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Detection Characteristics of the Random and Deterministic Signals in Antenna Arrays

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Abstract—In this paper, approach to incoherent signal detection in multi-element antenna array are researched and modeled. Two types of useful signals with unknown wavefront were considered: first one, deterministic (Barker code), and second one, random (Gaussian distribution). The derivation of the sufficient statistics took into account the linearity of the antenna array. The performance characteristics and detecting curves are modeled and compared for different useful signals parameters and for different number of elements of the antenna array. Results of researches in case of some additional conditions can be applied to a digital communications systems.

Keywords—Antenna array, detection curves, performance characteristics, quadrature processing, signal detection.

I. Introduction

DETECTION of useful signals that are not fully known has a great practical importance. This is typical for modern sonar or radar system [1]- [10]. The useful signal may depend not only on significant parameters, but also from the irrelevant (nuisance) parameters. In this case, the sufficient statistic can be obtained by averaging the likelihood ratio for irrelevant parameters [11]- [16]. If the nuisance parameter is the phase of the useful signal and all other parameters are known, incoherent, or quadrature matched filter is applied [9]. We have considered this scheme for narrowband signals, multi-element antenna array and with additional processing based on the information about the shape of the wave front. The planar wavefront assumption corresponds to finding the source of the signal in the far field. In this case, considering the known antenna array shape, it is possible to calculate the time delay of the signal relative to the first element of the array and the corresponding phase shift.

The narrowband signals review allows to simplify the problem and assume that the signals at the antenna array elements have the same amplitude and differ only in phase. In this case, the real signal can be replaced by the complex envelope.

II. Signal Model

Consider the narrowband linear M-element antenna array that receives the additive mixture of the useful signal S[n], where n=1,...,N

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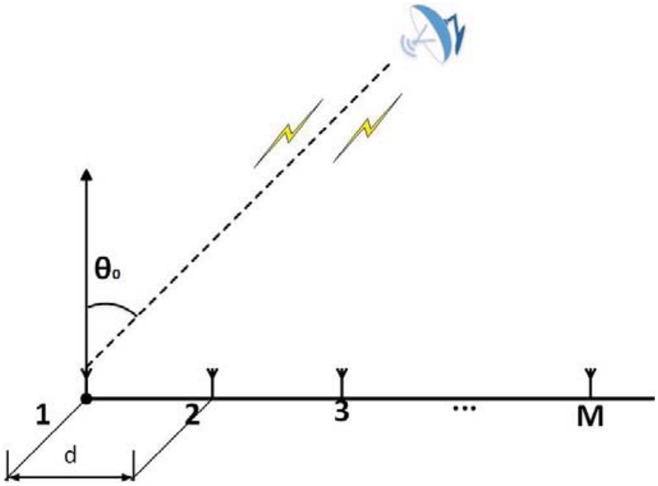

Fig. 1 Linear antenna array geometry

$$S[n] = \begin{pmatrix} S_1[n] \\ S_2[n] \\ \vdots \\ S_M[n] \end{pmatrix} = A[n] \begin{pmatrix} e^{j\psi_1(\theta_0)} \\ e^{j\psi_2(\theta_0)} \\ \vdots \\ e^{j\psi_M(\theta_0)} \end{pmatrix} \tag{1}$$

and complex Gaussian noise $\boldsymbol{\xi}[n]$ with zero mean and covariance matrix $\mathbf{C}$. Here n=1,...,N is the sample size, $\psi_m(\theta_0)$ is unknown phase on each m-th element of the antenna array, θ_0 - the angle of arrival of the useful signal (Fig. 1).

Consider two types of the useful signal: first one, with random amplitude A[n] distributed according to a Gaussian low (Fig. 2 (a)) and second one, in which amplitude A[n] is function, changing according to a certain law (Barker code, Fig. 2 (b)).

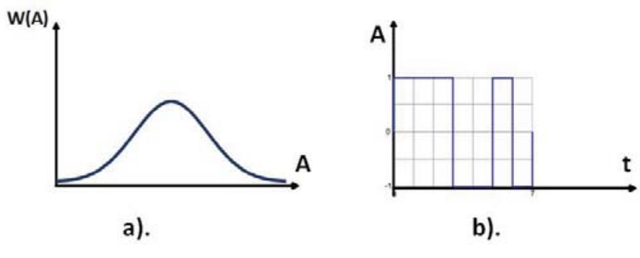

Fig. 2 Signal amplitude: (a) Gaussian distribution; (b) Barker code

The hypothesis testing problem can be formulated as a classical two-alternative:

$$\begin{aligned} H_0 &: \mathbf{x}[\mathbf{n}] = \boldsymbol{\xi}[\mathbf{n}] \\ H_1 &: \mathbf{x}[\mathbf{n}] = \boldsymbol{\xi}[\mathbf{n}] + \mathbf{S}[\mathbf{n}] \end{aligned} \tag{2}$$

The decision about signal presence or absence is made the decision is made after comparing the likelihood ratio Λ to a some threshold value Λ_{th}. In accordance with Neumann-Pearson's criterion threshold value Λ_{th} is defined for the given false alarm probability.

