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Decentralized fuzzy CFAR detectors in homogeneous Pearson clutter background

Hilal A. Meziani *, Faouzi Soltani

Laboratoire Signaux et Systèmes de Communication, Département d'Électronique, Faculté des Sciences de l'Ingénieur, Université de Constantine, Constantine 25000, Algeria

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ABSTRACT

In this paper, we analyze the decentralized CA-CFAR, GO-CFAR and SO-CFAR detectors using fuzzy fusion rules in heavy tailed homogeneous clutter modeled by a Pearson distribution. We generalize our study by considering a distributed detection system with 'L' detectors and using the 'maximum', 'minimum', 'algebraic sum' and 'algebraic product' fuzzy rules at the data fusion center. For each detector considered, we derive the membership function which maps the decision to the false alarm space and compute the threshold at the fusion center. From the Monte Carlo simulations conducted to assess the detection performance in homogeneous Pearson distributed clutter, we observe that the probability of detection increases with the number of detectors. However, no improvement is obtained beyond $L=11$ and GSNR >30 dB. In most decentralized fuzzy CFAR detectors considered, the distributed fuzzy SO-CFAR detectors with the 'algebraic sum' fuzzy fusion rule presents the highest probability of detection.

1. Introduction

In radar systems, detection procedures involve the comparison of the received signal with a threshold under the constraint of constant false alarm rate (CFAR). This constraint is impaired by the presence of clutter returns which arise from reflections from sea, land, etc. Since the clutter power is unknown, fixed thresholding techniques cannot be applied. One solution to this problem is to set the detection threshold adaptively. For this, the received signal is sampled in range by the range resolution cells. The clutter level in the cell under test is estimated by averaging the outputs of the nearby resolutions cells. The detection threshold is obtained by scaling the clutter power estimate with a constant T to achieve the design probability of false alarm. This is the conventional CA-CFAR (cell-averaging constant false alarm rate) detector proposed by Finn and Johnson [1]. This detector is optimal when the clutter is homogeneous Gaussian modeled, but degrades severely in the case of the presence of a clutter edge or interfering targets in the reference windows.

To alleviate these problems, a number of modifications of the CA-CFAR detector have been proposed. In [2], Hansen has proposed the GO-CFAR (greatest-of constant false alarm rate) detector to regulate the increase of the false alarm rate probability due to the presence of clutter edge. In [3], Trunk proposed the SO-CFAR (smallest-of constant false alarm rate) detector to improve the detection of closely spaced target.

In these adaptive thresholding techniques, the threshold is proportional to the mean power of the local clutter. Hence, the knowledge of the statistics of the clutter is important in order to properly design a CFAR detector. In real situation, the clutter statistics deviates from the Gaussian assumption. In many previous studies, the clutter

* Corresponding author. Tel./fax: +213 31 81 90 10.
E-mail addresses: hameziani@yahoo.fr (H.A. Meziani), f.soltan@yahoo.fr (F. Soltani).

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statistics were modeled as log-normal, Weibull [4,5]. Other studies [6,7] showed that the clutter can be modeled by a compound distribution. That is, the statistic of the clutter is the product of two components namely the 'speckle' and 'texture' also known as the K-distribution.

In the recent literature [8–10], the alpha-stable (α-stable) distribution was proposed as a statistical model for the clutter amplitude distribution when a high resolution radar operates at low grazing angles. The clutter becomes more impulsive. In [11], Pierce showed that for a X-band radar using horizontal polarization, operating at 0.9° grazing angle and looking into the wind, the probability density function (PDF) estimate from the collected clutter samples agrees with the PDF of the positive α-stable ($P\alpha S$) for $\alpha = 0.6$. Unfortunately, a closed form expression for the PDF exists only for the case of $\alpha = 0.5$ also called the Pearson (or Lévy) distribution. In the case where $\alpha \neq 0.5$, it was shown in [9] that the positive α-stable can be expressed as a mixture of the Pearson distribution. Tsakalides et al. [12] and Meziani and Soltani [13] gave an analytical analysis on the performance of some classical CFAR detectors namely the CA-CFAR, the OS-CFAR, the TM-CFAR and the GO-CFAR, the SO-CFAR, respectively, and showed that these detectors are CFAR in the presence of the Pearson clutter without any change in their structure. It is important to point out that the original structure of the CA-CFAR and the modified CFAR detectors were derived based on the assumption of the Rayleigh clutter [1–3]. This is of great importance since in practice, the only change to make is to update the value of the scale factor T in the lookup table of the electronic broads of the radar systems.

