antenna consists of four elements, made by a strip

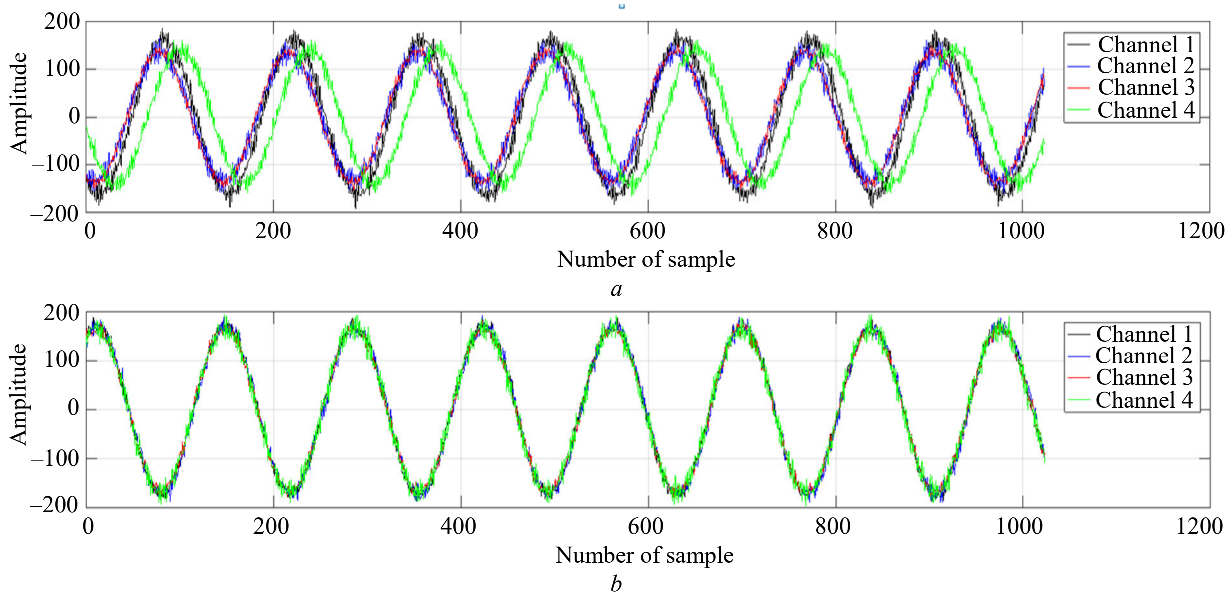


Fig. 14. Received channels signal: *a* – before calibration; *b* – after calibration