III. The Detection Circuit

We solve the problem of detection based on the well known classical scheme [1], [4], [9] for the signal with random initial phase (Fig. 3).

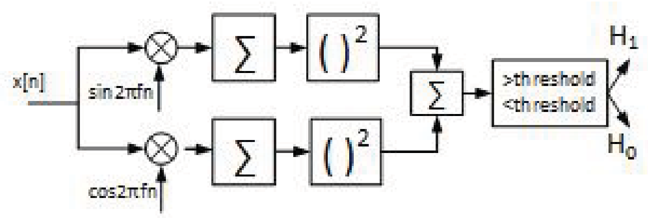

Fig. 3 Classical unknown phase signal detection

We were interested in multi-element antenna array, so this scheme was modified for complex vector data.

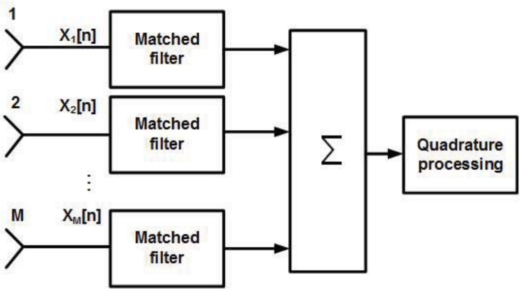

Fig. 4 The summation stage

Matched filtering performed on each element of antenna array. After that all outputs of the matched filters were summed. And only after that quadrature processing was done (Fig. 4). In addition, we used information on the linearity of the antenna. In the linear antenna array the phasor can be represented as

$$\mathbf{s} = \mathbf{e}^{-\mathbf{j}\phi} \begin{pmatrix} e^{j2\pi f \cdot 0} \\ e^{j2\pi f \cdot \tau_1} \\ \vdots \\ e^{j2\pi f \cdot \tau_1} \end{pmatrix} \tag{3}$$

where τ_i- known delay time in the propagation of the signal to the i-th element and ϕ- random uniformly distributed initial phase. So, it is possible to find the maximum likelihood angle of arrival (AoA) of a signal and compensates the corresponding phase shift. This can be taken into account before summation (Fig. 5).

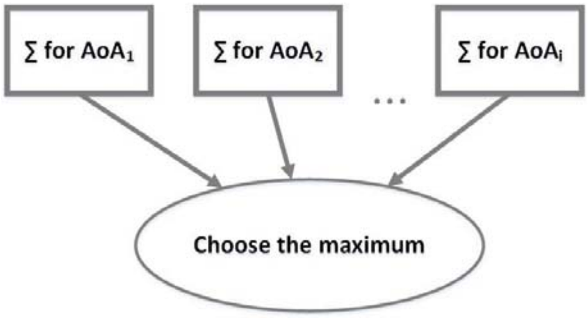

Fig. 5 Maximum sum choice

The decision about the presence of a useful signal is accepted if decision test-statistics exceed the threshold.

IV. Simulation Results

The above-described detection scheme is simulated in MATLAB environment. We considered 4-element, 16-element and 64-element antenna array, a complex white Gaussian noise with unit intensity and two types of signal: with random Gaussian amplitude and amplitude varying in accordance with a Barker code. The length of the Barker code data on charts is 13 credits.

Fig. 6 shows the detection curves for the two types of signals, direction of arrival of the signal is arbitrary.

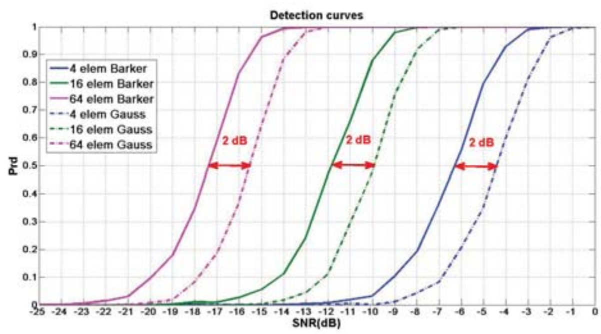

Fig. 6 Detection curves for Gauss and Barker signals for a different number of elements of the antenna array

A signal with random amplitude is harder to detect. The difference between the signal with a Gaussian amplitude and the signal with Barker code amplitude is consistently 2 dB, regardless of the number of array elements. In both cases, the increase in the number of elements in 4 times leads to gain is approximately 6 dB.

Figs. 7 and 8 present the detection curves for 4-element array in case of the signal with the determined angle. In Figs. 9 and 10, similar curves are shown for a 64-element array. Degradation (approximately 3 dB) for 40 and 50 degrees corresponds to the dips in the radiation pattern of the linear arrays. For 4-element array AoA for Gaussian signal does not matter, only possible deterioration due to the radiation pattern of the array. For the Barker signal "good" AoA (close to normal) gives a slight improvement of detection (slightly less than 1 dB). For a 64-element array, this gain is smoothed.