In the last two decades with the development of multistatic radar, the concept of distributed CFAR detection and data fusion has become an attractive subject of research in order to improve the detection performances of radar systems. In this distributed detection systems, each detector sends either a binary decision or a condensed information about the observations available at the detector to the fusion center, where a global decision about the presence of a target is made. The first contribution in this subject was done by Barkat and Varshney [14]. They considered decentralized detection systems constituted of two CA-CFAR detectors with a data fusion. The binary decision of each CA-CFAR is sent to a fusion where they are combined according to the 'AND' and 'OR' fusion rules to make the final decision. The simulations showed that the 'OR' fusion rule gives the best performances. In [15], Elias-Fusté et al. studied the case of distributed detection with data fusion using a combination of N different CFAR detectors in the Rayleigh clutter background.

A new CFAR detection scheme using the fuzzy concept was introduced by Leung and Minett [16,17]. In this detector, the crisp binary threshold (0 or 1) is replaced by a fuzzy continuous threshold on the interval [0,1]. This threshold is implemented as a membership function which maps the observations space to a false alarm space. The membership reflects the degree of membership to the two classes corresponding to the 'presence of target' or 'absence of target'. The membership function is defined to be the interference distribution function of the normalized input [18–21].

In this study, we deal with the analytical analysis of the performance of 'fuzzy cell-averaging-CFAR' (FCA-CFAR), the 'fuzzy greatest-of-CFAR' (FGO-CFAR) and the 'fuzzy smallest-of-CFAR' (FSO-CFAR) distributed CFAR detectors with a fuzzy data fusion center in the presence of impulsive homogeneous clutter modeled as the Pearson distribution. In [18,20,21], the authors considered only the case of two detectors, in order to determine the influence of this parameter on the detection performances. In our study, we will consider the decentralized detection system formed by 'L' fuzzy CFAR detectors.

The paper is organized as follows: in Section 2, the fuzzy CFAR problem formulation is introduced, then we derive the membership functions of the FCA-CFAR, the FGO-CFAR and the FSO-CFAR detectors in the presence of the Pearson distributed clutter. In Section 3, we derive the threshold at the fuzzy fusion center for the rules considered namely the 'maximum', 'minimum', 'algebraic sum' and 'algebraic product'. In Section 4, Monte Carlo simulations are conducted to assess the detection performances in homogeneous Pearson clutter background. Conclusions are drawn in Section 5.

2. Problem formulation

Recent studies in clutter modeling [8–11], have shown that impulsive data of many physical phenomena including radar sea clutter, can be modeled by the ($P\alpha S$) distribution. The $P\alpha S$ distribution is defined by its characteristic function:

$$\phi(\omega) = \exp\left(-\gamma|\omega|^{\alpha}\left(1+i\,\mathrm{sign}(\omega)tg\left(\alpha\frac{\pi}{2}\right)\right)\right) \tag{1}$$

where the parameter α is the characteristic exponent which varies over $0<\alpha<1$, γ is the dispersion parameter which varies over $0<\gamma<+\infty$, and $\mathrm{sign}(\omega)$ is the sign function defined as

$$\mathrm{sign}(\omega) = \begin{cases} 1 & \omega > 0 \\ 0 & \omega = 0 \\ -1 & \omega < 0 \end{cases} \tag{2}$$

The Fourier transform of the characteristic function leads to a compact form of the PDF only in the special case, $\alpha = 0.5$ namely the Pearson (or Lévy) distribution, given by

$$p(q) = \frac{\gamma}{\sqrt{2\pi}}\frac{1}{q^{3/2}}e^{-(\gamma^2/2q)} \tag{3}$$

In the conventional CFAR detector the output of the square law detector are sent serially into a tapped delay line. The estimate of the clutter level in these detectors is usually implemented by a suitable processing of a set of N samples q_i ($i=1,\ldots,N$), the so-called reference window surrounding the cell under test (CUT) q_0. The estimate is multiplied by a scaling factor T to achieve the desired probability of false alarm (P_{fa}). The resulting output is therefore compared to the content of the CUT in order to declare the presence or the absence of a target. Thus, we have the binary decision.