Error in the calibration of the receive paths due to nonlinear distortion of the transmitter at a multi-frequency control signal

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Abstract. Errors of amplitude calibration of the receive paths due to nonlinearities of the transmitter by simulation are considered. Calibration shall be carried out using a multi-frequency signal with elongated orthogonal subcarrier corresponding to the reference frequencies. Calibration is performed by evaluating the complex frequency response of the receiving path at control frequencies by dividing the samples of the output signal spectrum of the path by the corresponding samples of the input signal spectrum. To describe the terminal amplifier of a non-inertial transmitter, a polynomial model is used that takes into account the distortion of the amplitudes of the output signals.

1. Introduction
Almost any radio-engineering device consists of a receiver and a transmitter. Nowadays multi-channel radio-engineering devices are used, in which the number of reception channels is quite large. An example of such a multi-channel installation radar is one with digital antenna array. For the stable operation of the digital antenna array, it is necessary to minimize the difference in the amplitude-phase characteristics of the analogue part of the reception channels [1-4].

Calibration is thus an integral procedure in radio-technical devices that provide strict requirements for tactical and technical characteristics. The calibration of the receive paths is an integral part of the operation of the phased antenna array radars and multi-beam mobile satellite radio communication systems, as well as navigational receivers. In order to calibrate the receive path, a signal is given to its input and then the parameters of the output signal are measured. The amplitude-frequency characteristics of the receive path are evaluated on the basis of measurements of the output signal parameters. Adjusting coefficients for the digital antenna array are formed with the aid of the amplitude-frequency characteristic.

For measuring devices the concept of calibration is strictly defined in national standard [5]. Calibration is defined as the set of operations for determining the true values of the metrological characteristics of measurement devices [5]. The receive path is not a measuring tool, but it is an integral part of it.

In this article, receive path calibration is defined as the process of determining coefficients that describe the conversion of the complex amplitude of a signal at the input of the receive path as a frequency function. It follows that calibration involves obtaining the complex frequency characteristic of the receive path in some band [6-9].

There are different methods for calibrating the receive path. However, these methods are useful for narrowband paths at constant feeder parameters. This is because the applied reference signal sweep
This report will consider the calibration method, which consists of determining the ratio of the receive path output spectrum to the calibration signal spectrum. This method is free from the above disadvantage the analysis bandwidth. Different calibration signals may be used during calibration. In particular, such signal can be a multi-frequency signal with orthogonal subcarriers (OFDM). A multi-frequency signal with orthogonal subcarriers allows specific elementary frequency channels calibrating but has a larger peak factor (12-13 dB). Nonlinear distortions in the form of combined second- and third-order components occur during the passage of a calibration multi-frequency signal through the final amplifier.

The amplitude spectrum of the output signal of the final power amplifier will be enriched: in addition to the multi-frequency components, combined frequencies will appear. For multi-frequency signals with orthogonal subcarriers, third order combinations are observed at calibration signal frequencies and distort them [10]. When the receive path is calibrated by such a distorted calibration signal, there may be significant errors in the estimates of amplitude- and phase-frequency characteristics. This is the case when the receive path is calibrated in a dynamic range. The final amplifier is part of the transmitters, which can also be the source of the calibration signal.

The purpose of the report is to provide a qualitative and quantitative assessment of the influence of nonlinear distortions of the transmitter’s output signal on the results of the calibration of the receive paths when decimating frequency. The results of the calibration can be used to assess the performance of the paths as well as the conformity of the paths with the characteristics of the amplitude-frequency path.

2. Model of the calibration signal

Let the calibration signal \( s_c(t) \) with duration \( T_s \) be the sum of the time-concurrent radio pulses with the orthogonal subcarriers:

\[
s_c(t) = \text{Re} \left\{ \sum_{k=1}^{N} A_k \left( \cos \left[ 2\pi \left( f_0 + k\Delta f \right) t + \phi_k \right] + j \sin \left[ 2\pi \left( f_0 + k\Delta f \right) t + \phi_k \right] \right) \right\}, t \in [0, T_s]
\]

(1)

where

- \( N \) is the number of orthogonal subcarriers;
- \( k \) is the subcarriers summation index;
- \( A_k \) is the \( k \) subcarrier amplitude;
- \( \phi_k \) is the initial phase of the \( k \) subcarrier;
- \( t \) is the time of the calibration signal observation \([0, T_s]\);
- \( f_0 \) is the central frequency of the calibration signal;
- \( \Delta f \) is the frequency interval between the calibration signal subcarriers.

For certainty, we assume that the amplitudes of all subcarriers are the same and that the power \( P_{in\_dBm} \) (in dBm) of the calibration signal is equal

\[
A_k = \sqrt{2 \cdot 10^{-50 - 10\log(N)}}
\]

(2)

and the frequency interval between the subcarriers is equal

\[
\Delta f = \frac{1}{T_s}
\]

(3)

The initial phases of \( \phi_k \) subcarriers are a sample of the implementation of an uncorrelated random process with a uniform probability density in the range \([0, 2\pi]\).