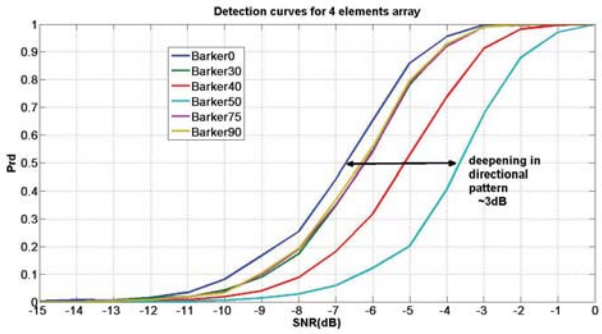

Fig. 7 Detection curves for Barker signals from determined angles for 4-element array

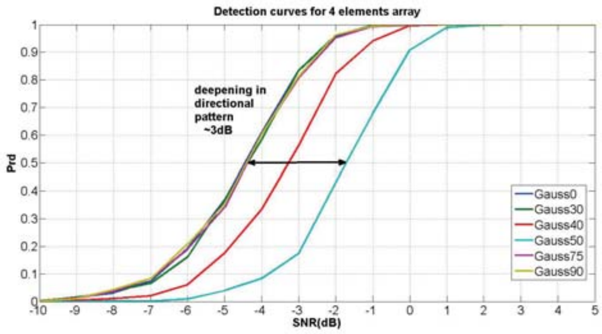

Fig. 8 Detection curves for Gauss signals from determined angles for 4-element array

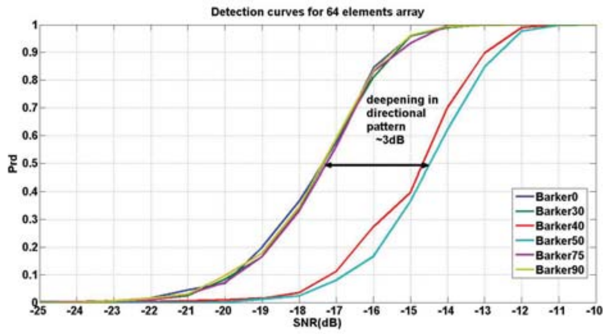

Fig. 9 Detection curves for Barker signals from determined angles for 64-element array

The difference in probability of right detection is shown in Figs. 10 and 11 for the same SNR values. In Fig. 11, small gain at normal incidence for the 4-element array is visible more clearly.

V. Conclusion

From the discussion above, where the detection of two types of useful signals with unknown phase were developed in MATLAB, stability of the algorithm and the possibility of its

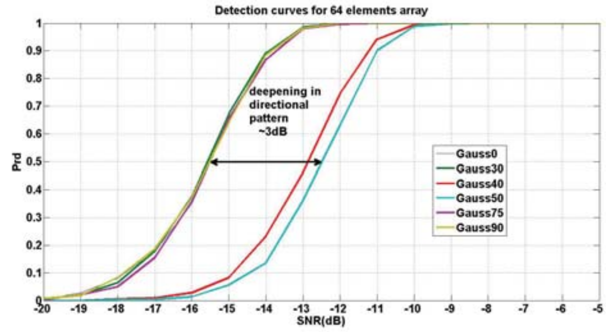

Fig. 10 Detection curves for Barker signals from determined angles for 64-element array

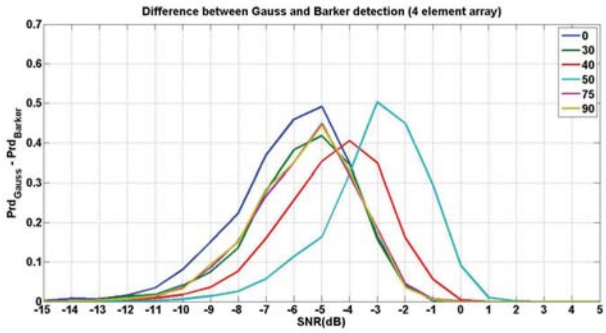

Fig. 11 Difference between Gauss and Barker detection for 4-element array

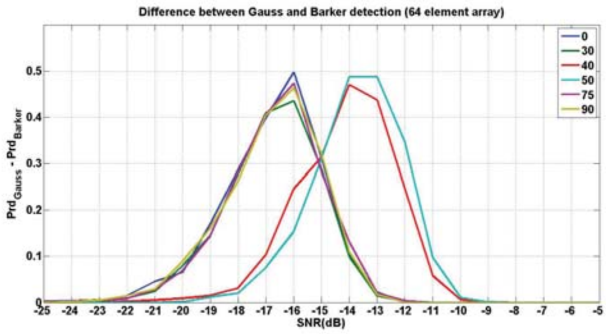

Fig. 12 Difference between Gauss and Barker detection for 64-element array

successful application in both cases can be concluded. Both signals are well defined even at low SNR. The average gain of a signal with known amplitude is 2 dB. For antenna arrays with a small number of elements, the dependence of the AoA of the signal is observed. With increasing number of elements, this dependence disappears.

Results of researches in case of some additional conditions can be applied to a digital communications systems.

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