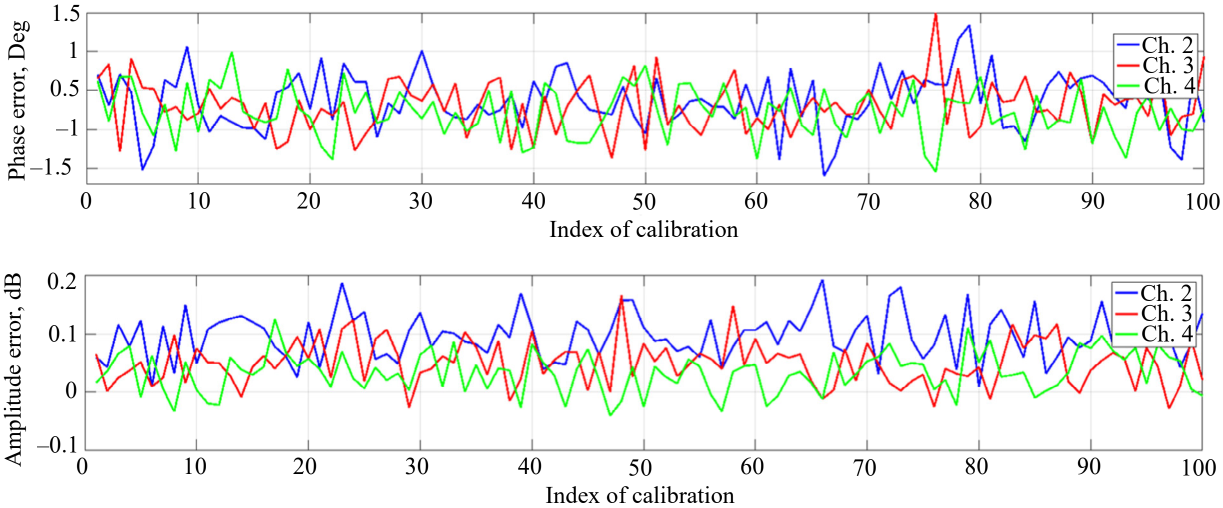
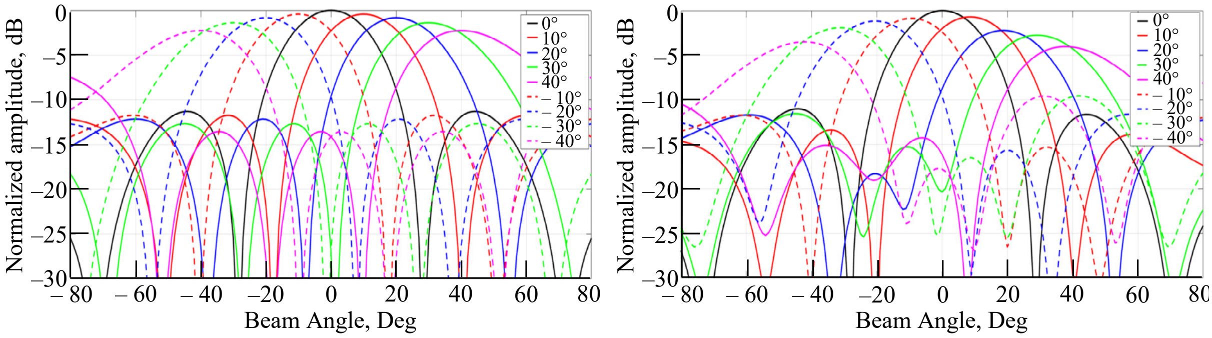


Fig. 15. Phase and amplitude error after calibration



a *b*

Fig. 16. Performing digital beamforming: *a* – Simulation; *b* – Experiment

circuit with a length of 30 cm. Therefore, the antenna's far field is greater than 2 m [14] (in the test, it was placed at a distance of 6 m).

The described calibration steps are performed, at the same time as observing the calibration results on a PC equipped with the Chipcore interface of the ISE software (almost similar to a digital oscilloscope). The results presented in Fig. 13 and Fig. 14 show that the channels after calibration have a good balance in terms of phase and amplitude. After calibration, the phase and amplitude parameters of the receiving channels are calculated and compared with channel 1. The results are shown in Fig. 15. The phase error was found to be less than 1.2, 0.9, 1.1° respectively; the amplitude error was found to be less than 0.2, 0.14, 0.12 dB, respectively. These errors are achieved with the cumulative number of Calsig samples $M = 10^5$. To reduce these errors, the number of cumulative samples M can be reduced by four times, then the obtained errors will be less than 0.3° and 0.05 dB [15].

The process of digital beamforming at angles 0, ±10, ±20, ±30, ±40° after calibration is shown in Fig. 16, *b*. Compared with the obtained radiation patterns given in Fig. 16, *a*, the error of main beam direction is less than 0.2°. These results confirm the feasibility of the proposed approach. In [16], we proposed technical solutions for the rational distribution of calibration signals with the purpose of further improving the calibration quality of the receiving channels and reducing the requirements imposed on the internal isolation of the TRM for preventing leakage noise. For example, the calibration signal coming from the T1 output of the TRM(*j*) module will be fed to the T2 input of the TRM(*i*) module, and so on. Then the required value of internal insulation can be reduced by many tens of dB.

Conclusion. Real-time calibration is a must for maintaining the high performance of modern DPAA systems. A solution using CalSig modulated by two codes BPSK and OOK was previously analyzed in [11, 12]. In this paper, we develop parameter estimation algorithms and calibration procedures, which are characterized by implementation simplicity and resource efficiency. The experimental results obtained using with a DPAA model consisting of four TRMs produced satisfactory results. The phase error and amplitude error were found to be less than 0.3° and 0.05 dB, respectively; the error of the main beam direction was less than 0.2°.

Author's contribution

Viet Hung Tran, member of the research team.
Minh Thien Hoang, scientific support including: experimental model and evaluation of results.
Van Bac Nguyen, member of the research team.
Bao Nguyen Phung, scientific advisor.

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