Non-energetic parameters of the calibration signal in this study do not influence the results of the evaluation and can be selected at random. For certainty, we assume the following non-energy parameters of the calibration signal: \( N = 15 \), \( T_s = 0.01 \) ms, \( f_0 = 70 \) MHz.

The initial phases of the OFDM signal were given at random, distributed uniformly in the interval \([0, 2\pi]\). The envelope of the calibration signal is rectangular.
3. Nonlinear amplifier model

Let the transmitter (calibration signal source) operate in nonlinear mode when its calibration signal input is affected. We assume nonlinear phenomena in the terminal amplifier of the transmitter inertia-free.

We shall take into account only the variation of the amplitude of the spectral constituents as a result of passing the terminal power amplifier. The power amplifier will be characterized by the amplification coefficient $G_p$ and its nonlinear properties by the output level of intermodulation of the third order OIP3.

In this case, the nonlinear properties of the terminal amplifier shall be described by the following static polynomial model

$$s_{out}(t, s_{in}) = a_1 \cdot s_{in} + a_3 \cdot s_{in}^3,$$

where

- $a_1$ is the coefficient of the input signal amplification;
- $a_3$ is the coefficient which takes into account the occurrence of the combined frequencies in the spectrum of the output signal.

In particular, we can take the coefficients as follows

$$a_1 = 10 \cdot \frac{G_p^{10}}{20},$$

$$a_3 = \frac{3}{4} \cdot \frac{G_p^{10}}{10 \cdot \text{OIP}3_{\text{dBm}} - 30 - G_p^{10}}. \quad (6)$$

When a two-frequency signal with frequency components $f_1$ and $f_2$ passes through a power amplifier with $G_p$ and OIP3 characteristics, the third order combinations at frequencies $2f_1 + f_2$, $2f_1 - f_2$, $2f_2 + f_1$ and $2f_2 - f_1$ will have a level relative to the useful signal equal to:

$$\Delta P = -20 \cdot \lg \left( \frac{4a_3}{6 \cdot a_1 \cdot \text{OIP}3_{\text{dBm}} - 30} \right). \quad (7)$$

4. Influence of nonlinear effects on calibration results.

Consider the qualitative nonlinear effects impact on the distortion of the estimation of the amplitude-frequency characteristic of the receive path. Let’s assume that the receive path amplifiers work in a linear mode.

In the transmitter, let the terminal amplifier have the following $G_p = 10$ dB and OIP3 = 30 dB. Internal noise of the receive paths and phase noises in transmitter heterodyne are quite negligible. A bandpass filter with even amplitude-frequency characteristic was used as the model of the receive path.

Due to the fact that the calibration signal consists of 15 subcarriers, it is possible to determine the error of estimating the amplitude-frequency of the receive path only for these subcarriers. Note that the error in estimating the amplitude-frequency characteristic of the receive path is systematic at the given initial phases of the OFDM signal. However, the error value at each subcarrier is determined by the specific implementation of the initial phases of the orthogonal components of the calibration signal (1)-(3).

The systematic error in estimating the amplitude-frequency characteristic (AFCH) of the receive path for different calibration signal power levels is shown in Figures 1-3.
Figure 1. Systematic error in estimating the amplitude-frequency characteristic of the receive path at the input signal power of $-21.76$ dB, $\Delta P = -78$ dB, $G_p = 10$ dB, OIP3 = 30 dB

Figure 2. Systematic error in estimating the amplitude-frequency characteristic of the receive path at the input signal power of $-11.76$ dB, $\Delta P = -58$ dB, $G_p = 10$ dB, OIP3 = 30 dB

Figure 3. Systematic error in estimating the amplitude-frequency characteristic of the receive path at the input signal power of $-1.76$ dB, $\Delta P = -38$ dB, $G_p = 10$ dB, OIP3 = 30 dB

The randomness of the initial phases of the OFDM signal causes a random change in the systematic error of path calibration. The correspondence of the maximum mean and root-mean-square error of calibration of the amplitude-frequency characteristic of the receive path on the signal level and the level of intermodulation components $\Delta P$ is shown in figures 4 and 5. In estimating the mean and root-mean-square values, a sample of 1,000 implementations of the random initial phases of the OFDM signal was used.
An analysis of the submitted material shows that nonlinear distortions of the calibration signal lead to random errors in the evaluation of the amplitude-frequency characteristic of the path. The randomness is caused by the nature of the distribution of the initial phases along multi-frequency signal of the subcarriers with orthogonal frequencies.

5. Conclusion
The following conclusions can be drawn from the materials presented. The systematic error in estimating the amplitude-frequency path due to nonlinear inertia-free distortions of the calibration multi-frequency orthogonal signal is determined by the level of harmonics at third-order combination frequencies relative to the power of the main harmonics of the useful signal. At the combined component level of 40 dB, the maximum mean error value of the amplitude-frequency path estimation reaches 0.3 dB, and the maximum root-mean-square error value reaches 0.1 dB.

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